

# An archival geomatics approach in the study of a landslide

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**Abstract** Geomatic approaches were used to investigate a landslide in the Emilian Apennines in northern Italy which occurred during excavation works for high-speed railway tunnels between 2002 and 2007. The landslide damaged three buildings located on the upper part of a hillside. At the site of interest, the high-speed railway system included three contiguous tunnels—the main tunnel and two connecting tunnels, “odd” and “even”—all crossing the “Chaotic Complex” formation. The archival multi-temporal digital photogrammetry technique was employed for photogrammetric surveys performed in 1998, 2004 and 2007, at a mean scale of about 1:8000. For all the surveys, stereo pairs of the area were available, and the black and white photo-frames were scanned using a Wehrli Raster Master RM2 photogrammetric scanner (12- $\mu$ m resolution). Digital images were obtained, with a ground resolution in the range of 9–10 cm. The reference coordinates of the Ground Control Points (GCPs), as required for the external orientation of the images, were measured in 2009 in a stable area using GPS methodology. Orientation of the images was carried out with SOCET SET software, obtaining orientation residuals in the order of a few centimetres. An approach based on the multi-temporal sets of photographs was used, comparing the coordinates and

amplitudes of the motion vectors. In doing so, 3D vectorial representations were obtained, providing displacements of about 14 cm in the initial period (1998–2004) and of about 25 cm in the latter period (2004–2007). From a chronological point of view, this data corresponded with both the beginning of the damage and the progression of the excavation of the tunnels, thus confirming the vulnerability of the *Chaotic Complex* to stress changes during the works.

**Keywords** Landslide monitoring · Damage buildings · Multi-temporal aerial photogrammetry · Displacement vectors

## Introduction

This paper analyses some geomatic approaches used to investigate the causes of damage to three buildings located on the upper part of a hillside in the Emilian Apennines in northern Italy, during excavation works, which were carried out between 2002 and 2007.

The hilly area under study belongs to the municipality of Pianoro (Bologna, Italy) and the works were being carried out for a high-speed railway, known in Italy as *Treno Alta Velocità* (TAV) (or “high-speed train”). Three tunnels needed to be excavated in this area: a main tunnel with a diameter of about 14 m and two secondary connecting tunnels, “odd” and “even”. The connecting tunnels have a diameter of about 11 m and run almost parallel to the main tunnel.

The main tunnel was excavated between February 2002 and October 2003, while the two connecting tunnels, odd and even, were excavated simultaneously, between June 2006 and March 2007. The connecting tunnels were excavated both from the north and south; the meeting of the two fronts

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met on 25 February 2007 for the odd interconnection and 27 March 2007 for the even.

During the excavation of the connecting tunnels, signs of damage became visible in some buildings located at the top of the hill, just above the layout of the main tunnel. A monitoring system to control the lesions was put in place in September 2006, and a precision altimetry control was set up in January 2007.

The Pianoro territory is affected by widespread instabilities caused by a hydro-geological vulnerability of the shallower soils, therefore it was not clear whether the damage had been caused by the tunnelling or by natural causes.

This study is a retrospective analysis of the available data with the aim of assessing the causes of the instability. Based on the archival aerial photogrammetric survey, geomatic approach was used to corroborate the results of conventional geotechnical stability analysis.

## The case study

### Morphology, geology and geotechnics

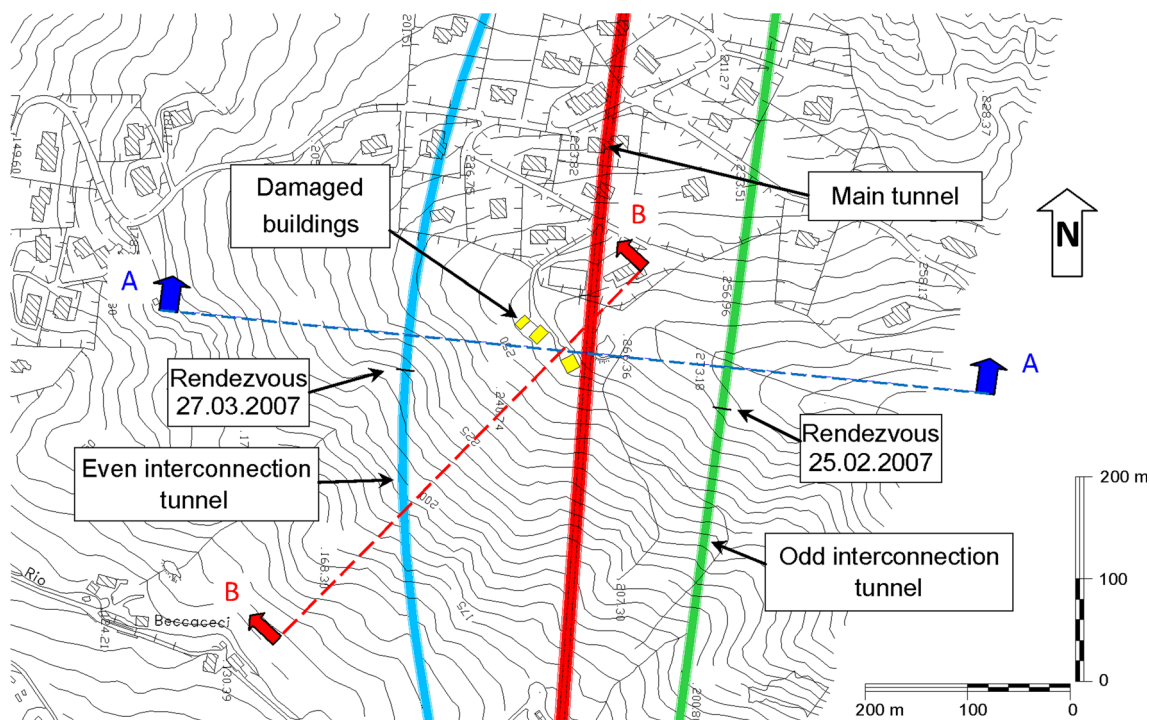
As mentioned above, the area of study is characterized by smooth hills belonging to the Emilian Apennines. To cross Mount Calvo, three parallel tunnels were planned, each at a different depth: about 103 m for the even connecting tunnel, 133 m for the main tunnel, and 148 m for the odd connecting tunnel. The even connecting tunnel is about 177 m from the

main tunnel axis, while the odd tunnel is about 136 m away. The north side of the hill has an average slope of about  $12^\circ$ , and the south side of about  $18^\circ$ , with a marked reduction towards the ridge of the slope.

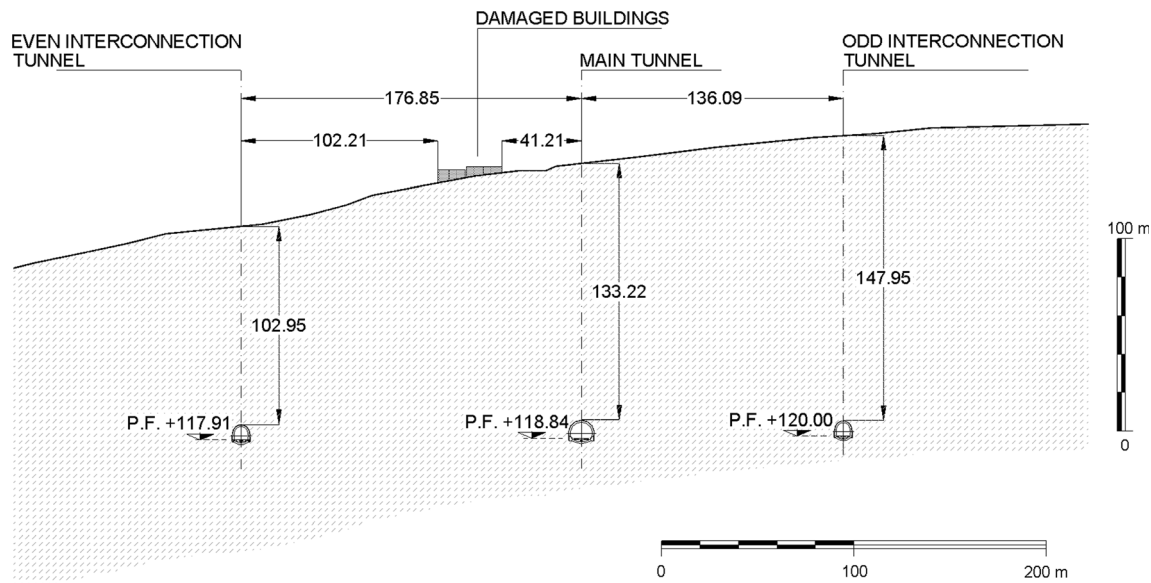
During the works, some damage was noticed in three buildings located at the top of the hillside, just above the track of the main tunnel. Figure 1 shows a planimetric representation of the high-speed railway system at the site of interest, while Fig. 2 shows the cross section A–A, as outlined in Fig. 1, orthogonal to the tunnel tracks, and highlights the positions of the damaged buildings. The meeting points of the fronts of the tunnels (which occurred between February and March 2007) were close to the location of the buildings (Fig. 1).

In the Pianoro territory, the high-speed railway crosses the *Chaotic Complex* (Lunardi and Focaracci 1999; Lunardi et al. 2009; Lunardi and Gatti 2010), a clay formation typical of central and southern Italy. Intense tectonic activity and changes in sea level affected the area; as a consequence, this area was remodelled about 10,000–20,000 years ago like a large part of the Apennines. The Chaotic Complex extends in depth for more than 200 m; due to geodynamic activity (faulting and folding), it is characterized by a pronounced *scaly shale* macrostructure and by a great number of arenaceous and calcareous blocks inside it.

The geomorphology is characterised by localized erosion (*badland slopes*) along both the north and south sides of the mountain, due to the washing action of rainwater runoff on soil affected by low permeability. Retrogressive instabilities are in progress in the lower parts of both the north and south



**Fig. 1** Map of the Emilian Apennines showing the study site at Pianoro (Bologna, Italy)



**Fig. 2** Cross section A–A as reported in Fig. 1

sides, while the upper parts of the slope are affected by creep phenomena which appear to be related to the progression of the erosion on the lower sides. Finally, given the very low permeability of the shallower formation, there is no groundwater circulation. This was also confirmed by the excavation of the tunnels, which took place with dry fronts.

The macrostructure and heterogeneity of the Chaotic Complex were the limiting aspects in the geotechnical approach, since extending the results from small scale (laboratory tests) to large scale (stability analyses) was not easy.

With reference to the geotechnical characterization, the authors refer about the results of laboratory tests on undisturbed samples carried out during the design and construction of the high-speed railway. The authors were provided with this data by the TAV designers in order to allow them to study the instability problems of the Monte Calvo slope.

The main geotechnical characteristic of this formation is its strongly over-consolidated nature; the unit weight, roughly homogeneous with the depth, is about  $\gamma=22 \text{ kN/m}^3$ .

The shear strength envelope appears to be non-linear; the peak shear strength is characterized by a cohesion  $c$  ranging between 10–80 kPa and an angle of shear strength  $\varphi$  between 11–15°. Due to the curvature of the failure envelope, the highest values of cohesion are generally associated with the lower values of the friction angle and vice-versa. These strength parameters are coherent with those obtained for the same shale formation during the excavation of the nearby “Raticosa” tunnel (Bonini et al. 2002).

#### Geotechnical stability analysis

The bi-dimensional stability of the most critical section B–B, along the maximum slope (Fig. 1), was firstly analysed by the

authors using the conventional overall limit equilibrium approach, carried out according to the modified Bishop method. The average strength parameters  $c=45 \text{ kPa}$  and  $\varphi=13^\circ$  were selected for the analysis, according to the stress level involved. As already stated, pore-water pressure was not taken into consideration due to the lack of ground water circulation within the formation.

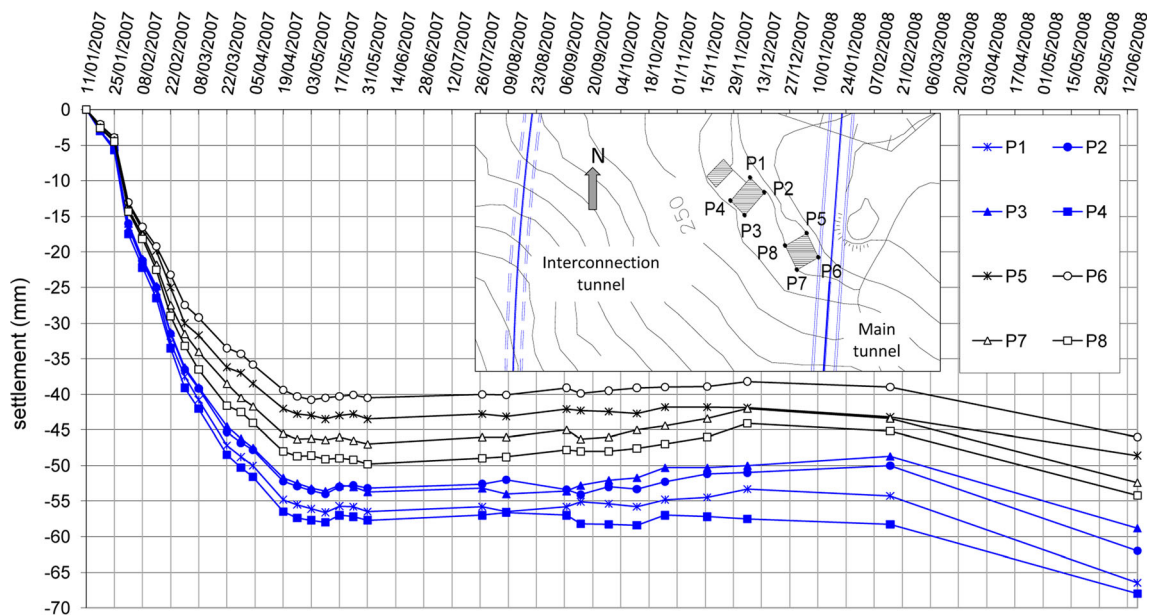
For this cross section, geotechnical analysis showed safety factors close to the unit, when the slip surface osculates the vault of the even connecting tunnel. This result seems to indicate that the excavation of the even connecting tunnel might have destabilized the lower portion of the slope, giving rise to a movement that would have progressively diffused up to the overhead buildings.

#### Objectives and methodology of the study

As already stated, the study was carried out in order to assess the causes and evolution of the ground movements which lead to the damage of the buildings.

Soil macrostructure and heterogeneity were limiting in modelling soil behaviour; moreover, the erosion of the hill slope did not give any certainty as to the causes of the instability. For these reasons, the results of the geomatic survey were therefore used to confirm the frame outlined by the geotechnical approach (Achilli et al. 2014).

A set of data was available from a precision altimetry control of the benchmarks installed in January 2007 at the corners of the buildings. Moreover, three aerial photogrammetric surveys, performed in 1998, 2004 and 2007, were available; they were processed and analysed in order to verify and integrate the data of the precision altimetry.



**Fig. 3** Precision altimetry control of the damaged buildings

Precision altimetry

Monitoring of the altimetry of the buildings began in January 2007: 12 benchmarks were set on the three buildings and a multi-temporal survey was performed with spirit levelling methodology starting from a benchmark located outside the sliding area. Precision levelling was carried out using Leica NA2 level. The measurements were performed by ENgineerig SERvice (Enser) on behalf of the general contractor CAVET (*Consorzio Alta Velocità Emilia Toscana*), to survey the building displacements. Thirty surveys were carried out from 11 January 2007 to 12 June 2008.

Digital aerial photogrammetry

From a general point of view, photographic archives are an important source of historical data that allow the ground surface

to be modelled at a local scale. Historical images can be processed using archival photogrammetry in order to obtain metric information of the study area (Chandler and Cooper 1988a, b; Walstra et al. 2004; Chandler et al. 2007; Baldi et al. 2008a).

Digital photogrammetry is one of the most powerful tools for measuring the coordinates of a large number of points, which are then used to extract high-resolution digital models. Automatic or semi-automatic procedures are used for this purpose, based on either well-defined shape comparison methodologies or on the grey/colour level distribution in the corresponding areas of the images (Heipke 1995; Kraus 1998). The common reference system, mainly for multi-temporal analysis, is obtained by identifying a large number of homologous tie points, which can be recognized on multi-temporal images and are located in what are presumed to be stable parts of the area under examination (Chandler and Cooper 1988a, b; Walstra et al. 2004; Chandler et al. 2007; Baldi et al. 2008b). These Ground Control Points (GCPs) were needed to carry out the orientation of the aerial photos.

**Table 1** The main characteristics of the three photogrammetric surveys and results of the orientation phase

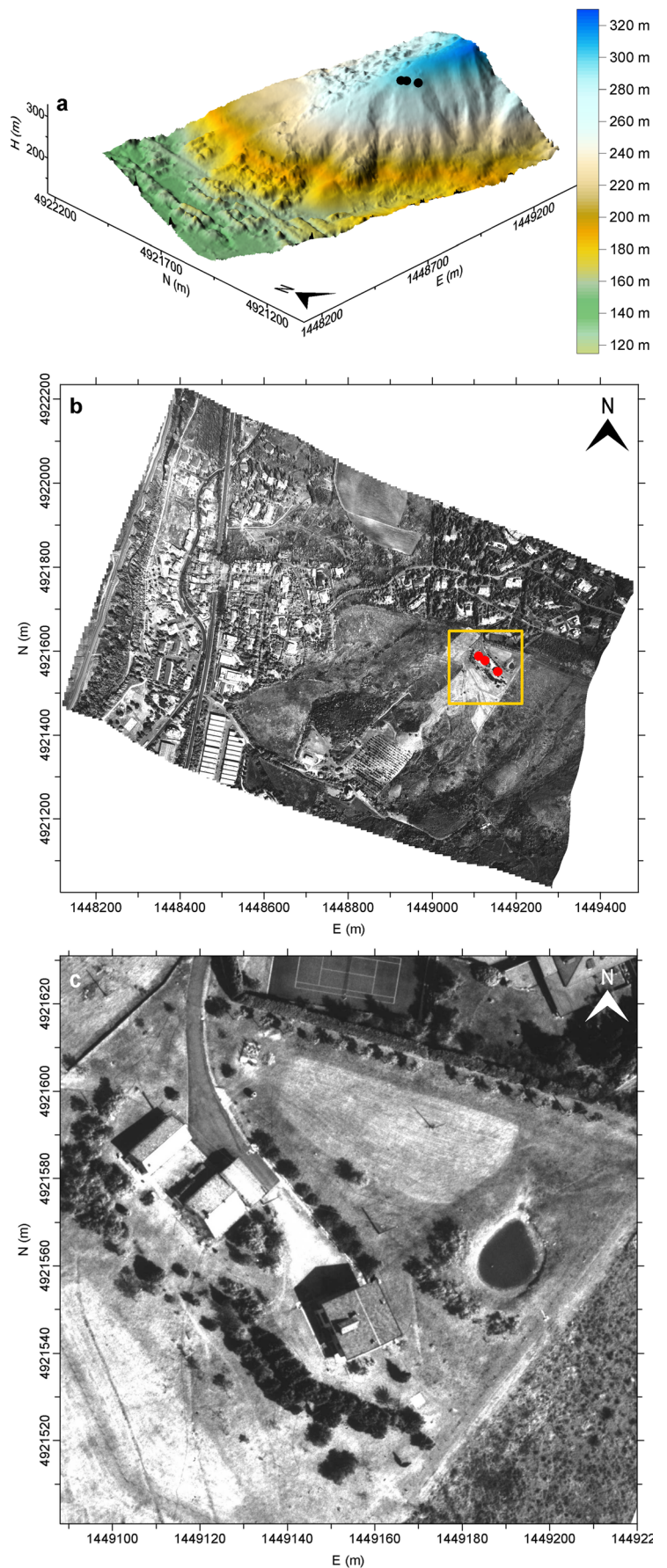
Date of survey	9 August 1998	13 July 2004	28 August 2007
Number of images	2	2	2
Calibrated focal length (mm)	152.93	153.28	153.28
Average scale	1:8500	1:7500	1:7400
Scans resolution (dpi)	2100	2100	2100
Ground pixel size (cm)	10	9	9
Number of GCPs	10	13	15
RMS values of GCPs and tie points coordinates (m)	E 0.04 N 0.04 H 0.03	0.03 0.02 0.02	0.02 0.02 0.03

**Table 2** Average and standard deviation values of the difference between the coordinates of the 30 natural points located in areas which were presumed to be stable

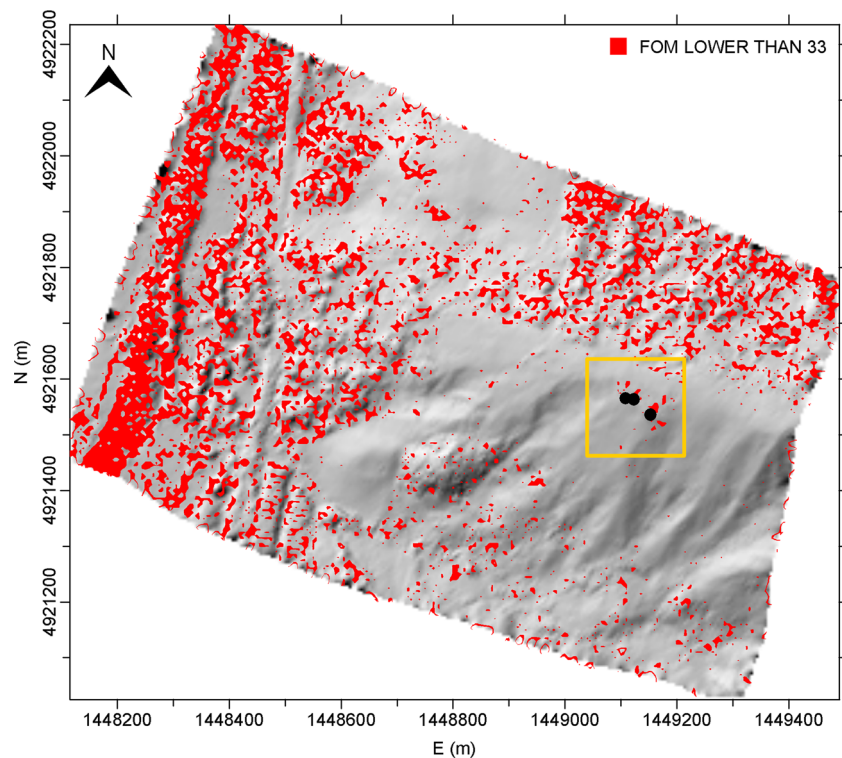
Comparison	Axis	Average (m)	St. Dev. (m)
1998–2004	X	0.09	0.18
	Y	0.11	0.20
	Z	−0.09	0.14
2004–2007	X	−0.13	0.15
	Y	0.10	0.18
	Z	0.08	0.16



**Fig. 4** **a** 3D representation of automatic DEM of the studied area (the *black dots* indicate the damaged buildings). **b** Large-scale orthophoto of the area. **c** Detailed orthophoto of the area with the three buildings under investigation



**Fig. 5** Points distribution with a correlation parameter FOM lower than 33



High-resolution models (Pirotti 2010; Pirotti et al. 2013a, b), acquired for an area undergoing significant displacements, can be used to evaluate ground displacements (Kääb et al. 1997; Baldi et al. 2005, 2008; Pesci et al. 2007, 2013; Fabris et al. 2010, 2014; Marsella et al. 2012). Displacement vectors of the ground points can be defined by measuring the position of natural and artificial points in the study area, using stereo viewing methods on multi-temporal stereoscopic images.

Theoretical accuracy can be evaluated using Kraus' equation (1998); to evaluate the mean vertical accuracy  $\sigma_z$ , the subsequent equation is used:

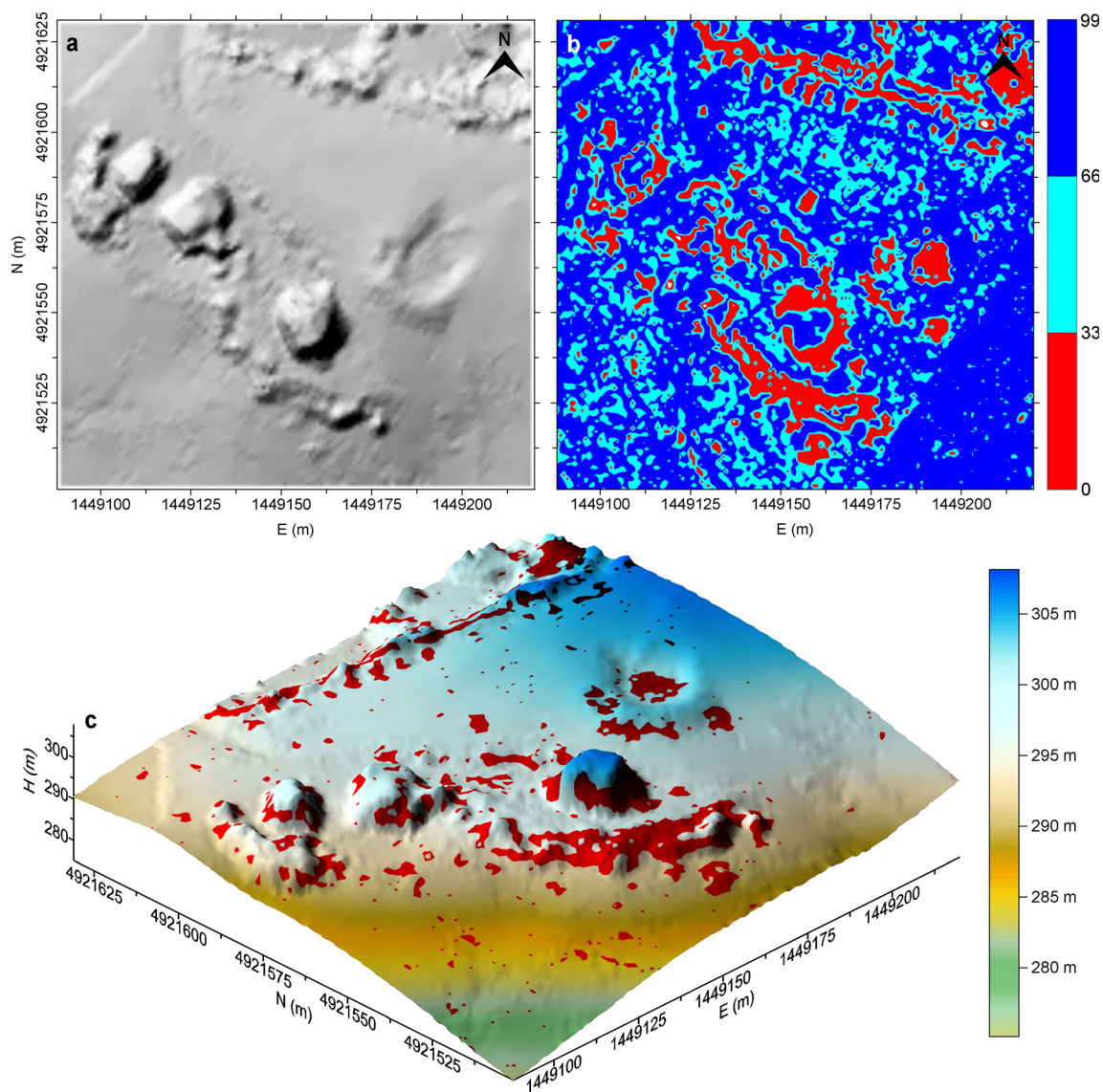
$$\sigma_z = m_b \cdot \sigma_p \cdot \left(\frac{z}{b}\right) \quad (1)$$

where  $m_b$  is the mean image scale,  $Z$  is the relative flight height,  $b$  is the distance between image centres (base of the stereo pairs photos) and  $\sigma_p$  is the horizontal accuracy.

In this study, photogrammetric data is elaborated by means of SOCET SET (SoftCopy Exploitation Tool Set) v. 5.4 software: in this case, the quality of automatic correlation for Digital Elevation Model (DEM) extraction is provided by a parameter representing the reliability of the elevation for each of the points extracted; this correlation parameter, called “Figures Of Merit” (FOM), can range between 0–99 (integer values only), and indicates the success of the correlation of the measurement. A FOM value greater than or equal to 33 indicates a successful automatic correlation and the values are therefore proportional to the correlation of the images. A FOM value lower than 33 indicate either failure of the

correlation algorithm, or that the results are questionable: in this case, an interactive review—carried out by an operator and based on stereo viewing methods—is required. The elevation of posts with FOM lower than 33 was obtained by means of an interpolation/extrapolation procedure, starting from the surrounding data.

To perform 3D displacement control of the three buildings, three aerial photogrammetric surveys, performed in 1998, 2004 and 2007, were processed. The second period (2004–2007) covered the excavation phase of the two interconnection tunnels, during which the damage to the buildings occurred. Conversely, in the first period (1998–2004), no damage to buildings was reported. Aerial photogrammetric surveys were performed on 9 August 1998 (scale 1:8500), 13 July 2004 (1:7500) and 28 August 2007 (1:7400). The black and white photos were digitized at a resolution of 12  $\mu\text{m}$  using a Wehrli Raster Master RM2 photogrammetric scanner, obtaining digital images with a ground resolution of about 9–10 cm. Stable GCPs were identified in the three surveys (mainly the corners of buildings and other objects that can be identified unambiguously in the images), located outside the unstable area. The coordinates of these GCPs were measured in 2009 using GPS methodology: two double-frequency Leica GPS System 1200 were used and the survey was performed in static mode at a sampling rate of 15 s and acquisition time of 60 min (elevation mask 15°). The points were chosen to achieve nearly ideal conditions (an unobstructed view of the horizon, avoidance of multipath effect, etc.) and were well-distributed within the area being analysed.



**Fig. 6** a DEM with 1-m grid size. b FOM distribution. c 3D representation of points with FOM lower than 33 (red areas) overlapping to the DEM

Permanent *Agenzia Spaziale Italiana* (ASI) GPS points were used as reference stations (masters), and baselines with distances of less than 8–9 km were measured. The data was processed with Leica Geo Office software, yielding the coordinates in the Gauss Boaga reference system.

#### Measurement of natural points

Information concerning the geomorphological changes which occurred during the period analysed can be obtained by generating digital models for the areas covered in each survey and comparing the data. Even though this approach provides information about the vertical displacements, no data can be obtained for the planimetric movements. Moreover, it should be taken into account that the expected deformations are very small, lower than the intrinsic precision of the method which

is also affected by the automatic processing limits (due to points with a correlation parameter FOM lower than 33).

To overcome these limitations, another approach was decided on, based on the identification of homologous points in multi-temporal sets of photographs. The coordinates of some natural points (the corners of the roofs of the three buildings) were measured using stereo viewing methods in photogrammetric models from 1998, 2004 and 2007.

## Results

### Precision altimetry

The evolution of the vertical displacements for two of the three buildings is plotted in Fig. 3. The monitoring highlights



how the most significant settlement, of about 60 mm, occurred between January and April 2007, and thereafter remained almost the same. It is interesting to note that the even connecting tunnel was being excavating in that same period, until 27 March 2007 when the fronts meeting took place.

#### Multi-temporal digital photogrammetry investigation

The characteristics of the three aerial photogrammetric surveys, together with the residuals of the external orientation, are shown in Table 1. The scale of the images in this study ranges between 1:8500 and 1:7400 and the scanning resolution is of 2100 dpi (corresponding with 12- $\mu$ m pixels in the image). Therefore, regarding the accuracy of the data, the real dimension of the pixels, at ground scale, ranges from 0.09 to 0.10 m (Table 1).

Adopting a value of horizontal accuracy of the order of the pixel size and using the equation (1), it is possible to obtain a mean vertical error of 13–18 cm, respectively, for the larger and the smaller image scales. Due to the differences between the normal photogrammetric case and the real case, the theoretical values were correct by means of empirical relationships (Kraus 1998) thus obtaining values ranging from 18–24 cm. These values were assumed as vertical errors for manual measurements.

The analysis of co-registration of the three photogrammetric models was performed using stereoscopic viewing to

measure 30 easily identified natural points located outside the unstable area and clearly visible in the three models.

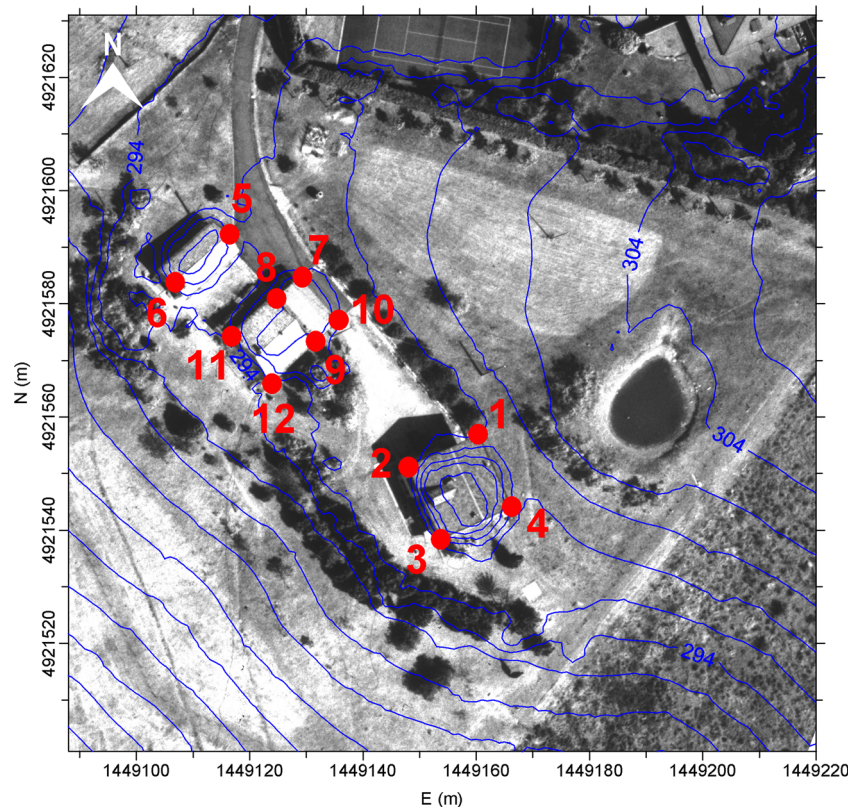
Average and standard deviation values of the difference between the coordinates of the 30 natural points are shown in Table 2 for the two periods of comparison. The results, summarized in Table 2, show a good co-registration of the three photogrammetric models, with the standard deviation lower than the theoretical accuracy.

A DEM, with a grid size of 5 m over the examined area, was extracted automatically from the more recent stereoscopic model (2007), in order to generate the correspondent orthophotos for both the large- and the small-scale area of the buildings (Fig. 4).

In the studied area, 34.8 % of the points of automatic DEM provided FOM values lower than 33, and belonged to nine different categories. The distribution of events, corresponding to an acceptable FOM value, reached a maximum FOM value of 88. The distribution of the points with a FOM value lower than 33, overlapping the correspondent shaded relief of DEM, is shown in Fig. 5. The points affected by an unsatisfactory FOM were located on either urban or densely vegetated areas as deducible by the comparison with Fig. 4b.

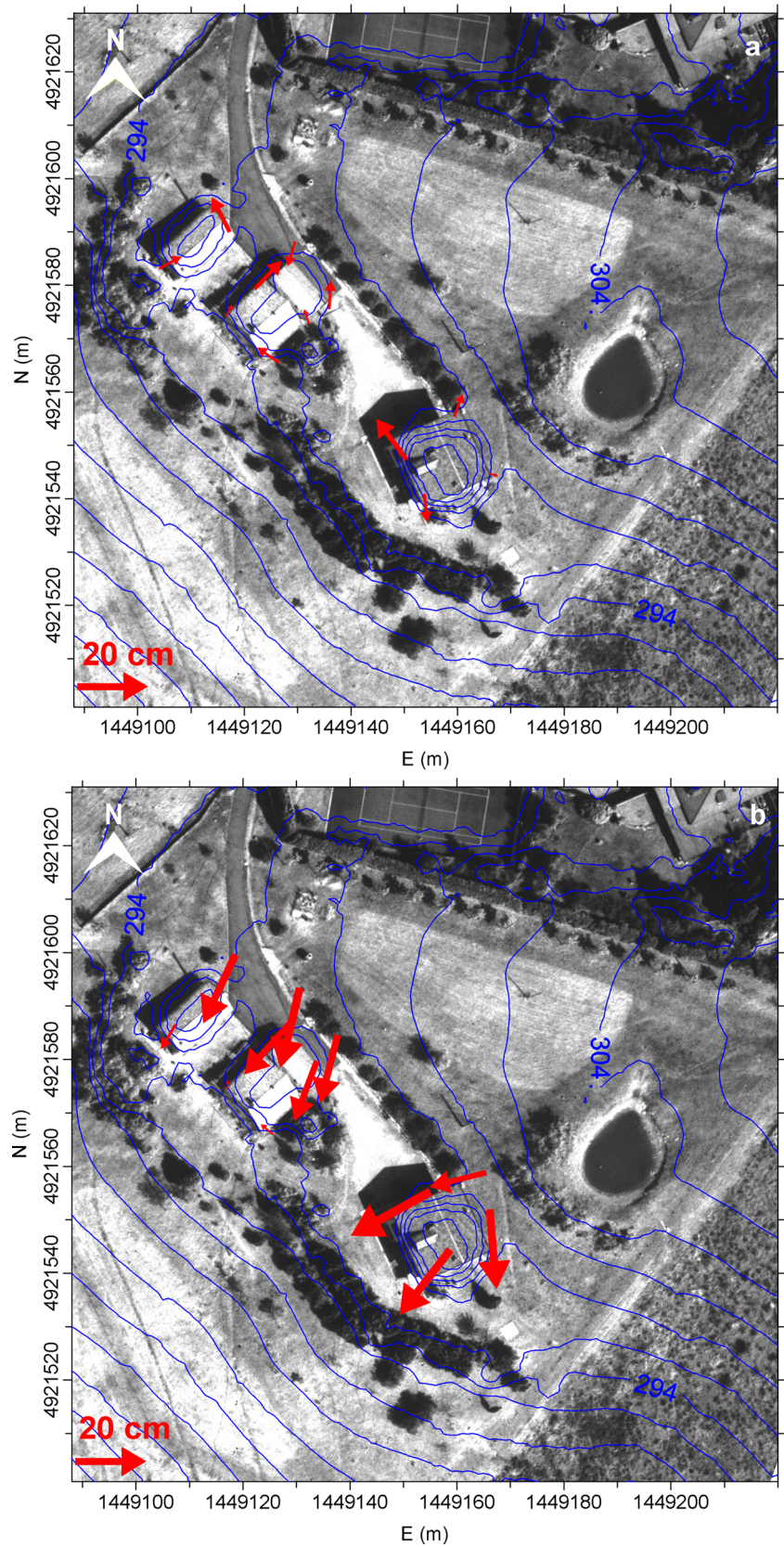
To obtain high-resolution data of the buildings under study, a DEM with a grid size of 1 m was extracted for the only area of Fig. 4c. In this case, the FOM distribution (Fig. 6b and c) show questionable points located mainly in the borders of the three buildings, as deducible by the comparison with Fig. 4c,

**Fig. 7** Location of the 12 natural points measured with stereo viewing methods





**Fig. 8** Displacements of the corners of the roofs of the buildings in the period 1998–2004 **a** and 2004–2007 **b** (yellow square of Fig. 4b)



probably due to the shadows on the images and stereoscopic lack for vertical walls.

DEMs with a grid size of 1 m were also extracted for the 1998 and 2004 stereoscopic models, thus obtaining results

which could be compared. The direct comparison between the 1998, 2004 and 2007 DEMs (1 m grid size) provides standard deviation of about 28 cm, and no considerable movements were detected for the buildings analysed from the residual maps.

### Measurements of natural points

As already stated, it was thought better to follow another approach, based on the identification of 12 homologous points in multi-temporal sets of photographs (the corners of the three buildings, Fig. 7).

The 3D vectors, representing the displacements of the selected points, were obtained by comparing their coordinates (Baldi et al. 2008a) from the 1998, 2004 and 2007 surveys. The results, concerning the period 1998–2004, provide movements in the order of  $1 \div 8$  cm eastwards,  $1 \div 11$  cm northwards and  $1 \div 7$  cm in the height variation. Likewise, in the period 2004–2007, the displacements were estimated to be about  $0 \div 17$  cm eastwards,  $3 \div 18$  cm northwards and  $5 \div 13$  cm for the height variation (Fig. 8). In the first period, the measured displacements were certainly within the limits of precision for this method while, in the second period, the maximum displacement, of about 25 cm, was close to the limits of accuracy of the photogrammetric method (Table 2).

### Discussion

A conventional geotechnical analysis was carried out within the framework of the limit equilibrium in order to quantify the safety factor of the hillside against instability. This analysis meant that a slip surface osculating the vault of the even connecting tunnel could be identified. Thus, a reasonable relationship between damage and tunnel works was outlined, due to the change in stress which occurred in the subsoil.

High-precision altimetry monitoring was used to describe the evolution of the vertical displacements in time of the damaged buildings. From a chronological point of view, it was highlighted that the major ground movements happened in the same period as the excavation of the interconnection tunnels was carried out.

However, this data alone was not sufficient to completely clarify the mechanism leading to the damage of the buildings. For this reason, it was thought helpful to reconstruct the field of displacements which occurred in the study area. This difficulty was overcome by carrying out a multi-temporal digital photogrammetry investigation, through which the ground displacements could be compared, even those which occurred before the start of the high-precision altimetry monitoring (January 2007). The processed aerial images, acquired in

1998, 2004 and 2007, were characterized by a similar mean scale and ground sample distance.

Following the automatic extraction of DEMs, it was not possible to evaluate the displacements of the three damaged buildings, due to the small size of the expected ground movements. Therefore, the comparison between high-resolution DEMs, did not provide suitable displacements.

To overcome these difficulties, it was thought to better follow a different approach, based on the displacement evolution of homologous points in multi-temporal sets of photographs. In this case, the measured displacements were certainly within the limits of precision of the photogrammetric method in the first considered period (1998–2004), while in the second (2004–2007), the maximum displacement was of about 25 cm. Although the results related to the latter period were very close to the limit of accuracy of the method, the direction of all the displacement vectors clearly indicated a sliding along the maximum slope of the hillside.

It is worth noting that any displacements in the neighbouring buildings could not be monitored with a geomatic approach because there were no historical identifiable ground points at the time of the construction of the tunnels. Likewise, no geotechnical monitoring of the displacements of the soil above the tunnels was operative during construction.

### Conclusions

Digital aerial photogrammetry was used to evaluate the displacements of three buildings damaged by the high-speed railway excavation in the Pianoro territory (Bologna, northern Italy). Multi-temporal analysis was performed for the period of 1998–2007. The processed aerial images, acquired in 1998, 2004 and 2007, were characterized by a similar mean scale and ground sample distance. Automatic DEMs, with a grid size of 5 and 1 m, and an orthophoto were extracted from the aerial photogrammetric surveys using SOCET SET software.

The correlation parameter of the automatic extraction indicates that the elevations of some points, located in urban and densely vegetated areas as well as on the three buildings, could have been questionable. Moreover, due to the small size of the expected ground movements, it was not possible to evaluate the displacements of the three damaged buildings by comparing the multi-temporal DEMs at 1-m grid size. Therefore, the direct comparison of high-resolution DEMs have not provided suitable displacements.

To overcome this difficulty, another approach was used: 12 homologous points (the corners of the roofs of the three damaged buildings) were identified on multi-temporal sets of photographs. A comparison of the respective coordinates allowed the 3D displacement vectors to be extracted.

In the first period (1998–2004), the measured displacements were certainly within the limits of precision of the photogrammetric method, while in the second (2004–2007), the maximum displacement was of about 25 cm. Although the latter results were close to the limits of accuracy of the method, all the displacement vectors clearly indicated a sliding along the maximum slope of the hillside, coherent with the kinematics revealed by the geotechnical limit equilibrium analysis.

Finally, this research indicates that in the case of retrospective analyses of geotechnical instabilities which have not been well-documented, the geomatic approach can be a suitable tool to outline slow ground movements in large areas, if identifiable ground points are available.

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