Author's Response - NHESS-2017-194 Salvini et al. "Use of a remotely piloted aircraft system for hazard assessment in a rocky mining area (Lucca, Italy)"

Comment to Reviewers

Point-by-point response to Reviewer #1

GENERAL COMMENTS:

This paper presents an interesting case study of the application of RPAS for rock slope characterization in a mine/quarry for hazard assessment. It highlights the advantages of using recently developed technologies (RPAS and SfM) in a mine/quarry.

In my opinion, the main contribution is related to the persistence of critical joints and the role of intact rock bridges in rock slope stability. This is a difficult topic, and lots of literature exists already. New characterization techniques, such as photogrammetry, bring new perspective and may allow better understanding of the role of rock bridges.

Therefore, I think that this manuscript is a topical case study, and the discussion (Section 5) is interesting.

However, before being published, I think the manuscript needs to be further completed.

I would suggest including a more comprehensive literature review on the topic of discontinuity persistence and rock bridges in the introduction (including the current paragraph Line 14-19 on Page 8). I would suggest reviewing recent case studies on rock bridges such as the one by Frayssines and Hantz (2006), Sturzenegger and Stead (2012), Tuckey and Stead (2016), and Matasci et al (2014). In particular, the results presented in Line 15-18 on Page 9 could be compared to rock bridge percentage estimate by the above authors.

As suggested, a more comprehensive literature review on discontinuity persistence and rock bridges has been included in the introduction (including paragraph line 9-19 on page 8 and line 5-11 on page 9). The following text has been added: "Nevertheless, there are controlling factors that can have a great influence on the stability condition of a block or slope that cannot be fully determined, such as discontinuity persistence. The presence of intact rock bridges, that represent intervals of intact rock between adjacent discontinuities (ISRM, 1978), can significantly increase the stability of a rock slope, since the cohesion of the intact rock is generally of at least two orders of magnitude greater than the shear strength of a discontinuity (Park, 2005). In general, joint persistence (K) is defined as the fraction area that is actually discontinuous (Einstein et al., 1983), and can be calculated with the following Eq. (1):

$$K = \lim_{A_D \to \infty} \frac{\sum_i a_{Di}}{A_D} \quad (1)$$

where D is a region of the plane with area AD and aDi is the area of the joint in D.

The limit of the application of this method is that the discontinuity area is practically impossible to measure deterministically in the field, for this reason persistence is commonly measured as trace length on rock outcrops. Jennings (1970) proposed the following Eq. (2) for persistence calculation starting from trace length values on rock exposure:

$$K = \frac{\sum JL}{\sum JL + \sum RBR} \quad (2)$$

where JL is the total length of the joints segment and RBR is the total length of rock bridges.

Mathematically, it is possible to consider the presence of rock bridges in terms of effective cohesion along the shear surface (Eberhardt et al., 2004) by using the following Eq. (3):

$$c_i = c\frac{A_g}{A} \quad (3)$$

where c is the intact rock cohesion, Ag the total area of intact rock bridges along the shear surface, and A is the total area of the shear surface.

Importantly, as recently reported by Tuckey and Stead (2016), in spite of the importance of intact rock bridges in slope stability, there are still no standard accepted methods for estimating the extent of rock bridges and incorporating rock bridges into slope stability analysis."

In addition, the indicated case studies have been added in the discussion section, for purposing of comparison: "Similar values of rock bridges percentage have also been found in different case studies, where back-analysis revealed low values of estimated rock bridge content at the moment of failure, in the order if 0 to 5 % (Frayssines and Hantz, 2006; Grøneng et al., 2009; Sturzenegger and Stead, 2012; Matasci et al., 2014; Tuckey and Stead, 2016). Therefore, a small amount of rock bridge may be sufficient for guaranteeing stability of a rock slope."

Finally, the specific comments listed below should be addressed.

SPECIFIC COMMENTS:

Page 1, Title: Is there a specific reason why the authors use “remotely piloted aircraft system” instead of UAV, which is more commonly used in the literature?

The choice of using "remotely piloted aircraft system" instead of UAV is done trying to be as closer as possible to the title of Special Issue.

The abstract is well written. I would suggest adding a sentence on the rock bridge analysis, which is an important aspect of this manuscript.

We agree with the suggestion. The following sentence has been modified as it follows: “A preliminary stability analysis, with focus on investigating the contribution of potential rock bridges, was then performed in order to demonstrate the potential use of RPAS information in engineering geological contexts for geo-hazard identification, awareness and reduction”

From Page 1, Line 33 to Page 2 Line 5: these sentences seem a bit vague. In what ways does alteration of geological structures by exploitation, or morphological features influence slope stability? In my opinion, the main parameter controlling slope stability is the relationship between the slope morphology and geological structures, as rightly explained in the third sentence.

The correction has been applied and the new sentences have been modified as it follows: " According to Zajc et al. (2014), for example, hazardous situations may occur when unfavourable sedimentological characteristics and geological discontinuities (e.g. joints, faults) of rock masses are made even more critical by extraction of the resource or ore material. In addition, Zheng et al. (2015) highlight the crucial role played by morphological features, such as sharp cuts and steep slopes, for potential triggering of rockfalls in mining areas. As widely demonstrated in the literature, the understanding of geometric relationships between geological discontinuities and slope morphology is essential to evaluate the potential occurrence of rock failures, since orientation of joint sets may influence both size and failure mechanisms of rock blocks prone to collapse (e.g. Stead and Wolter, 2015).".

Page 3, Lines 10-13: is it really necessary to add these sentences and to mention this accident? Safety is definitely very important for mining operation, but is this really relevant for the scientific contribution of this paper?

The suggestion has been applied and the sentences eliminated.

Section 3.1: Could “zenithal”, “parallel” and “frontal” be defined?

The correction has been applied and the new sentences have been modified as it follows: " In order to assess and localize the slope stability hazard in the rocky mining area, two RPAS surveys were carried out with direction of photo acquisition in zenithal modality (perpendicular to the open pit floor) and in frontal modality (perpendicular to the rock faces).".

Section 3.1: What is the exact meaning of Ground Sample Distance: is it the ground pixel size? Or the distance between points in the generated point clouds?

The sentence has been modified as it follows: "An average estimated distance between pixel centers measured on the ground (i.e. ground sample distance - GSD) of 2.4 cm was calculated.".

Section 3.2: I don’t think it is necessary to explain in detail every steps of the processing work using Agisoft. It may be better to explain the key steps and refer to Agisoft manual for more information. Details about the parameters and options selected in Agisoft could be listed in a table if necessary. In addition, I would consider including Section 4.1 here instead of in the Result section of the manuscript.

Considering that the title of the Special Issue is "The use of remotely piloted aircraft systems in monitoring applications and management of natural hazards" we have considered this part very important in order to explain as better as possible the main steps of image processing and the utilized methods. In addition, we prefer to explain the utilized methods (ex. topographic survey with GPS and Total Station, GPS post-processing, GCP correction to orthometric heights) more than just listing the parameters in a table. We consider Section 4.1 a description of the obtained results and not a method. For this reason we prefer to leave it as it is.

Section 3.3, Lines 16-17 and Lines 25-26 do not seem necessary.

We don't completely agree with these suggestions and we would prefer to leave them as they are, since they introduce the next sentences and steps of the analysis.

Page 7, Line 10: a table showing the parameters used to obtain the RMRb and GSI would be useful here. I assume the geometric parameters come from the RPAS, but what is the source of the non-geometric parameters?
The non-geometric parameters were manually collected in accessible areas; we added a sentence in the text to explain this. Moreover, we added a table (table 4) where RMR parameters are shown. We didn't add a table for the GSI parameters since it is a "qualitative" index. We don't think it is useful to add an image with the GSI chart in this paper, anyhow we included in the text a comparison with the Hoek et al. (2013) equation. To summarize, the text was has been changed as follows: "The final stereonet allowed identification of four discontinuity sets, whose properties listed in table 3 were obtained from traditional engineering geological survey carried out in accessible areas of the mine.." "..Based on the discontinuity characteristics derived from RPAS and traditional engineering geological surveys, the basic RMR (RMRb) and GSI index were calculated. The RMRb was found to be 67 (table 4), while the GSI was estimated to be between 60 and 65 using the modified chart proposed by Hoek et al. (2013). In addition, application of Hoek et al. (2013) equation for GSI quantification (GSI=1.5 JCond89 + RQD/2) confirmed the results of the qualitative chart interpretation with a value of 65."

Table 4. Parameters used for RMRb determination. Chosen index values are underlined.

	Parameter	**K1**	**K2a**	**K2b**	**K3a**	**K3b**	**K4**
A1	Strength of intact rock material				<u>7</u>		
A2	RQD				(75%) <u>17</u>		
A3	Spacing of discontinuities	<u>15</u>	20	20	20	20	15
A4	Condition of discontinuities	19	19	19	<u>18</u>	18	20
A5	Groundwater	<u>10</u>	15	15	10	10	10
	RMRb 67						

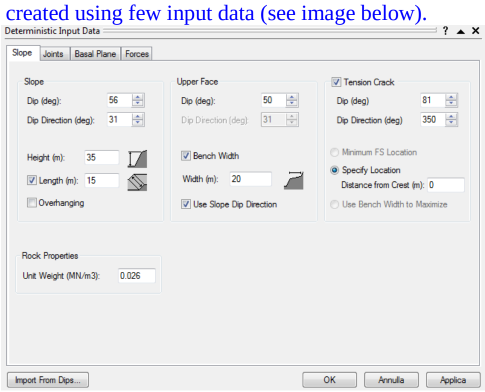
Page 6, Line 30: is the reproduction error resulting only from manual placement of GCPs or also to other parameters of the alignment process?
As described in Paragraph 3.2. the reprojection error does not result only from manual placement of GCPs but also from other parameters of the alignment process and from the characteristics of data acquisition. For these reasons the sentence has been modified as it follows: "The image alignment process, described in paragraph 3.2, resulted in a reprojection error of 0.41 pixel for the zenithal survey and 0.48 pixel for the frontal survey.".

Section 4.2: would it be possible to add a paragraph to discuss the results of the kinematic analysis? How do they compare with field-/SfM-based observations? What are the main failure mechanisms?
We added the following sentence: "Three different possible kinematic modes were identified, with K2b and K4 systems having the most influence on potential instability. The majority of the potential failures identified relate to planar sliding or wedge sliding, in agreement with field and SfM-based observations."

Page 7, Line 25: do the orientation of the faults and discontinuity basal plane correspond to specific discontinuity sets defined previously? I think the sentences Line 14-19 on Page 10 should appear here.
We agree with the suggestion. Therefore, the following sentence was included where indicated: "The basal plane appears not to correspond with any of the identified discontinuity sets, but is probably connected to planes of weakness of the marble in correspondence with a particular orientation of minerals crystallographic axes. The lateral and rear faults, however, may be associated with the K3a and K3b systems respectively. The rear fault may also be associated with the East-West fault system that characterizes the geology of this area of the Apuan Alps complex (Fig. 2)."

Section 4.3: it is not clear how Block A parameters shown in Table 5 were input in Swedge. What is the slope orientation? How were the geometric parameters of Table 5 used to generate the wedge shown in Figure 10? Can the "length" and "height" of the block in Table 5 be defined, or illustrated on Figure 9? How was Total Cohesion in Table 6 calculated?

In Swedge the block can be created using few input data (see image below).



We think that including explanation on how to insert data into Swedge is not necessary in this case. Moreover, the geometric characteristic of the block can be derived from bar scale of figure 9 and vertical and horizontal axes on figure 10. Nevertheless we added a sentence specifying the slope direction used in the analysis: "The geometry of Block A was deterministically re-created in Swedge using the geometrical information obtained from the point cloud provided in table 6, with a slope direction of 30 degrees.".

Concerning the cohesion values on table 6, they were calculated according to equation (3) $c_i = c\frac{A_g}{A}$.

The equation allows calculation of effective cohesion due to rock bridges. For example, if we consider 1 m^2 discontinuity plane with the 2 % of rock bridges, the effective cohesion of that plane will be equal to 16 MPa (intact rock cohesion) times 0,02/1 that is 0.32 MPa (effective cohesion considering 2% of rock bridge). This is the value to be used in Swedge. However, in our case study the basal plane is 510 m^2, therefore the total effective cohesion is 0.32 times 510, that is 163.3 MN. The driving force on table 6 instead, is mainly due to the effect of the block weight on the basal plane. In our opinion all these information are already present in the text, nevertheless we are willing to discuss eventual modification if needed.

TECHNICAL CORRECTIONS:

For clarity, I suggest subdividing the introduction into more paragraphs. I would start a new paragraph from (1) "Generally, ..." (Page 2, Line 5); (2) "However, ..." (Page 2, Line 13); (3) "Digital images..." (Page 2, Line 22); (4) "However, ..." (Page 2, Line 30), and I suggest deleting the word "however" here.

The suggestions have been applied

I suggest starting a new paragraph on Page 10, Line 10 at "In this work"

The suggestion has been applied

All references to figures in the text should be in brackets (Fig. X)

The correction has been applied

Sections 3 and 4 need to be reviewed for clarity and the English checked.

The text has been checked by a native English speaker and corrected where needed.

Page 2, Line 3: I suggest using either "geological discontinuities" (Page 2, Line 3) or "geological structures" (Page 1, Line 4), but being consistent

The suggestion has been applied

Page 2, Line 6: I suggest adding a period and start a new sentence from "Measurement"

The suggestion has been applied

Page 2, Line 10: "DP" should be "TDP" for Terrestrial Digital Photogrammetry

The correction has been applied

Page 2, Line 12: "rocky outcrops" should be "rock outcrops". Similarly, on Page 7 "rocky slope" and "rocky blocks" should be "rock slope" and "rock block".

The corrections have been applied

Page 2, Line 13: I suggest rephrasing this sentence, something like “A limitation of ground-based remote sensing is related to the survey of complex topography from suboptimal camera or scanner positions, resulting in occlusion zones..."
The correction has been applied

Page 2, line 16: I suggest deleting this sentence. It seems a bit redundant, and not really true, since the next sentences list several examples of the application of RPAS in open-pit mining.
The correction has been applied and the new sentence has been modified as it follows: "There are several photogrammetric studies using RPAS for the geomorphic feature characterization or mapping of the surface extent in open-pit mines (Lamb, 2000; Chen et al., 2015; Shahbazi et al., 2015; Tong et al., 2015; Esposito et al., 2017). Few of them concern the use of RPAS for discontinuity characterization of rock slopes affected by mining activity.....".

Page 2, Line 20: delete “an”
The correction has been applied

Page 2, Line 26: a word is missing “...multicopters results ARE particularly suitable...”
The correction has been applied and the new sentence has been modified as it follows: "In order to analyze rock outcrops, the use of RPAS multicopters results particularly suitable because it allows different geometric configurations for the image acquisition (i.e. zenithal, frontal, oblique).".

Page 2, Line 28: delete “both”
The correction has been applied

Page 2, Line 34: should read “ allow only a rough estimation of airborne camera external orientation”
The correction has been applied

Page 3, Line 1: I think the word “accurate” is not appropriate here, because SfM provide accurate models whether they are geo-referenced or not. I suggest rephrasing, something like “in order to geo-reference (or register) 3D models, ...”
The correction has been applied and the new sentence has been modified as it follows: "In order to obtain accurate and georeferenced the 3D models, the use of ground control points (GCPs) surveyed with geodetic GNSS receivers and total station (TS) is generally employed (Francioni et al. 2015).".

Page 3, Line 3: should be “dependent not only ON” (not “from”); same comment at the end of the line
The correction has been applied

Page 3, Line 3: I suggest rephrasing and use “a preliminary rock fall hazard assessment, requested...”
The correction has been applied

Page 3, Line 24: I suggest rephrasing “The bottom of the pit is located at 1,180 meters above sea level (masl) and the top of the excavated rock face is at 1,300 masl.
The correction has been applied and the new sentence has been modified as it follows: "The bottom of the pit is located at 1,180 meters above sea level (m.a.s.l.) and the top of the excavated rock face is at 1,300 m.a.s.l..".

Page 3, Line 29: “compressive tectonic phase WHICH originated...”
The correction has been applied

Page 3, Line 32: “fragile” should read “brittle”?
The correction has been applied

Page 4, Line 1: “motion” should read “displacement” or “offset”?
The correction has been applied and the word "displacement" has been used instead of "motion".

Page 4, Line 3-5: please rephrase with something like “AS involves the oldest LITHOLOGIES of the ..., INCLUDING pre-Alpine...”
The correction has been applied

Page 5, Line 5: would "baseline" be a better terminology for the "two points necessary for the roto-translation of the measured GCPs"?
The correction has not been applied since the terminology "baseline" is correct, especially for GPS measurements, but, in our opinion, less explicative than our long sentence to explain the concept of roto-translation.

Page 7, Line 20: where are the results of block shape and size? Do you mean to say that the results of the kinematic analysis highlight potential for discontinuity-controlled failure mechanism and "therefore the high resolution images and the dense point cloud were analyzed in order to locate possible block source areas"?
We wanted to say that since the traditional kinematic analyses don't allow localization of blocks source areas, the high resolution images were used to localize them. We don't think it is necessary to include the properties of each block, since the paper focus on the 2 bigger and most dangerous blocks. Nevertheless, the sentence wasn't clear, and it has been rewritten it in this way: "The results highlight the potential for blocks to form that may be subject to gravity induced instability but, as previously stated, traditional kinematic analyses do not identify the location of these unstable blocks. Therefore, further analysis of the high resolution images and the dense point cloud was performed in order to locate possible block source areas. More than 20 blocks were deterministically characterized in terms of size, shape and barycentric coordinates, varying from about a cubic meter to a few hundred cubic meters."

Page 7, Line 23: do you mean to say :"In particular, the adopted approach identified two large blocks..."?
The correction has been applied.

Page 7, Line 29-30: I suggest moving this sentence to Line 25, after "high persistence".
The correction has been applied.

Page 8, Line 14: I suggest wording "impossible to measure deterministically"
The correction has been applied.

Page 8, Line 15: I suggest saying that for this reason, persistence is commonly measured as trace length on rock outcrop, and use a more appropriate reference than Einstein et al (1983)
The sentence was rewritten in this way: "The limit of the application of this method is that the discontinuity area is practically impossible to measure deterministically in the field, for this reason persistence is commonly measured as trace length on rock outcrops. Jennings (1970) proposed the following Eq. (2) for persistence calculation starting from trace length values on rock exposure:"

Page 10, Line 10: "slope stability analysis" instead of "slope instability analysis"
The correction has been applied and "instability analysis" has been changed in "stability analysis" in the whole text.

Page 10, Line 25: the reference should be "(Kemeny and Donovan, 2005)"
The correction has been applied.

Figures 3 and 5 captions: "top view" should read "plan view"
The correction has been applied. Figure1 has been similarly modified.

Figure 5 needs to be referenced in the text; the caption should explain that the blue rectangles correspond to the photographs locations; there is not scale nor indication of the north on the figure.
Figure 5 was already referenced in the text (Pag. 5, Line 2). The caption has been modified and the sentence "blue rectangles correspond to the photographs locations, black lines to normals" has been added. A reference scale and the indication of the north have been added to the Figure 5a.

Figure 7: could you please clarify: the caption mention equal area, while the figure shows equal angle. In addition, Figure 7 uses Schmidt method while Figure 8 uses Wulff method.
That was a mistake, the figure has been changed and "Equal angle" corrected
Figure 7 uses Schmidt method since it represents a joint density analysis, while Figure 8 uses Wulff method since it refers to a slope kinematic stability analysis. They are both in theory correct.

Figure 9: "insect photo" should read "inset photo"

The correction has been applied

Figure 13 captions should read “Details of a series of tight discontinuities...”
The correction has been applied

Point-by-point response to Reviewer #2

Dear Authors,

This paper shows not only survey results of complex morphologies using RPAS and SfM-MVS but also a practical application for disaster prevention using those high resolution data, therefore, very interesting. Since detailed measurement procedures, advantages and disadvantages of RPAS and SfM methods are also well explained, I think that this paper is worth to be published. However additional explanations and reconsiderations for the following points should be desired.

Although high resolution 3 dimensional data were obtained using RPAS, does the present stability analysis need that high resolution data? Since the higher resolution of data, the higher costs of data acquisition, processing and handling, appropriate resolution according to the purpose would exist.

We consider high resolution of data always useful in slope stability analyses because it allows the identification and measurement, with high precision and detail, of joints and potential unstable blocks and rock masses at any height above the open pit floor. As written in the Acknowledgments section, that part of the present study has been undertaken within the framework of an agreement with USL1 of Massa and Carrara (Mining Engineering Operative Unit - Department of Prevention) aimed to that purposes. Furthermore, high detail and accurate geometrical data allow deterministic kinematic analyses and the creation of reliable stability models. RPAS photogrammetry is considered a low-cost alternative to traditional remote-sensing techniques given the low cost for digital cameras compared to laser scanners and their ease of use in the field. In this work, for example, we used a light compact Nikon CoolpixA with CMOS sensor that can easily be mounted on a small low-cost RPAS. In this context, the cost of low or high resolution data acquisition are similar, and the decision of decreasing the quality of the data for faster data processing may be adopted in a later stage, depending on the aims of the analyses. In this case for example, a medium-low performance computer (Intel i5 processor with 16 GB RAM) was sufficient for creating the high resolution 3D model. To conclude, costs of data acquisition, processing and handling are not a problem when using RPAS, and this is the reason why they are always more used in engineering geological investigations.

In order to take this aspect of RPAS into considerations we added the following sentences in the text:

Introduction section: “Indeed, RPAS photogrammetry for engineering geological investigations has became widespread mainly because it is a cost-efficient, high flexible and safe technique (Remondino et al., 2011; Siebert and Teizer 2014; Tannant 2015)”

Discussion section: “Nevertheless, in this work the 3D models have been obtained using a medium-low performance computer (Intel i5 CPU @ 3.20 GHz with 16 GB RAM), using images obtained from a light compact digital camera that can easily be mounted on a low cost RPAS. In addition, the use of GCPs overcame the necessity of an expansive IMU system for accurate image alignment. This confirms the reason of the widespread of RPAS for engineering geological investigation, mainly due to its low cost, speed and high safety.”

Page 3, lines 10-13: Even though this paper deals with management of natural hazard, detailed description of a real victim would be not necessary in this paper discussing survey method and its application.

The suggestion has been applied and the sentences eliminated.

Figure 4: Although GCPs are located only in the bottom of cliff, is there any effect on the accuracy of 3D model of the cliff?

This is actually a good point. It is true that this problem has repercussion on the final accuracy of the zenithal flight, since the GCPs are located only at the bottom of the cliff. We were aware of that, but the problem was that higher parts of the quarry were inaccessible due to safety reason. In order to overcome this problem GCPs were well spatially distributed, redundant, and the flight altitude was kept low. In addition, it must be considered that a number of photo were convergent and allowed us to build an accurate 3D model even in the surroundings of vertical quarry walls.

On the other hand, it must be considered that additional frontal flights, on the perpendicular to the rock faces, have been executed ad hoc and the related photos used to build a separate frontal model as shown in Figure 6. In that case we were able to collect GCPs at different heights using a total station, obtaining a very good

model of the cliff. It should be underlined that GCPs for both zenithal and frontal flights are projected in the same reference system. The result of all this is a final root mean square error calculated on the check points (Table 2) of about 6 cm for the zenithal flight and 3 cm for the frontal flights. Therefore, we obtained similar accuracy for the two models, which can be considered adequate for the purpose of the work.
In order to take this problem into consideration, we added the following text in the Discussion section:
"In particular, the final RMSE calculated on the check points (Table 2) was about 6 cm for the zenithal flight and 3 cm for the frontal flight. This small difference is mainly due to the fact that higher parts of the quarry were inaccessible for safety reason, and GCPs of the zenithal flight were only located at the bottom of the cliff. Anyhow, such problem was partially overcame by using GCPs well spatially distributed, redundant and a low flight altitude. In addition, it must be considered that RPAS allow acquisition of a number of convergent photos, that using SfM techniques permit to increase the quality of the model and to build an accurate 3D model even in the surroundings of vertical quarry walls.
Differently, the frontal flights, on the perpendicular to the rock faces, have been executed ad hoc and the related photos used to build a separate frontal model as shown in Fig. 6. In that case the GCPs were collected at different heights using a TS, obtaining a very good model of the cliff. It should be underlined that GCPs for both zenithal and frontal flights are projected in the same reference system. In the end, analysis of the results confirms the good accuracy level of the final model, widely adequate for the purpose of the work."

Figure 6: Although the number of GCPs looks too much, how did you decide their locations and number?
We decided to measure a great number of GCPs (21) because we had to orient, as more accurate as possible, 448 images of a complex morphology. GCPs location has been decided considering a balance between an optimum spatial distribution (Figure 6) both in space, considering the V shape of the "Piastrone" quarry, and elevation from the open pit floor, accessibility (GCPs for the zenithal flight) and easy identification of points on the images (GCPs for the frontal flights).
This aspect of the survey was explained in the Geomatic survey section with the following two sentences:
-"Eight artificial targets, 50x50 cm large, were located with the purpose of obtaining an optimum spatial distribution on the accessible zones of the study area (Fig. 4) and used as ground control points (GCPs) and check points."
-"As for the zenithal flight, a series of GCPs and check points (21 targets in total - Fig. 6) were measured using a reflectorless total station (TS). Their location was decided considering a balance between an optimum spatial distribution (Fig. 6), both in space and elevation from the open pit floor, and easy identification of points on the images. Due to the complex morphology of the slopes and the extent of the mining area, a large number of GCPs were used to orient the photogrammetric model."

Following, a marked-up manuscript version showing the changes made in the text.

Use of a remotely piloted aircraft system for hazard assessment in a rocky mining area (Lucca, Italy)

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Abstract. The use of remote sensing techniques is now common practice in different working environments, including engineering geology. Moreover, in recent years the development of structure from motion (SfM) methods, together with rapid technological improvement, has allowed the widespread use of cost effective remotely piloted aircraft systems (RPAS) for acquiring detailed and accurate geometrical information even in evolving environments, such as mining contexts. Indeed, the acquisition of remotely sensed data from hazardous areas provides accurate 3D models and high resolution orthophotos minimizing the risk for operators. The quality and quantity of the data obtainable from RPAS surveys can then be used for inspection of mining areas, audit of mining design, rock mass characterizations, stability analysis investigations and monitoring activities. Despite the widespread use of RPAS, its potential and limitations have still to be fully understood.
In this paper a case study is shown where a RPAS was used for the engineering geological investigation of a closed marble mine area in Italy: direct ground based techniques ~~couldn't~~could not be applied for safety reasons. In view of re-activation of the mining operations, high resolution images taken from different positions and heights were acquired and processed by using SfM techniques, for obtaining an accurate and detailed three-dimensional model of the area. The geometrical and radiometrical information was subsequently used for a deterministic rock mass characterization that led to the identification of two large marble blocks that pose a potential significant hazard issue for the future workforce. A preliminary stability analysis, with focus on investigating the contribution of potential rock bridges, was then performed in order to demonstrate the potential use of RPAS information in engineering geological contexts for geo-hazard identification, awareness and reduction.

1 Introduction

In open-pit or quarry areas, personnel and equipment involved in mining operations can be exposed to different types of slope instability processes. Rock collapses can be due to a series of predisposing and triggering factors, mostly depending on relationships between localized geological conditions and mining activities. According to Zajc et al. (2014), for example, hazardous situations may occur when unfavourable sedimentological characteristics and geological ~~structures~~discontinuities (e.g. joints, faults~~, bedding planes~~) of rock masses are ~~altered~~made even more critical by ~~exploitation. At~~extraction of the ~~same time~~resource or ore material. In addition, Zheng et al. (2015) ~~underlain~~highlight the crucial role played by morphological features, ~~like~~such as sharp cuts and steep slopes, for ~~the~~potential triggering of rockfalls in mining areas. As widely demonstrated in the literature, the understanding of geometric relationships between geological discontinuities and slope morphology is essential to evaluate the potential occurrence of rock failures, since orientation of joint sets may influence both ~~the~~ size and failure mechanisms of rock blocks prone to collapse (e.g. Stead and Wolter, 2015).
Generally, discontinuity characterization is carried out in the field by traditional engineering geological surveys (Priest, 1993~~); measurements~~). Measurements may be subjected to different source of errors which can result in either under- or over-estimation of the discontinuity geometrical properties (Tuckey and Stead, 2016). In order to avoid this deficiency Sturzenegger and Stead (2009) ~~suggested to couple~~suggest coupling traditional field measurements with remote sensing techniques. Indeed, techniques such as terrestrial laser scanning (TLS) and digital terrestrial photogrammetry (~~DP~~DTP) for

rock mass characterization are increasingly being used, especially in open pit mines where rock slopes subjected to excavation are analyzed (e.g. Kovanič and Blišťan, 2014; Salvini et al., 2015; Tuckey and Stead, 2016). TLS and ~~DP~~DTP allow accurate representation of ~~rocky~~rock outcrops by means of 3D point clouds or interpolated models.~~ However, it is worth noting that~~ A limitation of ground-based ~~acquisition of high resolution topographic data~~remote sensing is related to the survey of complex ~~morphologies may be very difficult to acquire because of occlusions and inaccessible~~topography from sub-optimal camera or scanner positions, resulting in occlusion zones (Passalacqua et al., 2015). A solution to this problem is provided ~~by the~~through use of remotely piloted aircraft systems (RPAS~~)~~), that can be used as a platform to acquire light detection and ranging (LiDAR) or photogrammetric data. ~~According to Chen~~Indeed, RPAS photogrammetry for engineering geological investigations has became widespread mainly because it is a cost-efficient, high flexible and safe technique (Remondino et al~~. (~~., 2011; Siebert and Teizer 2014; Tannant 2015~~) there~~). There are ~~only few published references related to RPAS applications in open-pit mining. The majority of~~several photogrammetric studies ~~deal with~~using RPAS for the geomorphic feature characterization or mapping of the surface ~~mine~~ extent in open-pit mines (Lamb, 2000; Chen et al., 2015; Shahbazi et al., 2015; Tong et al., 2015; Esposito et al., 2017~~). Few works concern~~), and few studies are also associated with the use of RPAS for discontinuity characterization of rock slopes affected by mining activity. Salvini et al. (2016), for example, used ~~an~~ RPAS to map discontinuities in a marble quarry and to subsequently build 3D discrete fracture network models. McLeod et al. (2013) explored the feasibility of using RPAS-acquired video images to derive 3D point clouds and to measure fracture orientations.

Digital images ~~acquired~~obtained from RPAS are commonly processed with the structure from motion (SfM) technique (Spetsakis and Aloimonos, 1991; Fonstad et al. 2013; Colomina and Molina, 2014; Westoby et al., 2012). SfM is based on sophisticated algorithms of image matching that use pseudo-random redundant images acquired from multiple viewpoints to reconstruct the three-dimensional geometry of an object or surface. In order to analyze rock outcrops, the use of RPAS ~~multicopters~~multicopter results are particularly suitable because ~~they allow~~it allows different geometric configurations for ~~the~~ image acquisition (i.e. zenithal, frontal, oblique). Multiple images obtained from different angles help ~~both~~ the image alignment procedure and limit non-linear deformations. Moreover, the relatively short distance to which multicopters can operate from rock faces allows acquisition of high resolution images that can be used for producing high quality topographic products~~. However, in~~ and subsequent interrogation.

In RPAS-SfM applications particular care is needed when geo-referencing the 3D model. As stated by Passalacqua et al. (2015), sensors such as cameras or lasers fixed to RPAS typically do not have onboard navigation systems with ~~a~~ sufficient accuracy for geodetic positioning. In fact, the global navigation satellite system (GNSS) and inertial measurement unit (IMU) devices typically mounted on RPAS are used for navigation and flight stabilization purposes and allow only a rough estimation of airborne ~~cameras~~camera exterior orientation (Gonçalves and Henriques, 2015). In order to obtain accurate and georeferenced 3D models, the use of ground control points (GCPs) surveyed with geodetic GNSS receivers and a total station (TS) is generally employed (Francioni et al. 2015). Nevertheless, the final accuracy is dependent not only ~~from~~on the GCP-related accuracy, density and distribution within the surveyed area, but also ~~from~~on image quality and percentage of overlapping between single frames. Therefore, careful planning of an RPAS photogrammetric survey plays a crucial role in providing accurate results necessary for subsequent analysis, such as determination of discontinuity measurements.

In this study, two RPAS-based photogrammetric surveys were carried out within an open-pit mine of the Apuan Alps marble district, Italy. These surveys aimed to obtain detailed topographic information of the area. The 3D data was then used to perform a preliminary rockfall hazard ~~evaluation~~assessment, requested in view of a potential restart of the mining operations interrupted some years ago. Indeed, the safety of the workforce represents a critical aspect for the exploitation of the marble quarries of the Apuan Alps. ~~In the last decades, many deadly rock failures involving personnel employed in the mining activity have occurred. The last accident occurred on April 14, 2016 (Petley, 2016). In this case, two workers were killed and another injured by a large rockfall involving around 2000 tons of marble, during the excavation of a fractured rock wall.~~ The geo-structural conditions of the marble predispose the rock masses to different types of failures with different magnitudes. Slope stability ~~analysis~~analyses are therefore essential to improve safety conditions for personnel employed in the mines. However, a complete analysis of all the slopes characterizing an open-pit mine is often problematic, given their spatial extension and limitations of numerical models. For this reason both geological and

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geomorphological information of the whole mining area are essential to detect and evaluate the most hazardous situations. RPAS-derived data were therefore integrated with those acquired in the field from a traditional engineering geological survey. The combined use of these ~~information~~data allowed preliminary 3D analysis and evaluation of the stability conditions of a large ~~rocky~~rock block that ~~posed~~was identified as posing a risk to the mining area. Nevertheless, there are controlling factors that can have a great influence on the stability condition of a block or slope that cannot be fully determined, such as discontinuity persistence. The presence of intact rock bridges, that represent intervals of intact rock between adjacent discontinuities (ISRM, 1978), can significantly increase the stability of a rock slope, since the cohesion of the intact rock is generally of at least two orders of magnitude greater than the shear strength of a discontinuity (Park, 2005). In general, joint persistence (K) is defined as the fraction area that is actually discontinuous (Einstein et al., 1983), and can be calculated with the following Eq. (1):

$$K = \lim_{A_D \to \infty} \frac{\sum_i a_{Di}}{A_D}$$

(1)

where D is a region of the plane with area A_D and a_{Di} is the area of the joint in D.

The limit of the application of this method is that the discontinuity area is practically impossible to measure deterministically in the field, for this reason persistence is commonly measured as trace length on rock outcrops. Jennings (1970) proposed the following Eq. (2) for persistence calculation starting from trace length values on rock exposure:

$$K = \frac{\sum JL}{\sum JL + \sum RBR}$$

(2)

where JL is the total length of the joints segment and RBR is the total length of rock bridges.

Mathematically, it is possible to consider the presence of rock bridges in terms of effective cohesion along the shear surface (Eberhardt et al., 2004) by using the following Eq. (3):

$$c_i = c\frac{A_g}{A}$$

(3)

where c is the intact rock cohesion, A_g the total area of intact rock bridges along the shear surface, and A is the total area of the shear surface.

Importantly, as recently reported by Tuckey and Stead (2016), in spite of the importance of intact rock bridges in slope stability, there are still no standard accepted methods for estimating the extent of rock bridges and incorporating rock bridges into slope stability analysis.

2 Geographical and geological setting

The study area is located in the Apuan Alps marble district, in the province of Lucca (Tuscany, Italy~~), -~~ Fig. 1~~.~~). The open pit or quarry, named "Piastrone", is characterized by a V shape, with two principal slope directions oriented 50/90 and 323/90 (dip direction/dip). The bottom of the pit is located at 1,180 meters above sea level (m.a.s.l.~~, but~~ .) and the top of the excavated rock ~~faces can reach and overcome~~face is at 1,300 ~~meters~~ m.a.s.l.. The rock mass is characterized by different sets of discontinuities with persistence values that can vary from a few meters up to decameters.

From a geological point of view (Fig. 2) the Piastrone open pit is located in the Apuan Alps metamorphic complex, precisely in the Mt. Altissimo Syncline (AS), belonging to the Apuane Unit (Meccheri et al., 2007~~), Fig. 2.~~). According to classical interpretation (Carmignani and Kligfield, 1990) AS resulted from a compressive tectonic phase which originated during the Tertiary continental collision between the Sardinia-Corsica block and the Adria plate. Successively, during the Early Miocene, a new ductile to brittle-ductile deformation caused by a post-compression tectonic uplift overprinted the earlier structures and generated a widespread network of joints and faults. In the Mt. Altissimo area, the main set of ~~fragile~~brittle deformation strikes SW-NE to W-E with sub-vertical dip, generally with negligible ~~motion~~displacement except ~~from~~for a few cases where offsets of some ten meters have been observed (Meccheri et al., 2007).

AS involves the oldest ~~terms~~lithologies of the Apuan unit sequence, ~~with~~including pre-Alpine basement rocks, Grezzoni dolostones, megalodont-bearing marbles with metabreccias and chloritoid-rich phyllites, local lenses of dolomitic marblems and Marbles sensu stricto of lower Liassic age (Meccheri et al., 2005). Due to the compressive tectonic phase, a penetrative S1 foliation is also present in all the lithotypes (except ~~from~~for dolostones).

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3 Methods

3.1 Geomatic survey

In order to assess and localize the slope stability hazard in the rocky mining area, two RPAS surveys were carried out with direction of photo acquisition in zenithal modality (perpendicular to the open pit floor) and in ~~a parallel direction~~ frontal modality (perpendicular to the rock faces ~~(frontal~~). The surveys were performed in December 2015 using the Aibotix™ Aibot X6 V1 multicopter, ~~composed by~~which has six electric rotors, and equipped with a Nikon™ CoolpixA digital camera (Table 1) and a GNSS/IMU system that allows recording of 3D coordinates (X0,Y0,Z0) and orientation of the camera (pitch, roll and yaw – ω ϕ κ) at every shoot or image.
The zenithal survey was preliminarily designed in the laboratory with the Aibotix™ Aiproflight planning software, and manually performed through single quasi-parallel flight lines. A total of 151 aerial images were acquired with a nominal overlap and sidelap of 80% and 60% respectively. Two flights were ~~needed~~required to cover all sectors of the mining area (Fig. 3).
An average estimated ~~ground sampling~~ distance ~~(~~between pixel centers measured on the ground (i.e. ground sample distance - GSD) of 2.4 cm was calculated. During the flight, a global navigation satellite system (GNSS) field survey was also carried out in order to ensure the necessary spatial accuracy ~~for the exterior orientation~~ of the resultant images~~, measuring a total of 8~~. Eight artificial targets, 50x50 cm large~~ uniformly distributed over~~, were located with the purpose of obtaining an optimum spatial distribution on the accessible zones of the study area (Fig. 4) and used as ground control points (GCPs) and check points.
The GNSS survey was carried out in ~~Real Time Kinematic~~real time kinematic (RTK), using geodetic receivers.~~ In particular, a~~ A reference station was set up, recording continuous signals from the GNSS satellite constellation ~~above~~for more than 3 hours. The positional information ~~acquired~~obtained by the reference station was then sent to a mobile receiver, using ~~a~~ radio modem communication. Each ground control point, GCP, was occupied for at least two minutes with a recording interval equal to 1 ~~sec~~second. The coordinates of the points ~~acquired with~~determined using this technique were corrected by post-processing procedures using contemporary data recorded by three permanent GNSS stations (La Spezia, Pieve Fosciana and Pisa) allowing centimetric accuracy. The orthometric heights were also calculated by using Convergo, an Italian code for full ~~coordinates~~coordinate conversion. The coordinates of the GCPs were collected in ETRF2000 and then converted ~~in~~to the Italian National Gauss Boaga system for ~~the exterior~~ orientation of the images and ~~the restitution~~subsequent determination of the inclination and position of slopes and ~~joints~~ orientation of discontinuities.
The frontal survey, with ~~directions~~direction of acquisition parallel to the rock ~~faces~~face, was carried out manually, without the use of the Aibotix™ AiProflight planning software. Six flights were ~~needed~~required in order to cover all sectors of the mining area, ~~for~~resulting in a total of 448 overlapping images. The flights were executed ~~according to~~in sub-parallel straight lines ~~about~~approximately 60 meters distant from the rock face (Fig. 5~~)~~), providing an average estimated GSD of 1.5 cm.
As for the zenithal flight, a series of GCPs and check points (21 targets in total - Fig. 6) were measured ~~by a reflectorless TS.~~using a reflectorless total station (TS). Their location was decided considering a balance between an optimum spatial distribution (Fig. 6), both in space and elevation from the open pit floor, and easy identification of points on the images. Due to the complex morphology of the slopes and the extent of the mining area, a large number of GCPs were used to orient the photogrammetric model. Two GNSS receivers, operating in static modality, were used to obtain the geographic coordinates of two points: the origin of the survey and its zero-Azimuth direction. ~~Also for~~For this survey, GNSS data were corrected using contemporary data recorded by permanent GNSS stations and ellipsoidal heights were converted to orthometric heights.

3.2 Application of structure from motion algorithms

The software Agisoft™ PhotoScan Professional version 1.2.5 (Agisoft 2016) was used to process the images obtained ~~with~~from the two RPAS surveys (two zenithal flights plus six frontal flights). This software is ~~able to solve~~capable of solving the camera interior and exterior orientation parameters and ~~to~~ generate georeferenced spatial data ~~like~~such as 3D point clouds, digital surface models (DSMs) and orthophotos. All the images acquired ~~in~~from the two surveys were processed with ~~an~~ identical

photogrammetric processing, in two distinct Agisoft™ Photoscan projects~~,~~; one for the zenithal flights and another for the frontal flights~~-~~.
The first processing step consisted ~~in the~~of image alignment, through which the interior and relative orientation parameters were solved. In order to improve the whole alignment process and to obtain low ~~reprojection~~re-projection error, millions of tie points were automatically extracted without setting a point limit. ~~As result of~~ Following image alignment, the ~~previous stage, all images were aligned. The~~ second processing step involved georeferencing of the 3D model in such a way as to solve the exterior orientation parameters by using the GCPs coordinates measured during the two GNSS-TS topographic surveys. For both surveys, a ~~part~~number of the measured points ~~was~~were used as check points to verify the model accuracy. Specifically, for the zenithal survey 2 of the 8 measured target points were used as check points, while for the frontal survey (with ~~directions~~direction of photo acquisition parallel to the rock faces~~,~~) 4 points out of 21 were used as check points. Both natural and artificial targets were identified directly on the images, assigning a 3D coordinate to each of them.
Subsequently, the ~~optimize~~‘optimize’ tool was utilized ~~in order~~ to adjust the estimated camera positions ~~for removing~~to remove possible non-linear deformations, minimizing the errors due to re-projection and misalignment of the photos. Moreover, the optimization was improved by deleting all the tie points with a ~~reprojection~~re-projection error greater than 1 pixel.
In a subsequent step, the zenithal and frontal dense 3D point clouds were generated with medium quality and aggressive depth filtering settings. No automatic classification of clouds was necessary: no infrastructure was present as the mine was not operational and there was no vegetation within the area of interest.
~~Lastly~~Finally, a polygonal 3D mesh model was created from the point cloud and used to create the orthophoto of the open pit area. The orthophoto has ~~the property of been removed from~~ image distortions removed due to camera characteristics (i.e. lens distortions), camera tilt and topographic relief displacement. Unlike an uncorrected aerial photograph with a perspective projection, an orthophoto is geometrically corrected ('orthorectified') and can be used to measure true distances since it is 'scale-corrected'. The corrected orthophoto image with a spatial resolution of 1 cm/pixel was ~~finally~~then projected into the Italian National Gauss Boaga system.

3.3 Engineering geological investigation

In order to characterize the rock mass within the open pit mine, a relatively large number of discontinuities ~~was~~were identified directly on the dense point cloud. The orientation of the selected ~~joints~~discontinuities was manually calculated by creating patches that best fit the identified discontinuity planes in the point cloud and extracting their orientation using the Leica™ Cyclone 9.0 software. ~~The discontinuity~~Discontinuity sets were then ~~recognized~~identified using stereographic representation (Schmidt equal-area method, lower hemisphere).
According to Mastrorocco et al. (2017), a manual deterministic fracture mapping was also adopted because it increases the level of control of the process, that is essential where the morphology of the quarry slope surfaces is largely artificial (smooth cut surfaces). The collected point cloud-derived data were then compared with those manually measured by traditional engineering geological surveys. On the basis of engineering geological data, ~~the~~ geological strength index (GSI - Hoek, 1994) and ~~Brown, 1997) and the~~ rock mass rating (RMR - Bieniawski, 1989) characterization were also applied, and a kinematic stability analysis was carried out using the Markland test (Markland, 1972). The latter testing was undertaken in order to identify potential kinematic failure mechanisms that characterize the slopes. The tests for planar sliding, wedge sliding~~,~~ and direct toppling were conducted for both principal slope directions (Eastern slope - dip direction/dip 50/90; Western slope - dip direction/dip 323/90).
Despite the importance of performing kinematic analysis to discover ~~the~~ possible block instability, one of the principal limitations of this stereographic method is the inability to locate the block source areas~~.~~ on the slope being analyzed. For this reason, the most critical blocks have been identified directly on the point cloud. The points representing the geometry of every single block were meshed in Leica™ Cyclone 9.0 and their volume estimated ~~in respect of~~using reference planes corresponding to the discontinuities that demarcate or shape the respective blocks.
The collected orientation data were finally used for preliminary stability analyses using Rocscience™ Swedge software. Swedge is a 3D software for ~~evaluating~~evaluation of the stability of surface wedges in rock slopes. It considers the intersection of discontinuities and allows the calculation of safety factors of

the formed blocks. The software is based on classical limit equilibrium methods that usually have some limitations, such as lack of consideration of in-situ stress, strains and intact material failure (Stead et al., 2006). Nevertheless, Swedge does allow ~~the~~ consideration of external forces, by applying a force (vector with given orientation and intensity) to the formed blocks. From this, preliminary analysis of the impact of water content or other forces can ~~be performed~~also be performed. The software can also be used to assess the stability of wedges formed by a basal plane.

4 Results

4.1 Photogrammetric modelling

The image alignment process, described in ~~paragraph~~section 3.2, resulted in a ~~reprojection~~re-projection error related to the manual placement of GCPs on the images of 0.41 pixel for the zenithal survey and 0.48 pixel for the frontal survey. The final ~~Root Mean Square Error~~root mean square error (RMSE) for the zenithal flights exterior orientation was equal to 0.042 meters; RMSE for the frontal flights exterior orientation was equal to 0.043 meters (Table 2).
The final 3D frontal and zenithal point clouds ~~are constituted by~~contain more than 18,000,000 and almost 13,000,000 ~~of~~ points respectively, with a mean point spacing varying from 1 to 4 cm.

4.2 ~~Rocky~~Rock slope engineering geological characterization

The orientation of 154 discontinuity planes manually selected on the point cloud was calculated through stereographic projection. The final stereonet allowed ~~to identify~~identification of four discontinuity sets, whose properties ~~are~~ listed in table 3~~. Figure 7 shows a comparison between the latter (b) and~~ were obtained from traditional engineering geological survey carried out in accessible areas of the mine. By comparing the ~~stereonet~~discontinuity planes obtained through traditional manual engineering geological survey (a~~), highlighting~~ in Fig. 7) and that identified on the point cloud (b in Fig. 7) a good level of congruence ~~that confirms~~has been highlighted, confirming the quality of the ~~taken~~ approach taken.
Based on the discontinuity characteristics derived from ~~the RPAS~~RPAS and traditional engineering geological surveys, the basic RMR (RMRb) and GSI index were calculated. The RMRb was found to be 67~~,~~ (table 4), while the GSI was estimated to be between 60 and 65~~, indicating in both cases~~ using the modified chart proposed by Hoek et al. (2013). In addition, application of Hoek et al. (2013) equation for GSI quantification (GSI=1.5 $JCond_{89}$ + RQD/2) confirmed the results of the qualitative chart interpretation with a value of 65.Both classifications indicate a rock mass of ~~good~~'good' quality. These results agree with the authors' field observations and what is described in the actual quarry excavation plan (Lorenzoni, 2012). In view of the rock competency, potential instability is not related to ~~general weaknesses~~the strength properties of the rock mass, but the intersection of discontinuity planes can locally ~~isolate rocky~~form rock blocks with the potential for sliding or toppling. For this reason, a kinematic stability analysis was performed. A discontinuity friction angle of 35° was used in the analysis: this agrees with data from previous studies carried out by the quarry's advisors (Lorenzoni, 2012; Dumas, 1999), by the Geomechanical laboratory of the Centre of GeoTechnologies of Siena University, and literature (Chang et al., 1996~~,~~; Perazzelli et al., 2009~~,~~; Mastrorocco, 2013~~) and.~~). Table ~~4~~5 shows the potential failures identified through kinematic stability analysis (examples are shown in Fig. 8) for both principal slope orientations.
~~Results~~ Three different possible kinematic modes were identified, with K2b and K4 systems having the most influence on potential instability. The majority of the potential failures identified relate to planar sliding or wedge sliding, in agreement with field and SfM-based observations. The results highlight the potential for blocks, ~~of variable shape and size, varying from about a cubic meter to a few hundred cubic meters,~~to form, that may be subject to gravity induced instability~~. –~~ but, as previously stated, traditional kinematic analyses do not identify the location of these unstable blocks. Therefore, further analysis of the high resolution images and the dense point cloud ~~were analyzed~~was performed in order to locate possible block source areas. More than 20 blocks were deterministically characterized in terms of size, shape and barycentric coordinates~~. The adopted approach also~~, varying from about a cubic meter to a few hundred cubic meters. In addition, the analysis identified two large blocks~~,~~ (Fig. 9), a few thousand cubic meters in size, with potential for sliding. These~~ are shown in Fig. 9, and~~ are formed by the intersection of two different faults and a discontinuity basal plane with 5 cm aperture, no infill, smooth surface and high persistence. The basal plane appears not to correspond with any of the identified

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discontinuity sets, but is probably connected to planes of weakness of the marble in correspondence with a particular orientation of minerals crystallographic axes. The lateral and rear faults, however, may be associated with the K3a and K3b systems respectively. The rear fault may also be associated with the East-West fault system that characterizes the geology of this area of the Apuan Alps complex (Fig. 2).
The geometric characteristics of the two blocks, including orientation of the intersecting discontinuities and volume of the meshed block, were obtained using Leica™ Cyclone 9.0 and are shown in table 6.
The first block, Block A, is of particular interest because it daylights in the face and prevents Block B from sliding (similar to an active-passive wedge; Prandtl's prism transition zone - Kvapil and Clews, 1979). A main road access to the quarry is located at the base of this slope, increasing the potential risk for the area.
~~The geometric characteristic of the two blocks, including orientation of the intersecting discontinuities and volume of the meshed block, were obtained using Leica™ Cyclone 9.0 and are shown in table 5.~~
Due to the particular geometrical configuration, Block A can be described as the key block as it daylights the rock face. In the actual setting Block B does not hold the potential for sliding as it does not daylight in the slope face, but it could play a significant role in terms of additional weight force. Nevertheless, the following preliminary stability analysis is focused on Block A. Further investigation would require an analysis of the effect of Block B on the potential for instability as this provides the 'active' component of the active-passive wedge.

4.3 Preliminary slope stability analysis

The geometry of Block A was deterministically re-created in Swedge using the geometrical information obtained from the point cloud provided in table ~~5.~~6, with a slope direction of 30 degrees. Initially the discontinuities were assumed to be fully persistent. This is a common approach in engineering geology, since reliable values of persistence are almost impossible to obtain from field mapping and most rock slope stability analysis assume that the 100 % persistent joint exists on failure surface (Park, 2005). Moreover, in this case two discontinuities (lateral and rear or back surfaces) correspond to geological faults and can be therefore considered fully persistent. However, the basal plane is a joint and the possible presence of rock bridges should be carefully considered. ~~In general, joint persistence (K) is defined as the fraction area that is actually discontinuous (Einstein et al., 1983), and can be calculated with the following Eq. (1):~~

$$\cancel{K = \lim_{A_D \to \infty} \frac{\sum_I a_{DI}}{A_D}}$$

~~(1)~~
~~where D is a region of the plane with area A_D and a_{DI} is the area of the joint in D.~~
~~The limit of the application of this method is that the discontinuity area is practically impossible to be determined in the field. For this reason, Einstein et al. (1983) proposed a rough quantification of persistence value by measuring trace length on a rock exposure. Jennings (1970) proposed the following Eq. (2) for persistence calculation starting from trace length values on rock exposure:~~

$$\cancel{K = \frac{\sum JL}{\sum JL + \sum RBR}}$$

~~(2)~~
~~where JL is the total length of the joints segment and RBR is the total length of rock bridges.~~
In this case the basal plane did not show the presence of segments of intact rock along its trace on the rock exposure, consequently application of Eq. (2) confirms a 100 % persistence of the basal plane, that was used in the first analysis.
The adopted limit equilibrium solution for the slope stability analysis was based on the Mohr-Coulomb shear strength model with a friction angle of 35° and a unit weight of 0.026 MN/m^3 (Ertag, 1980~~,~~; Dumas, 1999). It should be noted that the western lateral surface observable in the model was also necessary to re-create the block geometry in the software. It was assigned 0° friction angle so as not to induce a resisting force in the simulation. Water forces were also initially ignored within the preliminary analysis~~. The result of the analysis is shown in~~ (Fig. 10~~.~~).
The result highlights a possible condition of instability for Block A which does not match with field observations, since the block under study has remained stable in this position for tens of years. In order to investigate the effect of uncertainty or variability of the input parameters, a sensitivity analysis was performed. In a sensitivity analysis (Fig. 11) specific parameters are varied across a range of values and the effect on ~~safety~~the Factor of Safety is observed ~~factor~~. This helps to identify the parameters that have

the most effect on block stability. Since the geometrical inputs are well defined through the accurate 3D model, the subsequent analysis focused on waviness angle (it accounts for the undulations of the joint surface, observed over distances on the order of 1 m to 10 m; Miller, 1988), cohesion and friction angle of the basal plane and water pressure. These are also the parameters with the higher input uncertainty. ~~Figure 11 shows the result of the sensitivity analysis performed on the cited values.~~

As observed, the cohesion is clearly the parameter that has the most effect on block stability. For this reason, the effect of this parameter was investigated in more detail in the following analyses. ~~In practice, in rock slopes, the cohesion of intact rock bridges between discontinuous joints increases the shear strength of the surface. This can be one to two orders of magnitude greater than the shear strength available on the discontinuity (Park, 2005).~~ ~~Mathematically, it is possible to consider the presence of rock bridges in terms of effective cohesion along the shear surface (Eberhardt et al., 2004) by using the following Eq. (3):~~

$$\cancel{c_i = c\frac{A_g}{A}}$$

~~(3)~~

~~where c is the intact rock cohesion, A_g the total area of intact rock bridges along the shear surface, and A is the total area of the shear surface.~~ Application of Eq. (3) makes it possible to determine an effective cohesion dependent on the continuity of jointing. From this the contribution of eventual rock bridges on the block stability can be investigated starting from intact rock cohesion material value, that has been determined to be approximately 16 MPa (Lorenzoni, 2012; Dumas, 1999; data from Geomechanical laboratory of the Centre of GeoTechnologies of Siena University). Table ~~6~~7 shows the results in terms of factor of safety obtained from a parametric ~~instability~~stability analysis performed with increased values of effective cohesion, corresponding to 0, 0.5, 1, 2, 5, and 10 % of rock bridges on the basal plane (total area of 510 m^2), and a 20 % of water filled fissures (considered reliable after field observation and high resolution images analysis).

5 Discussion

The RPAS approach adopted in this case study, based on the combined use of high-resolution images from different perspective and accurate GNSS/TS topographic surveys, overcame data acquisition difficulties related to high steep quarry walls and provided high-resolution orthophotos of the site (1 cm pixel size). The application of RPAS instrumentation was extremely successful for ~~the~~ reconstruction of the complex morphology of the mine site where ground~~-~~-based techniques (e.g. terrestrial laser scanning, terrestrial photogrammetry) have limitations due to potential "shadow" effects and several inaccessible set-up zones due to safety reasons. GCPs measured using a TS and GNSS receivers permitted a high level of accuracy in the images external orientation, which is particularly important for subsequent discontinuity measurements. ~~-~~In particular, the final RMSE calculated on the check points (Table 2) was about 6 cm for the zenithal flight and 3 cm for the frontal flight. This small difference is mainly due to the fact that higher parts of the quarry were inaccessible for safety reason, and GCPs of the zenithal flight were only located at the bottom of the cliff. Anyhow, such problem was partially overcame by using GCPs well spatially distributed, redundant and a low flight altitude. In addition, it must be considered that RPAS allow acquisition of a number of convergent photos, that using SfM techniques permit to increase the quality of the model and to build an accurate 3D model even in the surroundings of vertical quarry walls.

Differently, the frontal flights, on the perpendicular to the rock faces, have been executed ad hoc and the related photos used to build a separate frontal model as shown in Fig. 6. In that case the GCPs were collected at different heights using a TS, obtaining a very good model of the cliff. It should be underlined that GCPs for both zenithal and frontal flights are projected in the same reference system. In the end, analysis of the results confirms the good accuracy level of the final model, widely adequate for the purpose of the work.

On the other hand, possible limitations in the use of RPAS system can be related to the need for a pilot license and user experience on topographic survey and imagery processing. Indeed, the accuracy of the final 3D model can be greatly affected by the quality of data collected (photos and GCPs), hardware and software capability and user expertise. Nevertheless, in this work the 3D models have been obtained using a medium-low performance computer (Intel i5 CPU @ 3.20 GHz with 16 GB RAM), using images obtained from a light compact digital camera that can easily be mounted on a low cost RPAS. In addition, the use of GCPs overcame the necessity of an expansive IMU system for accurate image

alignment. This confirms the reason of the widespread of RPAS for engineering geological investigation, mainly due to its low cost, speed and high safety.
~~Although~~In this work, the elaboration speed has been partially decreased to guarantee consistency and quality in the interpretation of discontinuities. In fact, although several authors have demonstrated the reliability of automatic and semi-automatic processing of imagery and 3D point clouds for fracture mapping (Mah et al. 2011; Vöge et al. 2013; Assali et al. 2014; Vasuki et al. 2014), a complete manual approach was adopted in this analysis ~~to guarantee consistency and quality in the interpretation of discontinuities. Note that~~because in most cases the flat and regular morphology of quarry walls only allow photointerpretation of discontinuity traces. ~~Final~~Moreover, final visual inspection and validation of outputs is always required, even when using codes for the semi-automatic extraction of joints (Salvini et al., 2016). ~~Therefore~~
In this work, the orientation of several discontinuity planes was calculated using Leica^{TM} Cyclone 9.0 on the point cloud, once its high positional accuracy level was demonstrated. This allowed for a more complete characterization of the rock mass than ~~the one~~ that ~~can~~which could be obtained through traditional engineering geological survey, due to limited safe access to the slopes within the site. This was particularly important also because ~~discontinuities~~discontinuity characteristics can vary at different heights of the rock mass due to stress relaxation induced by excavation activity. In this context, the possibility to inspect the mining area from different angles in high definition, allowed identification of critical areas to be analyzed in detail for safety purposes. Moreover, the possibility to use the point cloud for obtaining geometrical characteristics of blocks represented a major advantage, because it allowed the exact geometrical reconstruction of a 3D model to be used in specific software for slope ~~instability~~stability analysis.
In this work a potential significant risk was identified for the future workforce due to the presence of two major blocks with potential for sliding. In fact, with conservative assumptions the preliminary limit equilibrium analysis showed that the key Block A, in its present shape, is potentially unstable. This is mainly due to the fact that the basal plane dips out of the slope and daylights on the face, with a dip angle higher than the friction angle of the surface. Moreover, the block is separated from the rock mass by a major fault, that can be simulated in the Swedge analysis as a tension crack. The fault can be clearly identified from the orthophoto obtained from the application of SfM method. ~~Figure 12 shows an~~ An apparent motion has been identified on the back fault~~. From a geological point of view the fault can be contextualized in a East-West system that characterize this area of the Apuan Alps complex, as observable in~~ (Fig. ~~2.~~12). The presence of cataclasite with variable thickness can also be ~~interpreted as another sign~~an indication of potential for movement ~~that released the block from the rock mass, similarly to the fault that acts as lateral release surfaces~~on the fault surface.
In this ~~context~~stability analysis the major uncertainty is on the basal plane (Fig. 12). Despite the presence of a continuous trace line on the rock exposure, its full persistence in the rock mass is not clear. In general, the presence of rock bridges plays an important role in stabilizing the removable rock blocks. In particular, a rock block cannot fall or slide from a slope until the rock bridges have failed. The rock bridge failure involves the collapse or failure of the intact rock, which can be an order of magnitude stronger than the rock mass (Kemeny and Donovan, 2005). From the sensitivity analysis undertaken, cohesion of the basal plane was the parameter that ~~has~~had the most significant influence on the block factor of safety. This suggests that it may not be completely persistent in this case, since the block has remained stable over time. In this regard, the parametric analysis carried out increasing the cohesion values shows how a small rock bridge, corresponding to 1% of the basal plane surface (5.1 m^2 of intact rock) is sufficient for guaranteeing the stability of the block. This is mainly due to the fact that, despite the basal plane ~~dips~~dipping more than the friction angle of the surface, its inclination is not sufficient to avoid the generation of a high normal force that increases the shear strength of the discontinuity. Therefore, even a small area of intact rock increases the resisting force that leads to a condition of stability. In this case, 5.1 m^2 of rock bridge corresponds theoretically to a resisting force of 81.7 MN. Similar values of rock bridge percentage have also been found in different case studies, where back-analysis revealed low values of estimated rock bridge content at the moment of failure, in the order of 0 to 5 % (Frayssines and Hantz, 2006; Grøneng et al., 2009; Sturzenegger and Stead, 2012; Matasci et al., 2014; Tuckey and Stead, 2016). Therefore, a small amount of rock bridge may be sufficient for guaranteeing stability of a rock slope.
In reality, based on field observation and authors' experience in similar contexts, higher percentage of rock bridges may exist, that could lead to increased safety. Nevertheless, Hudson and Priest (1983)

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identified two kinds of persistence relative to impersistent or intermittent joints that should be considered. Differently from impersistent joints, intermittent discontinuities require a network of joint segments and intact regions on the same plane. However, as described by Mauldon (1994), the formation of intermittent joints is geologically unlikely, unless weakness planes exist within the rock mass. From this it follows that the cohesion of rock bridges in intermittent joints could be much lower than that of the intact rock. This could be the case of Block A, and the presence of a series of discontinuities with similar dip and dip direction to the basal plane~~, observable in Fig. 13,~~ seems to confirm the hypothesis of a preferential plane of weakness due to the geomechanical characteristics of the marble material in that portion of the mining area~~.~~ (Fig. 13).
Moreover, the progressive degradation with time of rock ~~bridges~~bridge elements could cause a progressive failure mechanism that has the potential to lead to a final rockfall event. This is particularly important in small engineered slopes such as the present one, where the rock mass may be continuously disturbed by excavation activity driving the slope to instability. Such mechanisms of progressive brittle fracturing of rock bridges are not considered in limit equilibrium approaches, and it is a known key limitation (Tuckey and Stead, 2016). The result is that when using the Mohr-Coulomb shear strength criterion, inclusion of a small content of rock bridges adds significant apparent cohesion to the failure surface (Elmo et al., 2011; Tuckey and Stead, 2016).
The aspects discussed in this section lead to the conclusion that a potentially hazardous situation should not be underestimated. Therefore, in case of re-opening of mining activities an in-depth engineering geological analysis, together with the installation of a monitoring system for observing the behavior of the rock mass over time should be considered.

6 Conclusion

The case study highlights the powerful use of RPAS technology for rock slope characterization and acquisition of accurate 3D data for subsequent ~~instability~~stability analysis. Specifically, an Aibotix™ Aibot X6 six-rotor multicopter was employed to obtain high resolution topographic data of a blocky rock mass located within a quarry prone to discontinuity-controlled instability mechanisms. A detailed 3D model of the area allowed accurate identification and geometrical measurement of the geological discontinuities that isolate significant volumes of ~~rocks~~rock. The stability analysis performed with Rocscience™ Swedge software showed that rock bridges can have a significant influence on stability conditions. The analysis highlighted the need for further detailed analysis and installation of suitable monitoring systems for future quarry operations.
These results confirm the reliability of the employed technologies to provide data for preliminary evaluation of the hazard affecting the study area. The RPAS allowed acquisition of high resolution topographic data in an area characterized by a complex morphology where ground-based techniques would have significant limitations (e.g. terrestrial laser scanning, photogrammetry). It is worth noting that in mountainous environments, the use of RPAS has to be evaluated according to the local atmospheric and topographic conditions. The high temporal and spatial variability of the atmospheric conditions at high altitudes, as well as the presence of vegetation or steep and irregular slopes, could endanger the flight operations. This requires pilots with relevant experience and RPAS equipped with innovative systems to manage emergency conditions. Future analysis at this site will concentrate on the evaluation of the most useful countermeasures to reduce the risk conditions, by monitoring the unstable slopes and undertaking further ~~instability~~stability analysis including more complex 3D discrete fracture network (DFN) evaluation to assess the effects of rock bridges and elasto-plastic numerical approaches to assess likely instability.

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Table 1. Utilized RPAS and camera specifications.

RPAS Type	Dimensions (cm)	Engines	Rotor diameter (cm)	Empty weight (kg)	Max. takeoff weight (kg)
Aibotix Aibot X6 v1	Width 105 Height 45	Brushless motors	30.48 (12")	2.45	6.5
Camera	**Sensor type**	**Sensor Size (mm)**	**Image size (pixel)**	**Pixel size (mm)**	**Focal length (mm)**
Nikon CoolpixA	CMOS	23.6 x 15.6	4,928 x 3,264	0,~~0048~~121	18.5

Table 2. Information related to the zenithal and frontal photogrammetric surveys and processing.

	ZENITHAL RPAS SURVEY	FRONTAL RPAS SURVEY
Number of images	151	448
GSD[1]	0.024 m/pixel	0.015 m/pixel
Relative flying altitude	93.9 m	60.7 m
# Tie Point	1,484,605	3,783,992
GCP[2] RMSE[3]	0.042 m	0.043 m
Check Point RMSE	0.065 m	0.03 m
GCP reprojection error	0.41 pixel	0.48 pixel

[1]Ground ~~Sampling~~Sample Distance; [2]Ground Control Point; [3]Root Mean Square Error

Table 3. Characteristics of the discontinuity sets measured on the study area.

Set	Dip Dir/Dip (degrees)	Aperture (mm)	Filling	Persistence (m)	Spacing (m)	JCS (MPa)	JRC	Weathering	Water
K1	231/60	0-1	None, hard filling	2-10	0.1-0.3	50	2-6	Slightly weathered	Damp
K2a	234/86	0-0.5	Hard filling	5.5	5-10	60	2-4	Slightly weathered	Dry
K2b	66/86	0-0.5	Hard filling	5.5	5-10	60	2-4	Slightly weathered	Dry
K3a	142/81	0-2	None	<20	10-15	50	2-6	Slightly weathered	Damp
K3b	177/84	0-2	None	<20	10-15	50	2-6	Slightly weathered	Damp
K4	291/67	1-2	None	1-3	0.5-1.5	55	2-4	Slightly weathered	Damp

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~~Table 4.~~

Table 4. Parameters used for RMRb determination. Chosen index values are underlined.

	Parameter	**K1**	**K2a**	**K2b**	**K3a**	**K3b**	**K4**
A1	Strength of intact rock material	7					
A2	RQD	(75%) 17					
A3	Spacing of discontinuities	15	20	20	20	20	15
A4	Condition of discontinuities	19	19	19	18	18	20
A5	Groundwater	10	15	15	10	10	10
	RMRb 67						

Table 5. Potentially unstable discontinuity systems along the two different slope orientations.

Slope	Planar sliding	Wedge sliding	Direct Toppling
50/90	K2b	K3a/K3b, K2b/K3a, K2b/K3b, K2b/K4, K2a/K4	K3a/K4, K1/K3a, K1/K4 (basal plane K2b)
323/90	K4	K1/K3b, K3b/K4, K1/K4, K2a/K4, K2b/K4	K3a/K3b, K2b/K3a, K2b/K3b, K1/K2b, K1/K2a, K2a/K2b (basal plane K4)

Table ~~5~~6. Characteristic of identified blocks A and B.

ID	Volume (m3)	Height (m)	Width (m)	Length (m)	Basal plane (Dip Dir/Dip)	Lateral release surface (Dip Dir/Dip)	Back discontinuity (Dip Dir/Dip)
A	2650	35	15	40	031/42	307/88	350/81
B	7500	40	20	32	031/35	307/88	-

Table ~~6~~7. Results of the parametric analysis increasing basal plane cohesion values.

Rock bridge %	**Intact rock (m^2)**	**Total cohesion (MN)**	**Driving force (MN)**	**Resisting force (MN)**	**Factor of safety**
0	0	0	48.4	35.9	0.7
0.5	2.~~5~~55	40.8	48.4	76.7	1.5
1	5.1	81.7	48.4	117.6	2.4
2	10.2	163.3	48.4	199.2	4.1
5	25.5	408.3	48.4	444.2	9.1
10	51	816.5	48.4	852.4	17.6

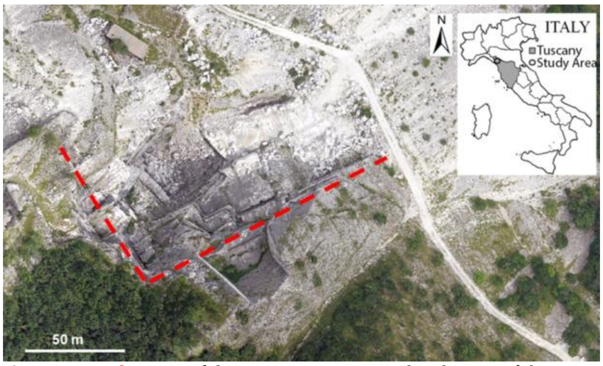


Figure 1. ~~Top~~Plan view of the Piastrone open pit with indication of the two principal slope directions (dotted lines). Inset map shows the location of the study area.

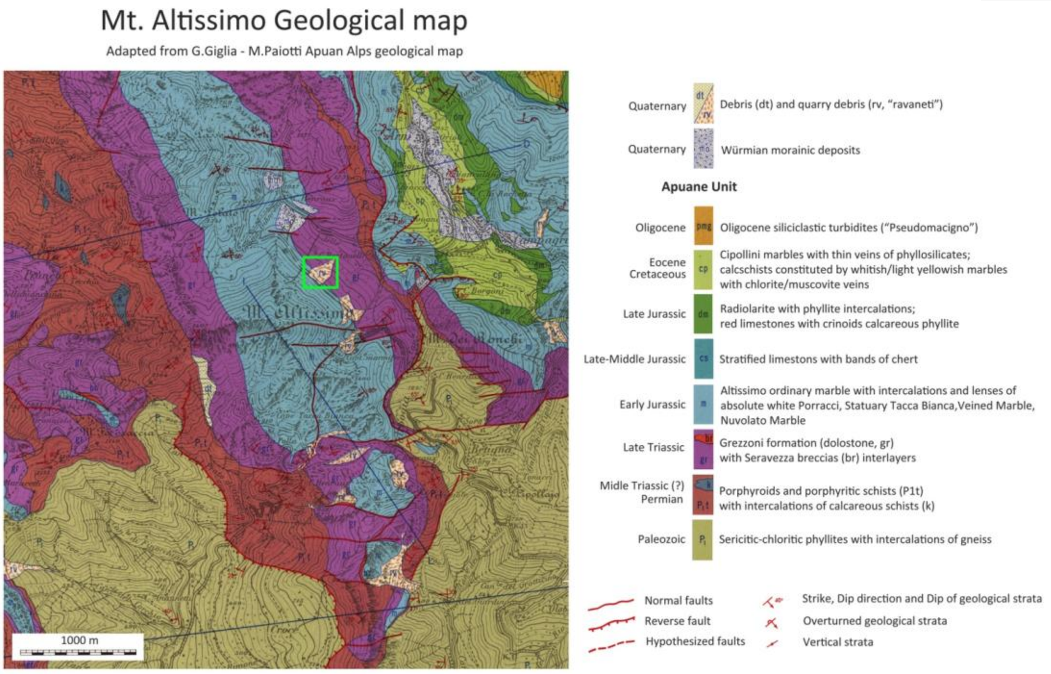


Figure 2. Geological map of the Mt. Altissimo area. The rectangle indicates the location of the quarry (modified from Giglia and Paiotti, 1963).

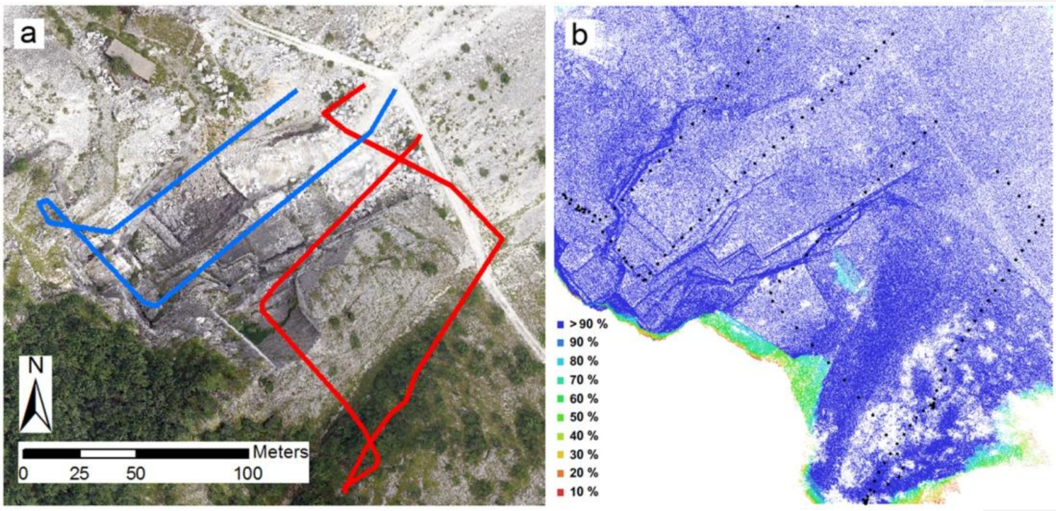


Figure 3. Flight paths of the RPAS zenithal surveys (a). ~~Top~~Plan view of the area with indication of camera locations (black dots) and image overlap percentage (b).

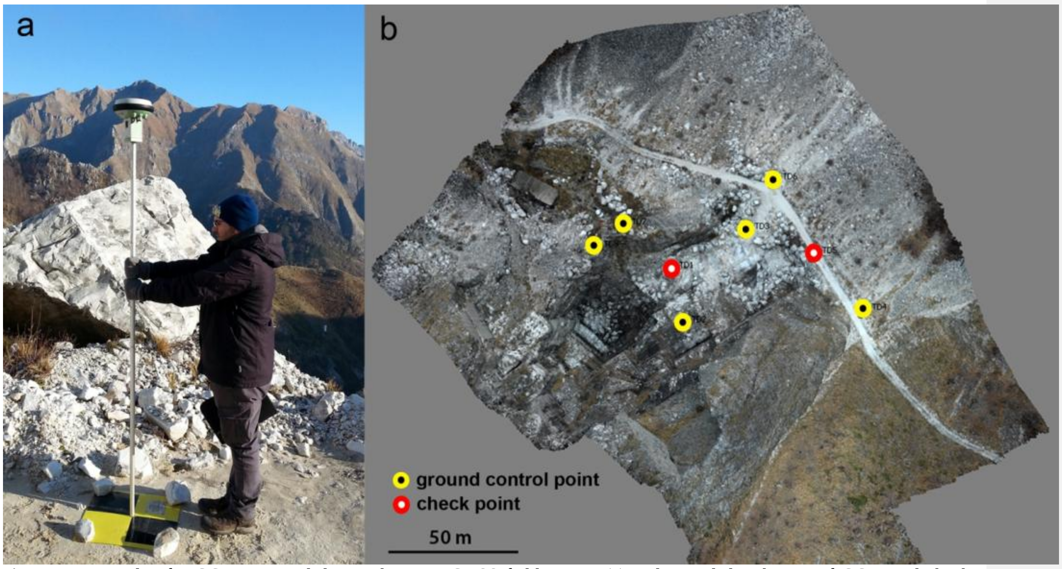
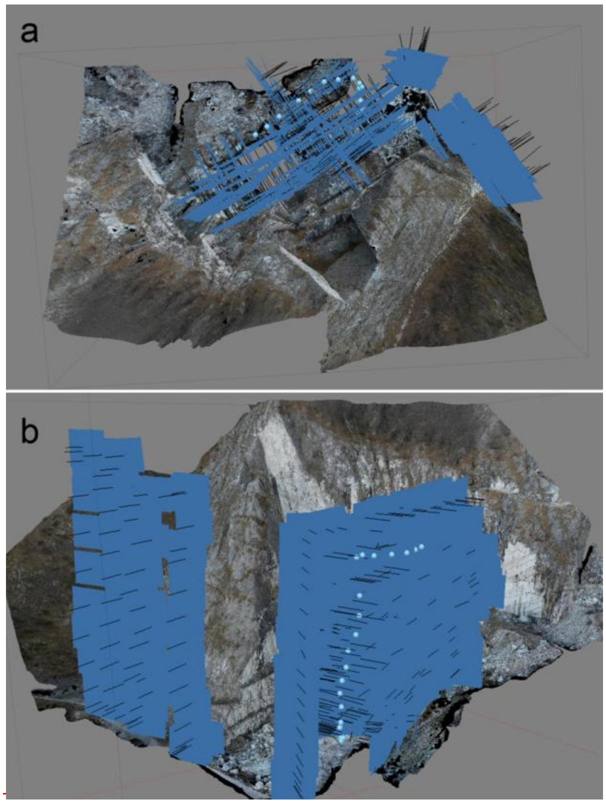


Figure 4. Example of a GCP measured during the RTK GNSS field survey (a) and spatial distribution of GCPs and check points for the RPAS zenithal flights (b).


a
b

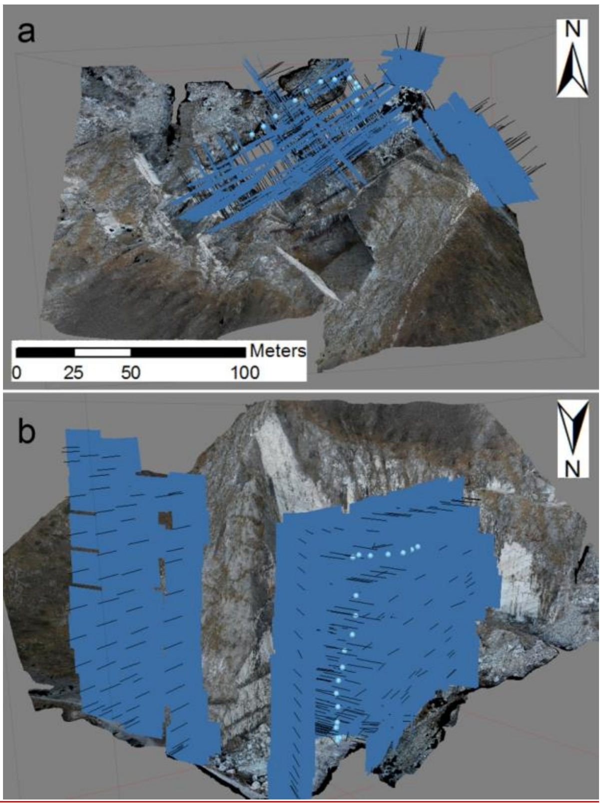


Figure 5. ~~Top~~Plan view (a) and perspective view (b) of the RPAS frontal surveys~~.~~ (blue rectangles correspond to the photographs locations, black lines to normals). Corresponding 3D point cloud produced with photogrammetric processing of digital images is shown in background.

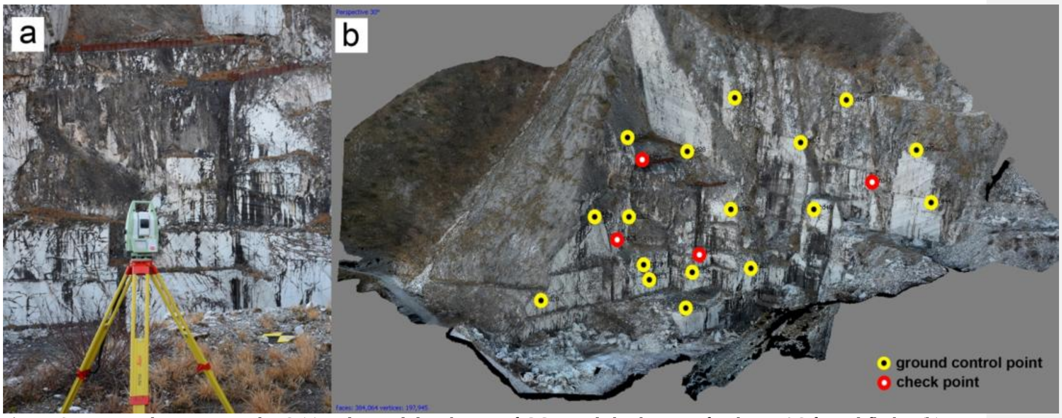


Figure 6. Topographic survey with TS (a) and spatial distribution of GCPs and check points for the RPAS frontal flights (b).

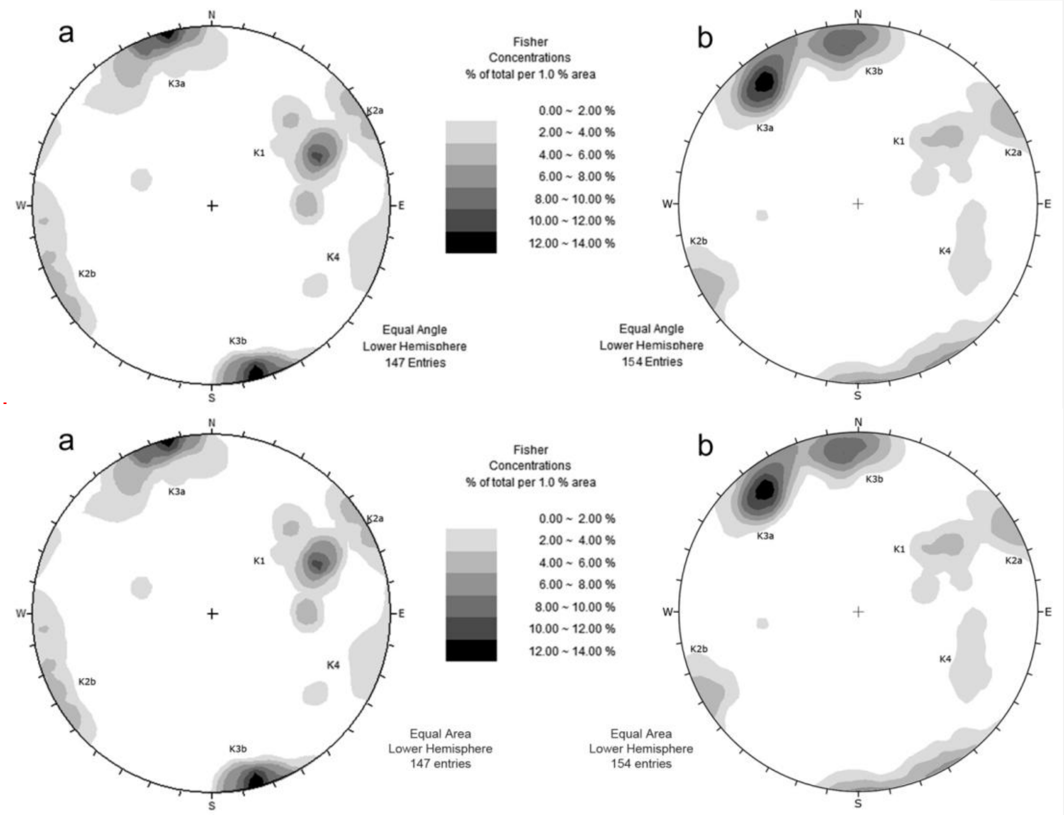


Figure 7. Stereonet plot of poles (Schmidt, equal area, lower hemisphere) of the discontinuities manually collected through classical engineering geological survey (a) and remotely collected by using photogrammetric data from RPAS surveys (b).

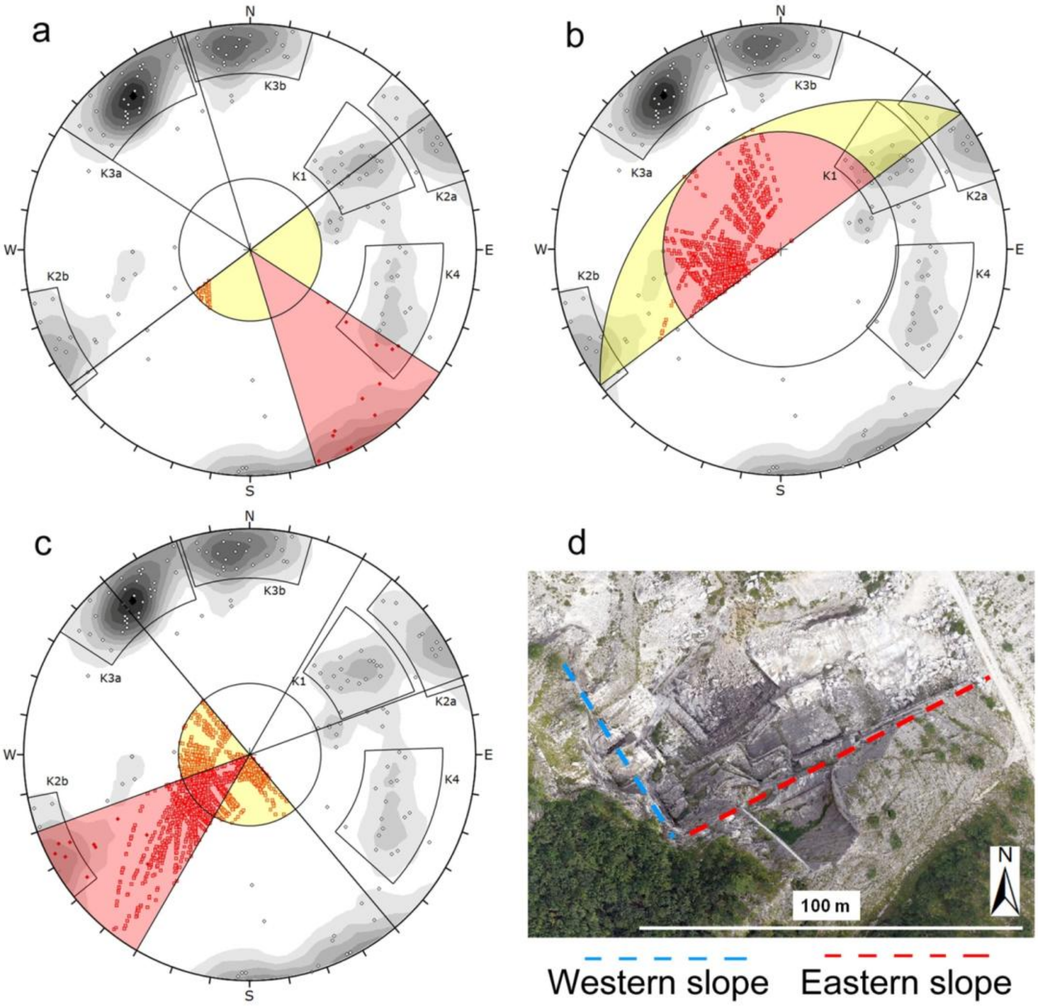


Figure 8. Examples of kinematic stability analysis carried out using Rocscience^{TM} Dips 6.0 stereographic projection through the Wulff equal-angle method (lower hemisphere); a) Planar sliding on the eastern slope; b) Wedge sliding on the eastern slope; c) Direct toppling on the western slope; d) Aerial photo showing the two principal slope orientations.

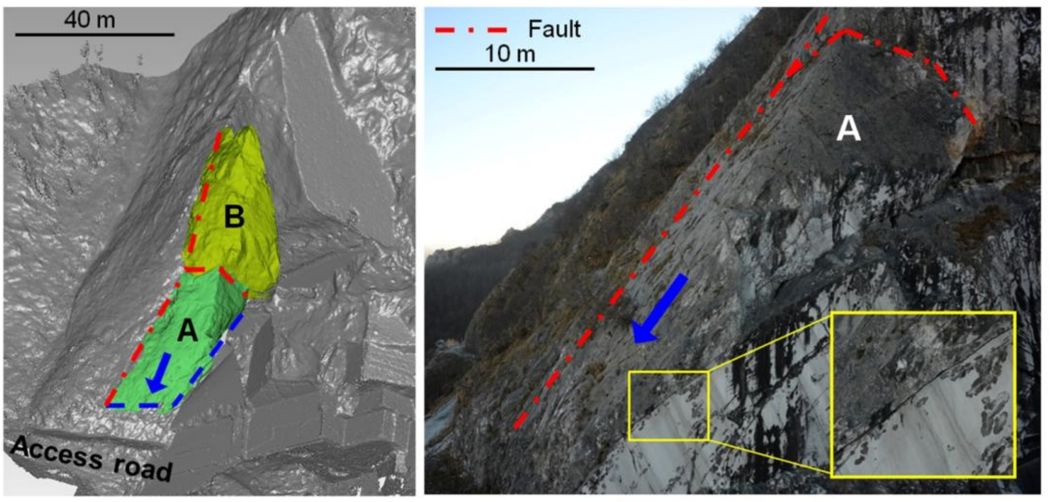


Figure 9. Identification of two large blocks with potential for sliding; ~~insect~~inset photo highlights the visible aperture of the basal plane.

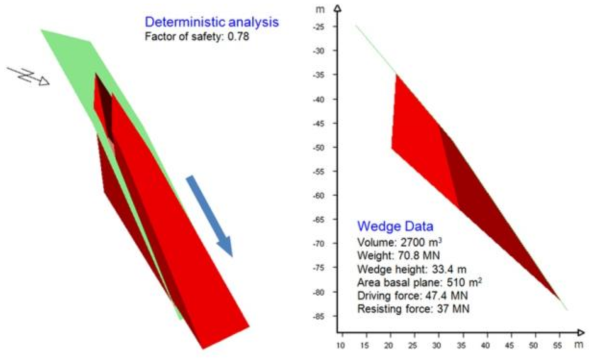


Figure 10. Result of Swedge 3D preliminary slope stability analysis.

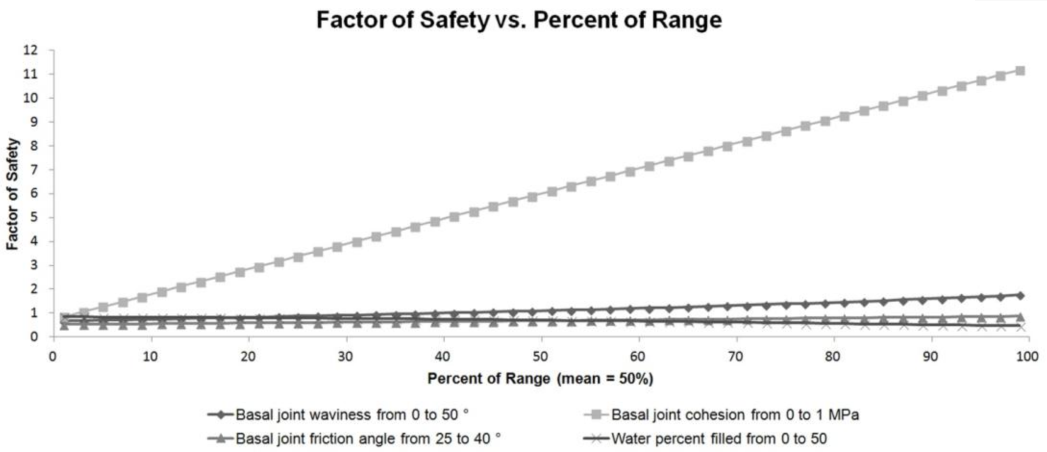


Figure 11. Result of sensitivity analysis relative to basal joint waviness, friction angle, cohesion and water percent filled parameters.

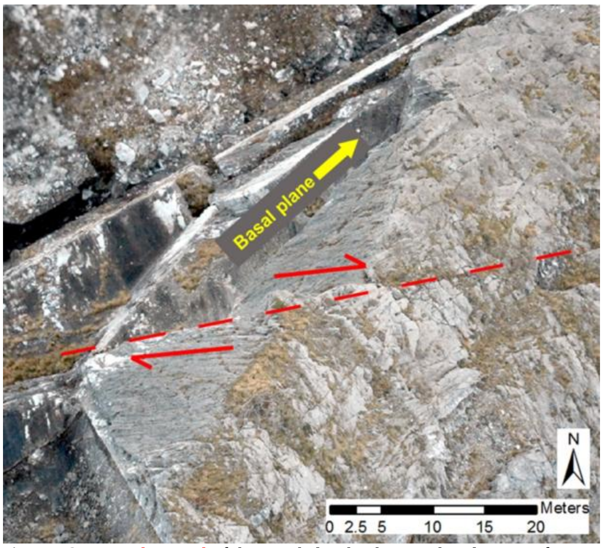


Figure 12. ~~Particular~~Detail of the zenithal orthophoto with indication of apparent motion of a major fault acting as back release surface for block A of figure 9.

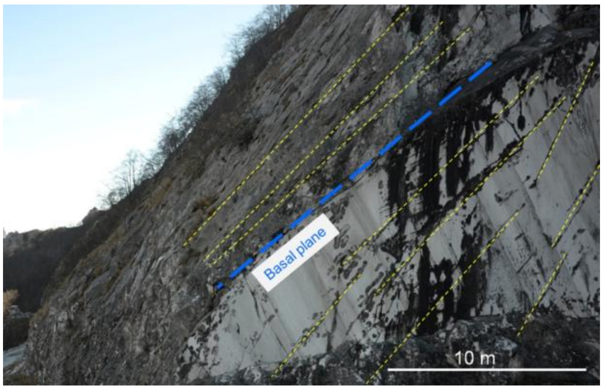


Figure 13. ~~Particular~~Details of a series of thigh discontinuities over and below the basal plane under study.

Formattato: Inglese (Regno Unito)