



## **An integrated remote sensing-GIS approach for the analysis of an open pit in the Carrara marble district, Italy: Slope stability assessment through kinematic and numerical methods**

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(Article begins on next page)

1 An integrated remote sensing-GIS approach for the analysis of an open  
2 pit in the Carrara marble district, Italy: slope stability assessment  
3 through kinematic and numerical methods  
4

5 Authors: Francioni, M. (a); Salvini, R. (b); Stead, D. (a); Giovannini, R. (b); Riccucci, S. (b); Vanneschi,  
6 C. (b); Gulli, D. (c).  
7

8 (a) Department of Earth Sciences, Simon Fraser University, Burnaby, BC, Canada.

9 (b) Department of Environment, Earth and Physical Sciences and Centre of Geotechnologies, University  
10 of Siena, San Giovanni Valdarno, AR, Italy.

11 (c) Regione Toscana - Operative Unit of Mining Engineering (U.O.I.M.) AUSL 1 Carrara, Tuscany, Italy  
12

13 Corresponding author: Francioni, M. Department of Earth Sciences, Simon Fraser University, Burnaby,  
14 BC, Canada, 8888 University Drive, Burnaby, B.C., Canada, V5A 1S6. E-mail: mfrancio@sfu.ca. Phone:  
15 778-782-7288  
16

17 **Abstract**  
18

19 Over the last decade, terrestrial laser scanning and digital terrestrial photogrammetry techniques have  
20 been increasingly used in the geometrical characterization of rock slopes. These techniques provide  
21 innovative remote sensing tools which overcome the frequent problem of rock slope inaccessibility.  
22 Comprehensive datasets characterizing the structural geological setting and geometry of the slopes can be  
23 obtained. The derived information is very useful in rock slope investigations and finds application in a  
24 wide variety of geotechnical and mine operations. In this research an integrated remote sensing – GIS  
25 approach is proposed for the deterministic kinematic characterization of the Lorano open pit in the Apuan  
26 Alps of Italy. Based on the results of geomatic and engineering geological surveys, additional  
27 geomechanical analysis using a 3D finite difference method will be presented in order to provide a better  
28 understanding of the role of stress-induced damage on slope performance.  
29

30 **Keywords:** Unmanned aerial vehicle; terrestrial laser scanning; GIS, deterministic kinematic analysis, 3D  
31 finite difference method; stress-induced damage.  
32  
33

## 34 **1. Introduction**

35

36 Surface mining represents a major important economic activity for many countries worldwide. With the  
37 high number of people working in the mining industry, safety in the workplace has become an over-riding  
38 priority. In this context, the use of new technologies to study and monitor mining and quarrying areas can  
39 play a very important role in risk assessment and management.

40 This paper, developed within the framework of the Italian National Research Project PRIN2009, provides  
41 a new approach for the study of open pit quarry slopes based on the integrated use of remote sensing  
42 techniques for deterministic stability analyses using combined simple kinematic analysis techniques and  
43 three dimensional Finite Difference Method (FDM) stress models. The research describes the case study  
44 of the Lorano open pit, characterized by a buttress- shaped remnant from previous excavation activities.  
45 The quarry is located in the Carrara district of the Apuan Alps (Italy) which is the most active marble  
46 quarrying region in Europe. Here several quarry walls reach hundreds of meters in height and are  
47 dominated by natural slopes with very complex morphology. In such an environmental context  
48 conventional structural and engineering geological surveys can only be executed at the foot of the slope;  
49 therefore, the data obtained from these surveys often provides an incomplete knowledge of the area. An  
50 alternative approach would be to have surveys carried out by technicians who are trained in rope access  
51 climbing on high rock slopes. There are however limitations and technical difficulties in the  
52 implementation of such rope access survey methods, including the close proximity to the quarry wall  
53 which compromises visibility and the ability to recognize large-scale geological features, as well as the  
54 unavailability of suitable cartographic maps. For these reasons, the use of remote sensing techniques has  
55 the potential to significantly increase the information on the geometry and the structural geological setting  
56 of quarry slopes.

57 In this research, two different remote sensing techniques have been used to complement the data obtained  
58 from traditional engineering geological surveys. The remote sensing methods used included Terrestrial  
59 Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) based Digital Terrestrial Photogrammetry  
60 (DTP). Several authors have demonstrated the use of TLS and DTP in the study of rock slopes and the  
61 advantages that these techniques offer in the structural geological and kinematic analysis of rock slopes  
62 [30], [3], [38], [20], [79], [50], [31], [54], [77], [78], [69], [71]. Although UAV technology has been  
63 increasingly used in the last few years there remain few published references related to the study of rock  
64 slopes [42], [60], [22].

65 Information gained from these remote sensing techniques was used in this case study for analysing the  
66 open pit and overhanging quarry slopes. Two different analyses were carried out; the first, a kinematic  
67 analysis to examine the most probable slope failure mechanism and the second a FDM study focused on

68 understanding the stress distribution within the slope. The kinematic analysis was performed using an  
69 integrated remote sensing – Geographic Information System (GIS) approach.  
70 This allowed for a deterministic kinematic analysis based on the geometry of the slope and joint sets.  
71 Based on a similar concept, different approaches were used by Brideau et al. [13] and Salvini and  
72 Francioni [70]. Brideau et al. [13] compared the wedge intersection vector orientations with the  
73 topographic surfaces from a DSM to understand the influence of three-dimensional topography on slope  
74 stability analysis. Salvini and Francioni [70] carried out a form of “kinematic back-analysis” using the  
75 joint attitudes to identify the areas on the slope that could be affected by future failures.  
76 The FDM analysis was carried out using a simplified 3D model derived from TLS and topographic map  
77 at scale of 1:2,000 and focused on characterisation of the rock slope stress distribution. It is known from  
78 literature how stress-induced damage due to excavation can be a frequent problem in mining and  
79 quarrying and the presence of such stress-induced fractures was observed in the study area in this and  
80 previous studies [18], [52] and [17]. These newly generated excavation stress-induced brittle fractures  
81 may be an important consideration in the stability of an area and their study could decrease the risk of  
82 failure and increase the quality of marble in future extraction works. The principal aim of this study was  
83 to understand the stress-induced damage caused by the in-situ stress acting in the area and/or the  
84 excavation processes. Several authors have studied the relationship between the acting in-situ stresses, the  
85 excavation process and brittle fracturing in excavation areas, particularly in underground mining [14],  
86 [15], [28], [29], [16]. In this research the Itasca<sup>TM</sup> FLAC3D code [49], was used for modelling of  
87 excavation induced stress in the quarry slopes.

88

## 89 **2. The Lorano open pit case study**

90

91 The Lorano open pit is located in the Carrara district where marble quarrying is the most important  
92 economic activity. Marble extraction in this area has a long history dating back to the Roman Empire (VI  
93 – II B.C). Today the Carrara district is the most important marble mining area in Europe with more than  
94 100 active quarries and a production of around 1,000,000 tons/year of blocks and aggregated gravels [18].  
95 Geologically, the Apuan Alps belong to the Northern Apennines and are a compressional fold-thrust belt  
96 formed during the Oligocene due to the collision between the Corsica-Sardinia microplate and the Italian  
97 peninsula [4], [52], [17].  
98 Evidence for two main tectonic phases can be found in this area. During the first so-called D1 phase (late  
99 Oligocene-very early Miocene), there was compression associated with under-thrusting of the Adriatic  
100 plate, and deposition following the North-East direction of the Tuscan Nappe and the Ligurids non-  
101 metamorphic units. In these conditions, limestone, dated at 180 My, was metamorphosed to marble.

102 Related to this event, is the formation of the metamorphic foliation (S1) that represents the axial plane of  
103 sheath folds (from microscopic to kilometre scale) that characterize the major part of the Apuan Alps. The  
104 general S1 direction is relatively constant from N 130° E to N 160° E. This metamorphic foliation  
105 represents a direction of weakness in the marble in the Carrara district and, although it is not a true open  
106 discontinuity set, it can have an important control on the nucleation and propagation of brittle fracturing  
107 [18], [52] and [17]. During the second phase (D2), which started in the early Miocene, compression  
108 continued so that all the structures that had developed during D1 were re-folded into complex, antiformal  
109 stack geometry with the presence of parasitic folds. Subsequently, compression ended during the last  
110 stages of the D2 phase and brittle rather than ductile tectonics occurred. This step was characterised by  
111 open and kink folds and normal extension faults with low and high dips. This extensional phase caused  
112 stretching, denudation and uplift phenomena, bringing higher and lower structures to the same level. In  
113 this context, the Apuan Alps now represent a wide tectonic window within the thickened Apennine Nappe  
114 [17].

115 The Lorano open pit is located in the normal limb of the “Pianza Anticline”, between the “Carrara  
116 syncline” in the South-West, and the “Vallini syncline” in the North-East. The open pit is characterized  
117 by a rock buttress shape, a remnant of previous excavation activities left to ensure the stability of the rock  
118 slope to the rear. The marble buttress is accessible from three sides and is approximately 150 m high and  
119 between 30 to 50 m wide (Figure 1). In the study area there are two different types of marble outcrops:  
120 the “Ordinario marble”, that characterizes the buttress, and the “Venato marble” a natural outcrop  
121 occurring on the mountain slope above.



122

123 Figure 1. Perspective view of the study area: Lorano open pit walls characterized by the rock buttress  
124 shape (the scale is indicative only); inset map shows the location of the study area.

125

### 126 3. Geomatic and engineering geological surveys

127

128 Most of the open pit walls in the study area are hundreds of meters high and are dominated by natural  
129 slopes with very complex morphology which can be a source of danger for workers below. In such an  
130 environment, engineering geological surveys are traditionally executed only in accessible areas at the foot  
131 of the slope. The data obtained from these surveys fails to provide complete information of the entire  
132 slope as required for deterministic slope analysis.

133 Quarry wall inspections are conducted once a year by rope access climbers but are often constrained by  
134 technical difficulties, low visibility compromising the recognition of large-scale geological features, and  
135 high cost. Remote sensing techniques can provide an excellent alternative and TLS and DTP in particular  
136 are being increasingly used in the study of such areas. Using these techniques it is possible to obtain very  
137 detailed information on the structural geological setting and slope geometry, even in the case of  
138 inaccessible steep slopes. The integrated use of DTP and TLS for the study of the buttress and the

139 overhanging slope will be shown in this paper. Special emphasis will be given to the use of UAV for the  
140 DTP survey.

141

### 142 3.1 Unmanned Aerial Vehicle for photogrammetric surveys

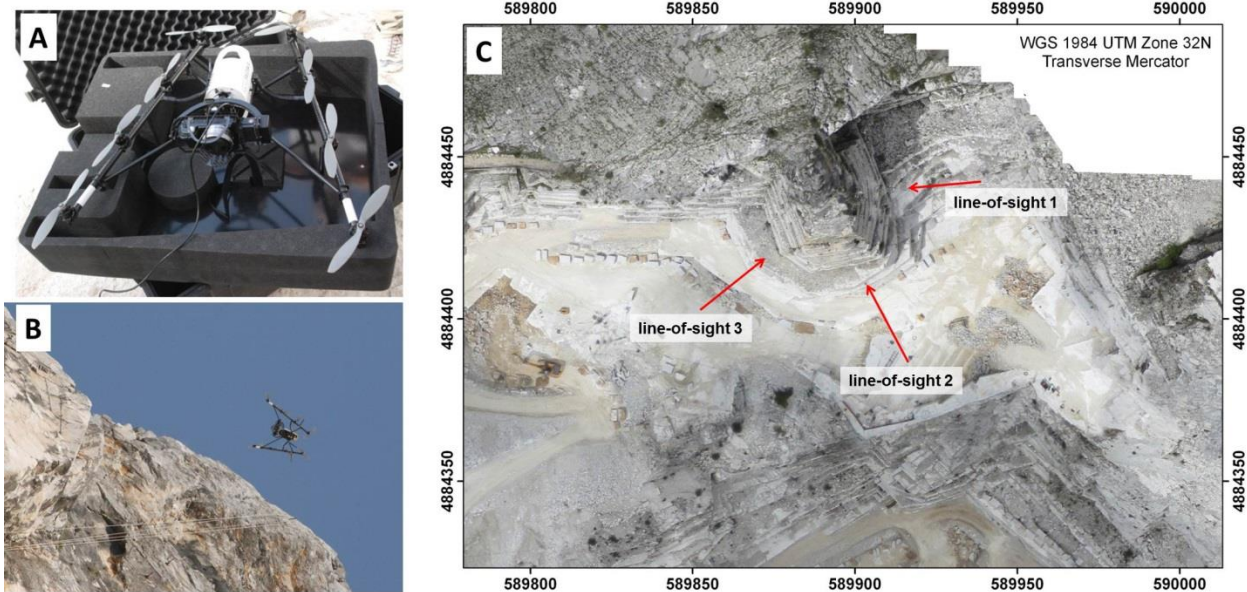
143

144 Digital terrestrial photogrammetry is a remote sensing technique in which the geometric properties of  
145 objects are determined by the measurement of photographic images. DTP is used in many different fields,  
146 including topographic mapping, architecture, engineering, and, more recently, engineering geology [67],  
147 [44], [76], [33], [34]. Slama [73], Linder [56], and Kraus [53] provide further details on the theory of this  
148 technique.

149 Given that pseudo-perpendicular directions of acquisition are necessary owing to the height and steepness  
150 of the slopes; traditional remote sensing techniques such as aerial photogrammetry are generally not  
151 suitable. The authors have previously discussed the advantages and disadvantages of using different  
152 methodologies for photogrammetric data acquisition depending on the slope morphology and the  
153 accessibility of rock faces [77], [78], [33], [34]. In this case, considering the elevation and the complex  
154 geometry of the buttress (Figure 1), an UAV was used to acquire high spatial resolution images. The  
155 survey was carried out by mounting a stabilized digital camera Sony NEX-5N onto a Falcon 8 (Asctec  
156 Gmbh) vehicle (Figure 2A and B). The physical CCD frame size of the cameras is 23.5 x 15.6 mm, while  
157 the resolution is 16.1 Megapixels.

158 Based on a flight plan, photographs were automatically taken in order to cover the whole site acquiring  
159 vertical strips of images with a minimum 70% overlap and 30% sidelap. Auto-positioning of the UAV  
160 was controlled by the integrated inertial measurement unit. Due to the complex morphology of the area  
161 and the buttress shape, three different lines-of-sight were used during the photogrammetric survey. Figure  
162 2C shows the orthophoto of the whole open pit and highlights the three different lines-of-sight.

163



164  
 165 Figure 2. UAV survey: the Falcon 8 with stabilized digital camera Sony NEX-5N (A), vehicle during the  
 166 flight on the right (B) and orthophoto of the open pit with the three different lines-of-sight used during the  
 167 photogrammetric survey (C).

168  
 169 Based on the sensor format, horizontal and vertical fields of view varied with the distance from the walls;  
 170 Table 1 shows the image size of the utilized camera.

	Image size (pixel)	Image size (mm)
Width	3935	333.2
Height	2620	221.8

171 Table 1. Photogrammetric image size (300 dpi).

172  
 173 With the objective of obtaining very precise output, 91 natural Ground Control Points (GCP) were  
 174 measured on the buttress walls using a Leica<sup>TM</sup> TCRP 1203+R1000 reflectorless Total Station. The GCPs  
 175 are points with known coordinates that must be recognizable on the photographs to facilitate their exterior  
 176 orientation process (procedure used to define the camera position, rotation and its line-of-sight at the  
 177 instant of the exposure [73], [56], [53]) that was executed by means of the Leica Photogrammetric Suite  
 178 (LPS) module of the ERDAS<sup>TM</sup> IMAGINE software. The Root Mean Square Error (RMSE) in image and  
 179 ground units (respectively pixel and cm) obtained for each strip during the absolute orientation process is  
 180 shown in Table 2.

181  
 182  
 183



Line-of-sight (degrees to North)	RMSE (image unit, pixel)	RMSE (ground unit, mm)
1 (270)	2.3	33
2 (330)	4.7	48
3 (50)	2.7	35

184 Table 2. Line-of-sight, image and ground RMSE.

185

186 3.2 Terrestrial laser scanning

187

188 In addition to DTP, terrestrial laser scanning was used to provide additional geometric information about  
 189 the buttress and to validate the data obtained from the photogrammetric survey. TLS is a survey technique  
 190 for rapidly obtaining the geometry of objects with high precision. Several types of laser scanner currently  
 191 exist with different measurement principles and technical specifications [7], [37]. In this paper, a Riegl™  
 192 Z420i laser scanner was used for the survey. This instrument uses time-of-flight technology to determine  
 193 distances to an object at a maximum distance of about 1 km.

194 Considering the geometry of the buttress, three point clouds were acquired to limit the occlusions in the  
 195 output data; the slope scanning resolution was set to 0.07 m at a distance of 300 m. Sturzenegger and  
 196 Stead [78] and Francioni et al. [34] discussed the complexity of aligning several point clouds in the same  
 197 reference system through the registration process. The integrated use of Total Station (TS), differential  
 198 GPS (Global Positioning System) can be adopted to overcome problems related to the registration  
 199 process. In this case study 15 High-Definition Surveying (HDS) targets were used in the TLS data  
 200 acquisition whose absolute coordinates were acquired by a TS topographic survey. The targets were  
 201 automatically recognized by the Leica™ Cyclone software (used also in the TLS data post-processing) so  
 202 that the registration could be easily computed by assigning them absolute coordinates. The topographic  
 203 survey played an important role in the registration process and will be described in more detail in the  
 204 following section.

205

206 3.3 Topographic survey

207

208 The topographic survey was carried out by means of the Leica™ TCRP 1203+R1000 reflectorless Total  
 209 Station and two geodetic Leica™ 1200 GPS receivers. They were essential for the acquisition of the HDS  
 210 targets and GCPs for photogrammetry. During the TS survey, the intersection method was used to relate  
 211 all the measurements to a unique reference system. Using this technique it was possible to locate the TS  
 212 in different positions (suitable for the acquisition of HDS targets and GCPs) and to relate all the  
 213 measurements to the first station (called “Master Station”). The use of the TS and the intersection  
 214 methods are explained in detail in Francioni et al. [36] and Francioni et al. [34].

215 The GPS survey was used to determine the absolute coordinates of all the points measured with the TS; to  
216 accomplish this, a GPS receiver was set up in the same position as the Master Station and the absolute  
217 coordinate of the latter determined. Subsequently, a second GPS receiver was utilized to obtain the zero-  
218 Azimuth for the TS and, finally, the absolute coordinates of all the measured points determined. The  
219 differential GPS surveys were performed in static modality with an acquisition time of up to 3 hours. The  
220 coordinates of the points acquired with this technique were corrected by post-processing procedures using  
221 contemporary data recorded by two permanent GPS stations (*Lucca* and *Borgo a Mozzano*). The  
222 orthometric heights of the Master and the zero-Azimuth stations were also calculated in collaboration  
223 with the Italian Military Geographical Institute.

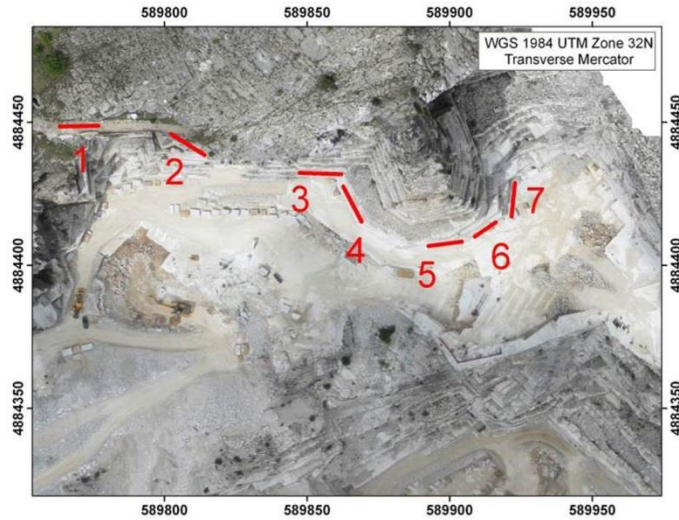
224

### 225 3.4 Engineering geological survey

226

227 In order to provide more information about the structural geological setting of the slope and the  
228 characteristics of the rock mass and joint surfaces, an engineering geological survey was carried out. Due  
229 to the inaccessibility of the area, it was possible to carry out the scan lines only at the toe of the slope  
230 (Figure 3). Seven scan lines were performed and more than 100 surfaces measured. Of these, only 77  
231 were then used for the definition of the main joint sets. The remain surfaces were identified as brittle  
232 fractures and, due to their different origin, irregular shape and unreliability in their measurement, they  
233 were not considered in the definition of the main joint sets. Data from scan lines was used for the  
234 characterization of rock mass according to the Bieniawski Rock Mass Rating (RMR, 1989) method. The  
235 RMR system is a rock mass quality classification developed by the South African Council for Scientific  
236 and Industrial Research [8] and subsequently updated in 1989 [78]. The Geological Strength Index (GSI)  
237 was also estimated based on the rock mass structure and the rock discontinuity surface condition. This  
238 method, used widely by the scientific community after its introduction [45], is not intended as a rock mass  
239 classification, but rather to reflect the rock mass quality. The GSI value was then applied to estimate the  
240 rock mass parameters in the Hoek-Brown strength criterion. The application and limitations of the GSI for  
241 underground openings and rock slopes were recently reviewed by Marinos et al. [57] and Hoek and  
242 Diederichs [47].

243



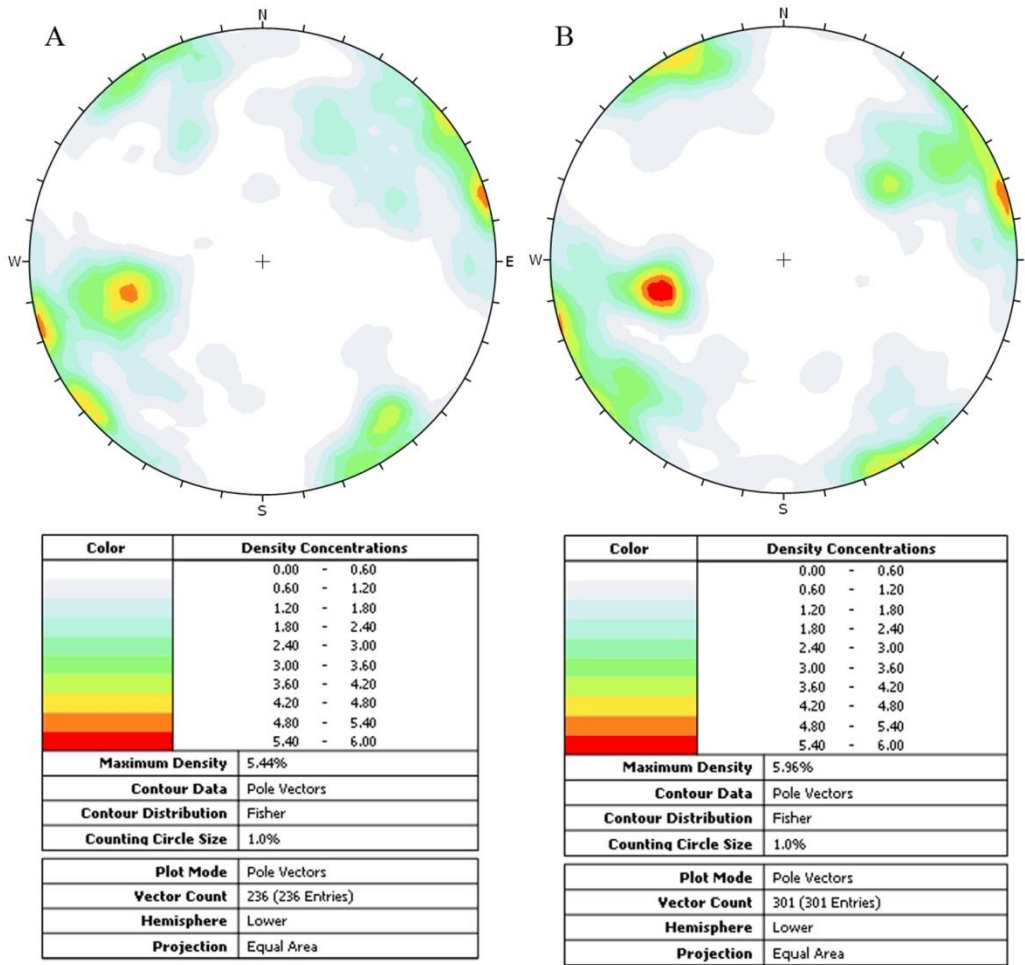
244  
 245 Figure 3. Orthophoto of the open pit with scan lines

246  
 247 **4 Data processing and deliverables**

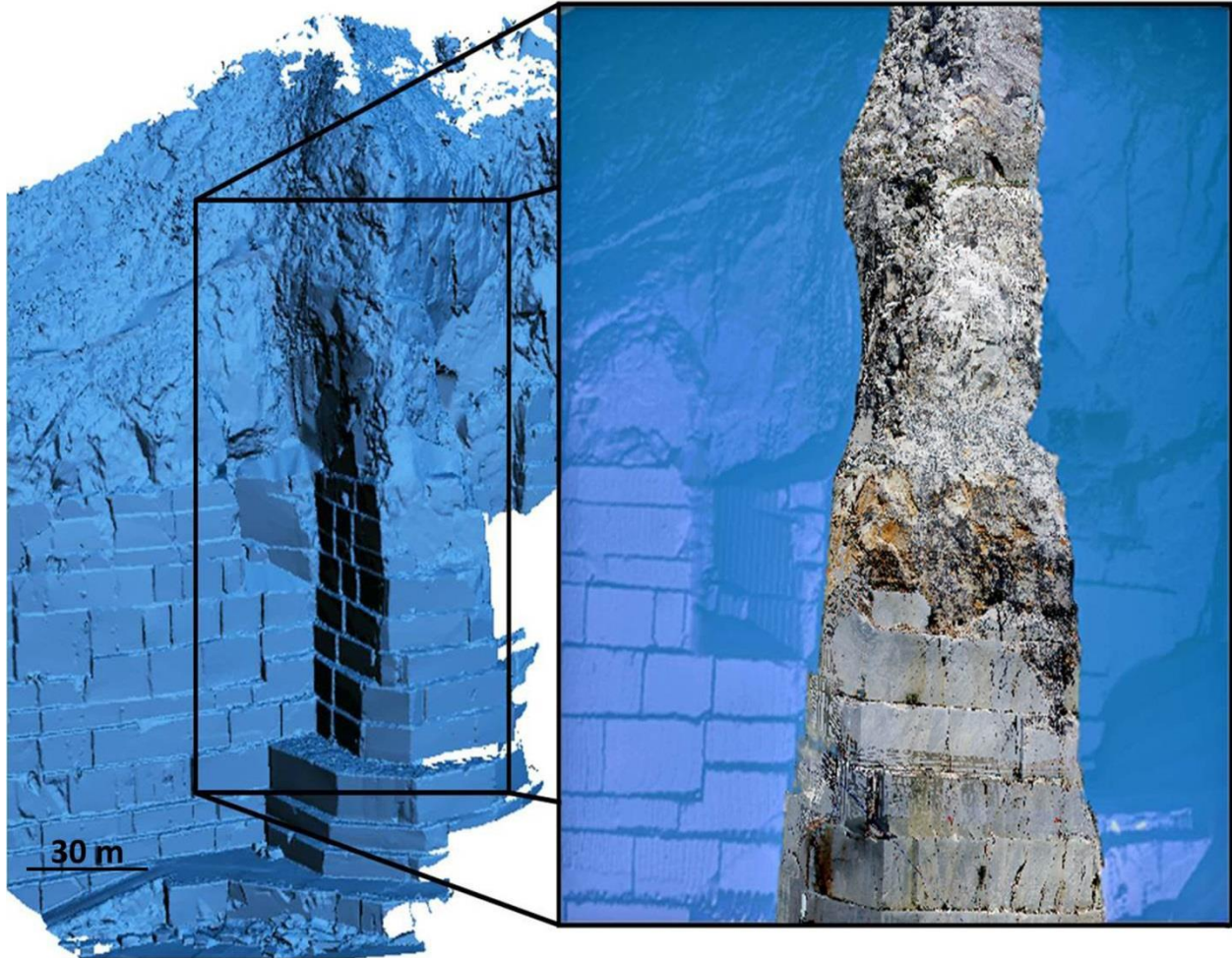
248  
 249 In this case study the UAV system, by limiting blind spots, played a very important role in the acquisition  
 250 of the photographs of the whole study area. The exterior orientation of the photographs was obtained  
 251 through the use of the 91 GCPs measured by the topographic survey. After the exterior orientation  
 252 process, a stereographic model of the buttress was built and used for the stereo-interpretation of structural  
 253 geological features including joint attitude, spacing and trace length. These features were stereo-restituted  
 254 using the Stereo Analyst module of ERDAS<sup>TM</sup> IMAGINE; the joint attitude was represented in the  
 255 stereoscopic model by triangles drawn co-planar with the discontinuities, while the spacing and trace  
 256 length were shown using 3D lines. Figure 4A shows stereographic representation of the discontinuities  
 257 measured on the slope using DTP. The three TLS point clouds acquired during the survey were registered  
 258 using the HDS targets and allowed the construction of a unique 3D model of the buttress. As mentioned  
 259 above, using the topographic surveys and the intersection method it was possible to align GCPs and HDS  
 260 targets in the same reference system with an estimated error of approximately 5 mm. In this way, the  
 261 stereoscopic model from DTP and the TLS 3D model were integrated and used for the construction of a  
 262 detailed full 3D model with high resolution orthophotos of the buttress (Figure 5).

263 The DTP approach provides a high level of data interpretability during the stereo-restitution but can be  
 264 prone to human error. For this reason, the attitude of the discontinuity surfaces and slopes was also  
 265 extracted from the TLS point clouds using the Leica<sup>TM</sup> Cyclone software through a semi-automatic  
 266 procedure. In practice, several points (at least three) representing the surface under investigation must be  
 267 selected on the point cloud; the software automatically recreates the surface and determines the attitude of

268 its pole. Figure 4B shows the stereographic representation of the discontinuities measured on the slope  
 269 using TLS.



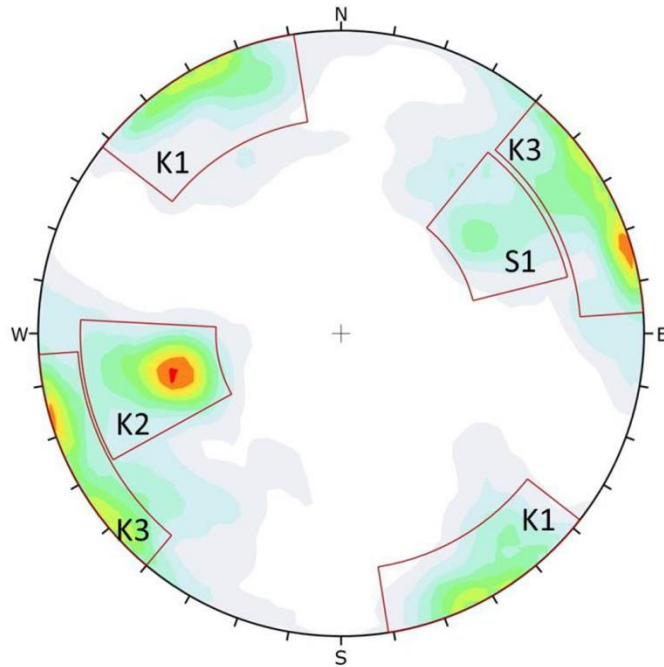
270  
 271 Figure 4. Stereographic representation of measurements obtained from DTP (A) and TLS (B).  
 272



273  
274 Figure 5. Integration of TLS and UAV photogrammetric data in the construction of the 3D model with  
275 aligned orthophotos of the buttress.

276  
277 All the measurements obtained from TLS and DTP were then integrated in a final stereographic  
278 representation and the joint sets determined (Figure 6 and Table 3). K1, K2 and K3 represent the three  
279 main joint systems surveyed with these techniques and S1 represent the structures associated with the  
280 metamorphic foliation S1 which characterizes the Apuan Alps (see section 2). Table 3 also shows the  
281 measurements of spacing and trace length carried out using the remote sensing data. However, due to the  
282 difficulty in defining the trace length in the photogrammetric model (especially when the joint spacing is  
283 small as often is the case in the Carrara marble district) and to fact that these parameters were required  
284 in the following analyses, these measurements should be considered as a preliminary approximate  
285 estimation only.

286  
287



Color	Density Concentrations
	0.00 - 0.60
	0.60 - 1.20
	1.20 - 1.80
	1.80 - 2.40
	2.40 - 3.00
	3.00 - 3.60
	3.60 - 4.20
	4.20 - 4.80
	4.80 - 5.40
	5.40 - 6.00
<b>Maximum Density</b>	5.49%
<b>Contour Data</b>	Pole Vectors
<b>Contour Distribution</b>	Fisher
<b>Counting Circle Size</b>	1.0%
<b>Plot Mode</b>	Pole Vectors
<b>Vector Count</b>	537 (537 Entries)
<b>Hemisphere</b>	Lower
<b>Projection</b>	Equal Area

288

289 Figure 6. Integration of measurements obtained from TLS and DTP.

290

Joint set	Dip (deg)	Dip Direction (deg)	Trace length (m)	Spacing (m)
K1	88	150	10 to 30	1 to 3
K2	54	077	10 to 30	1 to 3
K3	87	243	10 to 30	1 to 3
S1	52	235	2 to 20	1 to 10

291 Table 3. Data obtained from DTP and TLS.

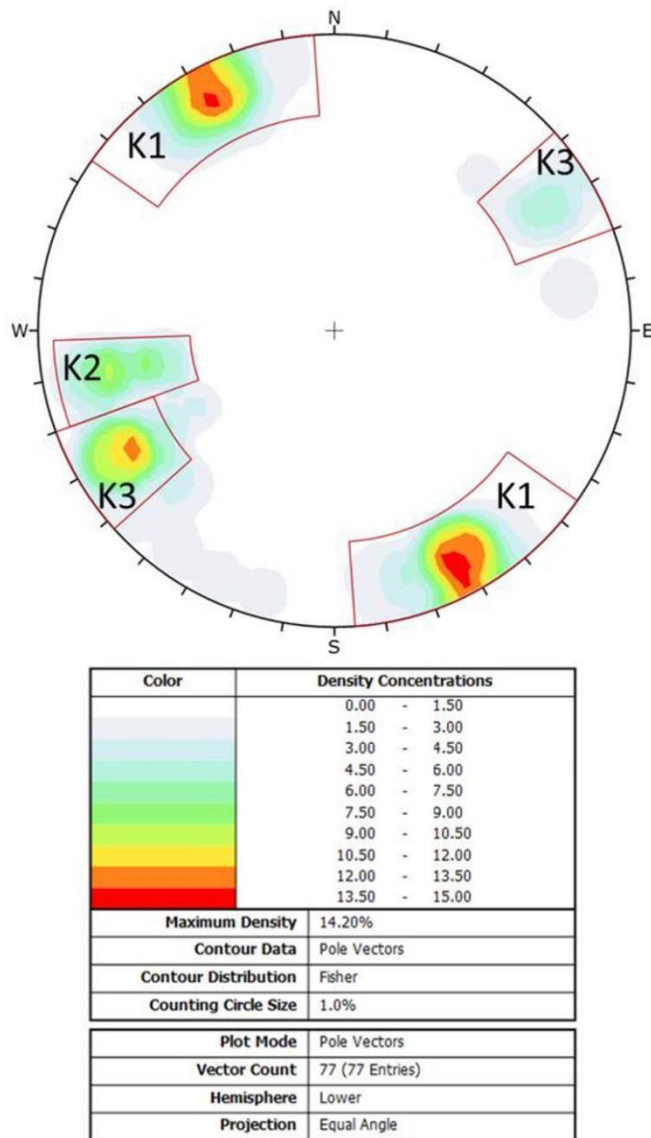
292

293 Conventional engineering geological survey was necessary to assess the accuracy of the joint sets present

294 at the toe of the slope and to physically and mechanically characterise the discontinuities according to the

295 RMR method. Data obtained from this survey is provided in Figure 7 and Table 4; the results gained from

296 the rock mass rating show a good quality rock mass with an RMR value equal to 76. However, Figure 7  
 297 and Table 4 also show that the joint set distribution at the toe of the slope was slightly different to that  
 298 determined from DTP and TLS. Therefore, data in Table 4 may not be fully representative of all the joint  
 299 sets illustrated in Table 3 since they refer to different locations within the study area. In fact, GSI values  
 300 also vary within engineered areas (i.e. open pit) compared to the natural rock outcrops (i.e. the above  
 301 slope). For this reason and considering in detail the characteristics of the marble the GSI was estimated to  
 302 vary between 50 and 60 in the natural slope and between 70 and 80 in the open pit face. This is probably  
 303 due to the degree of weathering of the natural slope surface and to the fact that the joint spacing usually  
 304 increases with depth.



305  
 306 Figure 7. Stereographic representation of measurements determined from the conventional engineering  
 307 geological survey.

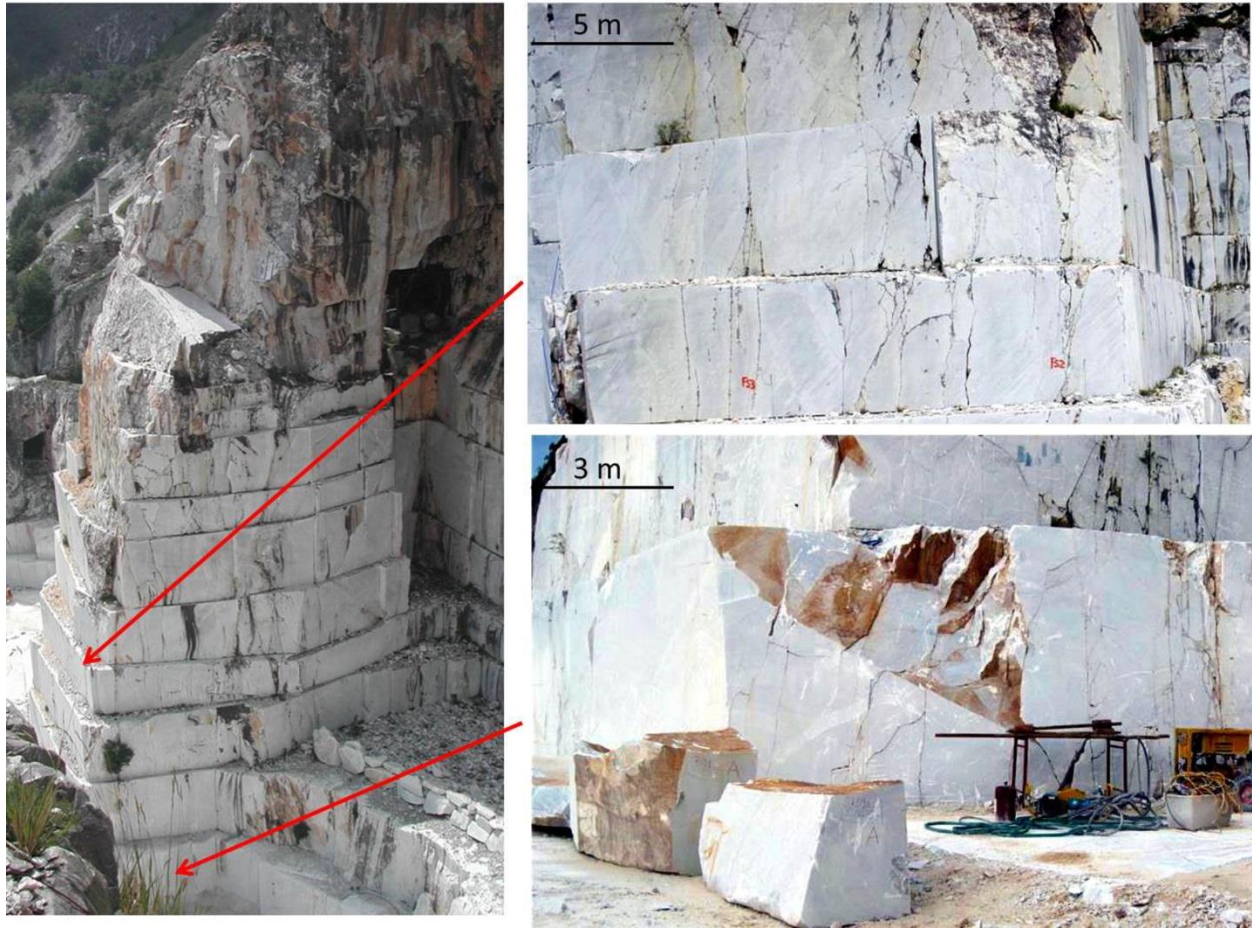
Joint set	K1	K2	K3
Dip/Dip Dir	90°/332°	71°/080°	84°/059°
Spacing (m)	1	1	1.5
Trace length (m)	10 to 20	10 to 20	10 to 20
Aperture (mm)	14	9	11
Infill	Absent	Absent	Absent
Weathering	Slight	Slight	Slight
JRC	4	9	5
JCS (MPa)	98	78	83
Water	Medium inflow	Absent	Medium inflow

309 Table 4. Data obtained from the conventional engineering geological survey (mean values).

310

311 During both the remote sensing and engineering geological surveys, brittle (stress-induced) fractures were  
 312 identified (Figure 8). It is possible to differentiate these structures from pre-existing discontinuities based  
 313 on their irregular shape and the lower trace length. These characteristics can make their mapping  
 314 sometimes challenging with a higher degree of uncertainty and, for this reason the measurements related  
 315 to the stress-induced fractures were kept separate from those associated with joint sets.





316

317 Figure 8. Stress-induced damage noted in the marble buttress during the engineering geological and  
318 photogrammetric surveys.

319

### 320 **5 GIS and kinematic stability analyses**

321

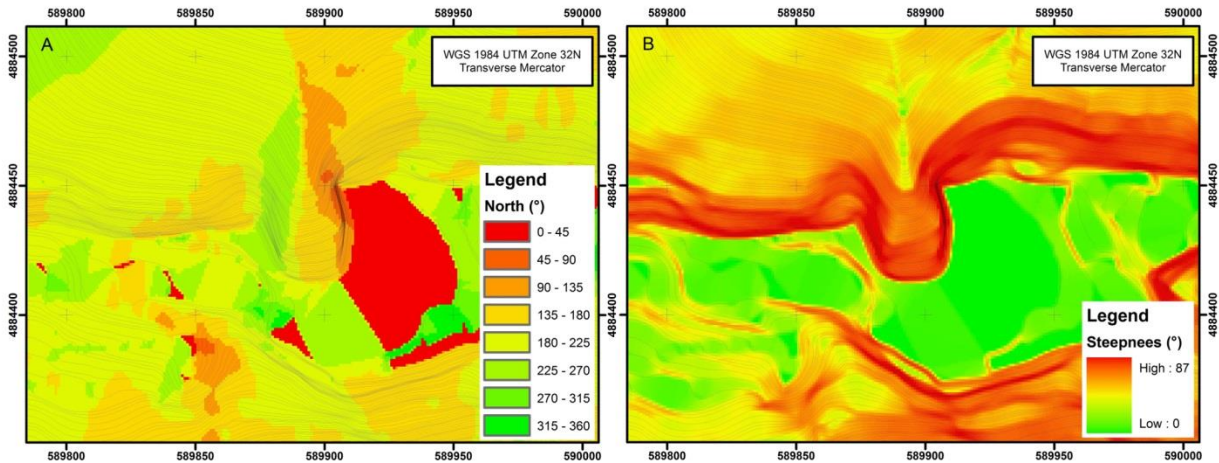
322 The kinematic slope stability analysis examines the potential for rock slope failures such as planar,  
323 wedge, and toppling due to the presence of unfavourably oriented discontinuities. The analysis considers  
324 the relative attitude of the discontinuities and the slope plus the effective friction angle along the joint  
325 surfaces. Stereographic projections for the kinematic analysis of these simple failure modes are described  
326 in Richards et al. [64] and Hoek and Bray [46]. Various widths of toppling envelope have been proposed  
327 by Goodman and Bray [40], Cruden [21], Goodman [39], and Maurenbrecher and Hack [58].

328 The results of this analysis are strongly influenced by the topography, as already documented by Brideau  
329 et al. [13] who proposed the use of software such as Matterocking [50], which compares the wedge  
330 intersection vector orientations with the topographic surfaces.

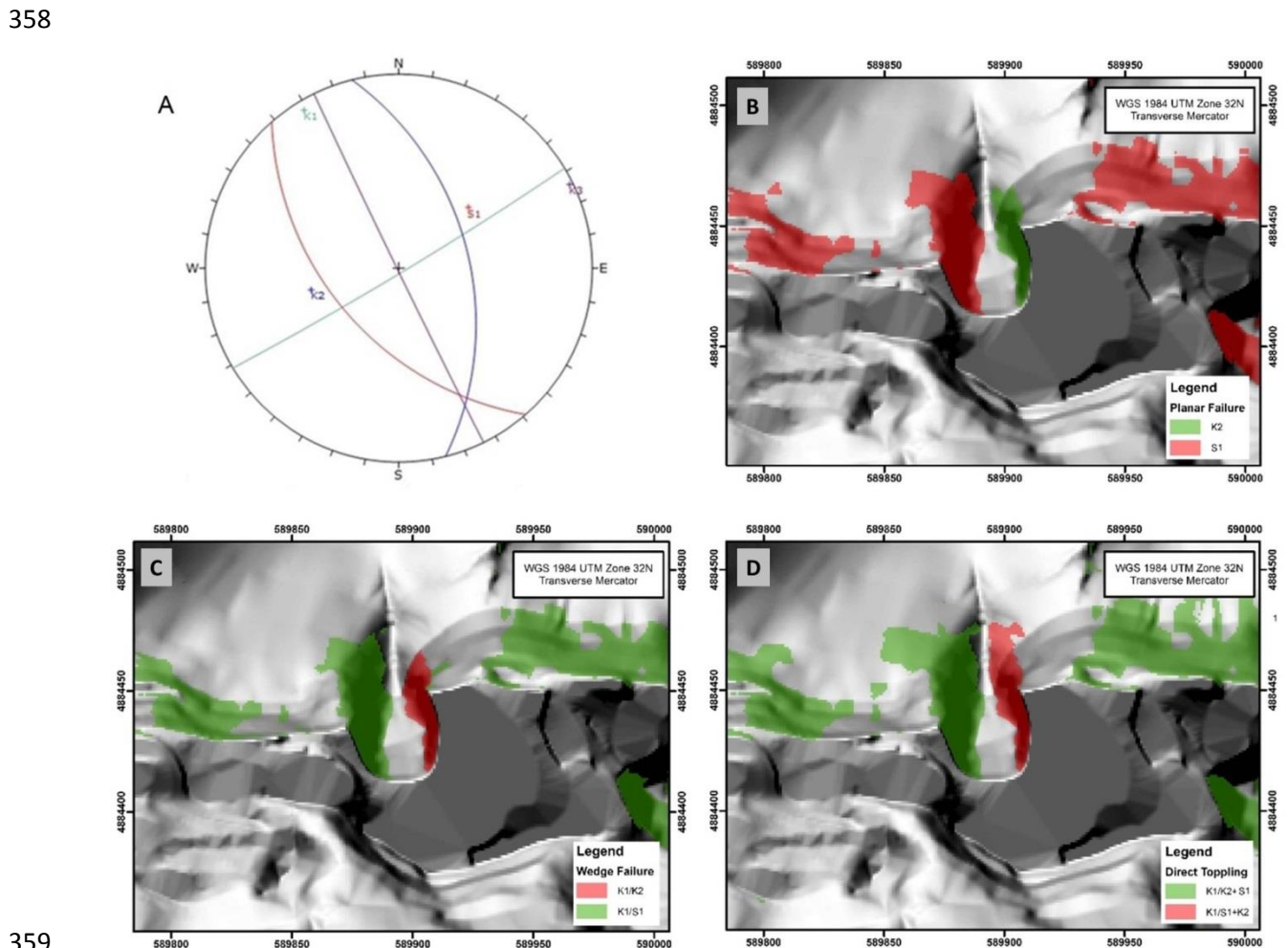
331 In this research, an integrated remote sensing – GIS analysis approach was proposed to overcome the  
332 problem of complex geometry. GIS techniques have been used by several authors for slope stability  
333 analysis [82], [81], [84], [85], [23], [6], since they provide various functions for capturing, inputting,  
334 manipulating, transferring, visualizing, combining, querying, analysing, modelling, and outputting of the  
335 geospatial data. The advent of new survey techniques (such as those used in this research) makes this  
336 technique even more attractive because they allow a wider range of data to be analysed. In this research  
337 the 3D model and the topographic map at scale of 1:2,000, gained from the TLS, were used in the  
338 construction of a simplified Digital Surface Model (DSM) of the pit slope.

339 Starting from the DSM, a GIS spatial analysis was performed to highlight the dip direction of the slope  
340 faces (Figure 9A). Different colours in Figure 10A represent slopes characterized by varying dip  
341 direction. Based on the orientation of the slope faces and using the geo-structural data derived from the  
342 geomatic and engineering geological surveys, it was possible to perform a kinematic GIS analysis of  
343 slope stability. For each slope face, the steepest safe angle was calculated using the stereographic  
344 projection of Dips 6.0 software [66]. The knowledge of the steepest safe angle is very useful for  
345 understanding the maximum angle that a slope can be quarried at before subject to potential failures due  
346 to interaction with discontinuities. This information was integrated with the steepness of the slope in  
347 order to ascertain which areas may be affected by failure. Consequently, a further GIS spatial analysis  
348 was carried out and the slope steepness calculated (Figure 9B). In this way, all the necessary information  
349 was available to understand where failure mechanisms could occur. A supplementary spatial analysis was  
350 carried out to combine the steepest safe angle with the slope steepness in order to further refine the  
351 results. The friction angle was assumed to be  $32^{\circ}$  (with  $5^{\circ}$  of standard deviation) for all the joint systems  
352 based on the published literature, [19], [62], [63], [32]. Figure 11 shows the results highlighting the  
353 stereographic representation of main joint sets used for the analysis (Figure 10A) and the areas that could  
354 be affected by planar (Figure 10B), wedge (Figure 10C), and direct toppling failures (Figure 10D).

355



356  
 357 Figure 9. Dip direction of slope faces (A) and slope steepness (B) calculated with GIS spatial analysis.



359  
 360 Figure 10. Results of the deterministic kinematic stability analysis: Stereographic representation of joint  
 361 sets shown in Table 3 (A); areas potentially affected by planar failure (B); areas potentially affected by  
 362 wedge failure (C); areas potentially affected by direct toppling (D).

363 Maps shown in Figures 10B and 10C highlight a strong similarity due to an important assumption in  
364 Rocscience™ [66] software regarding “pure” planar sliding on a single plane; in fact, in these types of  
365 analyses, the occurrence of release planes, such as lateral joints, or tension cracks is assumed to allow  
366 planar sliding. These planes are not explicitly involved in the conventional kinematic analysis for planar  
367 sliding, but it is important to be aware that a release mechanism must normally exist to allow removal of a  
368 block from the slope. This means that planar sliding can be considered as a special case of wedge failure  
369 where sliding takes place on only one plane, and other planes act as release planes. It should be noted that  
370 the foliation S1 was included in the analysis even if it is not a true open discontinuity set. This was  
371 undertaken to reflect the fact that the S1 foliation represents a direction of weakness in the rock mass  
372 which can have an important control on the dilation, nucleation and propagation of brittle fractures [18],  
373 [52] and [17]. This phenomenon is visible in the upper right of Figure 8 where low angle fractures (with  
374 irregular shape and direction similar to S1) seem to connect the high angle discontinuities that  
375 characterize the buttress face. For this reason, the authorities decided to leave in place wider benches at  
376 the base of the buttress with the aim to increase the overall stability and avoid the propagation of new  
377 generated fractures between system discontinuities.

378

## 379 **6 Three dimensional stress analyses using the finite difference method, FLAC3D**

380

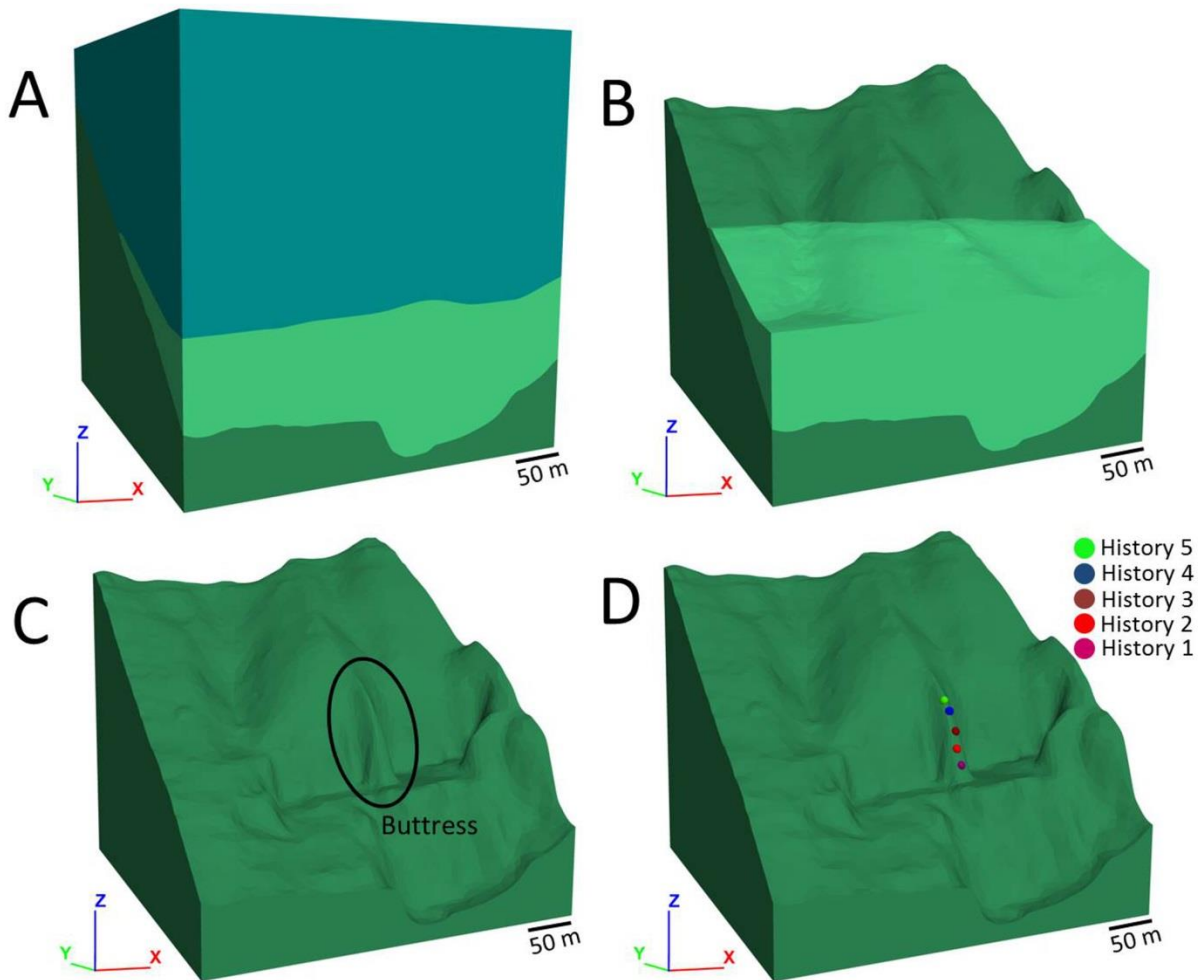
381 DTP, TLS and the engineering geological surveys provide fundamental data for an improved  
382 understanding of the structural geological setting of the area. Using these methods it was possible to  
383 analyse whether the fractures on the slope were related to the complex geological history of the area  
384 and/or to the recent excavation activity. In fact, the progress of the excavation can cause the formation of  
385 new brittle fractures due to the unloading stress. Their existence in the Carrara marble district (called  
386 “*forzature*” by the local technicians) has been the cause not only of damage within the extracted blocks  
387 and slabs, but also of several rock fall events as documented by several authors; see e.g. [17] and [18].  
388 In this research, the FLAC3D code [49] was used to analyse the stress distribution of the slope using the  
389 Finite Difference Method. Although FLAC is a continuum numerical modelling approach and is not  
390 appropriate to model a large number of fractures, selected discontinuities with simple intersections can be  
391 discretely included as interfaces [55]. Numerous authors have described the use of FLAC for the analysis  
392 of rock slopes and open pits [11], [43], [68].

393

### 394 6.1 Stress distribution using the induced lithostatic stress

395 In this study, Rhinoceros™ SR4 software [59] was used with the aim of creating a 3D model closely  
396 approximating the true geometry of the slope. TLS point clouds were processed to build the 3D model

397 and then exported into Kubrix software [49] to prepare for simulation using FLAC 3D [49]. Figure 11A-  
 398 D shows the 3D model created by Rhinoceros™ SR4 and Kubrix. Figure 11A shows the initial geometry  
 399 used to calculate the initial stress distribution. Figure 11B shows the reconstruction of the topography  
 400 before the marble excavation. Figure 11C and D show the geometry of the buttress and the “history  
 401 points” (points of interest) respectively; the latter were located at different elevations on the marble  
 402 buttress and interrogated during the excavation progress.  
 403



404  
 405 Figure 11. 3D model of the marble quarry and buttress created in Rhinoceros™ SR4 and Kubrix: Initial  
 406 model (A), topography pre (B) and post (C) excavation and history points located in the buttress (D).  
 407

408 The marble was modelled as an elastic material with a unit weight of  $27 \text{ KN/m}^3$  with joints not considered  
 409 at this stage. The isotropic elastic and material option, in FLAC3D, provides the simplest representation

410 of material behaviour and is valid for homogeneous, isotropic, and continuous material that exhibits linear  
411 stress-strain behaviour.

412 This decision was made after a careful examination of the literature and that, given the strength of the  
413 marble rock mass and the limited depth of the quarry, little yield should occur under compressive stresses.  
414 Moreover, this decision was also taken in agreement with the studies carried out by Wiles [83]. Wiles,  
415 after a long discussion on the use and reliability of simple versus complex constitutive criteria noted that  
416 the use of an elasto-plastic model makes the calibration of the model extremely difficult due the  
417 uncertainty of the additional parameters required, (E, V and density vs E,v. Density, intact cohesion,  
418 intact friction, dilation, rock mass cohesion, rock mass friction). In essence at this stage in our models we  
419 have focused on location of stress concentrations, not yielding of these stresses. The latter would have  
420 necessitated the assumptions inherent in scale-dependent downgrading of the rock properties and hence  
421 possibly obscured the results. Wiles suggests, for making stress predictions, the use of an accurate  
422 geometry and simple model (Homogeneous, elastic modelling is the best option since the only significant  
423 parameter that must be specified is the far-field stress state). Table 5 shows the rock properties used in  
424 this first simulation (called “Analysis 1”).

425

Parameters - Analysis 1	Value
Unit weight (KN/m <sup>3</sup> )	27
Deformation modulus (GPa)	48
Poisson's ratio	0.27
Shear modulus (GPa)	19
Bulk modulus (GPa)	34

426 Table 5. Rock material parameters used in Analysis 1

427

428 Since the elevation of the model was approximately 440 meters, the lithostatic vertical stress  $\sigma_z$  (or  $\sigma_v$ )  
429 was estimated to be almost 12 MPa at the base of the model. This value was gradually decreased from the  
430 bottom to the top so that to be zero at the surface of the initial model. The K values,  $K_x$  and  $K_y$  in this  
431 preliminary analysis were assumed to be equal to 0.4 (Equations 1 and 2).

432

433  $K_x = \sigma_x / \sigma_z$  Equation 1

434  $K_y = \sigma_y / \sigma_z$  Equation 2

435

436 The deformation modulus was calculated using the GSI value and RocData 4.0 software (Rocscience<sup>TM</sup>  
437 2014 and Hoek & Diederichs, 2006), while the Shear and Bulk moduli were calculated from equations 3  
438 and 4:

439

440  $G = E/2(1+\nu)$  Equation 3

441  $K = E/3(1-2\nu)$  Equation 4

442

443 where G is Shear modulus, K the Bulk modulus and  $\nu$  the Poisson's ratio.

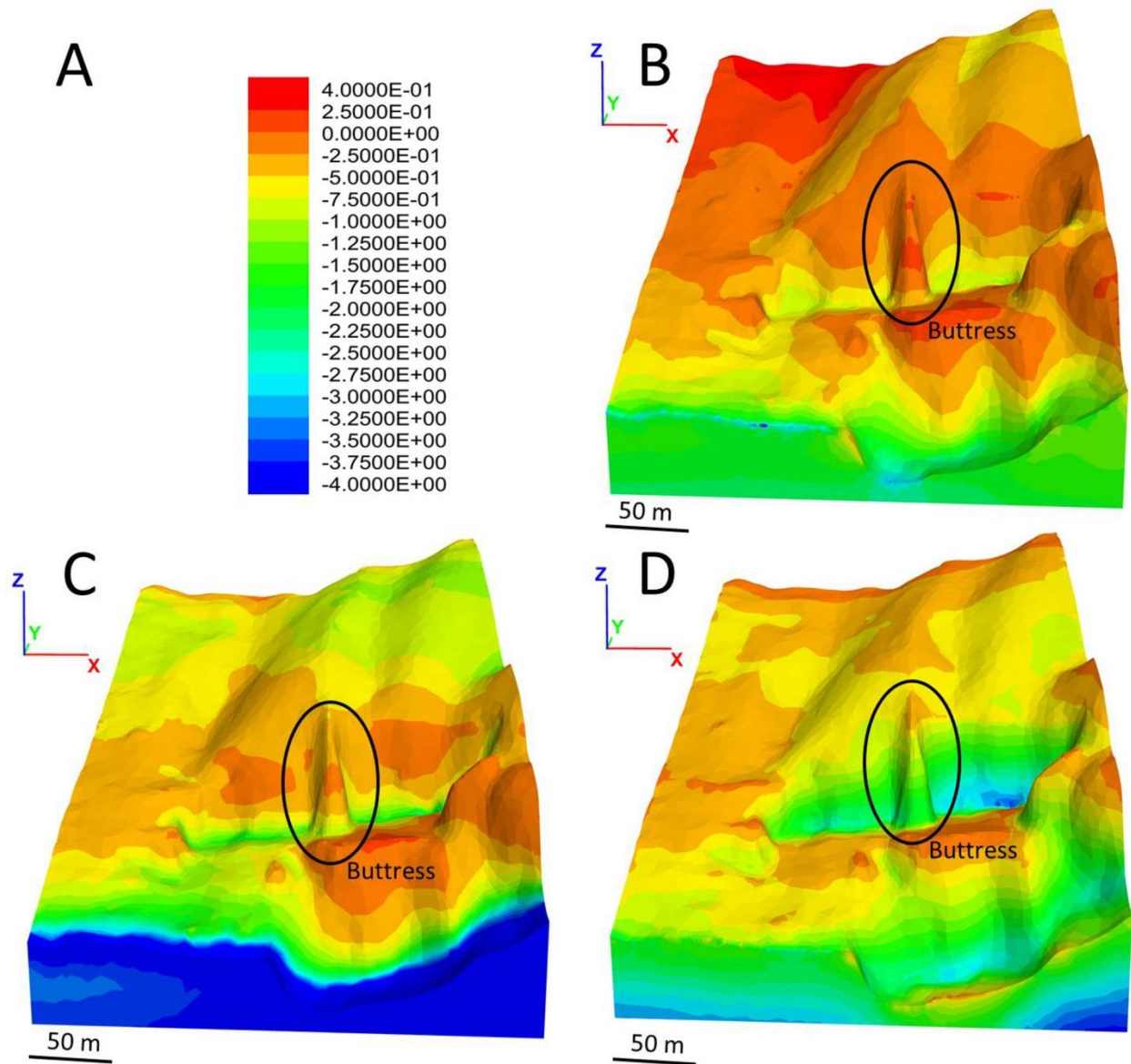
444

445 The FLAC 3D code allowed the analysis of the stress distribution in the X, Y, and Z directions. Figure 12

446 shows the simulated stress distributions obtained in Analysis 1 in the X (Figure 12B), Y (Figure 12C),

447 and Z (Figure 12D) directions respectively.

448



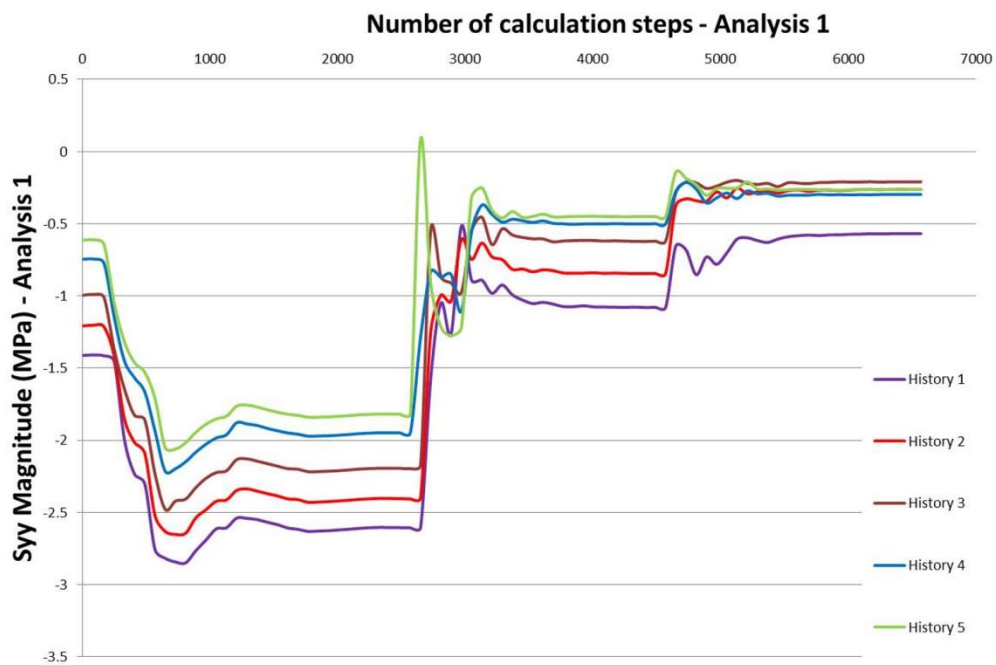
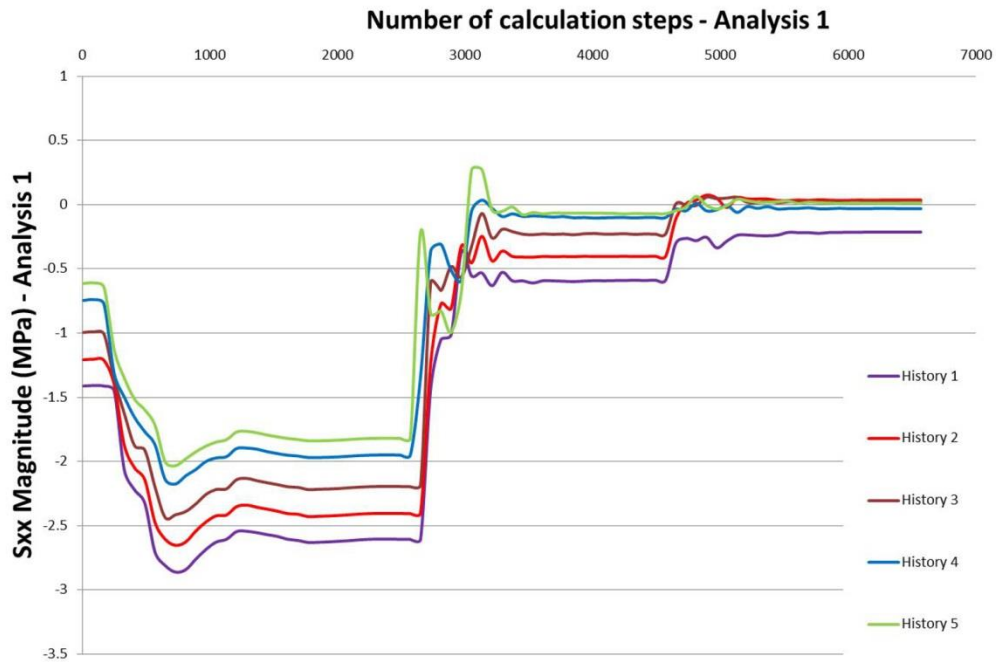
449

450 Figure 12. FLAC3D models for Analysis 1 showing the simulated stress distribution and magnitude;  
451 legend showing stress magnitude in MPa (A), stress distribution in XX direction (B), YY direction (C),  
452 and ZZ direction (D).

453

454 The stress values change from negative to positive indicating compressive and tensile stresses  
455 respectively. When positive values are present, the stress conditions are in tension and consequently, new  
456 fractures may be created, due to the unloading stress. Figure 12 shows positive tensile stress in the  
457 buttress with values in the X direction greater than in the Y direction. Figure 13 illustrates the stress state  
458 in the X and Y directions as measured at the history points (the x-axis represents the number of  
459 calculation steps in the analysis and the y-axis the value of stress in MPa).





460

461 Figure 13. Analysis 1: simulated XX (top) and YY (bottom) stress magnitudes measured at the history  
 462 points,  $K_x = K_y = 0.4$ . Location of history points 1 to 5 shown in Figure 11D.

463

464 The graphs show how the X-stresses (SXX) reach positive values at history points number 2, 3 and 5 (up  
465 to 0.04 MPa at the history point 2) and how they have very low negative values (compressive) at history  
466 points 1 and 4. Moreover, all the history points show that Y-stresses (SYY) are very low and close to  
467 positive values but that tensile stresses are not observed. It is important to note that, owing to the lack of  
468 field in-situ stress measurements these results assume an initial  $K_x=K_y$  value of 0.4 and do not take into  
469 account probable tectonic in-situ stresses; the results consequently show relative stress changes with  
470 excavation only and not the true absolute values.

471 In order to understand how the assumed in-situ stress ratio may influence the results of the study, further  
472 analyses were carried using different  $K_x$ ,  $K_y$  values and stress tensors. The software WinTensor 4.0.4 [23]  
473 was used for this purpose.

474

#### 475 6.2 Stress distribution analysis based on palaeostress tensor calculation and assumed K value

476

477 The main palaeostress tensor acting in the study area was estimated by the software WinTensor 4.0.4  
478 using a stress inversion technique based on fault and joint measurements. The inversion is based on the  
479 assumption that slip on a plane occurs in the direction of the maximum resolved shear stress [18]. The  
480 data used for this process are the strike and dip of the fault planes, the orientation of the slip line and the  
481 sense of movement on the fault planes (which can be determined from grooves or slickensides). Data is  
482 inverted to obtain the characteristic parameters of the reduced palaeostress tensor according to Angelier  
483 and Mechler [5] and Delvaux [24]. The derived parameters refer to the attitude of the three principal  
484 stress axes  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$  (where  $\sigma_1 > \sigma_2 > \sigma_3$ ) and to the stress ratio R (Equation 5) which expresses the  
485 magnitude of the intermediate principal stress,  $\sigma_2$  relative to the magnitude of the major and minor  
486 principal stresses  $\sigma_1$  and  $\sigma_3$  respectively. Some examples of the use of this software in the study of stress  
487 fields in different parts of the world are given in [59], [26], [24], [25], [76].

488

$$489 \quad R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3) \text{ with } 0 < R < 1 \quad \text{Equation 5}$$

490

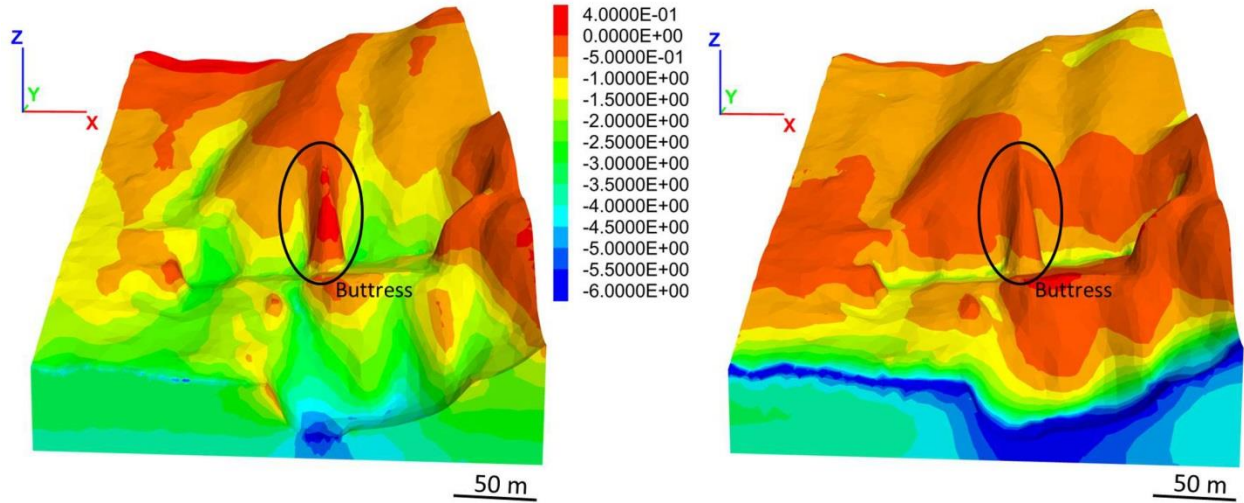
491 The analysis in WinTensor 4.0.4 was based on 20 measurements of kinematic indicators found on two  
492 different sides of the buttress and indicated two extensional regimes ( $\sigma_1 = \sigma_v$ ) with two different stress  
493 tensors (Table 6). From the geological evidence visible in the area and in accordance with Bigazzi et al.  
494 [10], Carmignani and Kligfield [17] and Ottria and Molli [61], it is suggested that these two stress tensors  
495 are related to two different tectonic stages (so-called “D2S1” and “D2S2”) within the D2 tectonic phase.  
496 During the older stage (D2S1), strike-slip and extensional movements with a general East-West  
497 orientation took place at the same time (stress tensor 1 in Table 6). During the subsequent D2S2 further

498 tectonic denudation and unloading changed the deformation style toward a multi-directional extension  
 499 which was probably North-South directed within the study area (stress tensor 2 in Table 6).  
 500

Stress Tensors	R	Type
1	0.5	Pure Extensional (nearly E-W orientation)
2	0.5	Pure Extensional (nearly N-S orientation)

501 Table 6. Stress tensors determined from analysis using WinTensor 4.0.4

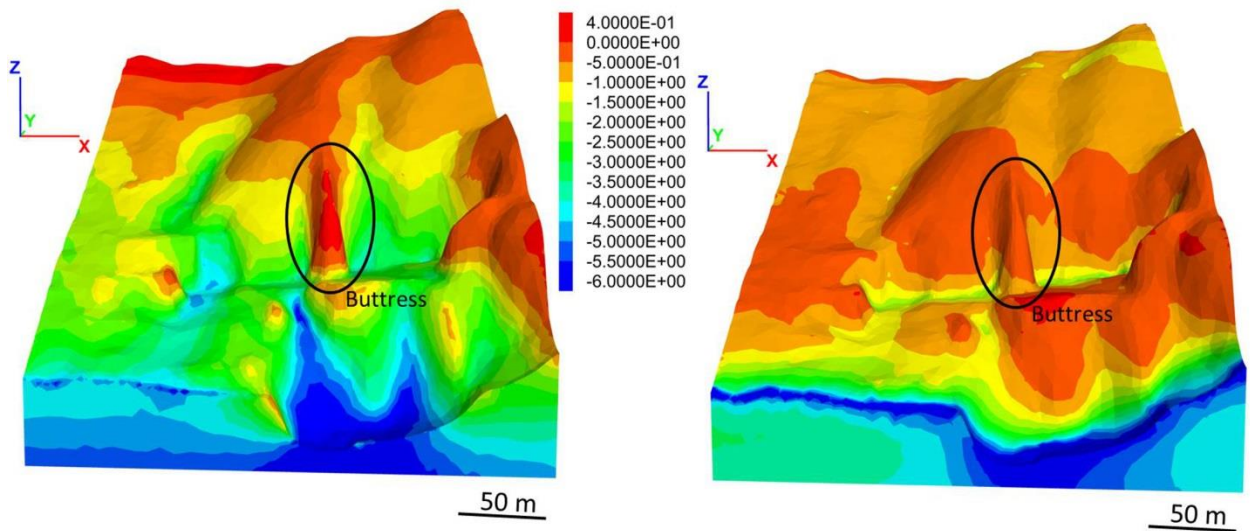
502  
 503 Based on these results, two further FDM analyses (Analysis 2 and 3) were carried out simulating the latest  
 504 extensional regime (North-South directed). As the Y axis corresponds, in this case, to the North-South  
 505 direction,  $\sigma_y$  was set as the minor principal stress ( $\sigma_3$ ) to reproduce the North-South directed extensional  
 506 regime. The same lithostatic vertical stress  $\sigma_v$ , adopted in Analysis 1, was used and the  $K_x$  and  $K_y$  values  
 507 were assumed as 0.6 and 0.4 respectively for Analysis 2 and 0.8 and 0.4 for Analysis 3.  
 508 Figures 14 and 15 show the results in terms of the simulated stress distribution in the X and Y directions  
 509 for Analysis 2 ( $K_x = 0.6$  and  $K_y = 0.4$ ) and Analysis 3 ( $K_x = 0.8$  and  $K_y = 0.4$ ). Figures 16 and 17 show the  
 510 simulated magnitude of stress values in Analysis 2 and 3 respectively at the same history points as used in  
 511 Analysis 1. The two simulations confirm that positive (tensile) stress values can be reached in the buttress  
 512 in the X direction (history points 2, 3, 4 and 5 for both Analysis 2 and 3). This agrees with field  
 513 observations of the presence of visible stress-induced damage in the marble buttress noted during the  
 514 engineering geological and photogrammetric surveys (Figure 8). Moreover, in these two analyses the  
 515 magnitude of the tensile stresses are greater than obtained in Analysis 1 (up to 0.15 MPa for the history  
 516 point 2 in the analysis 2 and up to 0.2MPa for the same history point in Analysis 3).  
 517



518

519 Figure 14: FLAC3D models for Analysis 2 showing the simulated stress distribution and magnitude; SXX  
 520 stress distribution in X direction (left) and SYY stress distribution in Y direction (right),  $K_x = 0.6$  and  $K_y$   
 521  $= 0.4$ . Units of stress in MPa.

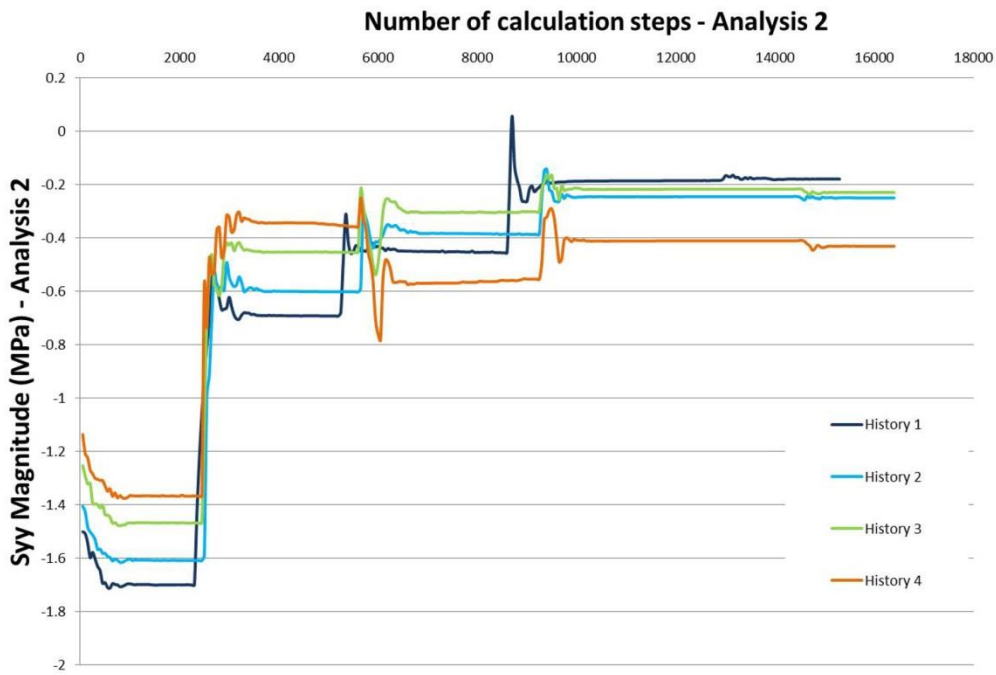
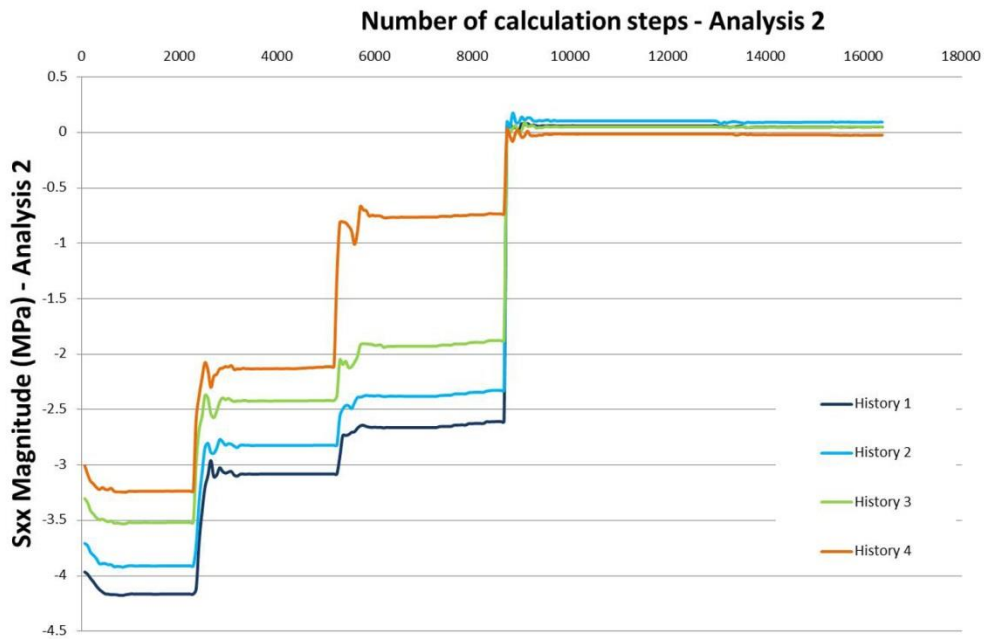
522



523

524 Figure 15: FLAC3D models for Analysis 3 showing the simulated stress distribution and magnitude; SXX  
 525 stress distribution in X direction (left) and SYY stress distribution in Y direction (right),  $K_x = 0.8$  and  $K_y$   
 526  $= 0.4$ . Units of stress in MPa.

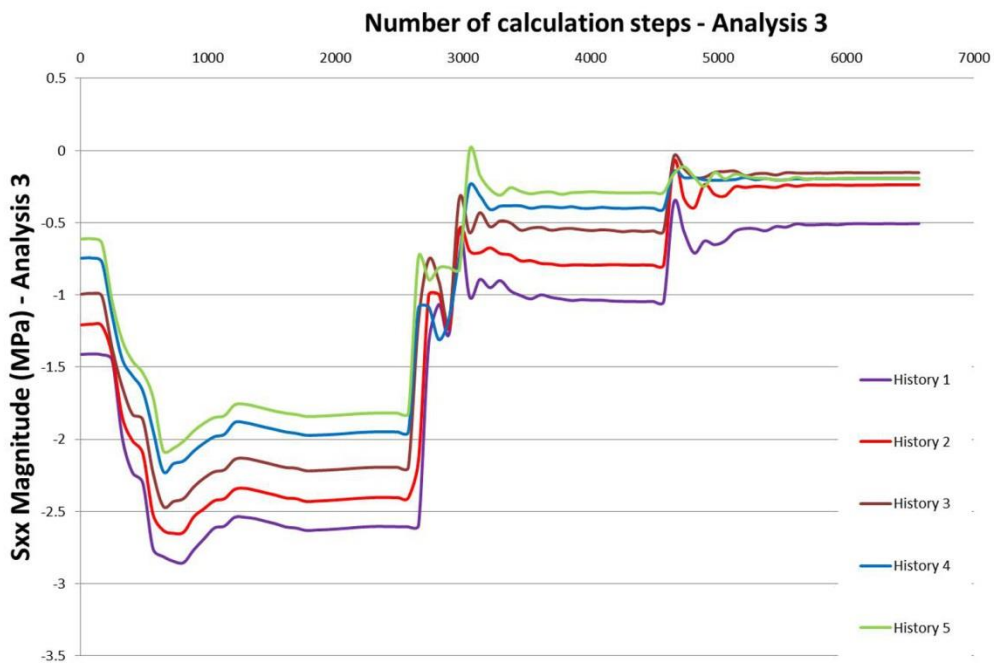
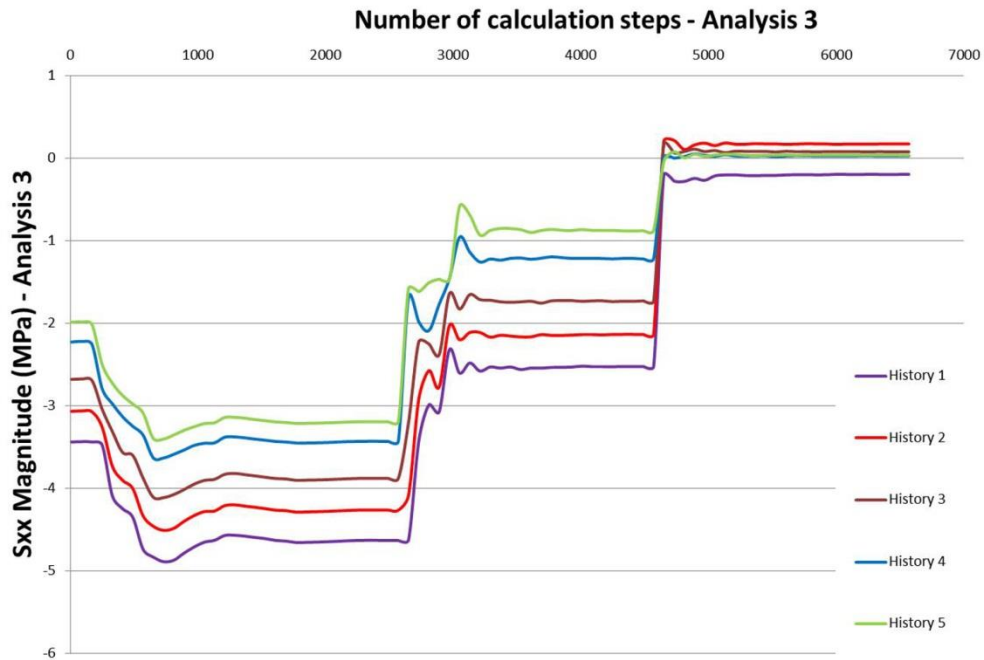
527



528

529 Figure 16. Analysis 2: simulated XX (top) and YY (bottom) stress magnitude measured at the history

530 points,  $K_x = 0.6$  and  $K_y = 0.4$ . Location of history points 1 to 5 shown in Figure 11D.



531  
 532 Figure 17. Analysis 3: simulated XX (top) and YY (bottom) stress magnitude measured at the history  
 533 points,  $K_x = 0.8$  and  $K_y = 0.4$ . Location of history points 1 to 5 shown in Figure 11D.

534  
 535  
 536

## 537 **7 Discussion**

538

539 This research demonstrates how an integrated remote sensing - GIS approach can improve the overall  
540 understanding and the quality of data available for rock slope stability analysis. Recently, several DTP  
541 techniques have been used by various authors to demonstrate their potential advantages in conducting  
542 surveys in high and complex geometry rock slopes. Sturzenegger and Stead (2009a and b) showed how,  
543 with the use of a tripod and long range focal length camera lenses, it is possible to calculate the joint  
544 attitude with accuracies similar to those obtained from TLS. However, in case of complex rock slope  
545 geometry and where problems of inaccessibility are encountered, this system tends to leave shadow  
546 (occluded) areas in the output. Firpo et al. [33] and Francioni et al. [34] showed how the use of an  
547 aerostatic balloon can solve problems related to the complexity of the slope, however, the inaccessibility  
548 of the area facing the object under study can be an insurmountable problem. Salvini et al. [69] and [71],  
549 clearly illustrated how the use of a helicopter can overcome the above mentioned problems. The use of  
550 helicopter systems can be both complicated and expensive and the orientation of the photographs less  
551 precise when compared to conventional terrestrial methods of survey.

552 In this context, the advent of UAV systems represents a very important innovation for remote sensing  
553 techniques since it provides a very powerful and flexible tool for the acquisition of high resolution  
554 photographs. Moreover, they are remotely controlled, thus avoiding the need of a crew and their cost is  
555 highly variable and dependent on the specific site requirements. The use of UAV technology in the earth  
556 sciences and more specifically in engineering geology has been documented in the literature [42], [60]. In  
557 this research the survey was executed using a vehicle that can work in an autonomous manner or be  
558 managed from the ground by remote control. Using this vehicle, it was possible to survey both the open  
559 pit surface, which is characterized by a very steep geometry, and an overhanging slope which has a  
560 complex morphology. All the photographs acquired by the UAV were oriented through the integrated use  
561 of TS and differential GPS surveys. This procedure provides a very powerful approach for increasing  
562 precision and accuracy of the photograph orientation and TLS registration procedures. The errors  
563 obtained during the exterior orientation of photographs, shown in Table 2, are considered acceptable  
564 given the survey distance and the complexity of the slope morphology. In fact, in spite of the accuracy  
565 obtained in the measurement of GCP by topographic survey, the UAV is a light and remotely controlled  
566 vehicle which can be prone to vibrations and instability phenomena during photograph acquisition. These  
567 problems can result in misalignment of photographs and significant errors during their orientation.  
568 Recently, the acquisition of a large number of photographs and the use of powerful software including  
569 image matching algorithms for the orientation process and the creation of DSM and orthophotos (see  
570 Agisoft<sup>TM</sup> Photoscan Professional [1]) has been shown to decrease these errors. However, if the attitude of

571 the UAV is properly controlled, the orientation of photographs permits the creation of accurate  
572 stereoscopic models and the stereo-restitution and measurement of geological features such as joint  
573 attitude, spacing, and trace length.

574 TLS was used in this research to obtain a very high resolution 3D model of the slope and to validate the  
575 results obtained from the stereo-restitution. Three different point clouds were acquired to avoid occlusions  
576 at the rock slope face and subsequently registered to a unique model thanks to the topographic survey.  
577 The maximum error estimated during the registration process was approximately 5 mm which is  
578 considered to be acceptable. Joint sets derived from DTP and TLS were compared (Figure 5) and show a  
579 good agreement in terms of both mean dip and dip directions.

580 To complement the geomatic surveys, engineering geological surveys were carried out to provide  
581 supplementary information on the physical-mechanical characteristics of the joints and the rock mass.  
582 Data obtained from these surveys was used in the characterization of rock mass according to the  
583 Bieniawski RMR method and for estimation of the GSI. The values of RMR and GSI made it possible to  
584 classify the rock mass as “good” in accordance with previous studies [63]. It must be highlighted that the  
585 engineering geological survey permitted the definition of the joint sets recognizable at the base of the  
586 open pit only and, consequently it is possible to observe some differences between the values obtained  
587 from DTP and TLS.

588 In addition, a kinematic analysis was carried out in order to analyse the stability of the buttress and the  
589 overhanging natural slope. Considering the quality and the amount of data available from the above  
590 mentioned surveys, this analysis was performed using a deterministic approach. The study area was  
591 subdivided into different zones based on a spatial analysis carried out by GIS techniques. The results  
592 obtained from this analysis are in agreement with previous studies carried out in the area by geologists  
593 and professional hand scaling personnel and with the mitigation work previously carried on the slope  
594 [63].

595 The last component of this research was a FDM analysis of the stress distribution in the buttress broadly  
596 representative of its geological history and recent excavation stages. It is known from literature how  
597 stress-induced damage due to excavation is a frequent problem in mining and quarrying activities and, as  
598 mentioned previously, the presence of such stress-induced fractures was found in the study area. These  
599 newly generated stress-induced brittle fractures may be an important consideration in the stability of an  
600 area and their study could decrease the risk of failure and increase the quality of marble in future  
601 extraction works. For this reason, with the aim of improving knowledge of the stress distribution in the  
602 marble buttress, FDM analyses were carried out using FLAC 3D. An initial analysis (Analysis 1) was  
603 performed using the induced lithostatic stress and  $K_x$  and  $K_y$  values both equal to 0.4. The simulation



604 results showed positive tensile stresses in certain positions on the buttress. Numerous researchers have  
605 recently noted the role of tensile damage on rock slopes [28], [14], [15], [74] [75].

606 It is important to emphasise that the concentration of tensile stresses may be increased if high in-situ  
607 tectonic stresses are present. Since in-situ measurements regarding actual tectonic in-situ stress are not  
608 available, it was decided to use the WinTensor software in an attempt to investigate the most probable  
609 main stress tensors in the area. The study of palaeostress carried out with the WinTensor software helps to  
610 understand how structures influenced the geological history of the area (e.g. based on the Anderson's  
611 classification – Anderson, [2]). It should be emphasised however the direction of palaeostress does not  
612 necessarily coincide with the current stress tensor acting today. Nevertheless, recent studies carried out in  
613 the Carrara marble district have confirmed that in this area there is a good correspondence between  
614 palaeostress data gained with WinTensor and the stress acting today [61], [48] [41], [31].

615 The analysis described in this paper has highlighted the presence of two main stress tensors: the first East-  
616 West directed and the second North-South. This result agrees with the theory that two different tectonic  
617 stages (D2S1 and D2S2) took place within the D2 phase [10], [17], [61]. Two further FDM analyses was  
618 then carried out (Analysis 2 and 3) simulating the most recent extensional regime (North-South directed)  
619 and using  $K_x$  and  $K_y$  values equal to 0.6 and 0.4 for the Analysis 2 and to 0.8 and 0.4 for the Analysis 3  
620 respectively. From the results of the FLAC3D simulation, it was possible to show how a relatively small  
621 change in in situ stress ratio,  $K$ , modifies the spatial stress distribution. In fact, when comparing the  
622 results of Analysis 1, 2 and 3, it is notable how in Analyses 2 and 3 the stress values measured in the X  
623 direction at history points 2, 3, 5 and 5 attain positive (tensile) values and how these values increase going  
624 from Analysis 1 to 3. This agrees with field observations of the presence of visible stress-induced damage  
625 in the marble buttress noted during the engineering geological and photogrammetric surveys.

626 It should be emphasised that the WinTensor analysis is based on only 20 measurements due to the  
627 difficulty in finding more slickenside kinematic indicators within the area (due to erosion and  
628 inaccessibility). For this reason and because of the major importance that direct measurement of stress can  
629 have on future slope analyses, it is clear that the described WinTensor stress study represents a first  
630 preliminary stage in improving the understanding of the in-situ stress acting in the area and that further in-  
631 situ measurements would be necessary to better clarify stress response and induced damage within the  
632 marble buttress.

633

## 634 **8. Conclusions**

635

636 In this research an integrated remote sensing - GIS approach was used to improve the overall  
637 understanding and the quality of data available for the analysis of the Lorano open pit. The methodology

638 described overcomes a frequent problem related to the inaccessibility of rock slopes, owing to their  
639 height, which can lead to erroneous evaluations of stability. DTP and TLS are shown to provide powerful  
640 modelling and analytical tools in the study of the geometry of the slope. DTP was carried out through the  
641 use of a UAV system. This technique overcomes problems related to elevation, steepness and complex  
642 geometry of slope; it is less expensive than other photogrammetric techniques showed in previous  
643 research such as aerostatic balloons and helicopters and with a good flight plan photogrammetric  
644 acquisition of areas can be obtained that would be impossible to survey with any other vehicle or  
645 methodology. TLS was performed using a long range laser scanner (up to 1 Km range) with three  
646 different point clouds acquired to avoid occlusions. The TLS model was overlapped with the  
647 photogrammetric model to create a high resolution 3D model useful in the definition of the main  
648 geological features and in the development of the 3D slope model to be used in subsequent kinematic and  
649 numerical analysis.

650 Kinematic analysis was carried out using GIS techniques. Using developed thematic maps, different  
651 kinematic analyses were performed according to the varying slope geometries so as to determine the  
652 steepest safe angles. As a result, this approach was able to overcome the common problem of complex  
653 slope geometry encountered in kinematic slope analyses.

654 Finally, a FDM analysis of the stress distribution in the buttress was performed to verify the possibility of  
655 tensile stress generation after the excavation phase. A study of palaeostress was carried out with the  
656 WinTensor software to understand how structures influenced the geological history of the area. Based on  
657 this study, a sensitivity analysis using different K values was performed in FLAC 3D to evaluate the  
658 influence of assumed in-situ stress ratio on the simulated stress distribution in the buttress. This research  
659 demonstrates that unloading due to erosion and slope excavation can lead to tensile stress in the marble  
660 buttress and that this will be amplified when high in-situ stress conditions are present. The FDM  
661 simulation shows that, even though the tensile stresses do not reach very high magnitudes and they might  
662 not be enough to generate brittle fractures in the intact rock mass (for the  $K_x$  and  $K_y$  values until now  
663 investigated), they are parallel to the X direction (West-East) which is approximately the same direction  
664 as the strike of the S1 foliation surfaces that characterize most of the Apuan Alps. As the S1 foliation  
665 represents the direction of weakness in the rock mass, it is suggested that S1 may have an important  
666 control on the nucleation and propagation of brittle fracturing. Moreover, as before mentioned, the new  
667 generated fractures, was observed connecting two adjacent system discontinuities.

668 This agrees with the field observations (often the brittle fractures in the Carrara marble district follow the  
669 same direction as S1) and previous studies carried out in the area [18], [52] and [17]. Although this  
670 research represents a preliminary study, it forms an important step and foundation for the analysis of the

671 buttress and a case example of stress analysis/damage in open pit slopes using a remote sensing/FDM  
672 approach.

673

### 674 *8.1 Future developments and works*

675 Field measurements of in-situ stress were not available for this research. As this data becomes available  
676 (in collaboration with the *Unità Sanitaria Locale* - USL1 of Massa-Carrara), further numerical modelling  
677 will be carried out to allow the absolute stress distribution during the quarry excavation phases to be  
678 better understood (particularly in order to evaluate the buttress behaviour in case of low and very low (up  
679 to  $\approx 0,1$ )  $K_x$  and  $K_y$  values [32].

680 Laboratory testing will be performed to improve the information on the mechanical properties of the  
681 marble and to better define the role of the S1 foliation in the tensile strength of the rock. Further  
682 numerical simulation will then also be undertaken using a FDEM-DFN (Discrete fracture Network)  
683 approach (e.g. Elfen and Slope Model [65] [49]) to allow simulation of stress-induced brittle fracture  
684 generation and propagation. Based on the research presented in this paper further protection works were  
685 carried out on the natural slope overhanging the open pit and three different monitoring systems installed  
686 which have been operational since 2012 [72]. The first is a geotechnical monitoring system comprising  
687 extensometers and crack-meters, and the other two are topographic systems consisting of a terrestrial  
688 interferometer and a robotic total station. Data from these instrumentation systems will form an important  
689 constrain for future rock slope damage research and constraining existing and future stability models of  
690 the buttress area.

691

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693

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699

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