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SETTLEMENTS AND BUILDING BEHAVIOR

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Since 1979

consultancy and technical assistance in geo-engineering projects

Italian and international experience

www.rocksoil.com

2007
A motorway tunnel was widened for the first time in the world from two to four lanes without interrupting traffic (A1 motorway tunnel at Nazzano, Rome)

2005
The excavation of 80 km of tunnels for the new Bologna to Florence high speed/capacity railway line is successfully concluded on time and to budget (ADECO-RS approach)

2007
The ADECO-RS approach is officially presented at Bergamo

1988
Fibre glass reinforcement of the advance core technology is experimented for the first time in the world (Talletto and Caprenne tunnels)

1988
The "RS method" of the pilot tunnel is presented in Florence

1985
Full face mechanical precutting is experimented for the first time in the world (tunnels on the Sibari-Cosenza mainline railway)

1990
Cellular arch technology is experimented for the first time in the world for the construction of the Venezia Station on the Milan Urban Railway Link Line

1986
The "RS method" of the pilot tunnel is presented in Florence

1983
Jet grouting performed horizontally is experimented for the first time in the world (Campiolo Tunnel)
PROGRAM of the DAY

1. Volume Loss and Ground Settlement (45’)

2. Damage Evaluation (45’)

3. Example of Evaluation for Line 2 in WAW (30’)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Evaluating Process

Geological & Geotechnical Conditions

Local geometrical conditions (overburden, D)

Excavation Method

Ground Loss Evaluation

Settlement Evaluation

Acceptable Settlement Limits Evaluation

Monitoring

Monitoring + Measures of Mitigation

Building Surveys

Vulnerability Assessment

Tender Documents

Survey Phase

Diagnosis Phase

Therapy Phase

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Ground Loss Evaluation ($V_L$)

- Any excavation carries out a ground movement in the surrounding.
- Specially, in correspondence with superficial tunnels a significative ground settlement occurs.
- Volume loss is a guide parameter that has to be hypothesized in design stage and continually checked during monitoring.

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Ground Loss Evaluation ($V_L$)

**Definition**

- Deformation phenomena due to stress redistribution during excavation
- The deformation generated during excavation propagates towards ground level
- Ground core behaviour plays a dominant role
  > plastic strains
  > Ground Loss
  > Ground Settlement
Ground Loss Evaluation \((V_L)\)

**Definition**

- Generally expressed as a percentage fraction of the excavated area of the tunnel

\[ V_L = \frac{V_s}{(p D^2 /4)} = \% \]

- Geological & Geotechnical Conditions
- Local geometrical conditions (overburden, \(D\))
- Excavation Method

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Ground Loss Evaluation \((V_L)\)

**Components**

**SHORT TERM COMPONENTS**

**LONG TERM COMPONENTS**

\[ V_L = V_{Ls} + V_{Lc} + V_{Lf} \]

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Ground Loss Evaluation (\(V_L\))

**Short Term Components**

- **Ground Loss behind the lining (\(V_{Lc}\))**: ground loss “behind the lining ring” (\(V_{Lc}\)), as convergence of the cavity in the tunnel section where the precast segments are placed, in case the backfilling is not properly applied to guarantee a perfect fill behind the lining (e.g., if the injection

- **Ground Loss around the shield (\(V_{Ls}\))**: ground loss “around the shield” (\(V_{Ls}\)) in the section of tunnel where the EPB TBM is present, associated with the closure of the excavation profile towards the extrados of the steel shield owing to the annular gap that is generally present between the external cutterhead and the TBM;

- **Ground Loss at the Face (\(V_{Lf}\))**: ground loss “at the face” (\(V_{Lf}\)) associated with extrusion and preconvergence which occur in the excavation chamber as a consequence of the behaviour of the core ahead of the face, as a function of the stabilisation pressure applied;

**1. Volume Loss and Ground Settlement**

**2. Damage Evaluation**

**3. Example**
Ground loss Evaluation

- VL is a function of the distance from the tunnel face
- Settlement (S) is a function of VL
- During excavation S varies till reaching S_{max}

\[ i = k \times Z_0 \]
\[ V_s = 2.5 \times i \times S_{\text{max}} \]

\[ S_{\text{max}} = \frac{(0.31 \times V_L \cdot D^2)}{(K \cdot (H+D/2))} \]
Ground loss Evaluation

Influence of each component

- Components values may change sensibly in function of the effectiveness of the conditioning and backfilling.
Ground loss Evaluation

Face pressure contribute

- In order to reduce plastic strains face pressure supplied by TBM play a fundamental role
- 27% < S/Smax < 50 % indicates plastic behavior

In general:
- > face pressure
- < plastic strains
- < ground settlements

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Ground Loss Evaluation (V_L)

Values coming from experiences

For TBM excavation

<table>
<thead>
<tr>
<th>VOLUME LOSS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,3</td>
</tr>
<tr>
<td>0,6</td>
</tr>
</tbody>
</table>

For TRADITIONAL excavation

<table>
<thead>
<tr>
<th>VOLUME LOSS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,0</td>
</tr>
<tr>
<td>2,0</td>
</tr>
</tbody>
</table>

WAW

0,6

- >VL ipotized → evaluation more cautelative

For TBM excavation:
In rare case in order to take into account malfunction of TBM
Ground Loss Control

- Appropriate measures must be adopted for the entire excavation process
- For each component of Ground Loss suitable design and monitoring criteria must be considered

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Face ground loss control

**Face pressure design methods**

- 3-D Analysis
- Limit Equilibrium Methods (e.g., Anagnostou & Kovari 1996)
- Axial symmetric evaluation
- Rapidity
- Accuracy

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Face ground loss control

Axial Symmetric Evaluation

Fixed:

1. Ground geotechnical parameters (effective)
2. TBM diameter
3. Overburden

And varying the face pressure value

From Face Extrusion

Mancinelli, Cassani, 2005

Ground Loss at the face

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
In function of the desired face ground loss the face pressure can be carried out.

Axial Symmetric Evaluation

Mancinelli, Cassani, 2005
Face ground loss control

Choice of face pressure value ($S$)

$s'_{E} < S' < s'_{k0}$

$s < S' + u$

$s = \text{total face pressure value}$

$u = \text{idrostatic pressure}$

$s'_{k0} = \text{thrust at rest}$
Cavity Ground Loss Control

Shield Zone
Critical element in controlling convergence of the cavity

Backfilling

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Cavity Ground Loss Control

SOIL CONDITIONING

- Good plastic deformation
- Low impermeability
- Soft consistent
- Low inner friction

Soil Conditioning effectiveness

- Presence of water
- Geotechnical parameters

Soil Conditioning Design Stage

- FER
- FIR

- Maintaining Face Pressure
- Minimising drive torque
- Wearing cutter tools

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Cavity Ground Loss Control

**BACKFILLING**

1. Suitable number of injectors
   - 4-6
2. Effectiveness of backfilling grouting
3. Control of backfilling volume
4. Control of backfilling pressure ($p_{gr}$)

**Material excavated / mix injected balance**

**Equation**

$$p_{gr} > (u + \gamma \cdot (H+D/2) \cdot K) \quad \text{with} \quad K_0 < K < 1$$

**1. Volume Loss and Ground Settlement**

**2. Damage Evaluation**

**3. Example**
Cavity Ground Loss Control

Control of EPB parameters becomes really important

EPB Parameters to be checked in continuous

- Chamber sensors pressure (bar)
- Direct control of face pressure
- Cutterhead torque (MNm)
- Cylinder Thrusts (kN)
- Penetration Rate (mm/rpm)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Green Settlement Evaluation

3D - Settlement range

Attewell & Woodman, 1982

\[ w(x, y, z) = \frac{V_s}{\sqrt{2\pi}i} \exp \left[ -\frac{y^2}{2i^2} \right] \left\{ F\left( \frac{x-x_i}{i} \right) - F\left( \frac{x-x_f}{i} \right) \right\} \]

\[ v(x, y, z) = \frac{-n}{z_0 - z} y \cdot w(x, y, z) \]

\[ u(x, y, z) = \frac{n V_s}{2\pi(z_0 - z)} \exp \left[ -\frac{y^2}{2i^2} \right] \left\{ \exp \left[ \frac{-(x-x_i)^2}{2i^2} \right] - \exp \left[ \frac{-(x-x_f)^2}{2i^2} \right] \right\} \]

Only 2 variables:
Loss Volume (VL) & Ground Coefficient (k)
Settlement Evaluation

- Green Field Settlement
- FEM or DEM 2D Analysis
- FEM or DEM 3D Analysis

Need of a rapid evaluation tool, effective, also based on monitoring data

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Empirical Green Settlement Evaluation

Settlement range can be well defined by two settlement curve:

1) Trasversal Subsidence Range Curve (TSC)

1) Longitudinal Subsidence Range Curve (LSC)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Empirical Green Settlement Evaluation

Trasversal Subsidence Range Curve (TSC)

\[ S(y) = V_s \cdot e^{\left( \frac{y^2}{2i^2} \right)} \]

\[ S_{max} = \frac{V_s}{2.5 \cdot i} \]

\[ i = k \cdot Z \]

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Green Settlement Evaluation

Trasversal Subsidence Range Curve (TSC)

\[ S(y) = S_{\text{max}} \cdot e^{-\left(\frac{y^2}{2i^2}\right)} \]

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Empirical Green Settlement Evaluation

*Trasversal Subsidence Range Curve (TSC)*

\[ S(y) = S_{\text{max}} \cdot e^{-\frac{y^2}{2\sigma^2}} \]

\[ S_{\text{max}} = \frac{V_s}{2.5 \cdot i} \]

\[ i = k \cdot Z \]

Vs = Loss Volume

**Granular soils:** \( k = 0.5 
Cohesive soils:** \( k = 0.25 \)

Stiff clays = 0.4
Soft clays, silty clays = 0.7

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Empirical Green Settlement Evaluation

Trasversal Subsidence Range Curve (TSC)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

Cohesive soils: $K = 0.25$
Granular soils: $k = 0.5$
Empirical Green Settlement Evaluation

Longitudinal Subsidence Range Curve (TSC)

\[ w = S_{\text{max}} f(-x/\lambda x) \]

- Cohesive soils: \( K = 0.25 \)
- Granular soils: \( K = 0.5 \)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Empirical Green Settlement Evaluation

2 Tunnels case

Settlement range may be linked

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Other types of Green Field Evaluation

2D FEM Settlement Analysis vs Attewell e Woodman, 1982

In this stage it can be useful to calibrate suitably and check data input as K and ground loss
Other types of Green Field Evaluation

2D FEM Settlement Analysis

Considering the buildings, mutual effect may be taken into account.
Other types of Green Field Evaluation

2D FEM Settlement Analysis

CALCULATION PHASES

0 – Litostatic phase
1 – Building foundation load application
2 – Tunnel SX excavation
3 – Tunnel DX excavation

Effect on mutual interference

Phase 2: Tunnel sx excavation

Phase 3: Tunnel dx excavation

Subsidence Range

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Evaluation

POSSIBLE CASES

- Not significantly affected
- Significantly affected
- Not significantly affected

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Evaluation

POSSIBLE CASES

1) Not significantly affected

   ➔ Nothing

2) Significantly affected

   ➔ To be monitored

   ➔ Mitigation measures to be considered
Design Settlement Range (DSR)

- Need to find a strip area along the tunnel alignment in order to detect immediately which buildings will be not affect by tunnel's excavations

- E.G. Monitoring a building in which a settlement <1.0mm should be useless and too expensive
Design Settlement Range (DSR)

1) **Total settlement limitation**

2) **Settlement and distortion criteria** (Rankin 1988)
Design Settlement Range (DSR)

Total settlement limitation criteria

A settlement limit value is fixed (eg 1mm)
**Design Settlement Range (DSR)**

*Settlement and distorsion criteria (Rankin 1988)*

<table>
<thead>
<tr>
<th>Category of Damage</th>
<th>Damage</th>
<th>Description of typical damage</th>
<th>$\beta_{\text{max}}$ [-]</th>
<th>$S_v \text{ max [mm]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aesthetic</td>
<td>Superficial damage unlikely</td>
<td>$&lt;1/500$</td>
<td>$&lt;10$</td>
</tr>
<tr>
<td>2</td>
<td>Aesthetic</td>
<td>Possible superficial damage which is unlikely to have structural significance</td>
<td>$1/500-1/2000$</td>
<td>$10-50$</td>
</tr>
<tr>
<td>3</td>
<td>Functional</td>
<td>Expected superficial damage</td>
<td>$1/200-1/50$</td>
<td>$50-75$</td>
</tr>
<tr>
<td>4</td>
<td>Structural</td>
<td>Expected structural superficial damage</td>
<td>$&gt;1/50$</td>
<td>$&gt;75$</td>
</tr>
</tbody>
</table>
Design Settlement Range (DSR)

Settlement and distortion criteria (Rankin 1988)

Position of each foundation is needed

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Design Settlement Range (DSR)

Settlement and distortion criteria (Rankin 1988)

\[ \beta = \frac{y \times S_{\text{vmax}}}{i^2} \]

\[ S_v = S_{\text{vmax}} \times \exp\left(-\frac{y^2}{2i^2}\right) \]

\[ S_v = 10\text{mm} ; \beta = 1/500 \]

\[ S_{\text{vmax}} = 0.313 \times V_L \times D^2 / i \]

Rankin (1988)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Design Settlement Range (DSR)

According Tender Document

Added up by the Designer

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
## Building Survey List

<table>
<thead>
<tr>
<th>buildings street number</th>
<th>Bartoszewicza 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Bartoszewicza 1A</td>
</tr>
<tr>
<td>3</td>
<td>Bartoszewicza 3</td>
</tr>
<tr>
<td>4</td>
<td>Bartoszewicza 5</td>
</tr>
<tr>
<td>5</td>
<td>Bartoszewicza 7</td>
</tr>
<tr>
<td>6</td>
<td>Bartoszewicza 9</td>
</tr>
<tr>
<td>7</td>
<td>Cicha</td>
</tr>
<tr>
<td>8</td>
<td>Dobra 26</td>
</tr>
<tr>
<td>9</td>
<td>Dobra 27</td>
</tr>
<tr>
<td>10</td>
<td>Dobra 28</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>Zajęcza 13</td>
</tr>
<tr>
<td>76</td>
<td>Zajęcza 7</td>
</tr>
<tr>
<td>77</td>
<td>Zamoyskiego 31</td>
</tr>
</tbody>
</table>

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Survey

Building Data Sheet Example

- General Info

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

Importance of the building?
Building Surveys

- **Architectural Data**

<table>
<thead>
<tr>
<th>3. ARCHITECTURAL DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3.1</strong> Type of housing</td>
</tr>
<tr>
<td><strong>3.2</strong> Shape in plan</td>
</tr>
</tbody>
</table>
| **3.3** Dimensions in plan | Front elevation – 46m  
Depth – 13m |
| **3.4** Floor number   | Above the ground: 4  
Underground: 1 |
| **3.5** Height above the ground | MIN.  
10,50m  
15,60m |
| **3.6** Height of the basement level (from the ground level) |  
ca 2,4m |
| **3.7** Depth of foundations | ca 3,1m |

Depth of foundation?  
Underground floors?
# Building Surveys

## Construction Characteristic

<table>
<thead>
<tr>
<th>Type of Structure?</th>
<th>Type of foundations? dimensions?</th>
</tr>
</thead>
</table>

## 4. CONSTRUCTION CHARACTERISTIC

### 4.1 Type of construction

<table>
<thead>
<tr>
<th>Traditional – masonry</th>
</tr>
</thead>
</table>

### 4.2 Type of construction system

- Longitudinal, wall-frame system, braced by structural system of longitudinal internal and external walls, transverse internal and gable walls and staircase walls creating structural shaft of the building.

### 4.3 Bearing elements

- **Foundations**
  - Masonry foundation strip under bearing and bracing walls and concrete spot footing under columns of building frame structure.
- **Basement walls**
  - Masonry of solid bricks, external 70-90 cm thick, internal longitudinal bearing walls 60-70 cm thick. Transverse bracing and staircase walls of 41 cm thick.
- **Walls of repeated floors**
  - Masonry of solid bricks, external 70-90 cm thick, internal longitudinal bearing walls 60 cm thick and transverse bracing and staircase walls of 41 cm thick. Partition walls masonry 15 cm thick.
- **Slabs**
  - Floors above basement – steel beams with ceramic plates – Klein type.
- **Stairs**
- **Roof**
  - Two pitched. Timber structure – Parlin/rafter frame.
- **Ring beams**
  - No possibility to check.
- **Balconies**
  - Reinforced concrete slabs.
Building Surveys

• **Condition of Construction**

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

<table>
<thead>
<tr>
<th>5. CONDITION OF CONSTRUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Damages on elevations</td>
</tr>
<tr>
<td>Front elevation – a brick elevation quite damaged, with many bricks missing, missing bricks on lintels, parts of cantilevered balcony slabs, with transverse cracks in the middle of the slabs. Balconies have the concrete parting from the reinforcement now visible and corroded. The wall from Dobra street is strengthen by a steel bar. Visible vertical and diagonal cracks between 1-5mm wide, running through the structural walls. Due to falling out of elements from elevations the protection canopy has been constructed on the ground floor. Courtyard elevation – also built of bricks, visible patches of old render. Bricks are missing from walls, lintels, and around window openings. Some area shows some burns.</td>
</tr>
</tbody>
</table>

| 5.2 ¹) Damages on stairs        |
| Cracks are – vertical on walls, above half landing, Crack on the flight of stairs, Transverse crack running from the landing to the door lintol, Diagonal crack on the top floor running from the beam through the wall, Leaks from the roof. |

| 5.3 ¹) Damages in basement     |
| Marks after the fire on the ceiling of the basement, corroded uncovered beams, and damp on the floor. |

| 5.4 General evaluation of the construction condition according to ITB classification |
| Scale: 4-5 |
Building Surveys

- Photo Documentation & Inspection

General

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

In details

Existing risky situations

Potential development of risky situations

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

**In details**

- Underground masonry wall condition
- Staircase cracks system

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

In details

State of structural element materials

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

Presence of structural protection elements

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- **Photo Documentation & Inspection**

  **In details**

  **Wall ties**

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

In details

Bowstrings

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Survey

• Photo Documentation & Inspection

In details

External crack system detection

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- **Photo Documentation & Inspection**

In details

External crack system detection

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

In details

State of bearing structure

Crack system on structural elements

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Photo Documentation & Inspection

In details

State of bearing structure

Dumpness inside bearing masonry walls
Building Survey

- **Architectural and Structural Documentation**
Building Survey

• **Architectural and Structural Documentation**

- Structural Elements (foundations included)

- Type
- Location
- Actual state

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Building Surveys

- Actual Building Situation
- Problems occurred during building lifetime
- Structural weakest aspects

General framework on the building is needed
Vulnerability Assessment

Need to turn Building Surveys info into a practic and useful comparison tool

Vulnerability = intrinsic building characteristic to withstand damages, indipendently from tunnel excavation interference
Vulnerability Assessment

Qualitative
judgement

Quantitative
score

Vulnerability Assessment

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
### Vulnerability Assessment

#### Qualitative Assessment

<table>
<thead>
<tr>
<th>Evaluating items</th>
<th>Critical</th>
<th>Moderately critical</th>
<th>Non Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>General State of the Building</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Importance of the Building</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Effectiveness of the foundation system</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Internal system of cracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External system of cracks</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Vicinity to the tunnel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*guide parameters to take as reference*

*In function of the result a more detailed vulnerability assessment could be carried out (as quantitative assessment)*

In function of the result a more detailed vulnerability assessment could be carried out (as quantitative assessment)

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
## Vulnerability Assessment

### Vulnerability List

A final judgment on each building has to be carried and it is listed properly.

<table>
<thead>
<tr>
<th>Building</th>
<th>Critical (75-100)</th>
<th>Moderately critical (50-75)</th>
<th>Non Critical (0-50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Building 2</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Building 3</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Building 4</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Building 5</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Building 6</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Building 7</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Building ...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building n</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Vulnerability Assessment

**Quantitative Assessment**

Guide parameters to be expressed in great detail

Each guide parameter has a proper importance

Assessment is defined by a score (0-100)

<table>
<thead>
<tr>
<th>Evaluating items</th>
<th>Weight</th>
<th>Score</th>
<th>Total (Weight x Score)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. General State of the Building</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2. Importance of the Building</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n. Foundation system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n.n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL BUILDING SCORE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Foundation Settlement Evaluation

Empirical Evaluation

Empirical Evaluation (first step) → Kind of Structure

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

Control Parameters

Rankin (1988) → $S_v \text{ max } ; \beta \text{ max}$

Better Reinforced concrete bearing buildings

Boscardin et al. (1989) → $\varepsilon h$

Better for Masonry bearing buildings
Foundation Settlement Evaluation

Empirical Evaluation

- Boscardin et al., 1989

Total horizontal tensile strain $\varepsilon_h$

$$\varepsilon_h = \varepsilon_b + \varepsilon_d$$

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Foundation Settlement Evaluation

Empirical Evaluation

• Boscardin et al., 1989

Building Simulation

Elastic Beam of height H

\[
\frac{E}{G}
\]

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

12.5
for reinforced concrete bearing structure

2.6
for masonry structure

E = Young Modulus
G = Shear Modulus
Foundation Settlement Evaluation

**Empirical Evaluation**

- Boscardin et al., 1989

### Strain evaluation

\[
\varepsilon_h = \varepsilon_b + \varepsilon_d
\]

- Shear strain:
  \[
  \varepsilon_d = \left( \frac{\Delta}{L} \right) \times \frac{1}{1 + \left( \frac{HL^2G}{18EI} \right)}
  \]

- Bending strain:
  \[
  \varepsilon_b = \left( \frac{\Delta}{L} \right) \times \left[ \frac{L}{12t} + \left( \frac{3EI}{2tLHG} \right) \right]
  \]

\( t = H \) hogging zone; \( t = H/2 \) sagging zone

\[
\varepsilon_{max} = \min \{ (\varepsilon_h + \varepsilon_b) ; (\varepsilon_h + \varepsilon_d) \}
\]
Foundation Settlement Evaluation

Empirical Evaluation

• Rankin et al., 1988

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Class Classification

Damage Class Classifications

- are based on observations on many buildings
- are based on a specific control parameters
- correlate control parameters value with the state of the building

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

Rankin (1988) $S_v$ max; $\beta$ max
Boscardin et al. (1989) gh
## Damage Class Classification

*Boscardin et al., 1989*

<table>
<thead>
<tr>
<th>Category of Damage</th>
<th>Damage</th>
<th>Description of typical damage</th>
<th>$\varepsilon_{\text{max}}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Aesthetic</td>
<td>Hairline cracks</td>
<td>0-0.05</td>
</tr>
<tr>
<td>1</td>
<td>Aesthetic</td>
<td>Fine Cracks generally restricted to internal wall</td>
<td>0.05-0.075</td>
</tr>
<tr>
<td>2</td>
<td>Aesthetic</td>
<td>Cracks easily filled, which can be visible external</td>
<td>0.075-0.15</td>
</tr>
<tr>
<td>3</td>
<td>Aesthetic /Functional</td>
<td>Cracks require some repairs; doors and windows sticking</td>
<td>0.15-0.3</td>
</tr>
<tr>
<td>4</td>
<td>Functional /serviceability</td>
<td>Cracks require repairs; doors and windows distorted. Some section of walls needs repairs</td>
<td>&gt;0.3</td>
</tr>
<tr>
<td>5</td>
<td>Structural</td>
<td>Complete rebuilding of some part of the building. Windows and doors broken. Danger of instability</td>
<td>&gt;&gt;0.3</td>
</tr>
</tbody>
</table>
# Damage Class Classification

**Rankin., 1988**

<table>
<thead>
<tr>
<th>Category of Damage</th>
<th>Damage</th>
<th>Description of typical damage</th>
<th>$\beta_{\text{max}}$ [-]</th>
<th>$S\nu_{\text{max}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aesthetic</td>
<td>Superficial damage unlikely</td>
<td>$&lt;1/500$</td>
<td>$&lt;10$</td>
</tr>
<tr>
<td>2</td>
<td>Aesthetic</td>
<td>Possible superficial damage which is unlikely to have structural significance</td>
<td>$1/500-1/2000$</td>
<td>$10-50$</td>
</tr>
<tr>
<td>3</td>
<td>Functional</td>
<td>Expected superficial damage</td>
<td>$1/200-1/50$</td>
<td>$50-75$</td>
</tr>
<tr>
<td>4</td>
<td>Structural</td>
<td>Expected structural superficial damage</td>
<td>$&gt;1/50$</td>
<td>$&gt;75$</td>
</tr>
</tbody>
</table>
Damage Class Classification

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

DCC
Damage Class Classification

Rankin, 1988

Boscardin et al., 1989

Negligible
Slight
Moderate
Severe

$S_v \text{ max}$
$\beta \text{ max}$
# Damage Class Classification

**DCC List**

<table>
<thead>
<tr>
<th>buildings street number</th>
<th>strain [%]</th>
<th>category of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.020</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.017</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.024</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0.013</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.031</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0.024</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0.139</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>0.063</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>0.033</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0.069</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>0.073</td>
<td>1</td>
</tr>
<tr>
<td>75</td>
<td>0.071</td>
<td>1</td>
</tr>
<tr>
<td>76</td>
<td>0.065</td>
<td>1</td>
</tr>
<tr>
<td>77</td>
<td>0.087</td>
<td>2</td>
</tr>
</tbody>
</table>

**Vulnerability to take into account**

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Class Classification

**DCC Criteria**

0, 1
- Non critical
- Critical

>2
- Moderate critical
- Critical

=2
- Further settlement evaluation

<2
- Only to be monitored

To be monitored + mitigation measures

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Class Classification

Further Settlement Evaluations

- DCC > 2
  - FEM or DEM 2D analysis
  - >2
    - Non critical
    - Mod. critical
    - critical
  - =2
    - FEM 3D analysis

- ≤2
  - Only to be monitored
  - >2
    - To be monitored + mitigation measures

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Class Classification

Further Settlement Evaluations

FEM or DEM 2D analysis

FEM 3D analysis

Settlement Control Parameters Values and building Structural Information

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
Damage Class Classification

**Definitive DCC List**

<table>
<thead>
<tr>
<th>Building Survey List</th>
<th>Final Damage Category</th>
<th>MON-LIST</th>
<th>MIT-LIST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>••</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>••</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>••</td>
<td>XX</td>
</tr>
<tr>
<td>73</td>
<td>1</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>0</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>2</td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

Monitoring and Mitigation Measures
 Designs may be optimized in function of the Final Damage Category value
Mitigation Measures

Most common soil improvements

Jet-grouting soil improvement

Injections soil improvement

Diaphragm barrier

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
BUILDING DAMAGE EVALUATION
- ON THE EXAMPLE
OF ZAMOYSKIEGO 29 BUILDING
1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

1mm iso-settlement curve

Zamoyskiego 29
UNIFIED CRITERION
OF BUILDING DAMAGE EVALUATION

FREE FIELD SETTLEMENTS
EVALUATION WITH EMPIRIC
METHOD

DAMAGE EVALUATION (BURLAND):
ε (CAUSED BY TBM ADVANCING)

DAMAGE > 2

CONSOLIDATION WORKS

DAMAGE ≤ 2

NO CONSOLIDATION WORKS

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
BUILDING DAMAGE EVALUATION
– INPUT DATA

1) Tunnel excavation method

2) Tunnel geometry:
   excavation diameter, tunnel shape and overburden

3) Soil conditions

4) Building conditions in relation to the tunnel
1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

Hc=9.9m (for the left and right tunnel)
SOIL CONDITIONS

The following K values have been assumed, for the settlement evaluation:

- \( K = 0.50 \) for Pliocene clay regions;
- \( K = 0.35 \div 0.45 \) for stratigraphy varying from sands to silty and clayey quaternary soils regions;
- \( K = 0.30 \) for sands and gravel regions.
SOIL CONDITIONS

Left tunnel

Right tunnel

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

K = 0.30 sands regions

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Rock type</th>
<th>layer</th>
<th>Main type of soil</th>
<th>I_p</th>
<th>I_L/L</th>
<th>I_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>I, II</td>
<td>Ia</td>
<td>I, Ia</td>
<td>-</td>
<td>&lt;0.15</td>
<td>&gt;0.4</td>
</tr>
<tr>
<td>1b</td>
<td>II</td>
<td>Ib</td>
<td>II , II</td>
<td>-</td>
<td>&lt;0.15</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>1c</td>
<td>III</td>
<td>Ic</td>
<td>III, II, Ps, Pr, Pd</td>
<td>&gt;0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>III</td>
<td>Ib</td>
<td>III, II, Ps, Pr, Pd</td>
<td>0.4-0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1c</td>
<td>IV</td>
<td>Ic</td>
<td>IV, IV</td>
<td>&gt;0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>IV</td>
<td>Ib</td>
<td>IV, IV</td>
<td>&gt;0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>V</td>
<td>Ib</td>
<td>V, V</td>
<td>&gt;0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>VI</td>
<td>Ib</td>
<td>VI</td>
<td>&lt;0.25</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>1b</td>
<td>VII</td>
<td>Ib</td>
<td>VII</td>
<td>&lt;0.2</td>
<td>&gt;0.2</td>
<td>&gt;0.2</td>
</tr>
<tr>
<td>1b</td>
<td>VIII</td>
<td>Ib</td>
<td>VIII</td>
<td>&lt;0.1</td>
<td>&gt;0.4</td>
<td>&gt;0.4</td>
</tr>
<tr>
<td>1b</td>
<td>nV</td>
<td>Ib</td>
<td>nV</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
1) **Tunnel excavation method**
   
   EPB – TBM volume loss $VL = 0.6\%$

2) **Tunnel geometry:**
   - **excavation diameter** $D = 6.3 \text{m}$ (area of excavation $A_{\text{exc}} = 31.17 \text{m}^2$)
   - **tunnel shape** circular
   - **overburden** $H_c = 9.9 \text{m}$

3) **Soil conditions** $K = 0.3$

4) **Building conditions in relation to the tunnel**
# BUILDING CONDITIONS

## 1. LOCATION

<table>
<thead>
<tr>
<th>1.1 district</th>
<th>Warszawa, Praga Północ,</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 address</td>
<td>29 Zamoyskiego Street</td>
</tr>
<tr>
<td>1.3 station/tunnel symbol</td>
<td>Directly above the tunnel</td>
</tr>
<tr>
<td>1.4 distance to a station/tunnel</td>
<td>minimum distance from external wall of a station/tunnel aM = 0,00 m</td>
</tr>
<tr>
<td>1.5 influence zone</td>
<td>„0”, „1”,</td>
</tr>
</tbody>
</table>

## 2. Volume Loss and Ground Settlement

## 3. Damage Evaluation

## 4. Example

### 3.5 Height above the ground

<table>
<thead>
<tr>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approx 13,80m</td>
<td>approx 16,5 m</td>
</tr>
</tbody>
</table>

### 3.6 Height of the basement level (from the ground level)

| approx 2.45 m |

### 3.7 Depth of foundations

| approx 3.35 m |

## 4. CONSTRUCTION CHARACTERISTIC

<table>
<thead>
<tr>
<th>4.1 Type of construction</th>
<th>Longitudinal type, 2-tracts (tract span), Traditional brickwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 Type of construction system</td>
<td>A Wall system in congested area, no expansion joint.</td>
</tr>
</tbody>
</table>
UNIFIED CRITERION OF BUILDING DAMAGE EVALUATION

FREE FIELD SETTLEMENTS EVALUATION WITH EMPIRIC METHOD

DAMAGE EVALUATION (BURLAND):
\[ \varepsilon \] (CAUSED BY TBM ADVANCING)

DAMAGE > 2
CONsolidation Works

DAMAGE \leq 2
NO CONSOLIDATION WORKS

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
GREEN FIELD SETTLEMENTS

- **VL**: Volume loss
- **$S_{max}$**: Maximum settlement
- **$i$**: Trough width parameter
- **$z_0$**: Depth to tunnel axis
- **$y$**: Offset from tunnel centreline
- **$z_p$**: Foundations level

It has been conservatively assumed that the building follows the ground settlement trough at the foundation level.

$$i = K (z_0 - z_p) = 0.3(H_c - z_p + D/2)$$

$$i = 0.3(9.9m - 3.4m + 6.3m/2) = 2.895m$$
GREEN FIELD SETTLEMENTS

Volume $V_s = \sqrt{2\pi} i s_{\text{max}}$

$V_L = 0.6\%$

$V_s = 1 \text{m} \times A_{\text{exc}} \times V_L \ 0.6\% = 0.187 \text{m}^3/\text{m}$

$s_{\text{max}} = V_s / 2.5 i = -0.026 \text{m}$

$S = s_{\text{max}} \exp \left( -\frac{y^2}{2i^2} \right)$

$D = 6.3 \text{m}$
SUBSIDENCE THROUGH ON FOUNDATION LEVEL \( z_p \)
DUE TO LEFT TUNNEL EXCAVATION

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
SUBSIDENCE THROUGH ON FOUNDATION LEVEL $z_p$
DUE TO RIGHT TUNNEL EXCAVATION
SUBSIDENCE THROUGH ON FOUNDATION LEVEL $z_p$
DUE TO TUNNELS EXCAVATION

Niecka osiadań

Odległość od osi (m)

Osiadanie (m)

-30 -20 -10 0 10 20 30

Lewy Tunel  Prawy Tunel  Suma

BUILDING DAMAGE EVALUATION

How settlements affect the structure?

We have to calculate the maximum tensile strain induced in the structure and corresponding category of damage!
STRAINS IN A BUILDING WITH A MAXIMUM RELATIVE SETTLEMENT $\Delta$

Burland et al. (1977)

$$
\varepsilon_b = \left(\frac{\Delta}{L}\right) \times \frac{1}{\left[\frac{L}{12t} + \left(\frac{3EI}{2tLHG}\right)\right]}
$$

$$
\varepsilon_d = \left(\frac{\Delta}{L}\right) \times \frac{1}{\left[1 + \left(\frac{HL^2G}{18EI}\right)\right]}
$$

where:

- $H$ = height of building;
- $L$ = length of building;
- $E$ = Young’s modulus of building;
- $G$ = shear modulus of building;
- $I$ = second moment of area of the equivalent beam ($I=H^3/12$ sagging zone, $I=H^3/3$ hogging zone);
- $t$ = furthest distance from neutral axis to edge of beam ($t=H/2$ sagging zone, $t=H$ hogging zone)

It is conservatively assumed that the building follows the ground settlement trough at the foundation level.
BUILDING DEFORMATION

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
TOTAL TENSILE STRAIN

The horizontal ground strains due to bored tunnel construction may also contribute to potential building damage and they can be calculated as average horizontal strain ($\varepsilon_h$). The average horizontal strain is combined with either the bending or diagonal strain.

The horizontal strain can be added directly to the bending strains giving:

$$\varepsilon_{bt} = \varepsilon_h + \varepsilon_b$$

where:

$\varepsilon_{bt} = \text{total bending strain.}$

Diagonal strains and horizontal strains can be combined by making use of Mohr’s circle. The total tensile strain due to diagonal distortion, $\varepsilon_{dt}$, is given by:

$$\varepsilon_{dt} = 0.35\varepsilon_h + \sqrt{\left(0.65\varepsilon_h\right)^2 + \varepsilon_d^2}$$

For Poisson’s ratio $\nu = 0.3$. 
# RELATIONSHIP BETWEEN CATEGORY OF DAMAGE AND TENSILE STRAIN $\varepsilon_{\text{lim}}$

*Boscardin and Cording, 1989*

<table>
<thead>
<tr>
<th>Category of damage</th>
<th>Normal degree of severity</th>
<th>Limiting tensile strain ($\varepsilon_{\text{lim}}$) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Negligible</td>
<td>$0 \div 0.05$</td>
</tr>
<tr>
<td>1</td>
<td>Very Slight</td>
<td>$0.05 \div 0.075$</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>$0.075 \div 0.15$</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>$0.15 \div 0.3$</td>
</tr>
<tr>
<td>4 to 5</td>
<td>Severe to Very Severe</td>
<td>$&gt; 0.3$</td>
</tr>
</tbody>
</table>
BUILDING CONDITIONS IN RELATION TO THE TUNNEL

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

 długość budynku [m]  L  22.5

 współrzędna lewej krawędzi budynku [m]  x sin  -9.5

 współrzędna prawej krawędzi budynku [m]  x dex  13
LEFT TUNNEL

$L_s$, $\Delta s$, $L_{H2}$, $\Delta h2$, horizontal displacements for point A, B, C → calculation of horizontal strain.
### LEFT TUNNEL

#### DATA - STRUCTURE

<table>
<thead>
<tr>
<th></th>
<th>H(m)</th>
<th>E/G</th>
<th>Is (m³)</th>
<th>lh (m³)</th>
<th>ts (m)</th>
<th>th (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hogging1</td>
<td>17.2</td>
<td>2.6</td>
<td>424.037</td>
<td>1696.15</td>
<td>8.6</td>
<td>17.2</td>
</tr>
<tr>
<td>sagging</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hogging2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table

<table>
<thead>
<tr>
<th></th>
<th>LENGTH</th>
<th>Lh</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VERTICAL DIS.LEFT</td>
<td>W1</td>
<td>0.00</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>VERTICAL DIS.RIGHT</td>
<td>W2</td>
<td>0.00</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>HORIZONTAL DIS.LEFT</td>
<td>Wh1</td>
<td>0.00</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>HORIZONTAL DIS.RIGHT</td>
<td>Wh2</td>
<td>0.00</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>MAX Delta</td>
<td>Dh</td>
<td>0.00</td>
<td>mm</td>
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</tr>
</tbody>
</table>

### 1. Volume Loss and Ground Settlement

### 2. Damage Evaluation

### 3. Example

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RIGHT TUNNEL

$L_{H1}, \Delta h_1, L_s, \Delta s, L_{H2}, \Delta h_2,$
horizontal displacements
for point A, B, C, D $\rightarrow$
calculation of horizontal strain

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

hogging 1
sagging
hogging 2

Niecka osiadań

Osiadanie (m)

Odległość od osi (m)
### RIGHT TUNNEL

#### DATA - STRUCTURE

<table>
<thead>
<tr>
<th></th>
<th>H(m)</th>
<th>E/G</th>
<th>Is (m³)</th>
<th>lh (m³)</th>
<th>ts (m)</th>
<th>th (m)</th>
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<tbody>
<tr>
<td></td>
<td>17.2</td>
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<td>424,037</td>
<td>1696.15</td>
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#### Table

<table>
<thead>
<tr>
<th></th>
<th>LENGTH</th>
<th>h</th>
<th>13.61 m</th>
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<tbody>
<tr>
<td><strong>hogging1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VERTICAL DIS.LEFT</td>
<td>W1</td>
<td></td>
<td>0.00 mm</td>
</tr>
<tr>
<td>VERTICAL DIS.RIGHT</td>
<td>W2</td>
<td></td>
<td>-15.63 mm</td>
</tr>
<tr>
<td>HORIZONTAL DIS.LEFT</td>
<td>Wh1</td>
<td></td>
<td>0.00 mm</td>
</tr>
<tr>
<td>HORIZONTAL DIS.RIGHT</td>
<td>Wh2</td>
<td></td>
<td>4.69 mm</td>
</tr>
<tr>
<td>MAX Delta</td>
<td>Dh</td>
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<td>9.53 mm</td>
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<table>
<thead>
<tr>
<th></th>
<th>LENGTH</th>
<th>s</th>
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<tbody>
<tr>
<td><strong>sagging</strong></td>
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<td></td>
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<tr>
<td>VERTICAL DIS.LEFT</td>
<td>W1</td>
<td></td>
<td>-15.63 mm</td>
</tr>
<tr>
<td>VERTICAL DIS.RIGHT</td>
<td>W2</td>
<td></td>
<td>-15.63 mm</td>
</tr>
<tr>
<td>HORIZONTAL DIS.LEFT</td>
<td>Wh1</td>
<td></td>
<td>4.69 mm</td>
</tr>
<tr>
<td>HORIZONTAL DIS.RIGHT</td>
<td>Wh2</td>
<td></td>
<td>-4.69 mm</td>
</tr>
<tr>
<td>MAX Delta</td>
<td>Ds</td>
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<td>10.14 mm</td>
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<table>
<thead>
<tr>
<th></th>
<th>LENGTH</th>
<th>h</th>
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</thead>
<tbody>
<tr>
<td><strong>hogging2</strong></td>
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<td></td>
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<tr>
<td>VERTICAL DIS.LEFT</td>
<td>W1</td>
<td></td>
<td>-15.63 mm</td>
</tr>
<tr>
<td>VERTICAL DIS.RIGHT</td>
<td>W2</td>
<td></td>
<td>-3.01 mm</td>
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<tr>
<td>HORIZONTAL DIS.LEFT</td>
<td>Wh1</td>
<td></td>
<td>-4.69 mm</td>
</tr>
<tr>
<td>HORIZONTAL DIS.RIGHT</td>
<td>Wh2</td>
<td></td>
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</tr>
<tr>
<td>MAX Delta</td>
<td>Dh</td>
<td></td>
<td>1.41 mm</td>
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</table>
LEFT TUNNEL

(LEFT TUNNEL) MAXIMUM HOGGING ZONE

Length of the (max) hogging zone
- Length of the hogging zone: 17,11 m
- Settlement_left: -15,63 mm
- Settlement_right: 0,00 mm
- Horizontal displacement_left: -4,69 mm
- Horizontal displacement_right: 0,00 mm

Horizontal strain (*): 0,027%
Δ h: 10,533 mm
Strain due to bending: 0,044%
Strain due to shearing: 0,058%

--- Total tensile strain: 0,072%

(*) se la def. orizzontale risulta negativa, per il calcolo delle def. di trazione viene posta a favore di sicurezza pari a 0)

(LEFT TUNNEL) SAGGING ZONE

Length of the sagging zone
- Length of the sagging zone: 5,40 m
- Settlement_left: -17,75 mm
- Settlement_right: -15,63 mm
- Horizontal displacement_left: 4,60 mm
- Horizontal displacement_right: -4,69 mm

Horizontal strain (*): 0,000%
Δ s: 9,029 mm
Strain due to bending: 0,079%
Strain due to shearing: 0,163%

--- Total tensile strain: 0,079%

(*) se la def. orizzontale risulta negativa, per il calcolo delle def. di trazione viene posta a favore di sicurezza pari a 0)

Maximum tensile strain
ε_{max} = 0,163%
(RIGHT TUNNEL) MAXIMUM HOGGING ZONE

**Length of the (max) hogging zone**: 3.11 m
- **Settlement_left**: -15.63 mm
- **Settlement_right**: -3.01 mm
- **Horizontal displacement_left**: -4.69 mm
- **Horizontal displacement_right**: -1.87 mm

**Horizontal strain (\(\varepsilon\))**: 0.091%

\[ \Delta h = 1.409 \text{ mm} \]

- **Strain due to bending**: 0.006%
- **Strain due to shearing**: 0.045%

\[ \varepsilon = \frac{\Delta}{L} \times \left[ 1 - \frac{L}{12t} + \frac{3EI}{2tLGH} \right] \]

\[ \varepsilon = \frac{\Delta}{L} \times \left[ 1 + \frac{HL^2G}{18EI} \right] \]

--- Total tensile strain: 0.097%

(*: se la def. orizzontale risulta negativa, per il calcolo delle def. di trazione viene posta a favore di sicurezza pari a 0)

--- Total tensile strain: 0.106%

(RIGHT TUNNEL) SAGGING ZONE

**Length of the sagging zone**: 5.79 m
- **Settlement_left**: -15.63 mm
- **Settlement_right**: -15.63 mm
- **Horizontal displacement_left**: -4.69 mm
- **Horizontal displacement_right**: -4.69 mm

**Horizontal strain (\(\varepsilon\))**: 0.000%

\[ \Delta s = 10.140 \text{ mm} \]

- **Strain due to bending**: 0.088%
- **Strain due to shearing**: 0.170%

\[ \varepsilon_{bt} = \varepsilon_h + \varepsilon_b \]

\[ \varepsilon_{dt} = 0.35\varepsilon_h + \sqrt{\left(0.65\varepsilon_h\right)^2 + \varepsilon_d^2} \]

--- Total tensile strain: 0.088%

--- Total tensile strain: 0.170%

(*: se la def. orizzontale risulta negativa, per il calcolo delle def. di trazione viene posta a favore di sicurezza pari a 0)

**Maximum tensile strain**: \(\varepsilon_{max} = 0.170\%\)
1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example

**KLASA**

- Murowany (E/G=2.6) $\varepsilon_{\text{max}} = 0.333\%$ (4)
- Szkieletowy (E/G=12.5) $\varepsilon_{\text{max}} = 0.341\%$ (4)

**ANALIZA BUDYNKU** ul. Zamoyskiego 29

**PARAMETRY OBLICZENIOWE**

- $H = 17.2$
- $K = 0.3$
- Murowany (E/G=2.6)
- Szkieletowy (E/G=12.5)
PREVENTIVE INTERVENTIONS OF SOIL IMPROVEMENT HAVE TO BE PERFORMED FOR ZAMOYSKIEGO 29 BUILDING
SOIL IMPROVEMENT

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
SOIL IMPROVEMENT

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example
SOIL IMPROVEMENT

1. Volume Loss and Ground Settlement
2. Damage Evaluation
3. Example