MONITORING OF TUNNEL CONSTRUCTION IN URBAN AREA

Prof. Sebastiano PELIZZA
Monitoring has an essential role in tunnelling.
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In a contest of great geological, technical and environmental variability and uncertainty, monitoring is the only means to enable the excavation project of a tunnel to be adjusted in an objective way during the construction works. Tunnel design and construction cannot exist without monitoring: *monitoring is the mirror that reflects the soul of the tunnel.*
PURPOSE OF MONITORING

Field monitoring is an indispensable action of modern tunnelling. His purpose may be:

• checking the structural behaviour with respect to safety and/or serviceability criteria, mainly during construction and in some cases during service life;
• the quantification of structural response to a specific method of construction and checking the effectiveness of specific support measures;
• the comparison of theoretical predictions with the actual structural behaviour and the assessment of the geotechnical parameters of the ground;
• checking adjacent structures and facilities for their safety and serviceability as a result of the construction of the tunnel.
Integrated real-time monitoring systems consist of a set of several in-situ measurements of displacements, stress and strain variations which occur in the ground in the tunnel supports and in the structures on the surface during the excavation activity.

Correct monitoring planning does not consist in the installation of a large number of measuring stations with modern and sophisticated instruments, but means the development of a specific monitoring design in agreement with the structural design and the contemporary critical reading of the measurement results to improve the construction design as the works progress.
The planning of a monitoring system should include the following steps:
- prediction of the mechanisms that control behaviour
- definition of the warning level (alert and alarm) of the measured values of the checked parameters (*)
- selection of parameters to be monitored
- prediction of the magnitude of changes
- selection of instrumentation and its accuracy
- instrument location plan
- redundancy of instrumentation
- data processing
- interpretation and report plan

(*) - **Alarm** level requires the adoption of the counter-measures specifically studied for the event in question.

- **Alert** level activates a specific control system in order to enable the more specific following of the event.
Monitoring in conventional tunnelling

Borzoli Cavern (Italy) (Grasso and Pelizza, 1998)
Geological Section

- Borzoli Cavern (≈100m)
- Rio Vareena
- Monte Gazzo
- Rio Bianchetta
- Bric del Corvi
- Rio Ciliegia

Legend:
- Calcareous schist
- Serpentinic schist
- Basalt
- Dolomitic limestone
- Principal fault
- Shale
- Argilaceous limestone
- Gabbro
- Ophiolitic breccia
Convergence

Monitoring
Convergence and extension of plasticized zones

Monitoring
### Hazard-Warning Levels and Counter-Measures

<table>
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<tr>
<th>OBJECTIVE</th>
<th>INSTRUMENTATION</th>
<th>TYPICAL LAYOUT OF INSTRUMENTS</th>
<th>READING FREQUENCY</th>
<th>WARNING LEVELS *</th>
<th>COUNTER-MEASURES</th>
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<tr>
<td>AXIAL LOAD IN TENSIONED CABLES</td>
<td>ANCHOR DISK LOAD CELLS</td>
<td>5 PER SECTION</td>
<td>DAILY OR WEEKLY</td>
<td>ATTENTION: 30% OF CAPACITY (450-600 kN)</td>
<td>ALARM: 80% OF CAPACITY (450-600 kN)</td>
</tr>
<tr>
<td>DEFORM. AHEAD OF THE FACE</td>
<td>INCREMENTAL EXTENSOMETERS</td>
<td>1 IN LATER, HEADING 1 IN CENTR. HEADING</td>
<td>DAILY DURING THE FACE ADVANCE</td>
<td>ATTENTION: 15% OF RADIAL DISPL.</td>
<td>ALARM: 40% OF RADIAL DISPL.</td>
</tr>
<tr>
<td>EXTRUSION OF THE FACE</td>
<td>TARGETS FOR OPTICAL READING DEVICE</td>
<td>1 IN LATER, HEADING 6 IN CENTR. HEADING</td>
<td>DAILY OR WEEKLY</td>
<td>ATTENTION: 15% OF LONGITUD. DISPL.</td>
<td>ALARM: 40% OF LONGITUD. DISPL.</td>
</tr>
<tr>
<td>LOAD IN FIBERGLASS TUBES</td>
<td>STRAIN GAUGES</td>
<td>1 IN LATER, HEADING 1 IN CENTR. HEADING</td>
<td>DAILY DURING THE FACE ADVANCE</td>
<td>ATTENTION: 30% OF CAPACITY (400 kN)</td>
<td>ALARM: 80% OF CAPACITY (400 kN)</td>
</tr>
</tbody>
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* IN RESPECT TO THE DESGN VALUE
## Hazard-Warning Levels and Counter-Measures

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<tr>
<td>3D DISPL. OF THE PRIMARY SUPPORT</td>
<td>TARGETS FOR OPTICAL READING DEVICE</td>
<td>5 TO 11 PER SECTION</td>
<td>DAILY OR WEEKLY</td>
<td>30% OF RADIAL DISPL.</td>
<td>80% OF RADIAL DISPL.</td>
</tr>
<tr>
<td>GROUND LOAD</td>
<td>PRESSURE CELLS</td>
<td>MAX. 15</td>
<td>WEEKLY OR MONTHLY</td>
<td>30% OF RADIAL LOAD</td>
<td>80% OF RADIAL LOAD</td>
</tr>
<tr>
<td>PLASTIC ZONE</td>
<td>INCREMENTAL &amp; MULTIPLE-POINT EXTENSOMETERS</td>
<td>5 PER SECTION</td>
<td>WEEKLY OR MONTHLY</td>
<td>1/4 OF PLASTIC ZONE RADIUS</td>
<td>3/4 OF PLASTIC ZONE RADIUS</td>
</tr>
<tr>
<td>CAST CONCRETE TEMPERATURE</td>
<td>THERMOCOUPLE</td>
<td>2 PER SECTION</td>
<td>HOURLY OR DAILY</td>
<td>VARIABLE</td>
<td>VARIABLE</td>
</tr>
</tbody>
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* IN RESPECT TO THE DESIGN VALUE
Through an urban area, a tunnel must be built at a shallow depth in soft ground. The most significant environmental problem that arises is the control of the settlement at the surface, which must be contained within values that are compatible with the safety of the buildings and/or structures on the surface.
As illustrated in the figure below, it appears obvious that the tunnel should be excavated using an “overall tunnelling system”, constituted by various elements. These are the working elements of the machine; they affect each other reciprocally, but must work in a coordinated manner in order to achieve the best result compatible with the surrounding environment.

The active elements of these “machines” are:
• the excavation machine (EPBS) producing the tunnel, which at the same time is the cause of “volume loss” in various zones of the machine, causing surface settlement;
• the soft ground which, together with the depth, transmits part of the “lost volume” to the surface, creating pre-subsidence;
• exploratory drill-holes and ground injections which can swell or depress the ground
• the pre-existing structure on the surface, which is negatively affected by pre-subsidence, transforming settlement into damage and/or buried structures, as sewage or cave or foundations near the tunnel;
• people, who may be disturbed by vibrations, noise and dust;
• trees, which may be affected in their radical apparatus and/or by dust.
The “overall tunnelling system” is an integrated real-time monitoring system.
Given that the goal of excavating the tunnel is to build a subterranean system to be used for mass transport services without causing irreparable or unacceptable damage to the pre-existing structures, the “overall tunnelling system” must be controlled in a homogeneous manner, monitoring all the active elements comprising it at the same time; the “machine” must function in a correct and compatible manner, providing the best product at the most convenient price.
To implement the complex monitoring system, a check-list of the fundamental monitoring programme components, on the basis of a wide-ranging experience in similar works, is reported below:

- define the project conditions: geology, geomorphology and geotechnical properties; groundwater conditions; and the status of nearby structures and services
- define the purpose of instrumentation
- choose variables to be monitored
- select instruments
- identify additional observations required
- select instrument locations
- select type of readings
- predict the likely behaviour to obtain a range of likely responses and to identify threshold values for construction and/or safety control
- list the specific purpose for each instrument, in accordance with the scope of monitoring
- prepare instrument specifications
- plan the installation of the instrumentation
- define the frequency of readings
- assign tasks and responsibilities
- effectively manage the monitoring results.
The monitoring aspects concerning what and how to monitor are listed just below:
• monitoring of the actual extent of the tunnelling-induced ground movements and associated impacts;
• monitoring and adjustment of the face-support pressure, considering that the potential instability of the excavation face is the major source of risk or severe damage to properties and/or infrastructures on the surface
• monitoring of the tunnel structure, including its stress-strain behaviour
• monitoring interactions with the TBM and the surrounding ground
• monitoring and control of the backfilling process, taking into account that an inefficient and untimely, or an ineffective, backfilling of the tail void is another major source of risk of instabilities and damage
• monitoring and control of the excavation by an EPBS.
For all works performed in an urban environment, priority is given to the necessity to limit the subsidence caused by the excavations (due to both face plasticization and the annular void between the excavation and pre-cast lining) and to make them compatible with the pre-existing structures on the surface.

\[ S(x) = w_{\text{max}} \cdot e^{-\frac{x^2}{2i^2}} \]

Settlements of the surface with a shallow tunnel in loose ground
Pre-settlement
0.25-0.30 S max
(in granular soil)
MONITORING OF THE SUBSIDENCE BASIN ON THE SURFACE
The system for monitoring the tunnel which is intended to be installed for the section in question is broken down into the following fundamental parts. The monitoring of the structural lining of the tunnel will involve the acquisition of all the data required to verify the compliance between that provided in the design and that effectively ascertained during the works. The control will be carried out through the implementation of current and principal sections of measurement, providing for the measurement of the tension and deformation parameters of the structure. It should be pointed out that the monitoring of the tunnel lining cannot be dependent upon the analysis of the deformation of the ground, and the measurement sections of the tunnel are thus integrated by points on level surfaces and sloping surfaces.

- monitoring of the mechanized excavations and the machine carried out directly by the automatic data acquisition system on the machine;
- monitoring of the tunnel lining;
- monitoring of the subsidence basin on the surface due to the excavations.
MONITORING OF THE MECHANIZED EXCAVATION

The main plant and equipment necessary for the EPBS and its back-up are:
• cutterhead
• excavation chamber, or Plenum, which temporarily contains the muck excavated from the face, thus giving support to the face
• screw conveyor: evacuates the muck (ground+additives) from the excavation chamber
• conveyor belt scales: provide the cumulative weight value for each excavation cycle and instantaneous debit of the conveyor
• pressure sensors: supply the face support pressure values, e.g. earth pressures in the excavation chamber
• precast segments assembler: positions the precast segments, thus assembling the lining ring.
Normal excavating conditions are considered as all the conditions in which the characteristic parameters of EPBS excavation fall within the “alert” thresholds. Normal conditions include the conditions that are intrinsic in the excavation restarting after maintenance interventions in the excavation chamber. *Anomalous* conditions are associated with:

- water influx under pressure through the screw conveyor
- sudden oscillations of the torque of the cutterhead
- blockage of the cutterhead
- anomalous pressure values in the excavation chamber
- sudden and significant variations of the muck density in the excavation chamber
- weight of the muck extracted by the screw conveyor surpassing the “alert” threshold
- insufficient pressure and/or volume of the grout injected behind the lining.
Excavation parameters control
The control parameters for excavation and their alert and alarm thresholds, verifies whether the tunnel progress status is normal or anomalous.
The parameters, to be verified via the sensors and sensing equipment, are:
- excavation face support pressure in the plenum, assessed as the pressure exerted by the excavated material temporary filling the excavation chamber and monitored by the pressure sensors installed on the rear bulkhead. Face-support pressure (pressure value in the plenum given by the chamber sensors);
- pressure and volume of the backfill grout of the annular void behind the lining, between the outer circumference of the lining and the excavated profile;
- weight and volume of the extracted material, coming from the excavation chamber, with relevant values for alert and alarm thresholds.
Soil and groundwater face pressure

At the face counter-pressure inside the “plenum” (excavation chamber)

Sensor to check the pressure of backfilling

Pressure sensors inside the “plenum”, along the screw conveyor and at the discharge gate

Scale

Known volume muck cars count
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