# A case study of monitoring tunnel wall displacement using laser scanning technology

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**Abstract:** Displacement monitoring is a common practice in rock engineering to observe the evolution in time of the rock mass behaviour and to predict potential stability problems that may occur in the future. This typically involves repeated measurements of the relative or absolute displacement of a limited number of reference points within the rock mass or on the excavation surface at different times.

The use of 3D laser scanners allows coping with practical constraints encountered in rock engineering since it provides quickly a realistic and permanent representation of excavation surfaces that can be used for topographic surveying, rock mass characterization and documentation purposes. Additionally, these systems do not require the installation of physical targets on the rock surface and have therefore the potential to be employed on a regular basis as an efficient and unique tool to record input data required for various engineering analyses.

The paper presents a case study where the Imager 5003 laser scanner of Zoller+Fröhlich was employed to measure surface displacements in an experimental tunnel throughout and after its excavation. The Imager 5003 3D laser scanner is particularly well adapted to applications in underground excavations because of its scanning principle (panorama scanner), the 3D-accuracy of single points (few millimetres), and its high performance (up to 625,000 points per second). The reliability of the method has been assessed by comparing displacement measurements provided by the laser scanner with those calculated from total station surveying of markers installed on the tunnel surfaces. The determination of absolute displacements has been made possible by referencing the data obtained from the laser scanner and the total station to an established coordinate system. The main objective of the work is to assess the potential of this technique in deriving time lapse surface displacement maps of rock outcrops with a high spatial resolution. The developed field methodology, processing algorithms and preliminary results are presented in this paper.

**Résumé:** La mesure de déplacements est une pratique couramment utilisée afin d'observer l'évolution temporelle du comportement des masses rocheuses et de prédire d'éventuels problèmes de stabilité. Des mesures du déplacement relatif ou absolu d'un nombre limité de points de référence situés au sein ou à la surface de la masse rocheuse sont ainsi réalisées régulièrement durant les travaux d'excavation.

L'utilisation de scanners laser 3D permet de surmonter plusieurs contraintes pratiques généralement rencontrées lors de travaux d'ingénierie en milieux rocheux. En effet, cette technologie fournit rapidement une représentation réaliste et permanente de la surface d'une excavation qui peut être ensuite utilisée à des fins de relevés topographiques, de caractérisation de la masse rocheuse et de documentation. De plus, ne nécessitant pas l'installation de cibles physiques sur la surface rocheuse, ces systèmes peuvent donc employés de façons régulière et efficiente afin de collecter des données utiles pour différents types analyses.

Cet article présente une étude durant laquelle le scanner laser Imager 5003 de Zoller+Fröhlich a été utilisé afin de mesurer le déplacement de surfaces dans un tunnel expérimental durant et après son excavation. Ce scanner est particulièrement bien adapté aux applications en milieu souterrain en raison de son principe de balayage (vision panoramique), de sa précision (de quelques mm) et de sa rapidité d'acquisition (625.000 points par seconde). La fiabilité de la méthode a été estimée en comparant les déplacements mesurés à l'aide du scanner avec ceux obtenus avec une station totale. Le principal objectif de ce travail est d'évaluer le potentiel de la technique pour la génération de cartes de à haute résolution spatiale reflétant l'évolution temporelle de la géométrie de parois rocheuses. La méthodologie de terrain, les algorithmes de traitement ainsi que des résultats préliminaires sont présentés dans cet article.

**Keywords:** Deformation, monitoring, tunnels, underground installations

## INTRODUCTION

Tunnel excavation in rocks induces disturbances of the in situ stress field which in turn generate various types of rock mass deformations. These deformations are usually detected by recording the displacements of points located within the rock or on excavation surfaces. In practice, the monitoring of such displacements is of great interest as it allows for the understanding of the mechanisms through which rock masses react to excavation-induced perturbations and for predicting potential stability problems. As a consequence, displacement monitoring is an important operation that is routinely carried out during engineering projects to track the evolution of the rock mass behaviour. This is traditionally achieved by measuring the displacement of a limited number of points. However, displacement monitoring of points located within the rock mass requires the drilling of boreholes and the installation of specific equipment. The measurement of surface displacements is therefore performed more frequently in practice. In this case, arrays of object points are firmly anchored within the first centimetres behind the rock surface at different locations along the surface. In any case, it is necessary to monitor a sufficient number of points to achieve a reliable interpretation of the rock mass behaviour. In addition to the number of points, the extent and the type of excavation-induced processes that can be monitored depend directly on the spatial distribution of these points.

Displacements can be measured either in a relative or in an absolute way. Relative measurements are based on the distance between a pair of object points (e.g. convergence measurements) and are relatively simple to carry out using extensometers that provide an accuracy of less than 1 mm. Unfortunately, distance variations between points located in different areas around the excavation are difficult to interpret since no information about the actual displacement orientation and magnitude of each point can be deduced from these measurements. As a consequence, the different mechanisms contributing locally to the displacement of the excavation surface cannot be identified. However, this type of investigation is possible if absolute displacement data are acquired. In this case, the coordinates of object points are surveyed at different times with respect to a local or global reference system. An accuracy of less than 1 mm can also be achieved provided that an automated total station is utilized. Crucial issues associated with this monitoring method include the definition of a stable reference system and the identification of appropriate reference points.

Laser scanning technology has the potential to be used for the monitoring of excavation surface displacements. The use of laser scanners allows for effective management of time and access constraints encountered typically during rock engineering projects since it quickly provides a realistic and permanent representation of excavation surfaces. The direct collection of digital data results in speeding up processing work through the use of readily available computer resources. Moreover, it requires only a reduced number of physical targets to be installed for data referencing purposes. Hence, it is particularly well adapted to the study of inaccessible and potentially unstable surfaces as mapping can be carried out at any time from a safe location regardless of the lighting conditions. Additionally, this technique could greatly improve the understanding of rock mass behaviour as it allows for the observation of displacements occurring over the entire excavation surface. Because data can be obtained with high spatial resolution, laser scanners can be used as well for rock mass characterization, topographical surveys and the documentation of excavation surfaces, which are also procedures carried out routinely during construction. Therefore, this technology has the potential to be employed on a regular basis as it can be used as an efficient tool to record data required for various routine rock engineering applications and analyses. Most of the studies undertaken so far to develop laser scanning applications in the field of rock mechanics have focused on geomechanical characterization of geological structures (e.g. Feng & Röshoff 2004, Slob *et al.* 2004, Lemy & Hadjigeorgiou 2004). The use of laser scanners in the monitoring of surface displacements is in its infancy and calls for an appropriate development and validation of the methodologies required for the acquisition, processing and analysis of data point clouds that describe the same rock surface at different times.

**Figure 1.** Imager 5003 laser scanner of Zoller+Fröhlich and overview of the excavated experimental tunnel

This paper relates to a case study where the 3D-laser scanner Imager 5003 of Zoller+Fröhlich (Figure 1) was used to map surface displacements in an experimental tunnel in the Mont Terri Rock Laboratory in Switzerland. Several experiments have been and are underway in this laboratory to investigate the behaviour of the Opalinus Clay as a potential host for a radioactive repository. In the case study, a circular tunnel with a length of 5 m and a diameter of 3.8 m was excavated in seven steps to examine the formation of induced fractures in the rock mass surrounding the underground opening in response to its excavation (Yong *et al.* 2004). The tunnel surface was scanned after each excavation step and two different views of the point cloud resulting from the scanning of the tunnel at the end of its construction are shown in Figure 2.

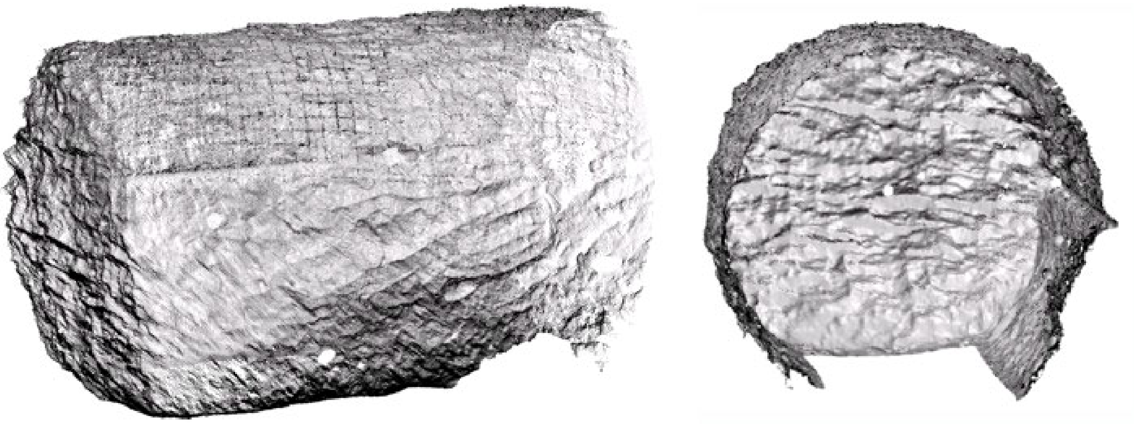


**Figure 2**. Point cloud representing the final geometry of the tunnel: exterior view of the tunnel, as seen from inside the rock mass, (left) and interior view of the tunnel (right)

A preliminary evaluation of the method in deriving displacements of the tunnel surface during and after its excavation was carried out. The main objective was to assess the potential of the technique in deriving high-resolution maps that display the evolution of the rock surface topography. These maps were produced from the comparison of scans taken at different stages of the tunnel construction. In conjunction with the laser scanning, total station surveying of a number of object points or targets installed in the tunnel surface was also carried out to assess the accuracy of utilizing the laser scanner as an alternative for displacement monitoring. The developed field methodology, data processing techniques and preliminary results are discussed in the following.

# GEOLOGICAL AND GEOMECHANICAL SETTING

The Rock Laboratory is constructed in the Opalinus Clay sequence located in the Mont Terri Anticline. During the formation of the anticline in the Cenozoic, the Opalinus Clay, a Mesozoic deposit, was internally folded and thrusted (Waber & Schuerch 2000). The Opalinus Clay is a thick sequence of claystones and marls consisting of 40 to 80% clay minerals, of which 10% have a tendency to swell (Thury & Bossart 1999). Bedding planes in the Opalinus Clay at Mont Terri are highly continuous (extending for tens of metres along the strike and dip) and thinly laminated with spacing of less than 20 mm (Martin *et al.* 2004). In the tunnel, the bedding has a dip of about 44º and falls outwards and downward from the face (Figure 2). Two major fault systems have been identified in the geological mapping of the tunnel (Nussbaum *et al.* 2005). The most prominent system, belonging to the best developed thrust system in the laboratory, is sub-parallel to bedding while the second system is sub-horizontal. Faults sub-parallel to bedding and intersecting the tunnel face can be seen in Figure 2. In situ, the water content is 6% while the plastic limit is 23% and the liquid limit is 38%. The overconsolidation ratio at Mont Terri is about 2.5-3.0. The uniaxial compressive strength is 16 MPa perpendicular to bedding and 10 MPa parallel to bedding while the elastic modulus is 4 GPa perpendicular to bedding and 10 GPa parallel to bedding. These values are summarized from Bock (2001) and illustrate the intensity of the bedding anisotropy.

The excavation disturbed/damaged zone at Mont Terri has been attributed to four modes of instability by Martin *et al.* (2004): 1) stress-induced breakouts, 2) extensile fracturing, 3) bedding plane slip, and 4) swelling and softening. The first three modes occur concurrently with the excavation and are related to stress redistribution whereas the last mode, swelling and softening, is time-dependent and related to the availability of moisture. Hence, in the Opalinus Clay, displacements occurring at a particular location on the rock surface can result from the superposition of several processes. The detection of these zones requires the construction of maps that display the distribution of the displacements along the rock surface.

# LASER SCANNER IMAGER 5003

Several issues have to be considered when selecting the most appropriate laser scanner for a specific application. Important considerations include the required accuracy, the scene geometry, the range interval, the time available for scanning (i.e. scanning performance) and the minimum point density. In most cases, these requirements have to be placed in order by a project-specific hierarchy. The range interval is often the first criterion. Owing to the final dimensions of the excavation, the maximum range did not exceed more than 10 m during the construction of the experimental tunnel. Frequently, accuracy is the second criterion and the determination of this accuracy is dependent on the type of application. In this project, laser scanning was employed for several applications, which encompassed displacement monitoring and rock mass characterization. A higher degree of accuracy was required for the monitoring of displacements than for the characterization of the rock mass. However, the characterization of geological structures necessitates a point density that allows for the recognition of all salient features (Lemy & Hadjigeorgiou 2004).

Finally, the scanning performance is of great importance as the time available for in situ measurements is usually restricted. During the tunnel excavation, the time allotted to laser scanning (including all necessary surveying work) was limited to two hours.

Given these requirements, the “Imager 5003” laser scanner of Zoller+Fröhlich (Figure 1) was identified as being particularly well adapted to applications in underground excavations since a 360° view (i.e vertical and horizontal) can be obtained in one scan (Schulz & Ingensand 2004a, Feng & Röshoff 2004). The scanner is based on a deflecting technique where the laser beam is deflected by a mirror that rotates around two axes (a horizontal axis and a vertical axis). For this reason, this laser scanner is called a panoramic scanner. The distance measurement system is based on the phase-shift principle, which limits the maximum range to a distance of about 50 m. The combination of the high-speed rotation of the mirror and the fast detection of distances by using the phase-shift principle results in a high-performance laser scanner with a scanning rate of up to 625,000 points per second. Therefore, the minimum angle increment is 0.02°, thus achieving a point spacing of up to 3 mm in a distance of 10 m. The accuracy for single points is less than 1 cm within the specified range of 10 m (Schulz & Ingensand 2004*a*, 2004*b*). Further investigations and results regarding performance, accuracy and instrumental errors of the laser scanner “Imager 5003” can be found in Schulz & Ingensand (2004*a*) and Schulz & Ingensand (2004*b*).

# DATA ACQUISITION

A major concern when measuring displacement data is the installation of an appropriate and stable reference system. This reference system is defined by control points, which are fixed in regions that would not be influenced by any construction work during the observation period. Based on previous convergence measurements made at the Mont Terri laboratory, zones not influenced by the excavation of the tunnel were identified and four control points (1, 2, 3, 4), defining a local reference system, were then installed in these regions (Figure 3). Additional points (1000, 1001) belonging to the surveying network of the Mont Terri laboratory were also included to transform local coordinates into the established reference system of the laboratory.

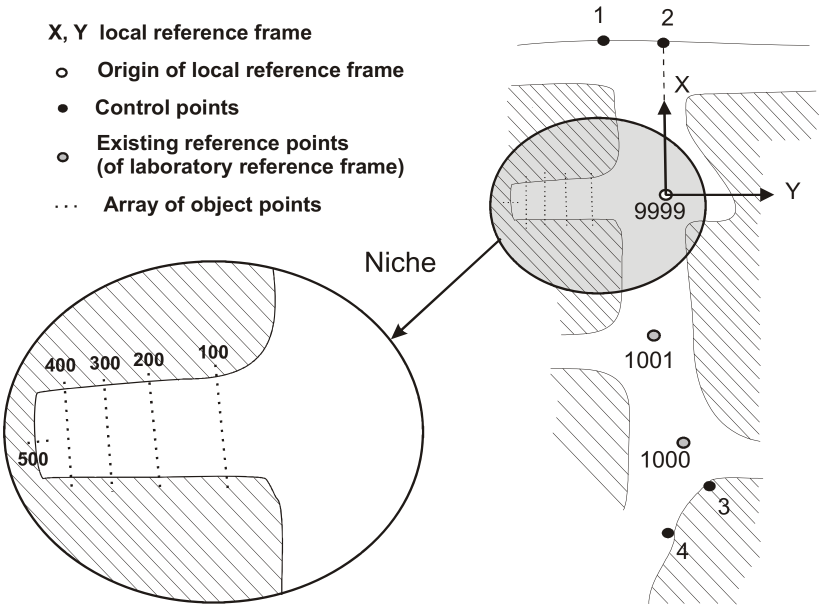


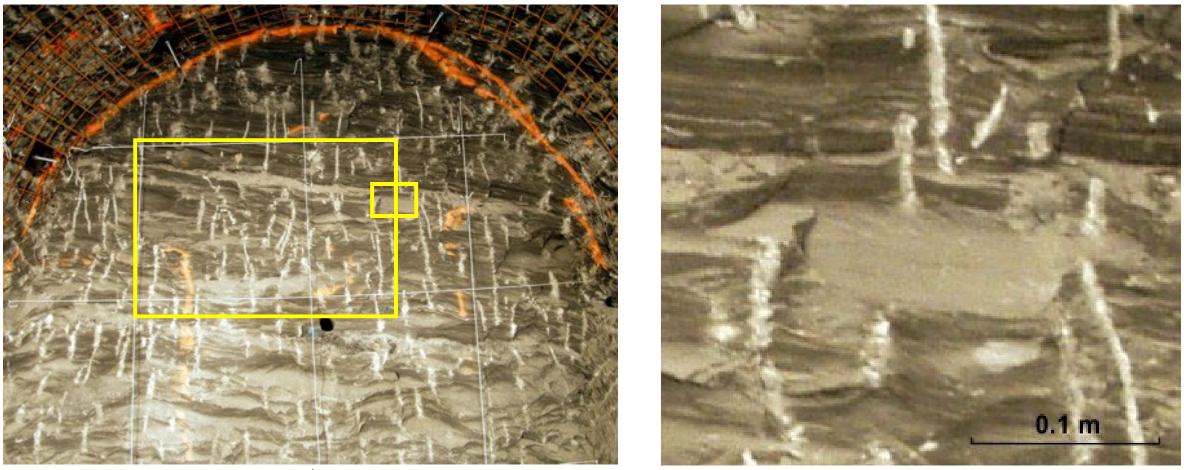

**Figure 3.** Location of the experimental tunnel, the reference points and the arrays of control points

Displacement measurements were achieved in two different ways, via geodetic measurements with a total station and via a laser scanner. Five arrays (100, 200, 300, 400, 500) of object points were installed during and after the tunnel excavation to assess the performance of the displacement monitoring using the laser scanner (Figure 3). In arrays 100 to 400, six object points were installed at 45° intervals above the finished floor. In array 500, three object points were installed near the centreline of the tunnel face and distributed over its height. The object points consisted of mechanically anchored bolts that were used to attach prisms for the total station and spheres for the laser scanner (Figure 1). Spheres were used for the laser scanner due to their attractive properties regarding their visibility in the point clouds and the derivation of their centre point. The diameter and the evenness of the surface of these spheres as well as a potential offset between the centre of the prisms and the spheres were previously calibrated.

For all measurement sessions, the total station was located outside the tunnel and the laser scanner was placed at the centre of tunnel; thus, the total station remained approximately stationary throughout the excavation while the laser scanner was progressively moved inwards. As a result, stable control points 1, 2, 3 and 4 (Figure 3) could be seen by the total station but not by the laser scanner. To cope with this constraint, intermediary object points equipped with spheres were installed in and around the tunnel at locations visible from the scanner position (Figure 1). The coordinates of these intermediary points were also measured with the total station to tie in the different surveys. The point clouds generated by the laser scanner consist of x-, y-, and z-coordinates transformed according to the established reference system thereby allowing for direct comparisons between the different laser scanning sessions.

# GENERATION OF DIFFERENTIAL ELEVATION MAPS

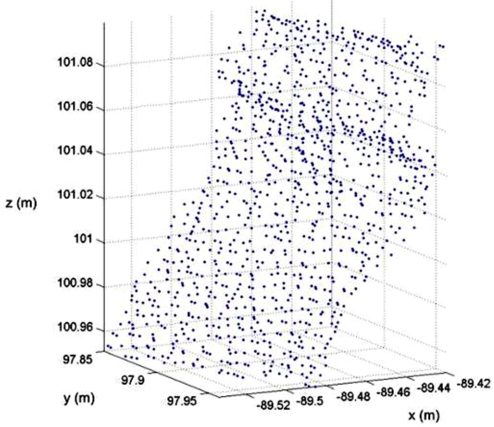
Understanding the rock mass behaviour can be greatly improved if the displacement distribution along the excavation surface is analyzed rather than considering the displacements of a few discrete points. For this purpose, time-lapse differential elevation maps of the rock surface are used. The procedure that was developed in the generation of these maps is outlined below and is illustrated by means of two point clouds representing a 12x16 cm area located in the face of the tunnel (Figure 4). This area is mainly composed of the relatively smooth surfaces of a fault and of a fracture parallel to the bedding.




a) b)

**Figure 4.** a) Location of the investigated area, b) close-up of the area

Point clouds (i.e. the raw data) of the surfaces scanned after different phases of the excavation are first generated and pre-processed (Figure 5). The average spacing between any two points in Figure 5a is about 4 mm. The first step in the pre-processing consists of automatically or manually detecting and deleting points representing blunders. Fortunately, this step was not necessary in this case as no significant blunders were observed in Figure 5a. The orientation of the best-fit plane of the investigated area is then calculated using the least-square method. The reference system is rotated so that the x- and y-axes lie in this plane and the z axis is normal to the rock surface. This is illustrated in Figure 5b where the origin of the x-y plane was set to zero. This operation is necessary to identify displacements occurring perpendicular to the surface. Subsequently, the point cloud is converted into a grid where each point is assigned a value corresponding to the local elevation of the surface model. These elevation values are calculated through the interpolation of the original point cloud. The result of this operation is illustrated in Figure 5c where the distance in the x-y plane between two neighbouring points is 2 mm. The selection of a spacing value smaller than the average point spacing of the original point cloud allows for preservation of local topographic details contained in the raw data.

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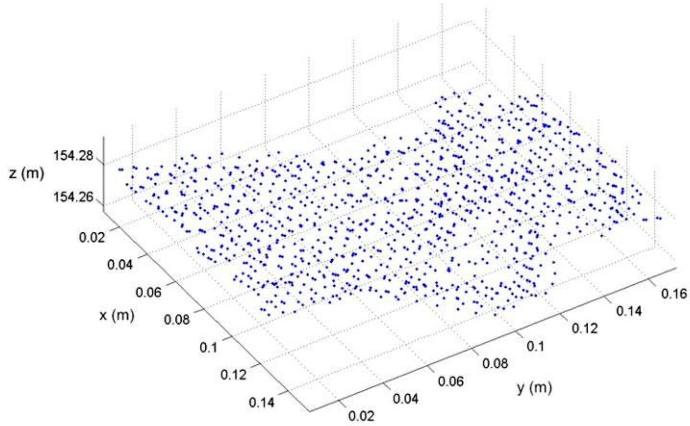


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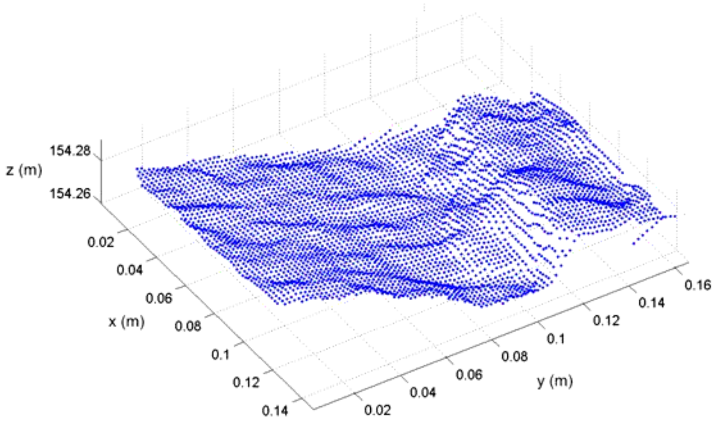
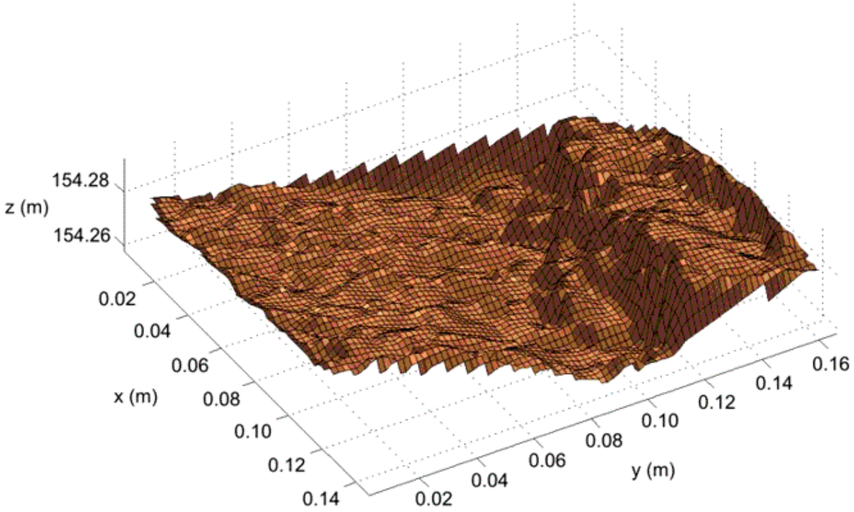


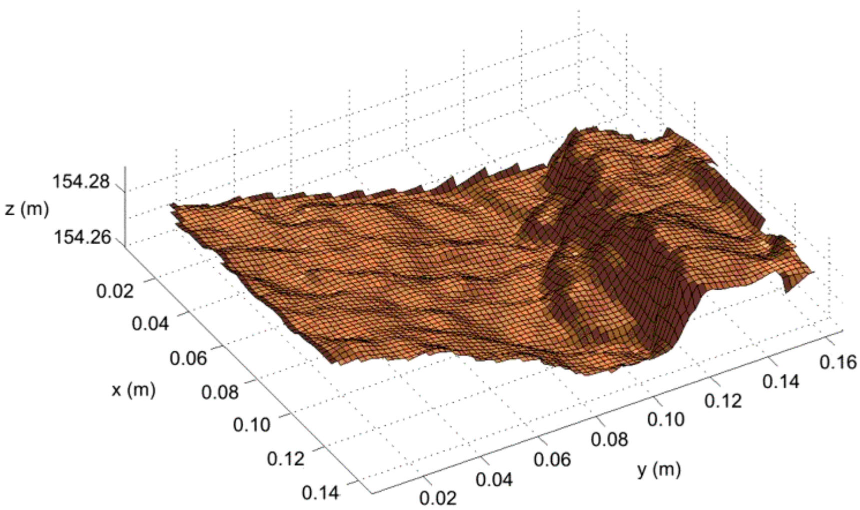

c)

**Figure 5.** Point cloud pre-processing: a) point cloud of the scanned surface, b) rotated point cloud, c) grid resulting from the interpolation of the rotated point cloud

Once the pre-processing is complete, data processing can commence with the main objective of noise reduction by means of a filtering process. This is an essential step as noise due to the natural limits of laser scanning affects greatly the quality of the point cloud by making sharp edges dull and making smooth surfaces rough. In the current version of the algorithm, the noise is partly removed using a median filtering process. This filter allows for the removal of isolated peaks while preserving edges in the image. This property is particularly important in the detection of geological structures reactivated (i.e. shearing surfaces) by the excavation. The result of filtering is a more uniform arrangement of points. Data processing is illustrated in Figure 6 where a surface model representing the point cloud of Figure 5c (Figure 6a) and a surface model resulting from the filtering of the same point cloud (Figure 6b) are shown. Most of the ridges and local peaks that are visible in Figure 6a were not observed in the field or in Figure 4b. Therefore, these topographic features can be attributed to noise inherent to laser scanning and should be eliminated from the point cloud. Figure 6b shows how these artefacts are flattened through median filtering while preserving the overall shape of the edges delimiting the surface of the geological structures. It is worth mentioning that the result of filtering is directly related to the size of the filter. In this example, a 5x5 filter was employed to process the data. Thus, elevation values corresponding to all the points located in 1 $cm^2$ windows were used to determine the value assigned to the point located in the centre of these windows.




a)




b)

**Figure 6.** Example of data filtering: a) surface model derived from the point cloud of Figure 5c, b) surface model resulting from the processing of the same point cloud using a 5x5 median filter

Finally, a map displaying the evolution of the surface topography is computed by comparing two point clouds representing the same area but acquired at different times. This is illustrated in Figure 7a showing two processed point clouds describing the surface shown in Figure 4b. In this example, the test object (red point cloud) was recorded six days after the acquisition of the reference object (blue point cloud). Figure 7c shows the differential elevation map produced by subtracting the z-coordinates of the reference object from those of the test object. This operation is only possible if the test object is first transformed into the same reference system as the reference object.

Figure 7c reveals that the major part of the investigated region is characterized by positive values indicating a global increase of the surface elevation. However, several zones in the map also show negative variations of the topography. In the current example, these zones are interpreted as artefacts due to the noise in the point cloud that was partially but not totally removed through data filtering. Additionally, positive changes of elevations greater than 10 mm are observed along the edge delimiting the fault surface in the upper part of the area. Cross-checking the map of Figure 7c with the point cloud superposition of Figure 7a, one can observe that these values cannot be explained by displacements greater than 10 mm along the z-axis but rather to relative movement of the edge in the x-y plane. In this case, the values of the elevation difference depend directly on the thickness of the geological layer undergoing displacements but not on the magnitude of these displacements. Therefore, the interpretation of differential elevation maps requires knowledge of both the movement direction and the surface topography.

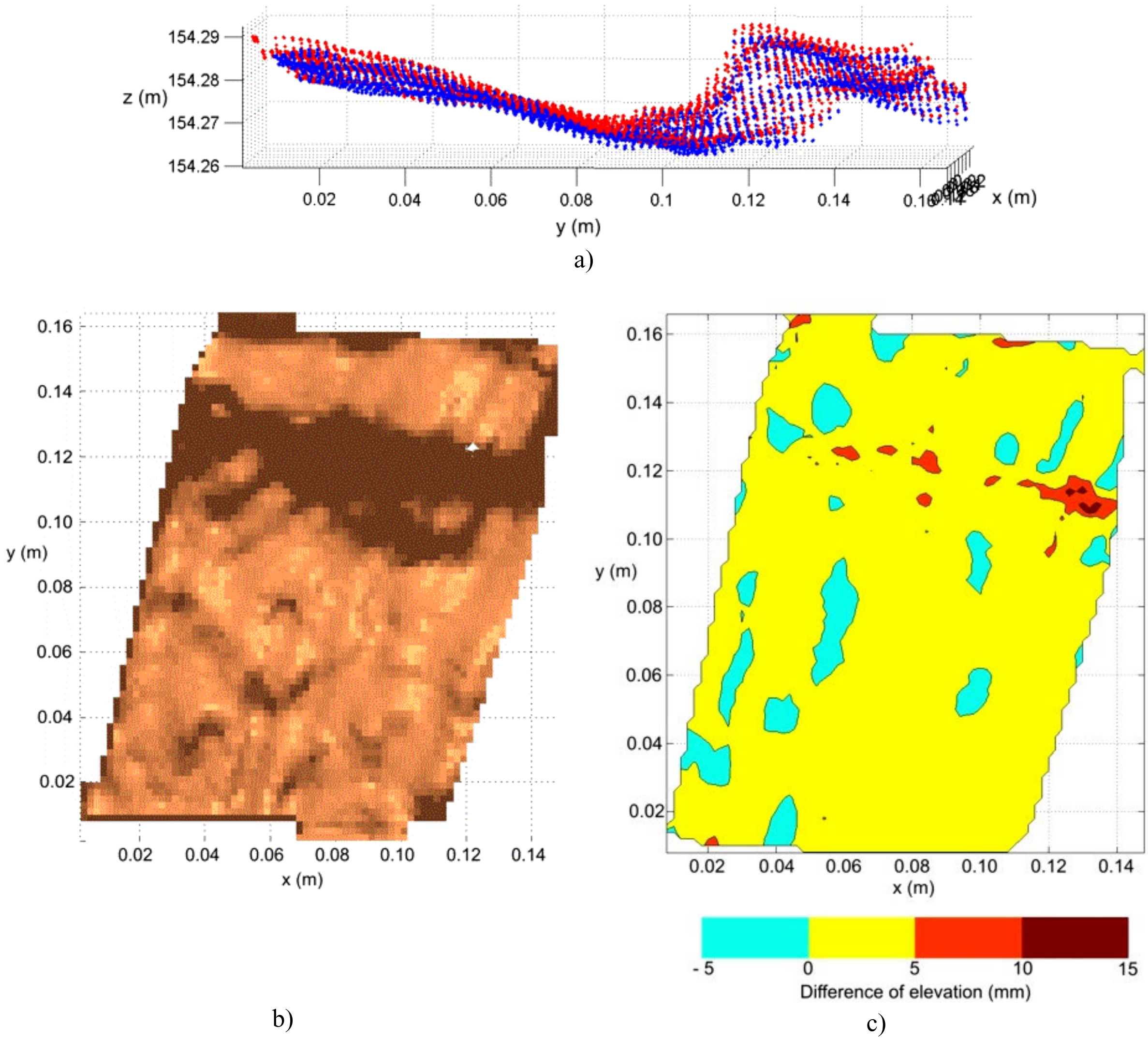
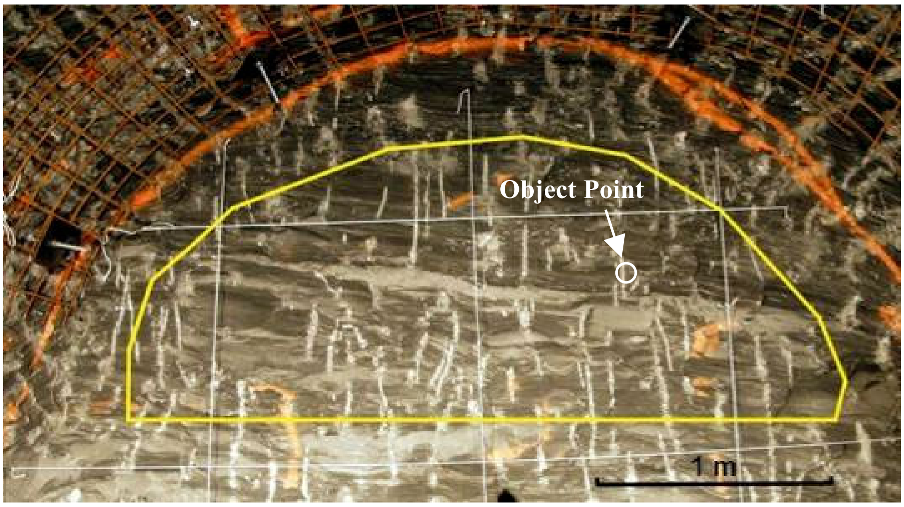



**Figure 7.** Generation of a differential elevation map displaying the evolution of the surface topography: a) superposition of two point clouds describing the same area at different times with the reference object in blue and the test object in red, b) surface model of the area (as seen in a direction opposite to the z-axis), c) differential elevation map resulting from subtracting the reference object from the test object

## CASE STUDY

Figures 8b and 8c show the differential elevation maps that were produced for the upper part of the tunnel face illustrated in Figure 8a. These maps were calculated based on scans acquired following the excavation of the last tunnel section (11th March–session 0) and two days later (13th March–session 1). In addition, a third scan was acquired six days later (17th March–session 2) following the excavation of the tunnel invert. The data of session 0 was used as the reference object for the generation of the two maps. Elevation differences for the point clouds of sessions 1 and 2 were then computed with respect to the reference object. In this case study, the spacing between each point of the grid was set to 5 mm and windows of 1.5x1.5 cm were used to filter the data.

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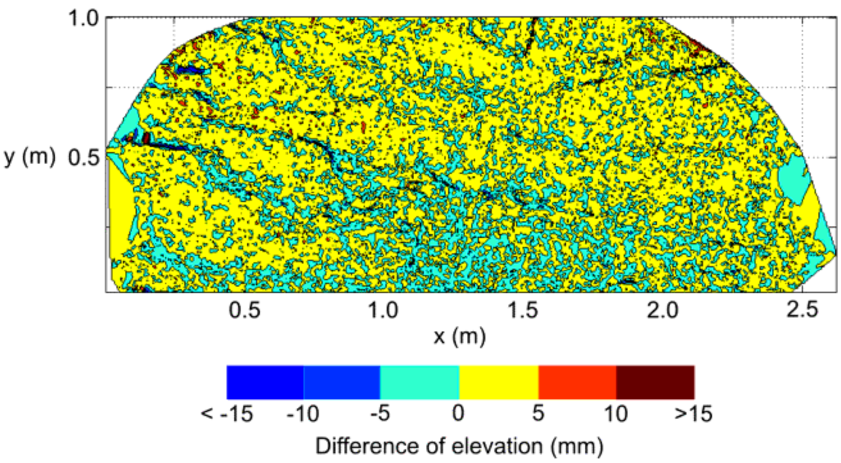


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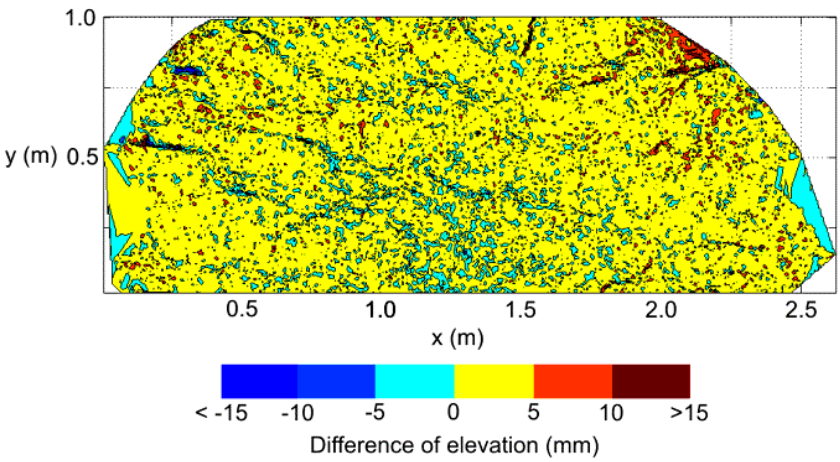
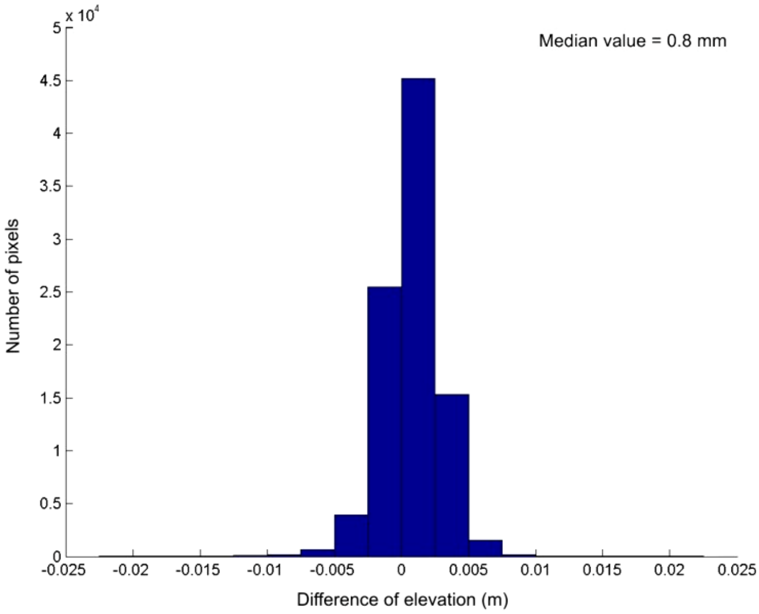


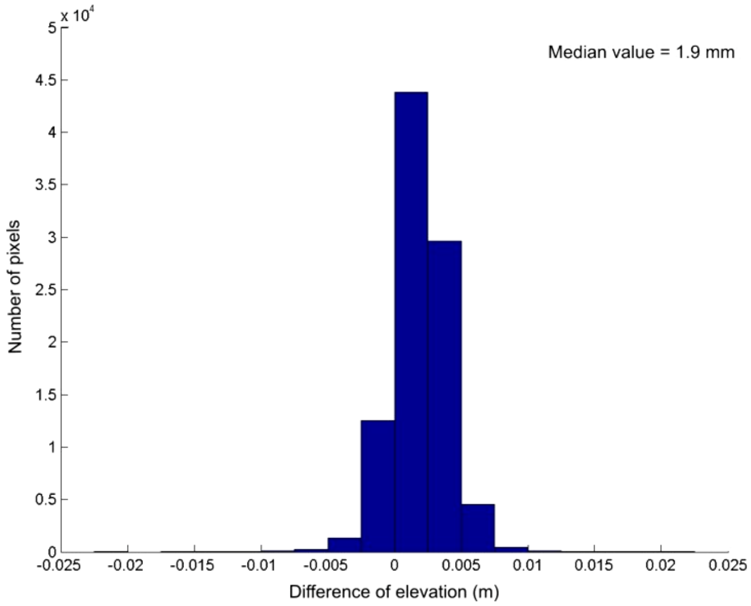

c)

**Figure 8**. a) Location of the investigated area, b) differential elevation map of the point clouds acquired during scanning sessions 0 and 1, c) differential elevation map of the point clouds acquired during scanning sessions 0 and 2

Figures 8b and 8c show that most surface elevation variations occurring during the investigation period lie in a range of -5 to +5 mm. These variations are of the same order of magnitude as the accuracy of the laser scanning for the determination of the displacements of individual points. However, they are in conformity with the magnitude of the z-component of the displacement measured at less than +1 mm with the total station for an object point located near the centre of the investigated area (Figure 8a). Furthermore, changes in the distribution of the yellow zones characterized by differences lying between 0 and 5 mm suggest that displacements increased with time and with distance from the centre of the tunnel face. The evolution of the displacements is also demonstrated by the evolution of the histogram showing the distribution of elevation differences (Figure 9) as the median values of this distribution increases from +0.8 to +1.9 mm between sessions 1 and 2. This observation is in agreement with the evolution of the displacements which is expected following the excavation of the tunnel invert. Therefore, trends are observable despite artefacts due to the noise generated during laser scanning such as those illustrated in Figure 7c.




a)




b)

**Figure 9.** Histograms of the differences in elevation between the point clouds acquired during scanning sessions 0 and 1 (a) and 0 and 2 (b)

Although the major part of the area is characterized by absolute values of differential elevation that do not exceed 5 mm, larger values are also identified locally on both maps. In several cases, large negative values are probably due to the fall of small rock blocks as observed in the field. Nevertheless, negative values smaller than -5 mm are sometimes detected along the trace of some of the fault/fracture intersecting the tunnel face. The significance of these values is the object of current investigations. Positive values greater than 5 mm are also distinguished at several locations in the maps. In the example of Figure 8, many of these zones are located in the upper right part of the studied area where several fractures parallel to the rock surface are observed in the field. These structures could be produced by extensile fracturing due to stress redistribution around the excavation that generates displacements outwards from the tunnel face.

# CONCLUSION

Laser scanning is a promising technology since it has the potential to be used for the collection of data required for several rock engineering tasks. This paper relates to a case study where the Imager 5003 of Zoller+Fröhlich was used in the Mont Terri Rock Laboratory to monitor surface displacements produced by the excavation of an experimental tunnel. This scanner typically produces an accuracy of less than 1 cm in the determination of the displacement of individual object points. Nevertheless, preliminary results suggested that displacements can be identified with a higher degree of accuracy by taking advantage of the large quantity of spatial data provided by the laser scanning. In the study presented in this paper, this was achieved by reducing the noise in the point clouds and subtracting the elevation values of point clouds representing the same area at different times of the excavation. It was found that the analysis of the resulting maps may possibly bring to light phenomena which are overlooked when using traditional monitoring methods and therefore could greatly improve the understanding of the rock behaviour. However, data interpretation requires knowledge of excavation-induced processes potentially occurring in the rock mass and of the movement type and orientation engendered by these processes. Additional crucial issues were also identified for the generation of accurate differential elevation maps including referencing to a stable reference system and coordinate transformation.

Current work concentrates on thorough analyses of maps indicating the evolution of rock surfaces located at different locations in the tunnel. Data examination will be facilitated by comparing the maps with the results of displacement monitoring of points that were measured using a total station. The results of this work will be further compared to the results provided by other field investigation methods such as geological surface mapping, borehole image analysis, core logging and borehole geophysics, and to numerical models simulating the rock mass behaviour around the tunnel. It is expected that this investigation will lead to a better assessment of the capability of laser scanning in monitoring displacements of rock surfaces.

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