MONITORING SYSTEMS IN UNDERGROUND WORKS

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# INDEX

## I-INITIAL STUDY

1. **INTRODUCTION**

2. **UNDERGROUND TUNNELS AND MINES**

3. **FORESEEABLE MOVEMENTS**

4. **SURFACE EFFECTS**

5. **ANTISETTLEMENT MEASURES**
   - 5.1 Reinforcement of the structures.
   - 5.2 Surface loading terrain improvement.
   - 5.3 Depth loading terrain improvement.

## II-SURVEY MONITORING

1. **INTRODUCTION**

2. **SURVEY MONITORING**
   - 2.1 Survey Equipment.
   - 2.2 Communication.
   - 2.3 Control Software
   - 2.4 Control Method

3. **CONTROL POINTS**

4. **TOTAL STATION**
   - 4.1 Atmospheric corrections
   - 4.2 Orientation
   - 4.3 Survey
   - 4.4 Orientation and Reading Cycles

5. **GNSS**

6. **DATA MONITORING**

7. **DATA MANAGEMENT AND ANALYSIS PROGRAM**
   - 7.1 Control de los Instruments
   - 7.2 Database
   - 7.3 Calculation of Coordinates
   - 7.4 Data Analysis
   - 7.5 Consultations
Initial Study
1-INTRODUCTION

During the building of a tunnel or in underground mines, the extraction of material results in the initial state of the terrain being altered, and this in turn leads to movements in the surroundings in order to restore the tensional balance of the ground.

The approximately radial land movements, towards the center of the tunnel and in accordance with its magnitude, can lead to deformations that are dangerous for the buildings, installations or accesses on the surface of the terrain. These radial movements result in surface settlements as well as horizontal movements, which constitute what is known as subsidence. The surface settlements can reach considerable magnitudes of between tenths of millimeters and tens of centimeters.

The final movements largely depend on:

- **Excavation type.**
- **Characteristics of the terrain.**
- **The presence of water.**
- **Building Process.**

During the extraction of material, the surface settlements are measured by means of the loss of ground or the area of the settlement trough resulting from terrain convergence.
2- UNDERGROUND TUNNELS AND MINES

A tunnel is defined as an open underground passage that has been artificially opened to establish a connection either under a river or through a hill or any other obstacle.

Due to the vacuum generated within the mass element, a new balance of forces is established between its immediate surroundings, leading to a tunnel convergence that will inevitably be transmitted to the surface, creating the settlement trough.

Monitoring systems center on determining the tunnel's internal convergence and on reading the settlements that have taken place on the surface.

In the case of various tunnels having been built within the same affected area such as the tunnels and shafts of a mine, the total convergence is the maximum area that can be reached by the settlement trough resulting from the sum of all the convergences. Its effects are usually mitigated by the depth of the tunnels and upper shafts.
The effects of gas and petrol works are similar although, depending on the depth and the type of pocket, these effects will be transmitted to the surface or be mitigated by their considerable depth.
3-FORESEEABLE MOVEMENTS

Prior to sizing the monitoring systems that will control the advance of the works, one must carry out an initial study to calculate the foreseeable movements of the terrain during the building of a tunnel or mine.

The settlement curve of a terrain corresponds to a concave formation with turning points at an "x" distance "x" from the excavation axis. The area of this inverted bell corresponds to the loss of ground around the extraction.

Dimension "x" varies lineally with the "z" depth of the excavation and is independent from the building model. Thanks to the empirical verifications made, "z" and on a very general basis, it is possible to determine the lateral affected area by taking a 45º transverse angle from the lowest perforation point to the surface and a 42º frontal angel from the lowest extraction point to the surface to demarcate the scope of the front or the excavation progress.

In the multiple tunnels and shafts built in a mine, the affected fringe area would be that resulting from the juxtaposition of all the contours.

In oil and gas works, the affected area will also depend on the dimensions of the pocket to be worked, on the depth and on the pressure of the environment on the field.
4-SURFACE EFFECTS

The effects on the surface depend on various elements, such as the terrain type, the presence of water, the construction type and the depth of the excavation, among other factors, but it is here where, starting with these variables, one must study the structures affected by the settlement trough and their distance from the excavation axis.

Whereas differential settlements and horizontal tractions or compressions can be very serious in relatively small measures for structures of few or no foundations, these very same settlements can be intolerable in other types of buildings and facilities.

The tolerability of the movements in building foundation is of an empirical nature in which the magnitude of the possible structural damage is decisively influenced by the following variables:

- The distance from the vertical of the excavation to the affected structure, taking into account fringes ordered according to their settlement level with parallel lines to the perforation alignment.
- The length of the building since, if this is very short in relation to the settlement curve, what results is merely a turn without any angular distortion and causing no damage.
- Due to the concrete content of the buildings, the distortion suffered in traction areas – ”x” distance in relation to the excavation axis – is usually much more harmful than in compression areas.
• The foundation and rigidity of the structure and the ground type sustaining them.

In the case of singular elements such as buildings with a high architectural and cultural value or sensitive industrial facilities, detailed studies can be made of each one of them. In other cases, it is more practical to establish potential damage fringes with a classification of possible damages due to differential settlements.

If the performance area does not correspond to urban surfaces or relevant structural elements, no detailed study on this is necessary even if it is advisable to determine foreseeable settlements and future actions to take place on the land.

5-ANTISETLEMENT MEASURES

Once a study has been made of the possible effects that may result from an underground excavation under a land that lends itself easily to structural damages, one must study what measures can mitigate such effects.

5.1-Reinforcement of the structures.

Reinforcing the structures mainly consists in making them rigid by, for instance, creating a concrete slab of a thickness of more than 1 meter, encompassing existing foundations and being able to absorb the tensions from the tractions as well as foreseeable differential settlements.

Such reinforcements can be executed during the foundation stage before the construction of the structures. Otherwise, if the buildings already existed prior to the perforation, such reinforcements are difficult to execute.
5.2-Surface loading terrain improvement.

Another method that would make it possible to improve the resistance of existing structures against differential settlements lies in improving the mechanical performance of the ground with the injection of concrete bulbs or the insertion of micropiles.

While highly effective, this method requires a thorough follow-up during the injection and subsidence-compensation process as, at the beginning of this, an inevitable breakage of the terrain will take place, leading to a greater settlement than that initially foreseen. Injection compensation must be constant until the settlement balance is reached.

5.3-Depth loading terrain improvement.

A similar method to the above is that of creating piles, screens and injection wells so as to transmit the loads of the existing foundations to lower levels.

As in the previous case, in injection wells it is also necessary to study the effects of a possible breakage of the terrain, continuing with the injection until terrain balance is reached.

These methods are highly effective but require a considerable economic investment. They can be applied to the protection of singular structures or buildings of high architectural value.
II

Survey monitoring
1-INTRODUCTION

Once the most adequate excavation system has been chosen and a subsidence forecast has been made, it is convenient, after the works have started, to check that the land movements remain within the limits foreseen.

For this purpose, one will have to continuously collect data, recording the movements that have taken place. Once the data have been recorded and the movements determined, one must assess if these movements lie within the forecast or exceed the margins established.

2-SURVEY MONITORING

In the interests of a thorough control of the possible movements, an automated follow-up is needed, providing constant information on the movements.

2.1-Survey Equipment

The control system is carried out with a set of survey instruments: the Total Station, control prisms and/or GPS.

2.2-Communication

This device connects the Survey Instruments with the Control Center, sending the data recorded and receiving new reading instructions.

2.3-Control Software

a.i) Control Server

A Control Terminal for receiving, recording, calculating, analyzing and displaying the set of data. It also transmits the new reading instructions to the instruments.

a.ii) Consultation Terminals

A software application for consulting data to observe the monitoring progress in real time. Its display may be made by means of a Web connection.
2.4-Control Method

Due to the long data collection forecast, the system is designed in a fully automated manner and it records, manages and informs on possible movements without any need for an on-site operator.

The function of the Total Station is that of measuring the set of prisms distributed in the area to be monitored in keeping with a pre-established observation cycle. Once each one of the readings has been recorded, it sends the measurements, by means of the monitoring device, to a management center that processes and analyzes the data, modifying, if necessary, the reading cycles and sending the new instructions to the Total Station via the monitoring device itself.

The results are compared against pre-established tolerances. Should the movements exceed those foreseen, the system will generate a warning signal, classifying the movement, according to the threshold reached, within green area (foreseen movement), amber area (movement increase alert) and red area (alarm from instability or possible structural damage).

The system may optionally have a GPS GNSS to obtain absolute coordinates and thus detect movements that may even encompass the area where the Total Station has been established.
3-CONTROL POINTS

It will be necessary to have a set of control points fixed on the affected surface. The movement of these points will be studied, which means that the modeling and extrapolation of a movement forecast model will require an analysis of the position each one of them must be in and the subsequent comparison between the vector movement of each point with the model foreseen.

In order to maintain a state of measurements on the points, the latter will be materialized with prisms and/or GNSS antennae anchored on the terrain.
4-TOTAL STATION

The **Trimble S8** High Precision total station (1” angular accuracy) is the high-range instrument that has been specifically designed for monitoring. The S8 Trimble Station will be used for measuring the prisms distributed in the area to be monitored.

The function of the total station is that of reading the position of the prisms, recording the horizontal angle, vertical angle and slope distance. These polar variables will be subsequently transformed into a Cartesian system of coordinates.

The **Trimble S8 Vision** model, besides, has an internal camera with which one can remotely observe on video the visuals being carried out by the instrument and, thanks to SETTOP M1 monitoring device, observe the objective in real time.

The accuracy level of this instrument is at a sexagesimal second in angular accuracy and 1 mm plus 1 ppm (parts per million) of the distance collected, which means that, if we carry out an average reading at a length of 100 m, we will obtain a maximum-probability point target of:

- **Transverse Deviation (angular)** = 100m x Tg (1”) x √2 ≈ 0.7mm
- **Longitudinal Deviation (distancemeter)** = 1mm + 1 x 0.1 ≈ 1.1mm

4.1-Atmospheric corrections

Survey instruments have a distancemeter, which very accurately measures the length between the main axis of the instrument and the prism. Basically, the distancemeter emits an electromagnetic wave that is reflected in the prism and returns to its starting point. The difference in amplitude between the wave emitted and that received determines total length.

As their means of propagation is air, the waves are affected by atmospheric pressure, temperature and, to a lesser extent, the percentage of humidity of the air, being forced to correct each one of the distances collected with these variables.

The **Trimble S8** station has a barometer, with which the only determination made is of the temperature – as well as, optionally, the humidity percentage - to correct the distance. For this purpose, it is advisable during any monitoring to install a weather station to provide the temperature and humidity percentage data and thus, along with the value of the pressure, calculate the distance corrected in all the readings.

In order to convey information from the weather station, the sensors are connected to the M1 monitoring device and this, in turn, sends the data to the control center, which will calculate the distances corrected.
4.2-Orientation

Before starting the readings on the points to be monitored, the instrument must be orientated so that it works on the basis of a pre-established Cartesian system. There are three possibilities:

a) Arbitrary orientation: The orientation is not specified, and we use that shown by the instrument by default or edit one directly.

This is a valid orientation for determining the differentials between successive points but it is not advisable for observing the absolute movements of the points to be monitored.

b) Direct orientation: Having established the coordinates of the instrument and of the orientation point, we carry out a visual verification, making the orientation of the instrument the same as that of the calculated between the two points. After one or several cycles, the instrument will carry out another reading of the reference point in order to update the orientation.

This system allows us to determine the movements of the points to be monitored in absolute terms. One must make sure that both the instrument and the orientation base lie outside the affected area. Should this be impossible, a second GPS GNSS should be installed for updating the coordinates of the instrument and/or the orientation point.

*Azimuth: A polar angle that stems from the source point (instrument) with reference to the North of the Grid (very close to the Geographical North) until the orientation point is reached.
c) Reverse Intersection: Having determined the coordinates of several reference points, we shall make readings of the set of bases in order to assign coordinates and azimuthal orientation to the instrument.

This method updates the coordinates and orientation of the instrument after each cycle of reference prism readings. It is recommended for areas in which the instrument lies within the affected area as long as the orientation points are located outside this sector.

Otherwise, the coordinates of the orientation bases should be restored by means of a GPS System on a regular basis so that the instrument periodically collects readings of these bases with updated coordinates.
4.3-Survey

Once the instrument has been properly oriented, one must read the prisms distributed within the affected area. The first “0” reading cycle will serve the purpose of determining their approximate location, while in the next cycles, a search system based on the reflectivity of the prisms will once again record the reading on the objectives. The instrument will subsequently carry out a fully automated relocation and measurement of the same control points taken in the first cycle.

The first reading will calculate the source data that will serve the purpose of comparing the data that are successively collected. Thus, during a terrain consolidation process, the graphics would detect the movement taking the first readings as the starting point.

In order to ensure that the results reach the nominal precision of the equipment, it is advisable to carry out several readings of one single objective. It is likewise highly recommendable to carry out Direct Circle ad Reverse Circle readings – which process is also known “Bessel”- calculating the average of them all.

4.4-Orientation and Reading Cycles

It is advisable for occasionally verify the orientation of the instrument or simply reorient it. This is highly important if we are to detect possible anomalies regarding disorientations or subsidence in the area where the instrument has been placed.

For this reason, once all the objectives have been taken, one must establish the orientation and reading cycles, that is, the number of times the instrument is to record all of the objectives every time its orientation is renewed.
5-GNSS

The Global navigation Satellite System or GNSS, better known as GPS, contributes the absolute position of a base. It is suitable for large control extensions or whenever one must check if the area where the instrument is located and/or some of the orientation points lie within the settlement trough.

If this be the case, the GNSS system should contribute a regular updating of the absolute coordinates of the reference bases. In such a case, the antenna would be preferably situated en la vertical of each one of the orientation prisms and/or within the proximity of the instrument.

Its nominal precision lies within the region of 1 cm in Post-Process mode and 2 cm in Real Time (RTK). For this purpose, the positioning of the reference antennae must be far enough for its precision not to affect the determination of the instrument’s orientation.

If the instrument lies within the affected area, the antennae may be arranged as follows:

a) Direct orientation: A GNSS antenna is installed next to the instrument and another one is placed vertically in relation to the orientation prism. The antennae will determine the differential movements of the instrument as well as the orientation azimuth.

b) Reverse Intersection: A set of antennae are established vertically in relation to the reference prisms. The instrument will update the coordinates supplied by the GPS and, following the reading of the prisms, recalculate their position and orientation.
6-DATA MONITORING

Once each one of the data has been recorded, they will have to be sent remotely to the control terminal. The device that carries out communication between the instrument and the control terminal is the **SETTOP M1**.

**SETTOP M1** is a reference GNSS receiver with a remote control of the Total Station. It makes it possible to manage GPS data while also controlling the monitoring of the Total Station via various communication ports such as:

a) **Wi-Fi or WiMAX** for large extensions without GSM coverage.

b) **Ethernet network cable**.

c) **GSM telephony**.

It is fully configurable by means of a web interface.

M1 is the device for communicating the instrument with the control center. On the one hand, it sends the data recorded and, on the other hand, it provides new instructions. It can also carry out the double Base-Mobile function with connection to a double frequency receiving antenna. Moreover, thanks to its multifunction concept, it can connect multiple sensors such as weather stations or geotechnical sensors.
7- DATA MANAGEMENT AND ANALYSIS PROGRAM

SETTOP MONITORING is the data management and analysis program. It may be said that it serves as the brains of the whole monitoring process. Monitoring would not be possible without SETTOP MONITORING. This software makes it possible for one to open a work, configure the geodesy, edit the monitoring parameters such as orientation, prisms to be monitored, repetition cycles, control Survey Instruments and sensors and then record, calculate, analyze and show the set of data received.

7.1-Control of the Instruments

Before beginning the survey, it is necessary to indicate the readings to be taken by the instrument or instruments used for the MONITORING. Once the reading cycles have been established, SETTOP MONITORING will send the instructions on the Survey Instruments so that the survey is begun. Parallel to this, once the process has been initiated, it will record the data for subsequent analysis. In turn, it will also receive the data of the GNSS receivers as well as of the weather stations and other sensors.


7.2-Database

The software consists in a Database that records and manages the large amount of data to be transmitted by the Total Station and the GNSS receivers. This database will be classified in a list with a temporal reference where the relevant consultations may be made.

The database systematically takes down all of the records so that they may be subsequently used in a fast, simple and structured manner.

Being a database, it permits such operations as updating, deletion and adding as well as some of the basic reference actions.

7.3-Calculation of Coordinates

Once the data have been recorded, the next step is that of calculating the coordinates. For this purpose, if the data have been obtained with a Total Station, the software will reduce the distances with the atmospheric variables. Likewise, sphericity and refraction corrections will be applied to the vertical angles and, if a geodesy has been selected, it will assess its anamorphosis coefficient.

If the data have been obtained with GNSS receivers, the corresponding Datum change will be effected and the coordinates will be changed to the projection selected.
7.4-Data Analysis

With the coordinates calculated from the corresponding geodesy, SETTOP MONITORING will process and analyze the data, generating movement-time graphs to obtain the vector velocities of each one of the control points. The results will be compared with a forecast of movements in which, if necessary, an alarm signal will be generated in the event of their exceeding limits that have been pre-established in accordance with a calibration (green, amber or red).

7.5-Consultations

The data can also be consulted by other terminals where they will be displayed in a fast, intuitive manner. These results will be observed on easily readable graphs where analyses will be made of daily, weekly, monthly and even annual data. The purpose is therefore that of obtaining general trend graphs where one may observe the stabilization asymptote of the terrain and be able to predict the quasi-stabilization of the environment.

Consultations may be made via web server, it being possible to observe the process from any terminal that has access to the consultation of the monitoring data.