Monitoring system for the construction of the Underground Line II in Warsaw

Warszawa, November 2011
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Monitoring System

- Execution of **measures** repeated over time with adequate **instruments** supporting:

  Design
  Construction
  Running Time

of Geotechnical Constructions.
- Terzaghi (1940’s): learn-as-you-go method
  - How and according to what criteria a project during its development can be economically executed based on an increasing knowledge of the properties and behaviour of the ground.

  - Initial design based on most probable conditions, together with prediction of behaviour.
  - Identify contingency plans and trigger values for the monitoring system.
  - The response time for monitoring and implementation of the contingency plan must be appropriate to control the work.
...it is *sometimes appropriate* to adopt the approach known as ‘the observational method’, in which the design is reviewed during construction.

When this approach is used the following requirements *shall* all be made before the construction is started:

- the *limits of behaviour* which are acceptable shall be established.
- the *range of possible behaviour* shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.
Eurocode 7 - UNI ENV 1997

- a *plan of monitoring shall be devised* which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage and with sufficiently short intervals to allow contingency actions to be undertaken successfully. The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution if the system.

- A *plan of contingency actions* shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits.
Difference between designed and measured values should remain within acceptable limits. Exceeding of limits will trigger contingency plans which may be classified as ‘countermeasures’ or ‘rationalizations’.

Ikuta, 1994
Monitoring design for the construction of Underground Line II in Warsaw.

Project design defined:

1. Structures and ground to be monitored (area of investigation)
2. Quantities and thresholds
3. Instruments
4. Installation and measuring points
5. Frequency of readings
6. Emergency procedures
1 Structures and ground

1a Stations: impact zones are defined according to the guidelines of the Building Research Institute (ITB) – Three impact zones are specified:

- Zone 0 – located directly above the planned station or excavation
- Zone $S_1$ – direct impact on existing development
- Zone $S_{II}$ – indirect impact, secondary impact zone

The width of the $S_1$ zone equals to 1,0 Hw and the width of the secondary impact zone $S_{II}$ amounts to 2,0 Hw

$$S_1 + S_{II} = 3 \text{ Hw}$$

Hw = Excavation depth
Fig. 1a: Buildings within the impact zones of the station C12 NOWY ŚWIAT
1b TBM LINE: impact area of the TBM line has been defined according to geometry of the boring section and the characteristics of the excavated ground.

Fig. 1b: Buildings and ground within the impact zones of the TBM line.
Fig. 1c: Buildings and within the impact zones of the TBM line.
2 Quantities and thresholds

Quantities and thresholds are defined by the expected behaviour of:

- structure under construction,
- ground within the impact zone,
- existing structures within the impact zone.
2a Stations: Quantities and threshold

(1) Lateral movement profile induced beneath the building foundation
(2) Vertical movement profile induced beneath the building foundation

- Building
- Struts
- Excavation bottom
- Wall deflection
- Retaining wall
- Deformation vector of soil
- Both vertical and lateral movements are induced
2a Stations: Quantities and threshold

- Quantities

**Diaphragm walls**: orizzontal displacement.
**Ground**: horizontal and vertical displacement, water table monitoring.
**Buildings**: horizontal and vertical displacement, rotations, cracks.

- Thresholds

**Diaphragm walls**
- Alert: exceeding of 10% of designed deformations
- Alarm: exceeding of 20% of designed deformations

*Thresholds have been grouped based on construction phases.*

**Ground**

*Ground settlements are not directly connected to alert or alarm conditions.*
2a Stations: Quantities and threshold

Buildings
Classification of buildings depending on position respect to impact zone \((S_1, S_{II})\), date of construction, state of damage.

Vertical displacements and rotations threshold defined as percentage of Ultimate Limit State
Tipical boundary values:

- Alert: \(\sim 15 \text{ [mm]} / 1:1200 \text{ [rad]}\)
- Alarm: \(\sim 25 \text{ [mm]} / 1:800 \text{ [rad]}\)

Horizontal displacements are dependent on the level of measuring point. Boundary values:

\[\theta = 1/600 \text{ L} \text{ for SLS values} \]
\[\theta = 1/300 \text{ L} \text{ for ULS values} \]
2b TBM Line: Quantities and threshold

• Quantities

   Ground: horizontal and vertical displacement, water table monitoring, surface and in-ground deformation monitoring.
   Buildings: horizontal and vertical displacement, rotations, cracks.
   Lining: stress and strain condition of the tunnel lining. (No thresholds)

• Thresholds

Ground level settlements: the trigger and alarm limit values that will be assumed for ground surface settlements are summarized in the following table

<table>
<thead>
<tr>
<th>Passage of</th>
<th>Alert threshold</th>
<th>Alarm threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM 1</td>
<td>10 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>TBM 1+2</td>
<td>18 mm</td>
<td>24 mm</td>
</tr>
</tbody>
</table>

No thresholds setted for horizontal ground settlement and water table level.
2b TBM Line: Quantities and threshold

**Buildings**: Alert and alarm values are considered respect to maximum settlement, distortion and relevant rate per day. Classification of buildings depending on position respect to impact zone and state of damage:

<table>
<thead>
<tr>
<th>Deformation</th>
<th>Alert Value</th>
<th>Alarm Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Settlement</td>
<td>10 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>Angular distortion</td>
<td>1:1200</td>
<td>1:800</td>
</tr>
<tr>
<td>Rate of total settlement</td>
<td>2.0 mm/day</td>
<td>3.0 mm/day</td>
</tr>
<tr>
<td>Rate of crack opening</td>
<td>0.5 mm/day</td>
<td>1.0 mm/day</td>
</tr>
</tbody>
</table>

**Sensitive building and structures**

<table>
<thead>
<tr>
<th>Deformation</th>
<th>Alert Value</th>
<th>Alarm Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Settlement</td>
<td>18 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>Angular distortion</td>
<td>1:1800</td>
<td>1:600</td>
</tr>
<tr>
<td>Rate of total settlement</td>
<td>3.0 mm/day</td>
<td>4.0 mm/day</td>
</tr>
<tr>
<td>Rate of crack opening</td>
<td>0.5 mm/day</td>
<td>1.0 mm/day</td>
</tr>
</tbody>
</table>

**Others building and structures**
3 Instruments

The choose of instruments to use for monitoring system is connected to the quantities to be observed, the range of values expected (thresholds) and the object to be monitored.
3a Stations: Instruments

Diaphragm walls: Inclinometers, benchmarks.
Ground: Ground pins, piezometers.
Buildings: Levelling pins, optical target, mini prisms, crackmeters.

3b TBM Line: Instruments

Ground: Inclinometers, assestimeters, piezometers, ground pins, piezometers.
Buildings: Leveling pins, optical targets, mini prisms, wall clinometers, crackmeters.
Lining: Strain gauges.
3 Instruments

List of instruments for monitoring system during construction of Stations and TBM Line:

- levelling pins
- levelling staffs
- ground pins
- optical targets
- mini prisms

- inclinometers
- piezometers
- crackmeters
- assestimeters
- wall clinometers
- strain gauges.

→ **Topographical devices**

→ **Geotechnical devices**
3 Topographical devices

**Levelling pins**

Iron bar embedded in concrete surface. On the external tip a spherical nail is welded for the support of the stadia. Monitoring of *vertical displacements* with the precision of ~0.3 mm.
3 Topographical devices

Levelling staff

Invar bar with bar code, anchored to the element to be monitored. Monitoring of vertical displacements with precision of ~0.5 mm
3 Topographical devices

Ground pins

Steel bar embedded in the ground. The length of the bar should be enough to get a depth where no influence of surface displacements may affect the measure. Monitoring of vertical displacements with the precision of ~0.3 mm.
3 Topographical devices

Optical Target

Plastic sheet glued to a surface to be monitored. Measured by a theodolite, gives elevation and coordinates of the point. **Horizontal** and **vertical** displacements.
3 Topographical devices

Mini Prisms

Reflecting prism. Reflects the laser signal of a total station (tacheometer). Anchored or stuck to the measuring point. Monitoring of vertical and horizontal displacements. Precision depending on the positioning of the total station.
3 Geotechnical devices

Inclinometer

Probe equipped with two inclinometric sensors. Running along an in-ground pipe allows the measure of the shape of the pipe. Difference of measure between successive readings is interpreted as displacements of the pipe. Monitoring of horizontal displacements. Precision of 1mm each 10 meter of pipe.
3 Geotechnical devices

Piezometer

A borehole instrumented with a filter at bottom of the pipe. Through the filter the water flows into the pipe up to the acquifer’s water level. Depth of water level is measured by freatimetric probe.
3 Geotechnical devices

Crackmeters

Monitoring of existing cracks. Is observed the relative distance between the anchoring points straddling the crack. Electrical, mechanical, wire crackmeters depending of width, position of the crack and frequency of readings.
3 Geotechnical devices

**Assestimeters**

Fiberglass rods anchored in boreholes. Displacement transducers at top of the borehole. Absolute settlement by surveying of ground level. Monitoring of *vertical* displacements.
3 Geotechnical devices

Wall clinometers

Inclinometric sensor into a steel bar. The bar is anchored to the structured to be monitored, in vertical position. Clinometers monitor the inclination of the vertical planes parallel and transversal to the surface. Monitoring of rotations.
3 Geotechnical devices

Strain gauges

An electrical resistance, which change is related to the strain by the quantity known as *Gauge Factor*:

\[ GF = \frac{\Delta R}{R_G} \frac{1}{\varepsilon} \]
4 Installation and measuring points

Once the designers had chose the objects to be monitored, quantities to measure and instruments to use, they give indications/criteria about the installation points. The feasibility of the single installation and opportunity to modify position will be evaluated by the monitoring team and eventual modifications to the design will be adopted.
4a Stations: Installation and measuring points

Fig. 4a: Installation of levelling pins and prisms at C12 - Design
4a Stations: Installation and measuring points

Fig. 4b: Installation of levelling pins and prisms at C12 – As Built
4a Stations: Installation and measuring points

Fig. 4c: Installation of Inclinometers at C12 – Design
4b TBM Line: Installation and measuring points
**4b TBM Line: Installation and measuring points**

**MONITORING PIERŚCIENIA - SZCZEGÓŁ**
RING MONITORING - DETAIL

**SPACE VIEW**
**RYSUNEK POGŁĄDOWY**

**PRZYKRÓJ B-B / SECTION B-B**

**PRZYKRÓJ A-A / SECTION A-A**
4b TBM Line: Installation and measuring points
4b TBM Line: Installation and measuring points
5 Frequency of reading

When and how often take readings? Designer indicates frequency of reading per single instrument during different execution stages. Frequency of monitoring may change in case of alert situations or if behaviour doesn’t comply design previsions.
5 Frequency of readings

In case of high frequency of readings, *remote data collection* is implemented.

A certain number of instruments are connected by wire to a Data Acquisition Unit (UAD).
Frequency of readings

UAD are connected via GSM Network to monitoring center. Data management, data validation, system configuration, frequency management, real time data acquisition....
Total Stations are automated tacheometer used to monitor the position of mini prisms. Possibility to measure 70 prisms per hour at a max distance of ~100m.
6 Emergency procedures

When data show exceeding of Alarm or Alert Threshold, according to the spirit of observational method, contingency plans or corrective actions are to be taken.

After verification and validation of data, the people involved in construction process will receive alert/alarm notification in form of mail, sms or report.

A meeting of specialists will analyze data and phenomena; corrective actions may foresee suspension of work, changes in design assumptions, change in construction modalities.
6 Emergency procedures

A web-based application has been developed in order to enable access to monitoring data from any location.