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Geodetic monitoring of underground excavations: 70 years after Terzaghi’s innovative techniques at the Chicago Subway Tunnels

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ABSTRACT: In the late 1930’s Karl Terzaghi, during the construction of the Chicago Subway Tunnels in soft rocks, introduced a new technique: he adapted excavation parameters to geodetic observations of ground settlement. This innovative technique, subsequently called by Ralph Peck ‘observational method’, revolutionized tunnel excavation, till then confined to fully pre-determined models. Major progress in the observational method, however, occurred since the advent of electronic and automatic, real-time monitoring techniques, mostly based on geodetic instrumentation. A number of examples indicate the significance of this method, very popular in our days, in different types of underground works, with monitoring data used in feedback analyses, optimization of the geotechnical modeling and eventually, prediction of deformation.

1 INTRODUCTION

In the last 70 years measurement and evaluation of the ground deformation became one of the most essential tools for planning and construction of safe and low-cost underground structures: the ground response to excavation and the ground/support interaction are measured, and this information is feedback in the geotechnical model; this permits both optimization of the excavation methodology and successful decision making upon appropriate remedy measures.

The concept of displacements observation and feedback in design of tunneling was first introduced by Karl Terzaghi at the Chicago Subway in the late 30’s (Terzaghi 1942). Excavation parameters (rate, support etc.) were adapted to the results of simple leveling measurements of the ground surface in a zone 6 m wide above the tunnel axis. Care was taken for surface subsidence not to exceed the limit of 10 cm, while leveling data were transmitted nearly in real-time to the excavation crew, by telephone; in the case of high deformation the advancement rate was reduced, or even the whole excavation was stopped. By this invention Terzaghi became the father of what was later named ‘the observational method’ (Terzaghi & Peck 1948; Peck 1969).

2 ‘THE OBSERVATIONAL METHOD’ – AN INNOVATIVE APPROACH TO GEOTECHNICAL PROBLEMS

In most cases geotechnical problems are solved using deterministic approaches following practices used in most other fields of Civil Engineering (Fig. 1; Szechy 1973). However, the poor knowledge of rock conditions at depth may prove the deterministic models non realistic, leading either to expensive constructions, or to failures. An example is the earthen Mactaquac Dam in New Brunswick, Canada. Unexpected deformations and cracking observed during dam operation could not be explained by the geotechnical model alone. For this reason, an integrated monitoring system was installed and displacements recorded were incorporated in the analysis of the structure permitting to understand the failure mechanism (Chrzanowski et al. 1989; Chrzanowski & Szostak-Chrzanowski 1993).

Thus, an alternative approach to tunnel design is to define an excavation model and test and modify it, if necessary, by deformation measurements (Fig. 1). This inductive method in underground constructions introduced by Terzaghi represents a new philosophical approach, especially valuable in modern tunnel construction in demanding or difficult conditions (shallow tunneling beneath historical buildings, weak rocks etc.); a method that became very popular with the advent of modern electronic surveying instruments.

3 TUNNEL EXCAVATION COMBINED WITH THE MONITORING TECHNOLOGY

The evolution of electronics of the last decades has led to an enormous advance of surveying and other (geotechnical etc) monitoring systems. The new generation of surveying instruments used in underground works, electronic and robotic total stations and electronic levels, permit accurate, fast and low-cost results...
Figure 1. Flowcharts of the deterministic and the observational method for tunneling. Following the observational method, in case of high displacements, monitoring data are feedback to the geotechnical model for the modification of the excavation parameters. Only when observed deformation is below certain limits excavation is continued.

referring to a common reference system (in contrast to older techniques permitting estimations of relative displacements only), and even continuous or robotic measurements in large-scale projects. Furthermore, combination of simultaneously operating instruments permit redundant observations (targets measured by more than one instruments), while reflectorless instruments permit to monitor non-accessible points (high towers, building facades, railway lines; Preece et al. 2004). Yet, the most important achievement is probably the real-time acquisition and processing of a large volume of data (for instance a few thousands of targets) using GIS and other software (Kaalberg et al. 2003).

Recently, laser scanners opened up new opportunities in deformation control by mapping not single points but whole structures; an application especially useful in monitoring highly deformed tunnel sections. A representative example is a lined tunnel in Kalgoorlie, W. Australia: at an about 50 m long segment of this tunnel, excavated at the depth of 1 km, high convergence, floor heave and cracking were observed and were mapped by comparison of two laser scanner surveys (J. Franke, unpubl.).

4 CASE STUDIES

Examples of application of the ‘observational method’, i.e. of decisions as to whether the excavation process in various types of underground and open-pit excavations should be modified, or even abandoned on the basis of monitoring results are presented below.

4.1 Experience from Metro constructions

A primary task during Metro construction is the safety of buildings, especially the historic ones, lying above or close to the tunnels. Therefore, minimization of ground settlement is a critical parameter of the construction design, and excavation methodology is adjusted to the results of monitoring of surface areas in order to cause minor disturbance to the existing structures.

4.1.1 Tunneling close to the Big Ben tower, London

Excavation of a metro line station close to Big Ben, the famous clock tower, and the New Parliament Building was a great challenge and the absolute test for
the observational method. The reason is that tunneling through London clays was expected to produce significant surface differential settlements (Mair & Harris 2001) which might prove fatal for this ∼55 m high tower, a very brittle construction made of bricks. Extensive, continuous monitoring of the tilting of this building during tunnel excavation with independent monitoring systems and very carefully planned and executed grouting in its foundations permitted soil recovery and compensation for ground loss due to tunneling and a safe excavation of the metro station (Burland et al. 2001; Mair & Harris 2001).

4.1.2 Construction of a new underground Aigaleo Metro station in Athens

For the new Aigaleo Metro station in Athens, an about 100 × 20 × 12 m wide Station Hall at the depth of 10 m was planned in weak rocks (alluvium, mostly of the historical period). This Hall was excavated as a series of three corridors, each about 7 m wide, with partitioning steel and concrete walls between them. A few weeks after the opening of the galleries, a gradual removal of the two supporting walls was planned. High frequency (nearly continuous) geodetic observations of surface settlement (leveling) and measurement with total stations of tunnel convergence permitted the two steel walls to be successfully removed with minor surface settlement and no problems in the nearby multistory buildings, confirming the validity of initial design parameters and the quality of excavations (G. Papastamos, unpubl.).

4.1.3 Tunneling beneath historical buildings in Athens

The excavation of a new Line for Athens Metro using TBM through alluvium was planned to pass close (∼10 m) to three ∼30 m high, old chimneys made of brick and considered as parts of the recent historical heritage of the city. Monitoring targets were installed at the corners of each chimney, at three different levels (bottom, middle and top) of each structure (Fig. 2) to measure tilting and control the excavation. Measurements before the tunnel reached this area revealed that oscillations of the structures due to wind and various errors were responsible for real or apparent displacements of the order of several mm at the top of the chimneys, a value defining the measurement background noise.

With the excavation face approaching, a gradual tilting of the chimneys towards the tunnel was observed, with up to 15–18 cm maximum cumulative displacement of the monitoring stations. With the distance of face of excavation from the chimneys increasing, sense of tilting was reversed, and when tunnel face had advanced ∼30 m, cumulative tilting was stabilized at lower levels and no damage occurred (G. Papastamos, unpubl.).

Figure 2. One of the chimneys lying close to the new Athens Metro line. The arrows indicate geodetic monitoring targets at the middle and top level of one façade of this structure.

4.2 Experience from road tunnels

The main concern in road tunnels not crossing inhabited areas is the rate and total amount of section convergence. The latter is planned not to exceed certain levels, is time dependent and tends to reach a stabilization level usually four to five weeks after section opening (Sakurai 1978; Muir Wuid 1993, Kontogianni & Stiros 2002). Convergence, however, in weak rocks may reach high values, occasionally leading to failure (for instance the Tymfristos tunnel, Greece; Kontogianni et al. 2004), and systematic monitoring is necessary to select the right measures to respond to unforeseen deformations, avoid failures and permit a safe and low-cost project.

4.2.1 Driskos tunnel, Egnatia highway, N. Greece

At a specific spot of the Driskos tunnel, opened through flysch mainly consisting of sandstone, two months after the stabilization of a certain control section, additional ceiling subsidence of >40 mm was
observed (Fig. 3). Measurements were double-checked and repeated to eliminate any errors.

The possibility of local disturbance (local excavations, bolt failure, local ground instability effects, for instance due to water flow or swelling rocks) as a cause of this resumed deformation was readily excluded. The only effect that could have caused such additional deformation was strain propagating from the excavation front (see Kaiser 1993; Kontogianni & Stiros 2004), at a distance of 20–30 m, where high deformation (70 mm two days after its excavation) was observed (Egnatia Odos S.A., unpubl.). Geodetic monitoring data permitted an early alarm for deformation exceeding specified limits at this and other spots, and led to strengthening of the support system on the basis of prestressed bolts and additional shotcrete along a cumulative length of about 300 m, preventing from possible further complications (G. Chatzigiannelis, pers. comm.).

4.2.2 Predicting weak zones

Tunneling through weak fault zones produces high section convergence, responsible for further loosening of the rock mass and progressive failure of the support measures. The question arising is whether extreme closure can be foreseen and failures can be avoided on the basis of systematic monitoring before the tunnel reaches, or while crossing a fault zone. An answer to that question comes from geodetic data of the Tymfristos tunnel, Greece: excavation of a certain section was followed by crown subsidence with a rate of >15 mm/day and a cumulative displacement of >180 mm in 12 days. Such high strain rates were a clear ‘sign’ of the adverse ground conditions at that section and of forthcoming excavation problems; strain exceeded the critical levels of 2% two weeks after the section excavation and significant disturbance of the surrounding rock induced even higher deformations (>3%), increasing even after the section ring closure (Kontogianni et al 2004; Fig. 4).

Furthermore, certain investigators argue that analysis of 3D displacement data, especially of variations of the orientation of displacement vectors, may permit a prediction of the rock mass quality in front of the tunnel, especially in cases of heterogeneous rocks (Schubert & Riedmüller 1997). Based on this theory, geotechnical models for several tunnels constructed through fault zones in Austria were improved by continuous monitoring of the recorded deformation during excavation (Moritz et al. 2004).

4.3 Experience from mining

Monitoring has recently been extensively adopted in major mining activities as well. The reason is that the need for minimum cost leads to limited, and in many cases only temporary support, while excavations are made at critical levels of rock strength and excavation geometry. Under such conditions failures, occasionally with a death toll, are usual and monitoring is critical for making mining activities safer. Two examples are presented below.

4.3.1 Decision for abandonment of a coal seem based on monitoring data

During the exploitation of a steeply inclined, narrow coal seam in Canada cavings and cracks appeared along the hill surface. An extensive geodetic monitoring system and FEM analysis revealed that ground deformation observed along the hill surface was due to slip along a concealed fault cutting the coal panel (Fig. 5). The upper part of this fault had been ‘reactivated’ by the excavation, and continuation of mining would lead to further slip, failure and blockage of galleries (Chrzanoski & Szostak-Chrzanoski 1985). Inevitably, panel exploitation was abandoned for safety reasons.

4.3.2 Slope stability in deep, open-pit mines

The main concern in open-pit excavations is to maximize slope angle and hence minimize cost, keeping at the same time slope instability effects to minimum.
levels—reduction of the slope of a 1–2 km deep mine by one single degree would raise the cost of production by hundreds of million of dollars! The only way to obtain critical stability (occurrence of small-scale but not major slumps) is the extensive monitoring of the slopes, usually on the basis of numerous targets continuously surveyed by total station instruments, robotic in major projects (Coggan et al. 2001).

5 CONCLUSIONS

The new technique introduced by K. Terzaghi for the excavation of the Chicago Subway tunnels, 70 years ago, subsequently called ‘observational method’ by R. Peck, revolutionized tunnelling and other mining activities.

This technique, merely representing an inductive method, suitable for materials the characteristics of which are rarely known, is in contrast to previously dominating deterministic methods (e.g. Szych 1973). In the observational method the excavation parameters are not inflexibly determined prior to the excavation, but observations of deformation (i.e. of results of the excavation) are used to check excavation models, characteristics of materials, even theoretical predictions. If the observed deformation exceeds certain limits, or has a certain pattern, the corresponding information is fed back and modelling is improved.

The observational method became very popular, if not dominant in the last years, for it permits reduced cost and increased safety, and it can provide solutions to excavations in difficult conditions; for instance in built environment and weak or highly stressed rocks. It can also provide answers to questions such as to whether additional costly measures should be taken, or even whether a project should be stopped, or abandoned.

The success of the method, however, is at least partly due to the advent of a new generation of electronic, mostly geodetic, monitoring instruments.

ACKNOWLEDGEMENTS

This is a contribution to the research project PRAXE of the Greek Secretariat for Research and Technology. We are indebted to George Papastamos, George Chatziigiannelis and Jochen Franke and to Egnatia Odos S.A. for providing unpublished data.

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