Case Studies of Tunnel Instability and Interaction with the Ground Surface and Manmade Structures

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1 author:

Giovanni Barla
Politecnico di Torino

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CASE STUDIES OF TUNNEL INSTABILITY AND INTERACTION WITH THE GROUND SURFACE AND MANMADE STRUCTURES

G. Barla
Former Professor of Rock Mechanics, Politecnico di Torino, Torino

ABSTRACT

The purpose of this paper is to address four forensic cases dealing with tunnels and underground excavations. The interest stems first from problems met during excavation in terms of stability conditions of the tunnel face and of the crown, with reference to excavation by conventional methods. Then, consideration is given to cases where tunnelling resulted in interaction with the ground surface and manmade structures. The role of the geotechnical engineer as a forensic expert is underlined with reference to the collection of geological and geotechnical engineering data including the results of observation and monitoring, and evaluation of failure scenarios, not disregarding considerations on the causes and responsibilities.

1. INTRODUCTION

The paper deals with "forensic geotechnical engineering", with the understanding that "*geotechnical engineers must apply science and engineering within the rules and practice of the legal system in order for their work to be effective in representing reality and resolving conflicts*" (Lacasse 2016). The attention is dedicated to tunnels during excavation in terms of stability conditions of the tunnel face and of the crown, with reference to excavation by conventional methods. Also considered are cases where tunneling resulted in interaction with the ground surface and manmade structures.

It is important to underline here that reference is made first to cases of serious work-related incidents at construction sites and then to design issues and problems in terms of difficulties met due to the interaction of tunnels with manmade structures, which resulted in important damages and failures. It is noted that the interest stems from cases where the need to ascertain the cause or responsibility for a failure or of a damage during construction of a tunnel, not disregarding the ascertaining of the economic consequences for one or several parties.

The importance of using good science and engineering is underlined in conjunction with the need to presenting findings and to answer different questions. It is to be kept in mind that in these cases questions are generally posed by a layperson (a prosecutor, a judge, a lawyer,…) and that the answers need be given in a clear and easily understood manner, providing a well-documented presentation of facts by using the investigation methods which are needed.

2. PRELIMINARY REMARKS

Tunnelling and underground works in general are difficult both at the design stage and during construction. It is not only a question of geological, hydrogeological, and geotechnical conditions along the tunnel alignment or at a given site. The need arises to understand in quantitative terms the reaction/response of the ground (soil, rock mass) to excavation and to assess the hazards associated with excavation (i.e. failure modes, magnitudes and characteristics of displacements, stresses in the supporting structures, etc.).

It is also important to understand that incidents during construction may lead to injuries and fatalities, including the additional obvious consequences in terms of time overruns and increase in cost, with lawyers and courts becoming increasingly involved. It is true however, that today methods are available for investigation of ground conditions at the design stage and during construction, which should allow one to identify the hazards in advance and adopt the measures in the form of appropriate excavation and support methods.

It is clear that our ability to cope with a variety of problems in geotechnical engineering, and thus with tunnelling, has been enhanced through the years. This ability, which need indeed be used at the design and construction stages, is as well important in forensic geotechnical engineering, when the geotechnical engineer is to provide assistance in the understanding the cause of a failure, the responsibility at the design stage for something that went wrong, including in cases the settlement of disputes.

Today, new tools are available for geological and geotechnical investigations, including acquisition and visualization of discontinuity data and rock mass characterization, such as stereoscopic imaging by means of specially designed cameras (Gaich & Pischinger 2016) or terrestrial laser scanning (Barla et al. 2016a). These tools have reached high accuracy and resolution levels; given the reduced acquisition and processing time, they can be adopted underground, to reduce the presence of people at the tunnel face and thus increase safety.

At the same time, systematic and frequent monitoring at the ground surface and underground is possible continuously and in real time. Conventional monitoring (by borehole inclinometers and extensometers, piezometers, strain meters, etc.) is used, associated with computerized data acquisition. Improved and advanced techniques such as robotic total stations and reflective targets may provide three-dimensional displacement plots, which can be well visualized. Similarly, the Interferometric Synthetic Aperture Radar from both satellite and ground based may provide high precision time series of ground movements (Barla et al. 2016b).

We can observe that the increase of computer power facilitates the use of numerical methods in geotechnical engineering (Barla 2016). With the above investigative and monitoring tools used in the field, associated with more advanced investigations methods in the laboratory (Barla et al. 2010a, b), data can be obtained to ensure that the calculations performed by such methods lead to realistic results, which can be checked and well understood. Given these fortunate conditions, which were not those of the time when numerical methods were initially developed, it is our duty to calibrate our models with real data and use them as forward prediction tools.

3. TUNNEL INSTABILITIES AT THE FACE

Tunnelling by conventional methods, i.e. drilling and blasting or mechanised excavation (e.g. with a road-header), implies sequential or full face advance each run, depending on the ground conditions encountered and the type of pre-support/pre-consolidation measures adopted, when needed, in order to keep the face stable. In all cases, a support in the form of rock bolts/rock dowels and/or steel sets and shotcrete lining is installed. Miners generally work in the near vicinity of the face and under the tunnel crown, which need be stable at all times as failures of any type could result in injuries and even fatalities.

The first case study described deals with a face instability occurred in a tunnel excavated by conventional methods, with the primary support consisting of steel sets and shotcrete. The type of failure resulted in serious injuries of a miner during installation of the support. With the second case study, the roof instability near the face of a drilling and blasting tunnel during installation of rock bolts is illustrated. This incident resulted in a miner's death.

3.1. Case Study 1

Figure 1 left shows the face of the Ceppo Morelli Tunnel (Italy), in the NW Alps, where a rock block instability did occur which, as anticipated, was the cause of very serious injuries to a miner. The rock mass consists of mica-schist and para-gneiss, not significantly weathered but fractured, with a Rock Mass Rating (RMR) index in the range 33-47, i.e. from Fair to Poor rock mass quality. As shown in Figure 1, the tunnel had been excavated full face, following the TBM excavation of a small size exploratory tunnel (3.5 m diameter).

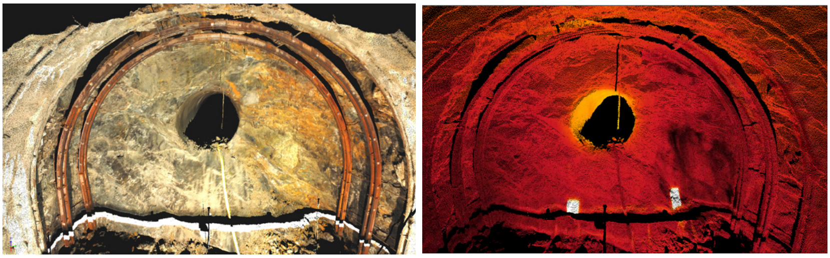

Figure 1. Rock mass at the tunnel face where the accident occurred during placement of the tunnel support. Point cloud obtained with the TLS, colored with of the optical camera images (left) and on the false-color infrared thermal map (right).

The scope of the forensic geotechnical engineering evaluation was *to ascertain, based on the technical investigations needed (technical visits, collection of available data, field observations and technical investigations, etc.), the causes of the rock instability.* In addition, it was asked *to assess the predictability and possible avoidance of the incident, from both the technical point of view and the compliance with the applicable legislation.* In other words, the task was to come to an opinion as to the factors that led to the rock instability and were ultimately responsible for what occurred.

With the intent to investigate the rock mass conditions, in addition to other investigations, a

3D geomechanical model of the rock mass was created, to identify instabilities forming at the tunnel face and along the tunnel perimeter. Both Terrestrial Laser Scanning (TLS) and Infrared Thermography (IRT) were used. TLS scanning was done from points, located at a distance of 14 m and 6 m from the face, and allowed the acquisition of a 22,106 point cloud, as shown in Figure 1. Note that the 3D geometry of the rock face was textured with the IRT thermal images.

The work performed at the site in the zone of the incident allowed the rock mass conditions to be studied in detail, without the need to access the area, i.e. by standing at the minimum distance of 6 m. This means that most of the rock mass discontinuity data obtained in a conventional geological mapping work, can be interpreted safely and reliably. Figure 2, as an example, gives on the left the stereographic plot of all the discontinuities in the rock mass in the area of interest, compared to the corresponding plot on the right obtained by conventional mapping during excavation of the tunnel up to the incident area.

The analysis of the weighted distribution of the discontinuity poles detected by TLS highlights the presence of at least seven different discontinuity sets. The comparison highlights that, similar to the TLS results, seven main discontinuity sets are also present in the plot obtained with the conventional mapping data, although all the discontinuities are not indentified in a single tunnel section. In all cases the schistosity planes (S1 - KA) and the discontinuity set (S4 - KC) are well identified in both cases. A greater variability is visible in the schistosity orientation based on the TLS data.

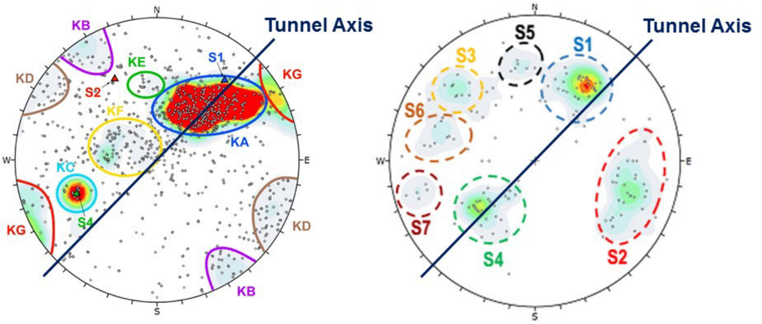

Figure 2. Stereographic plot of discontinuities based on TLS survey (left) compared to the corresponding plot obtained by conventional mapping (right).

The TLS point cloud, in particular, could be used to determine the distance between the extrados of the steel ribs and the excavation contour as shown in Figure 3 (left). In this manner, it was possible to identify a typical sector along the tunnel profile with very significant over break (the maximum distance from the steel ribs reaches 1.4 m). This important geometric anomaly along the tunnel contour was interpreted as evidence of rock blocks detachment. This did allow reconstructing the source of instability, performing kinematic analysis at the roof, on the sidewalls and on the tunnel face. As example, Figure 3 (right) illustrates the rock blocks which formed on a selected portion of the tunnel, together with the onset of the instability modes identified.

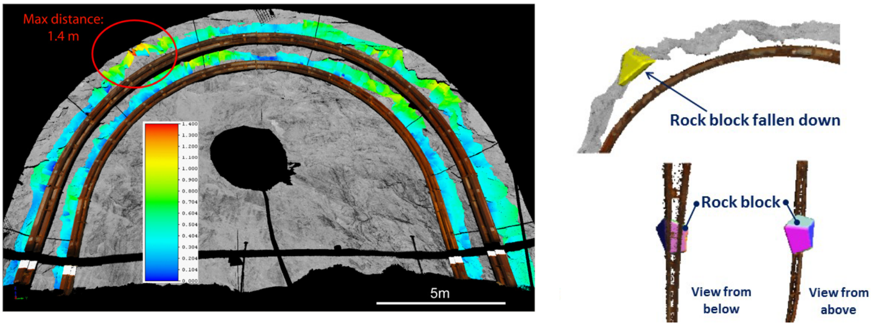

Figure 3. Point cloud obtained with the TLS (left), showing a typical sector along the tunnel profile with very significant over break. Detail (right) of the kinematic analysis performed.

The work done as part of the investigations performed, briefly illustrated above, allowed one to identify the zone of instability at the tunnel contour and the over break occurred, essentially due to the inappropriate scaling procedures adopted. The absence of shotcrete placement at the face and along the tunnel perimeter prior to resuming the working stage, including placement of steel sets, was indicated as a possible cause of the incident occurred at the face, this together with inadequate compliance with the approved safety standards.

3.2. Case Study 2

The scene of the rock detachment from the roof of the Bocciol Tunnel, near to Gravellona Toce (Italy), is shown in Figure 4. Two equipment used for rock bolts installation (photograph on the left) were badly damaged due to a free fall of a rock block (estimated volume of 2m^3 approximately) from the crown. A miner was killed. The rock mass consists of granite, with a RMR index of 60-70, i.e. Good rock mass quality. The tunnel had being excavated full face, by drilling and blasting, with rock bolting and shotcreting as support.

The scope of the forensic geotechnical engineering evaluation, quite similar to that reported for case study 1, was *to ascertain, based on the technical investigations needed (technical visits, collection of available data, field observations and technical investigations, etc.), the causes of the crown instability.* In addition, the forensic geotechnical engineer was asked *to report, from a technical point view, if the rock fall could be anticipated and in particular, to highlight any possible non-observance of the safety regulations regarding the work activities carried out in the tunnel.*

As for case study 1, attention was placed first on the description of the rock mass conditions in the area of the incident, along the tunnel length already excavated, not disregarding a study of the geological and geomechanical conditions along the tunnel alignment, prior to and following the tunnel chainage reached with the excavation. In addition, due to the type of support adopted, a detailed study was undertaken on the drilling and blasting method adopted and the rock bolting-shotcreting sequence being applied.

Figure 4. Zone of the incident near the tunnel face. Two equipment badly damaged (left). Detail of the rock detachment area at the tunnel roof (right).

In this case, again in line with the intent to provide an objective and well-documented study of the rock mass, a three-dimensional data acquisition was performed. Now, the remote image-based measurement system was used (Gaich & Pischinger 2016). The investigated area comprised the tunnel face, sidewalls and crown at the excavated chainage. An example of the generated 3D images showing the overall tunnel face situation and giving also the rock mass structure is illustrated in Figure 5.

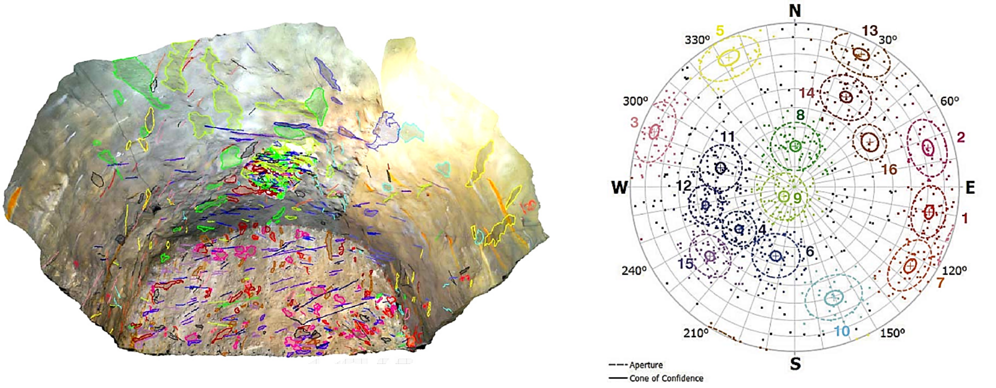

Figure 5. Zone of the accident near the tunnel face. Structural map showing the rock mass discontinuity sets (left). Stereographic plot of the discontinuity sets (right).

In particular, it is of interest here to bring the attention on the configuration of the structures at the detachment area analyzed separately as depicted in Figure 6. In this manner an analysis of the rock surface, with the only measurements performed in the detachment area is obtained, by rejecting structure sets with five or less measurements. It is found that all sets of the set concentrations II and III, and parts of the sets of set concentration IV dominate the rock mass structure in the detachment area. Surprisingly, the subvertical sets are only subordinarily present although the free face orientation in this area would favor their appearance.

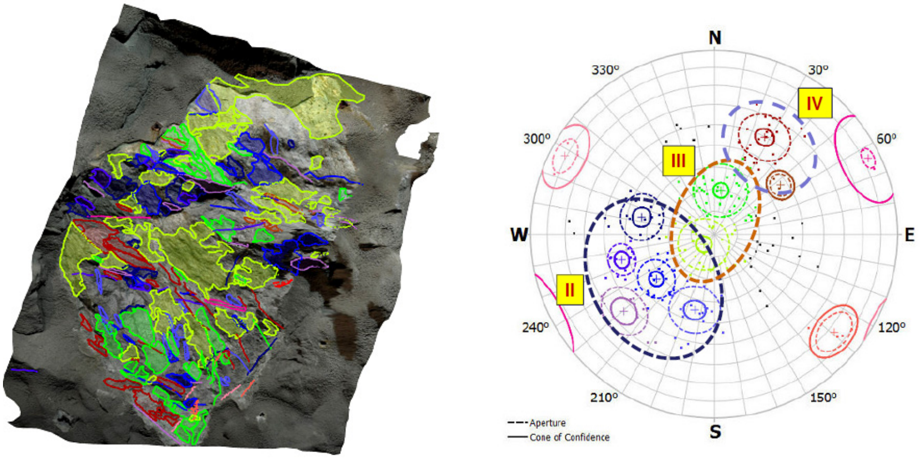

Figure 6. Structure map showing the detachment area (left). Stereographic plot of the fracture orientations with the predominant horizontal discontinuities III (right).

As one would expect, most of the arguments, raised from the results of the forensic investigations briefly reported above, were dedicated to the nature and origin of the predominant horizontal discontinuities III shown in Figure 6. The question posed was: the horizontal discontinuities, which obviously caused the detachment of the $2m^3$ rock volume (a rock slab) from the tunnel crown, were "intrinsic" to the rock mass or rather "induced" due to inappropriate blasting operations.

The work done as part of the investigations performed allowed one to study the zone of detachment at the tunnel crown in detail as indicated above. In addition, a thorough analysis of the entire process of tunnelling by drilling and blasting, with bolting and shotcreting of the tunnel crown, was undertaken, showing in each case the appropriate perfomance. The one lesson learned is that presenting the facts in a documented manner and possibly in understandable way is the best tool available to the forensic geotechnical engineer.

4. INTERACTION WITH GROUND SURFACE AND MANMADE STRUCTURES

In cases, tunnels are excavated near the ground surface, as in urban tunnels. In other cases, given the alignment chosen at the design stage, tunnels are excavated in mountainous areas, where deep-seated landslides may be present. In addition, tunnel excavation may take place under inhabited areas or in the near vicinity of existing manmade structures, such as infrastructures. In all these cases, the likely interaction of the tunnel during excavation need be anticipated and appropriate measures adopted to avoid any possible damage.

With the third case study, the attention is dedicated to a tunnel excavated in an urban area, where a collapse of a heading during excavation took place and resulted in the damage of an apartment block. There were no injuries or fatalities to the workers or the public. Finally, the fourth case study is on the excavation of a large size twin tunnel, in complex geological, hydrogeological and geotechnical conditions, which resulted in progressive ground movements on the ground surface due to the reactivation of deep-seated landslides.

4.1. Case Study 3

This case study is concerned with the 3.1km twin tube tunnel, part of the Sydney orbital highway. The interest is on the collapse at the intersection of the MC5B ventilation adit and the rising MCAA exit ramp as shown in Figure 7 (left). The cover at this point is some 17m. The incident occurred initially with small blocks of rock and shotcrete falling from the crown. Workers evacuated the heading as the fall progressed and reached the surface.

A cavity was formed under the corner of a three-storey apartment block and under the retaining wall of an exit ramp as illustrated in the photograph of the same Figure 7 (right). The rock mass in the area is a jointed weak shale. Of importance is the presence of an almost vertical, low-strength dolerite dyke cutting across the wide 17m-20m diagonal span of the intersection (Figure 8).

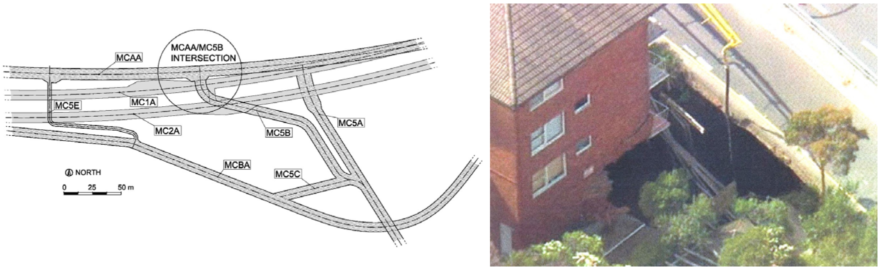

Figure 7. Zone of the incident. Intersection of the MC5B ventilation adit and the MCAA exit ramp (left). Photograph of the corner of the three-storey apartment block (right). WorkCover Lane Cover Collapse Incident Report 2006.

The scope of the evaluation was *to provide an expert opinion on the collapse by means of a model, which was to simulate the likely behavior of the tunnel in the as found conditions. This was to be done assuming the tunnel had been excavated and constructed in accordance with the tunnel design.* This expert opinion was part of the proceedings in front of the Supreme Court of North South Wales, Australia. These proceedings were commenced by the joint venture (responsible for the design and construction of the tunnel), against the engineers responsible for the structural design of the works; the engineers responsible for monitoring ground conditions; and the engineers in charge of verifying the designs.

In line with the scope of this paper, the model implemented, by means of a Distinct Element Method (DEM) analysis, in three-dimensional conditions, will be briefly presented without providing details. The purpose of the modelling has been to assess the stability conditions of the excavation. The reliability of the modelling therefore depends on the level of understanding achieved in describing the rock mass conditions and the methods adopted for the analysis of stresses and displacements around the tunnel and in the supports.

As shown in Figure 8, the modelling involved a detailed simulation of the excavation and construction sequence. It is worth to note that included in the model is the support of the

MC5B and MCAA tunnels and of the intersection, all of this in accordance with the chosen rock-bolting lengths and patterns, including the shotcreting installation and sequence. This implies that in each face advance shotcreting and rock bolting was taking place as per the tunnel design. The weak shale including bedding planes and joint sets was represented in the DEM model as illustrated in Figure 8 (right).

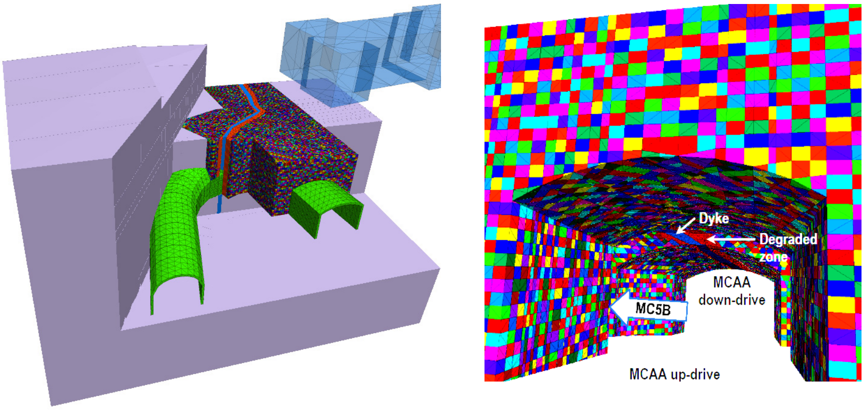

Figure 8. Illustration of the three-dimensional DEM model. Intersection zone showing the almost vertical, low-strength dolerite dyke (left). Detail of the rock mass represented as a discontinuum (right).

A visualization of the modelling results is given in Figure 9 where plotted are the displacement distributions around the tunnel, in the intersection, and at the ground surface at the end of excavation. The modelling shows that the maximum displacements, before a stable condition is reached, would occur at the midpoint of the intersection zone and propagate toward the corner of the three-storey apartment block, also shown in the plots.

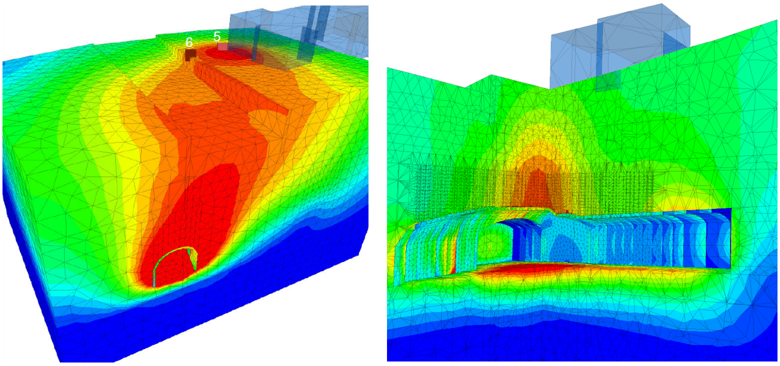

Figure 9. Displacement distribution around the tunnel and at the ground at the end of excavation View from above (left). View from the intersection (right).

The modelling work done as part of the expert opinion shows that the tunnel is stable if the tunnel design, including excavation and construction of support (shotcrete and rock bolts) is implemented. The modelling also shows that the roof in the intersection zone is stressed, resulting in shearing along the beddings and in the anchoring points of some of the bolts reaching the limits of their capacity. It is noted that the bolts form one component of the tunnel support, which is formed by the combination of the fibre reinforced shotcrete, the tensioned rock bolts, and the anchoring points of those bolts.

4.2. Case Study 4

This case study considers a large size twin tunnel (each tunnel with 160m^2 cross section) along the new length of the A1 Highway between Bologna and Florence, opened to traffic in December 2015. These tunnels were excavated full face with systematic reinforcement of the face and of the tunnel surround, with the final lining casted close to the face. Excavation was through a flysch rock mass (sandstone and mudstone layers. The rock mass at the tunnel face was generally Poor to Very Poor, with the RMR index in the range 25-30.

As shown in Figure 10, the two tunnels were excavated under a slope with inhabited areason top, where deep-seated landslides, inventoried as “quiescent landslides” in the landslide database, were present. During excavation of the two tunnels, with one face preceding the other one of 80m, surface and subsurface movements occurred, resulting in the reactivation of the landslides and damages to the houses and infrastructures on the ground surface.

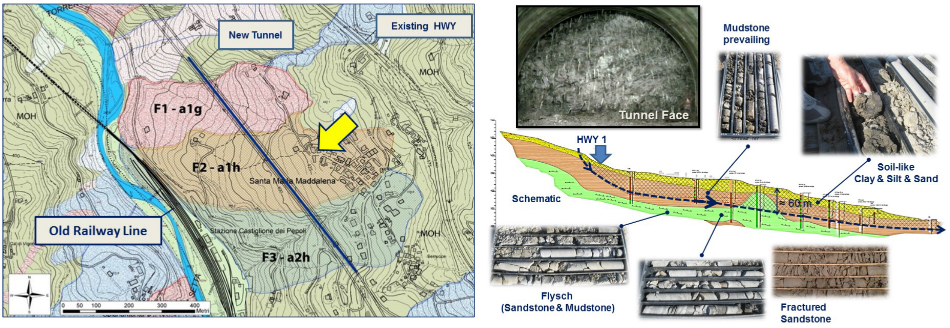

Figure 10. Area with the new tunnel, the landslides (F1, F2, F3), the inhabited areas, and infrastructures (left). Slope cross section following geotechnical investigations (right).

One of the objective of the forensic geotechnical engineering investigation was to ascertain, based on the available and newly obtained data, if *the reactivation of the landslides, and therefore the damages to the houses/infrastructures on the ground surface were caused by the excavation of the new tunnels.* In addition, the investigation had to ascertain if *the design of the tunnels was negligent in any ways, given that the reactivation of the landslides was not predicted, including the considerations of defects in the actions taken by the different parties involved during construction.* Only the first aspect, dealing with the link between tunnel excavation and landslides reactivation, is addressed in the following.

With the interest to underline the investigative and monitoring data, and tools that have been used in order to ascertain the reactivation of the landslides due to tunnel excavation, it is remarked that the area shown in Figure 10 (left) had been heavily instrumented with conventional equipment such as inclinometers and piezometers. In addition, a number of Robotized Total Stations (RTS) were installed. This allowed for the close interpretation of the temporal evolution of slope displacements of target points placed on a number of sensible structures and buildings on the ground surface as a basis of early warning systems.

Of particular interest, in order to cover the entire period of tunnels excavation, by going back in time, were the Interferometric Synthetic Aperture Radar (InSAR) data from both ascending and descending geometries by three different satellites (or satellite constellations) during about a decade (Barla et al. 2016b). Figure 11(right) shows a typical temporal map of points on the ground surface with different velocity, while Figure 11 (right) gives for a chosen time span a plot of the displacement history.

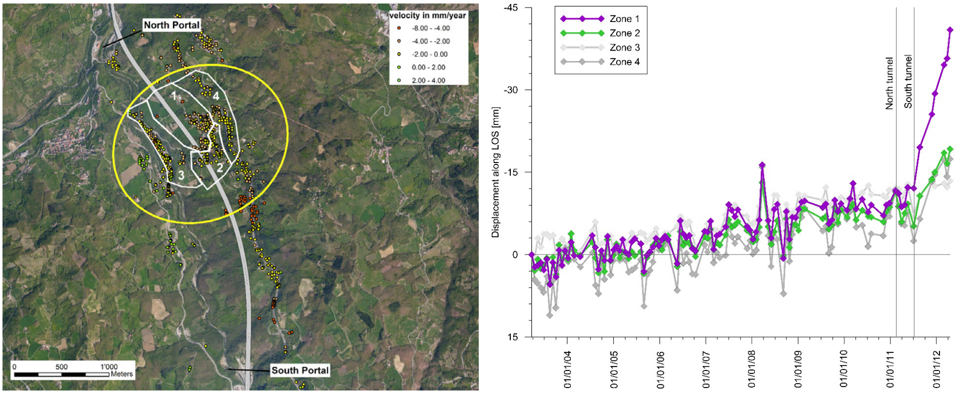

Figure 11. Area of interest above the tunnels with superposed points undergoing different velocity (left). Displacement history along the line of sight (LOS) for points in areas 1, 2, 3, and 4 (right).

The main results obtained from the analysis let one conclude that before tunnel excavation, prior to the installation of any other conventional monitoring instrumentation, a displacement rate of few mm/year was observed in the area of interest. However, a sudden acceleration was observed during tunnel excavation, starting from 2011 (displacement rate up to 60 mm/year between 2011 and 2013). In accordance with tunnel excavation and face advance, surface movement developed progressively, with clear evidence of reactivation of the deep-seated landslides.

It is of interest to remark here that with the suite of geological and geotechnical data becoming available progressively, including characterization studies and monitoring on the ground surface as underlined above and at depth (Figure 10), a three-dimensional numerical model could be implemented (Barla 2016). The intent was to back analyze the early data of surface (essentially based on INSAR and RTS data) and below surface movements (from inclinometer data), in order to gain insights into the interaction between tunnel excavation and surface movements.

5. CONCLUDING REMARKS

The main purpose of this paper has been to give a picture of the complexities, through real life examples, taken from personal experience of "forensic geotechnical engineering", associated with tunnelling problems during excavation. The choice has been to describe first problems dealing with the stability conditions of the tunnel face and of the crown, during construction. These resulted in serious work-related incidents. Then, the attention moved to problems and difficulties met due to the interaction of tunnels with the ground and manmade structures, which resulted in important damages and failures.

The importance of using "good science and engineering" has been underlined, complemented with the adoption of novel investigative and monitoring methods, which are progressively becoming available. The use of modelling, e.g. "realistic numerical modelling" in particular, has been highlighted. The point raised here is that these tools, which should be responsibly used at the design stage for forward predictions, have a very important role in "forensic geotechnical engineering" for the purpose of providing, in a clear and easily understood manner, documented presentations of facts.

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