A STRATEGY FOR DETECTION AND MEASUREMENT OF THE CLIFF RETREAT IN THE COAST OF ALGARVE (PORTUGAL) BY PHOTOGRAMMETRY

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ABSTRACT

Sea cliff retreat is mainly caused by the occurrence of landslides of different types and dimensions, which are a significant constraint for human activities and a source of considerable natural risk. With the increasing use of cliffy coastal areas in recent decades, mainly with urban areas and leisure resorts, this problem has growing importance in many areas of the world, in terms of natural risk reduction and of related environmental, landscape and heritage preservation issues.

The Algarve cliffs were subject of detailed studies based on systematic comparison of aerial photos from 1947 to 1991 performed with simplified methods. The inventory built with the gathered information provided a very rich database allowing the cliff retreat to be modelled, but it did not help to assess the measurement errors involved. To set up methods for cliff instability identification and measurement with the required accuracy, a photogrammetric study was made in the 16 km long Burgau-Lagos cliff-dominated coast in southern Algarve in order to achieve 3D results of the morphology changes. Several aerial surveys covering the area are available having different dates, scales and quality. The available complementary information includes camera calibration certificates for the more recent surveys and a set of ground control points identifiable in the 2002 flight.

First results of this study made it possible to establish a reference status of the coast based on the ground control information of 2002. Several events that were already mentioned in the inventory dating from 1991 were correctly detected, as well as new events occurred in the period 1991- 2002.

INTRODUCTION

Sea cliff retreat is mainly caused by the occurrence of landslides of different types (1) and dimensions constituting a significant constraint for human activities and a source of considerable natural hazard.

The increasing use of cliffy coastal areas in recent decades, not only as leisure resorts, but also as urban areas including high buildings, turned the cliff retreat into a problem with growing importance in several areas of the world. Natural risk reduction, landscape and heritage preservation and related environmental issues request coastal monitoring to derive scientifically based planning regulations and to support the projects of prevention/stabilization measures as well as monitoring their performance.

By analogy with landslide hazard assessment (2,3,4), cliff instability hazard assessment should include spatial, time and magnitude components. These are mainly computed with empirical models based on the analysis of systematic inventories of past events, which are scarce in the literature (5,6,7).

The Algarve cliffs (Portugal) are one exception. They were subject of detailed studies based on systematic comparison of aerial photos dating from 1947 to 1991 (6,8,9) performed with simplified methods (10). The used methods provided a very rich database upon which a cliff retreat model could be established. Nevertheless, the results were very dependent on the skill of the operator who acquired the data. Furthermore the method did not enable a continuity of the cliff retreat monitoring with the required objectivity and measurement accuracy.

To overcome these problems and to set up objective methods for cliff instability identification and measurement with the required accuracy, photogrammetric procedures were tested in a selected section, the 16 km long Burgau-Lagos cliff-dominated coast in southern Algarve. From west to east, the cliffs are composed by alternating beds of Cretaceous marly limestone and marls, overlain by Miocene weak calcarenites, heavily affected by karst features, which are partially filled with Plio-Pleistocene sandy deposits. The cliff height varies between 20 m and more than 100 m, and corresponds mainly to irregular cross profile slopes, with a general dip of 60° to 80° in the Cretaceous rocks, and near vertical with frequent overhanging sections in the Miocene rocks (Figure 1) (11).

The frequency of cliff instabilities is not very high (45 events between 1947 and 1991), providing average cliff retreat rates of 10^{-2} to 10^{-3} m/year. As an indication of the magnitude of the cliff failures to identify and measure, the horizontal area lost at the cliff top in each event varied between 3 m^2 and 76 m^2, and volumes of displaced material between 50 m^3 and 12000 m^3 (9).

Figure 1: Example of the morphology of the cliffs in the test region (Miocene).

The chosen region represents the most complicated one from the whole southern coast in terms of discontinuities of relief due to the very complex geomorphology of the sea cliffs. The aim of this first study was to establish and evaluate a strategy to automatically detect events of the above dimension occurred between two epochs, providing the location, the amount of lost area on the top of the cliff and the volume of the displaced mass of rocks and soils. The dating of each event can be achieved by nesting the available dated flights until a significant difference in the morphology in a particular location appears. Dating accuracy varies according to the time interval between both aerial surveys before and after the event.

A photogrammetric approach for the measurement of the cliff retreat is a multi-temporal task with many unusual aspects needing special consideration. The quality of the results depends not only on the temporal resolution of the data but also and mainly on the quality of the photos and complementary information. Especially older aerial surveys tend to be problematic from this point of view. Although highly important as a testimony of how it was like five or six decades ago, they are often not suitable for photogrammetric studies, since calibration data or fiducial marks are not available. Another problem is the fact that most of the available flights were planned for other purposes, presenting therefore inconvenient scales or flight directions for this kind of study. Furthermore, the 3D evaluation of the sea cliff retreat involves the generation of DEMs. A cliff region presents a difficult surface behaviour to be modelled by a DEM algorithm. So, different approaches have to be applied in order to find the most suitable one.

DETECTION OF SEA CLIFF INSTABILITIES

Figure 2 shows the strategy that is being applied for the automatic detection of occurred landslides (slides and rockfall events) by means of photogrammetry.

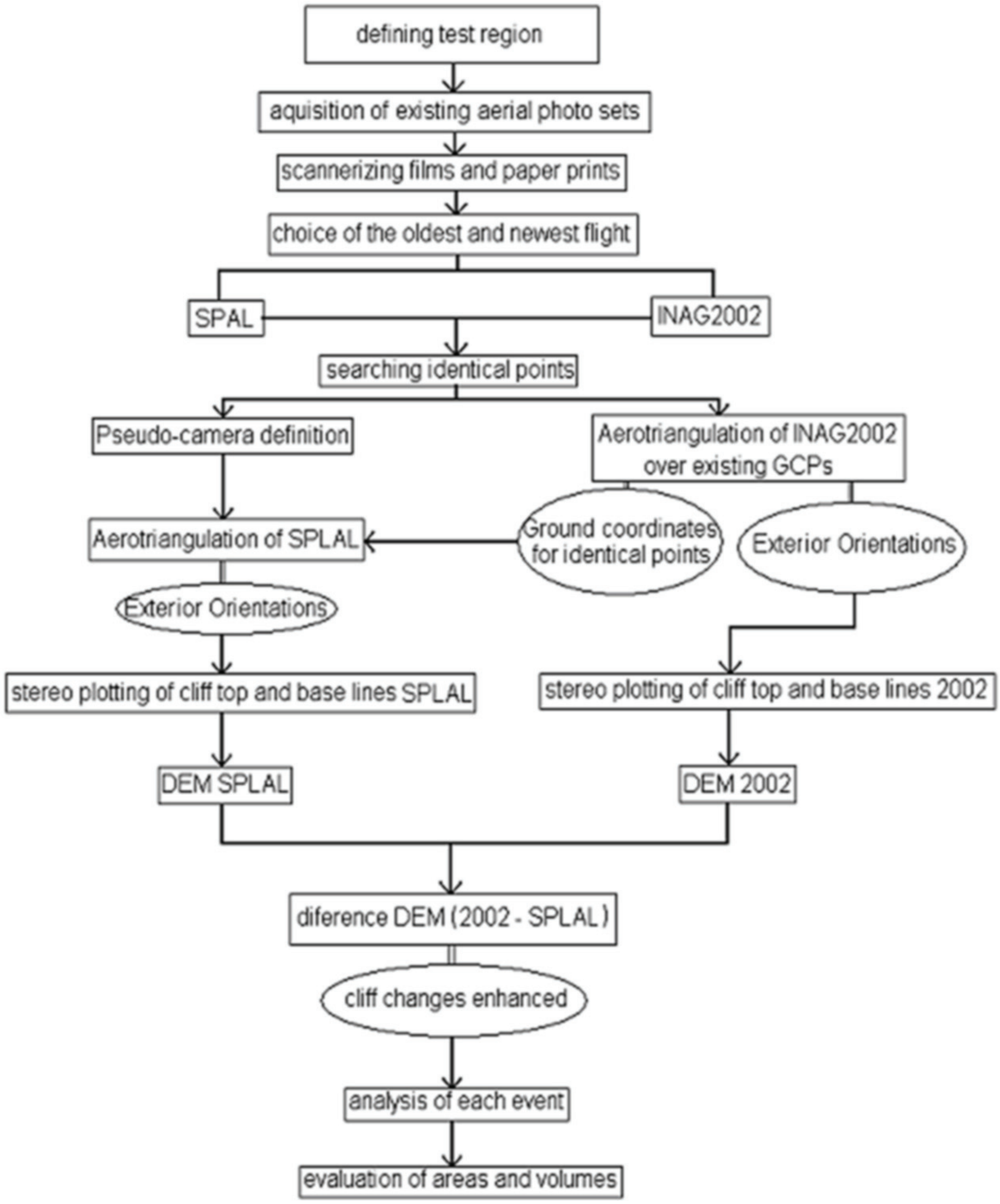

Figure 2: Flowchart of the operations in the project.

First of all, the existence of aerial photo coverages from several epochs is required. The spatial orientation of the flights has to be determined by aerotriangulation. Having the spatial orientation of each photo, digital elevation models (DEM) for each epoch can be calculated. A great number of break lines and filter resistant points has to be previously stereo plotted so that automatic DEM algorithms based on stereo correlation are able to produce suitable relief models of the cliffy coast. After harmonising the cell dimensions of the several DEMs and the reference coordinate systems, a difference-DEM between two epochs reveals the height changes in the coast strip and their distribution in planimetry. A thorough interpretation of the results makes it possible to separate the changes due to human activity (new buildings and roads) from those corresponding to actual events in the region of interest. A statistical analysis can then be pursued in order to quantify the movements.

Location and description of the test region

The 16 km long Burgau-Lagos strip is situated on the southern coast of Portugal. It belongs to the natural region of Algarve and is limited in the south by the Atlantic Ocean (Gulf of Cadiz). It has a predominantly west-east orientation being about 0.5 km wide landwards (Figure 3).

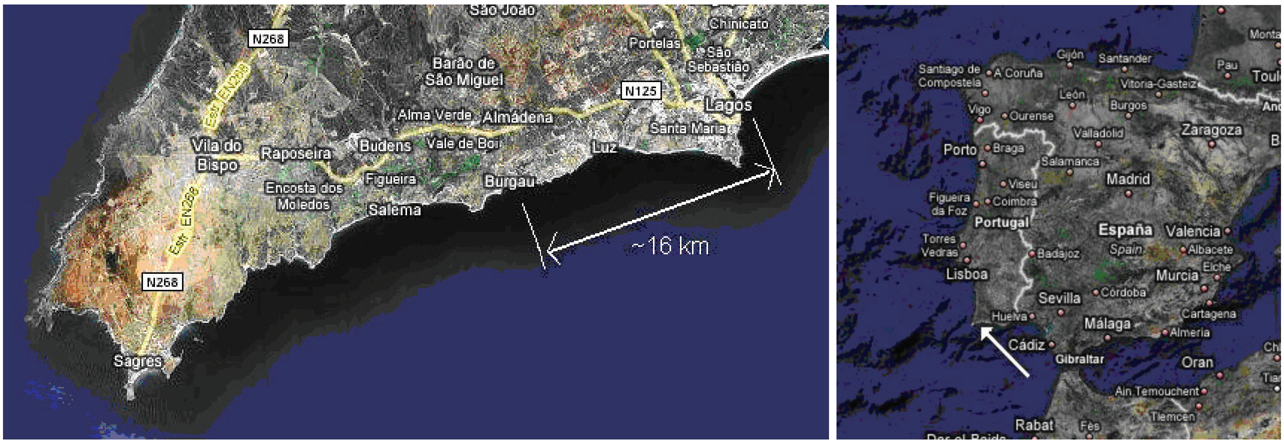

Figure 3: Location of the Burgau-Lagos coast in Portugal (images: Google Maps).

Due to the geological characteristics of the terrain as well as to erosion actions, the coast is formed by near vertical to vertical cliffs with the base limited by usually small beaches or submerged (plunging cliffs), and populated with several fallen blocks. Small sandy beaches alternate with the plunging cliffs. In the eastern extremity, sinkholes and arches build a very complex morphology, a landscape that is very favourable for tourism but problematic for photogrammetry.

Aerial coverage and ground information

For the multi-temporal study of the coast, several aerial surveys were available in paper format. After considerable efforts it was possible to locate the original films and to scan them in a photogrammetric scanner Vexcel Ultrascan 5000. Unfortunately, the original film of the oldest flight could not be scanned so that the existent paper prints had to be scanned for this study. Table 1 resumes the characteristics of the several aerial surveys.

Most of the photos were already analysed and interpreted during the study from 1947 to 1991 (9). However, no other spatial orientation than the approximated location of the landslides in a 1:25.000 scale map was determined (Figure 4).

The latest flight, INAG 2002, was flown for coastal mapping purposes. Therefore, a set of ground control points (GCPs) was also available. Camera calibration reports were available for all flights except for SPLAL and RAF that constitute the first known aerial coverages of the country.

Table 1: Aerial surveys and Ground Sample Distance (GSD) of scanned images

Name	Date	Scale	Format/ emulsion (cm × cm)	Focal length (mm)	Camera	Scanner	GSD (m)
SPLAL	1938-1948	1:18 000	18x18 BW (paper)	204.4	n/a	EPSON Perfection V700 Photo	0.41
RAF	1947	1:30 000	23x23 BW	154.2	Fairchild K17 (?)	---	---
USAF	1958	1:30 000	23x23 BW	152.04	n/a	---	---
DGSFA	1972	1:15 000	23x23 BW	152.05	WILDRC8	---	---
DGSUI	1974	1:15 000	23x23 BW	152.08	n/a	---	---
FAP	1980	1:15 000	23x23 BW	153.36	n/a	---	---
FAP	1983	1:30 000	23x23 Color	153.36	n/a	---	---
IGP	1991	1:30 000	23x23 BW	151.64	WILDRC10	Vexcel Ultrascan 5000	0.67
IGP	1995	1:15 000	23x23 BW	152.73	WILDRC10	Vexcel UltraScan 5000	0.34
INAG	2002	1: 8 000	23x23 Color	153.073	WILDRC20	Vexcel UltraScan 5000	0.18

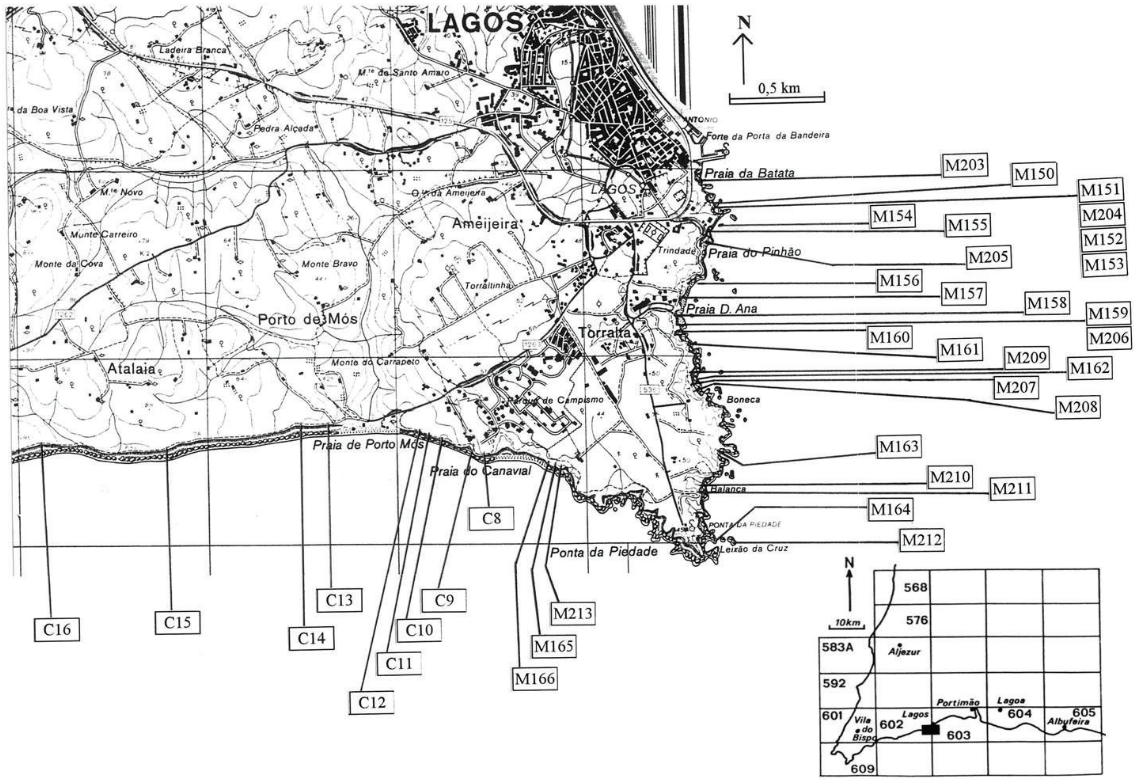

Figure 4: One of the 9 pages of the 1947-1991 inventory of cliff movements in the Algarve (9) showing their approximate location and identification code.

Spatial orientation of the main flights

SPLAL and INAG 2002 were chosen as main flights for this study because they limit the widest available temporal window that could be analysed based on aerial surveys. In fact the 1991 study involved SPLAL and the flights until 1991. The SPLAL flight is not precisely dated but the respective flying company existed between 1938 and 1948. It is therefore possible (and some sparse clues seem to indicate it) that it is older than the RAF flight (1947). Although part of the RAF film is already available in digital form, SPLAL presents a more favourable scale and a better radiometry being therefore preferred for the study.

The test region is covered by eight short strips with N-S orientation. Except for the eastern one, all strips available were composed by just one stereo pair with 60% overlap. Side overlaps were variable, between 20% and 60% (Figure 5).

SPLAL presented several problems regarding interior and exterior orientation: no calibration information except for the camera focal length registered on the photos; a fiducial mark not visible in all photos; visible distortions in some photo prints. Furthermore, there are no documented GCPs for this flight and half of the photos include 70% to 90% of water.

To overcome the existing failures that prevented recovering the original interior orientation of the photos, a strategy had to be applied in order to locate the approximate principal point. The SPLAL photos have a dimension of 18 cm x 18 cm and contain black fiducial marks in the middle of the four sides, each mark containing a white dot. Both positions in the frame and shape (Figure 6) resemble fiducial marks from later Zeiss RMK aerial film cameras. In every single photo of the block there were just three of the four white dots visible. Nominal coordinates of the white dots were unknown. At the time of the flight, before 1950, according to the literature (11,12) it was not usual to include nominal coordinates of fiducial marks in the calibration certificates. Analogue plotters used to process the photographs did not need those coordinates to carry out the interior orientation. Specifications for contemporary aerial mapping cameras (11) say that the intersection of the lines joining pairs of opposite markers (fiducial marks) should intersect at an angle of 90° ± 30” to 1’ and locate the principal point with a probable error less than 25 to 30 microns. However, digital photogrammetric software does not consider perpendicular conditions for those straight lines. It rather requires measuring a set of image points with known original photo coordinates to calculate the parameters of a geometric transformation, normally affine, between the measured coordinates and the photo coordinates. Since the 4 symmetrical white spots of the fiducial marks were not visible in every photo and their nominal coordinates were unknown, another set of symmetrical points that could be measured in each photo has been defined (Figure 6). The nominal coordinates for each mark were approximated by the mean value of the photo coordinates measured in 56 available digitised photos. For this operation only photos free from visible distortions were chosen. The set of mean values and the printed focal length of 204.4 mm were then used to define a pseudo-camera in the software. Assuming the original camera fulfilled similar specifications as their contemporaries there was no need to consider the principal point offset since our images were digitised from paper prints with a pixel dimension of 22 microns, that is a similar magnitude as the tolerable offset. Radial distortion could not be considered either.

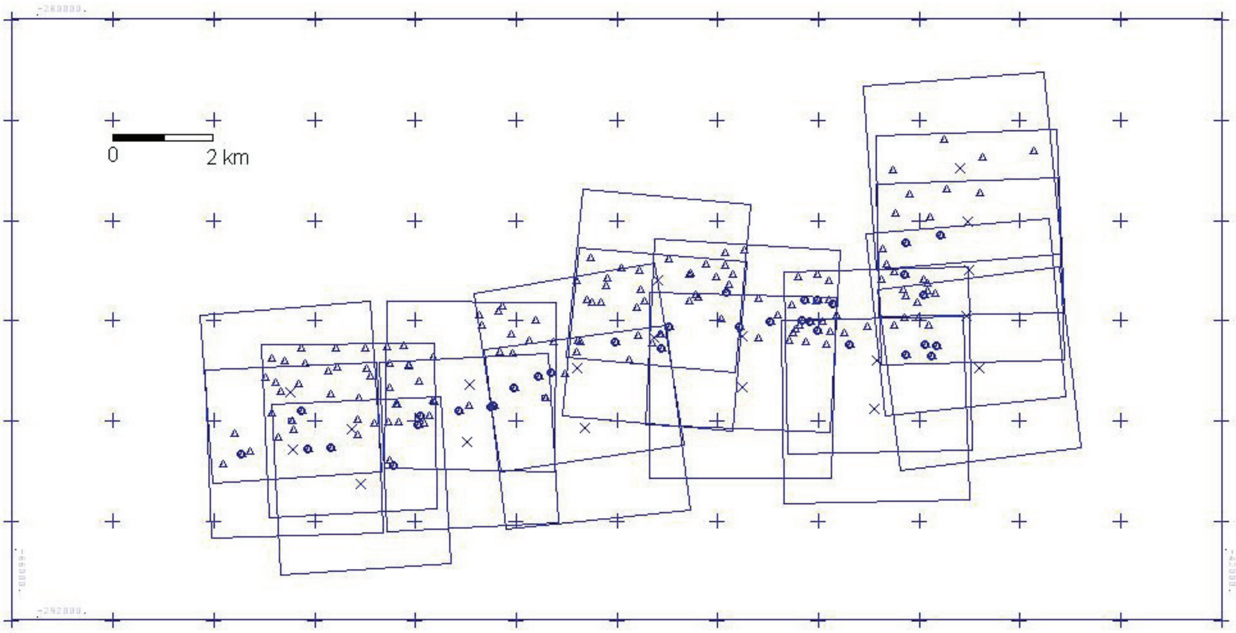

Figure 5: SPLAL flight over the test region showing tie (o) and control points (Δ).

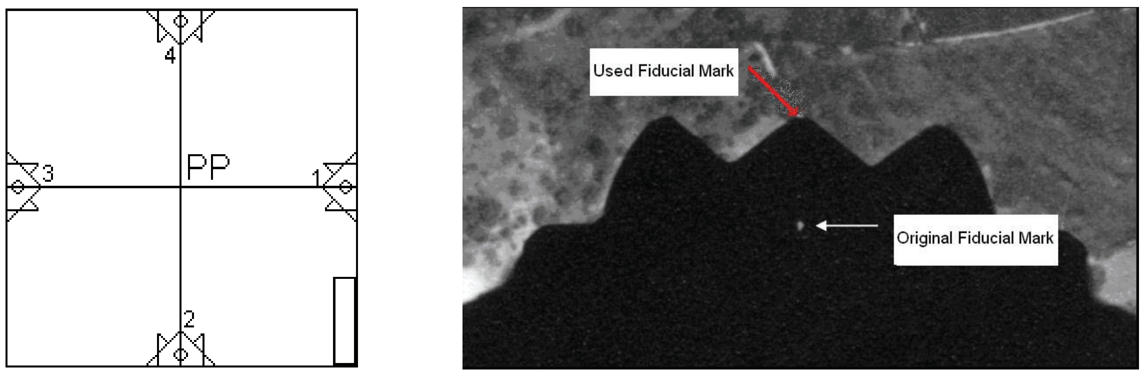

Figure 6: Fiducial marks in SPLAL photos. The used 4 point set was aligned with the straights joining the original white dots.

INAG 2002 has the better GSD of all flights (about 0.18 m), and a set of 30 documented and identifiable ground control points. The test region is covered by 7 strips with variable orientation along the coast and 60% end lap. The strips overlap in two models at the extremities (Figure 7).

Although *pugs* are present in all strips being visible in every second scanned photo, they could not be used as GCPs because a precise identification on the remaining photos was extremely difficult for a monoscopic measurement of the photo coordinates.

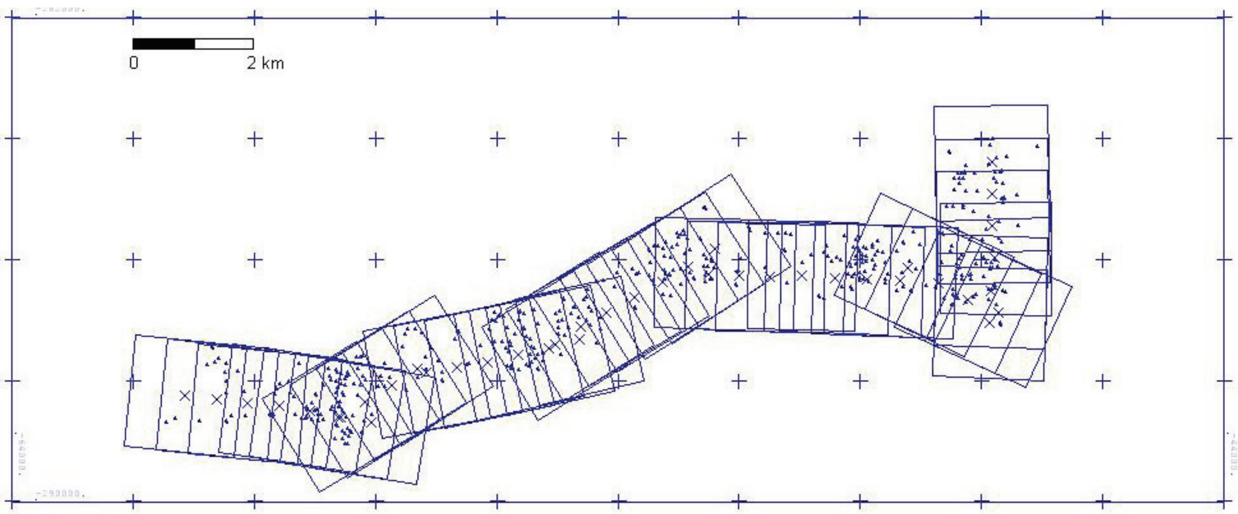

Figure 7: Flight INAG 2002 over the test region showing pass points.

The GCPs from INAG 2002 are not identifiable in the SPLAL flight since they mostly consist of points on urban objects that did not exist 60 years before (Figure 8). Therefore, a set of 80 well distributed common points between both flights had to be identified and collected.

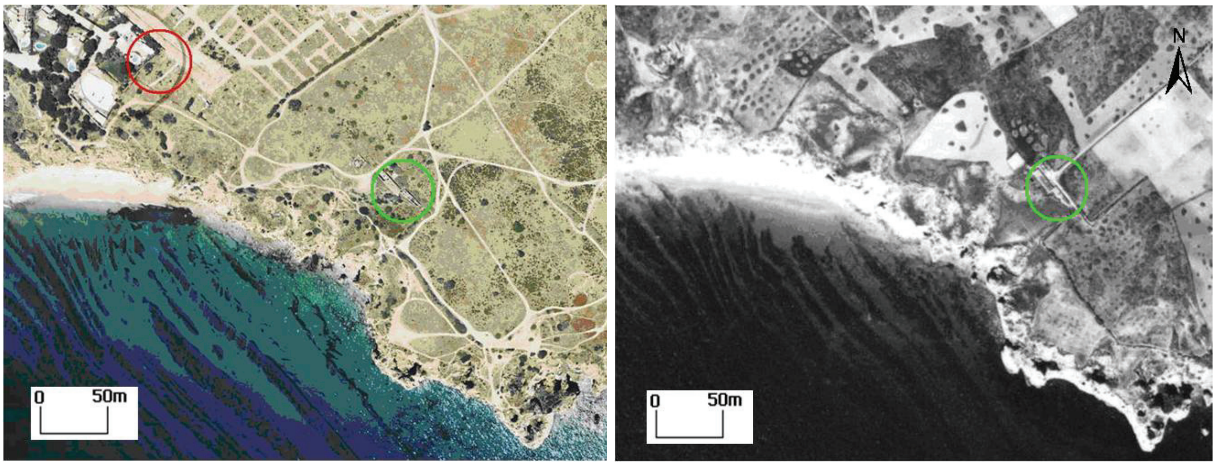

Figure 8: The same zone in both flights: INAG2002 on the left, SPLAL on the right. Red circle: a GCP that does not exist in the older flight. Green circle: a common object in both epochs.

Table 2: Statistical results of the aerotriangulation for INAG 2002 and for SPLAL

	AT INAG 2002	AT SPLAL (Control points resulting from AT INAG 2002)
RMSE X	+/- 0.109 m	+/- 0.800 m
RMSE Y	+/- 0.117 m	+/- 0.670 m
RMSE Z	+/- 0.258 m	+/- 1.362 m
Sigma 0	18 µm	22.56 µm
Control Points	30	36
Pixel	22.5 µm	22 µm
GSD	0.18 m	0.41 m

Using the set of GCPs, the INAG 2002 block was triangulated by means of the software LISA/BLUH (http://www.ipi.uni-hannover.de). As a result, the ground coordinates of the common points were obtained. These points were then used as ground control for an aerotriangulation of the SPLAL block. While an automatic pass and tie point extraction could be applied to the INAG 2002 block, the operation did not work well for SPLAL due to the extension of water and to the block geometry. Especially tie points had to be collected manually. Table 2 resumes the results for both aerotriangulations (AT).

In view of all the adversities presented by SPLAL and the size of the changes to detect, the results were considered satisfactory. Except for visual evaluation, it was the first time that photos from this flight could be actually oriented and integrated in photogrammetric studies. It is to assume that the same proceeding applied to the scanned originals (instead of the prints) would yield better results for the AT.

Generation of DEMs

The strategy used so far resulted in a spatial orientation for all SPLAL photos in the same coordinate system as INAG 2002. Stereo models could be built in both flights and the top of the cliff as well as the base have been stereo plotted. By overlapping the plotted lines of 2002 with the stereo models of the older flight, a 3D interactive sample check has been made. Discrepancies between the old cliff top and the plotted lines corresponded, in fact, to events that were already inventoried or to new movements that were clearly identifiable in the INAG 2002 photos.

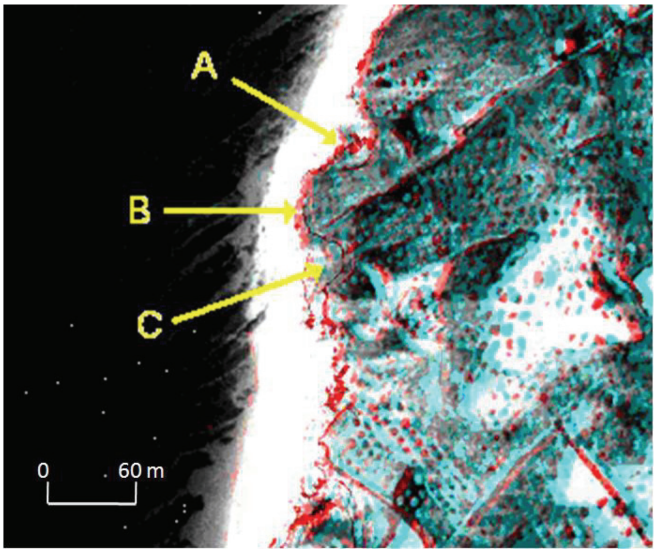

Figure 9: (Anaglyph) SPLAL stereo model and cliff top from 2002. A and B - movements inventoried in (9); C - large movement occurred in 1997.

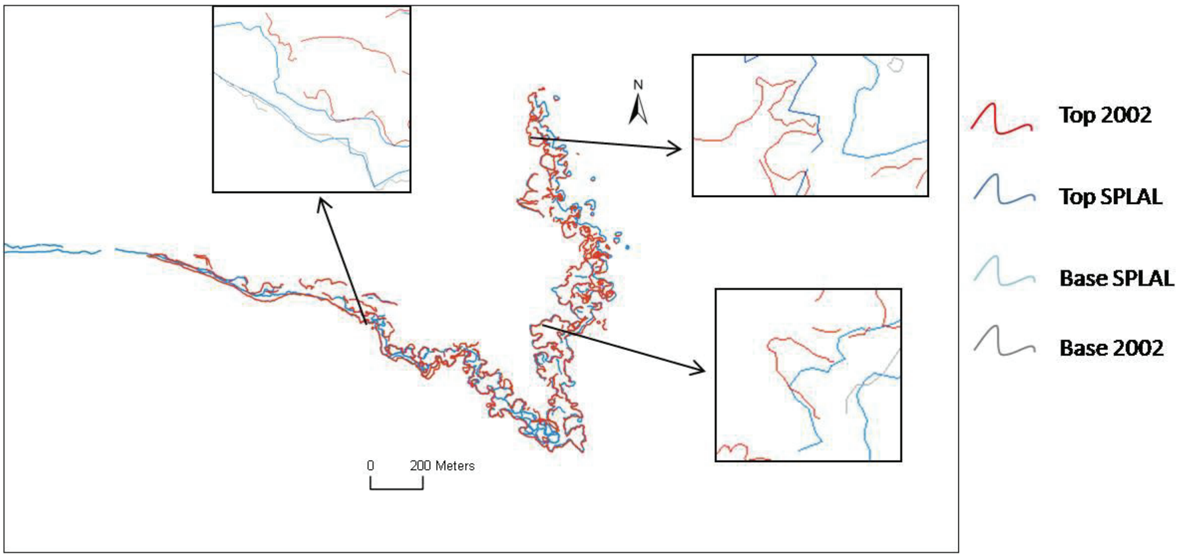

Figure 10: Lines corresponding to the top and base of the cliff in both epochs showing considerable differences in some sites.

The elevation models were automatically generated by image correlation with the software LISA. The plotted lines were integrated as break lines. Although the image correlation algorithm applied in the extraction of tie points for the AT did not work well in the SPLAL photos, the results of the image correlation with spatial intersection were quite good: seldom points on the sea and a dense inland point cloud. Some underwater structures near the coast have also been detected presenting false heights, due to water refraction.

The top of the sinkholes was correctly detected but the bottom, filled with water, could not be correlated (Figure 11). This fact showed the necessity of defining a mask with constant height (0 m) for the bottom of the sinkholes in order to avoid false heights to be assigned by the following interpolation step.

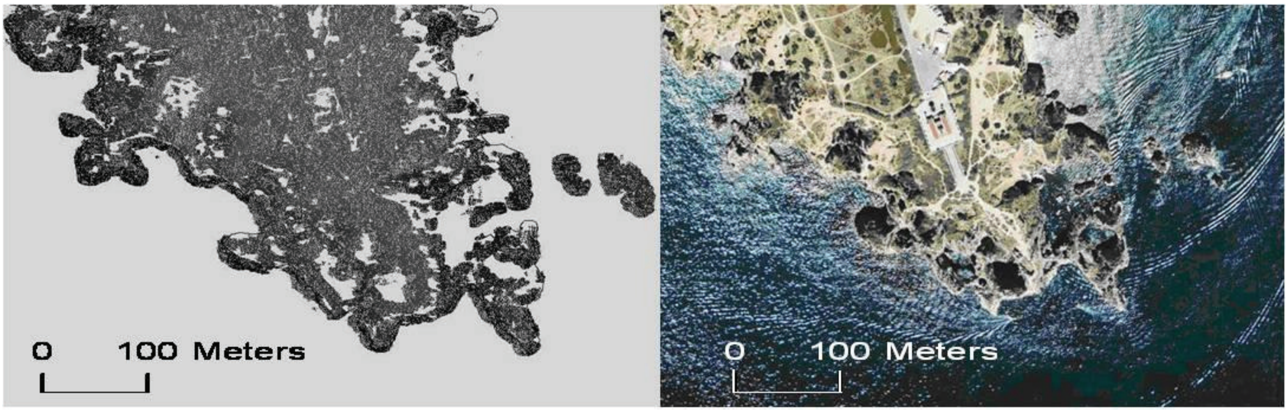

Figure 11: Sinkholes in DEM SPLAL (left) and in INAG2002 (right).

A reference DEM was generated for INAG2002 with a resolution of 20 cm. For the 3D comparison, DEMs with less resolution were used for both blocks. The optimal resolution for the comparison DEMs had to be established according to the dimension of the events to detect, the GSD of the flights involved as well as the dimension of the area to study. It is intended to use bigger cell sizes just for detecting the events in a long strip and refine the DEMs for a more accurate study of each detected event.

Finally a difference DEM could be built and interpreted. Figure 12 shows the difference between DEM INAG2002 and DEM SPLAL for a sample area. Dark red zones indicate an increase in height and dark blue and violet zones show a loss in height. The 3D visualisation was very useful in the analysis made by geologists. Anaglyphs of the stereo pairs as well as chromostereoscopic representations of the DEMs and difference DEMs were used to present results and discuss their reliability. The overlay of an orthophoto with the difference DEM made it possible to interpret the inland height changes as caused by buildings and roads not existing in SPLAL as well as some bigger volumes related with earthwork occurred in the last decades. Through this analysis, it was possible to verify the quality of the older DEM, which had been causing some uncertainty, leading to the conclusion that it was adequate for the purpose.

At the coast, an alignment of neighboured blue and red spots indicates the sites of interest for this study (Figure 12, left). In fact, for each loss in the cliff top there is mostly an increase in height on the base caused by debris deposits, except when these are taken away by man or by the waves. That explains the close vicinity of blue and red zones in a small area.

RESULTS

For a sample coastal section approximately 3.6 km long where the first detailed analysis were accomplished, the difference DEMs enabled the identification of several locations where cliff retreat may have occurred. From the 22 cliff retreat events identified in the1947-1991 study (9), 19 had a full correspondence in the difference DEM, suggesting that the methods used are suitable for sea cliff and coastline evolution monitoring. The differential DEM also enabled the detection of 23 presumably new events that require further confirmation.

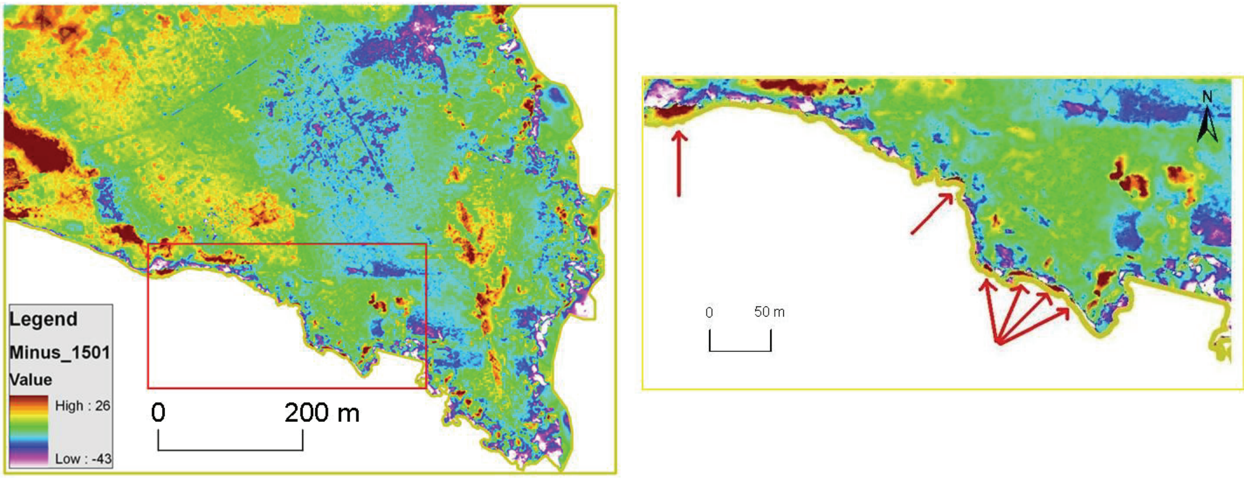

Figure 12: Difference DEM in a 2 km x 1.8 km tile; cell size: 0.55 m. On the left, red spots near blue ones reveal coastal change.

The detected events are analysed one by one, in order to confirm the instability and determine the lost area on the cliff top in the period of time between SPLAL and INAG 2002, assumed to be 54 to 64 years. Figure 13 exemplifies one type of event under analysis in Praia do Camilo. It is an intermediate dimension landslide (red arrows). The example shows the coincidence of the information layers from independent sources: the stereo plotted cliff top from SPLAL (dark blue line), the stereo plotted cliff top in 2002 (red line), the difference DEM showing a loss of volume (blue/violet) and the orthophoto showing how it looked like in 2002. The difference DEM enables also the estimation of the volume of rocks and soils displaced by each event. The areas of lost and gained volume are automatically computed from the difference DEM (Figure 14, upper left). The elementary volume of moved mass (gained or lost) results from the product of the DEM pixel area on the ground and the pixel value in the difference DEM. These estimates are also very interesting data for other studies, mainly concerned with sources of sediments for coastal processes, including sediment near shore processing and transportation.

Quality assessment in a multi-temporal task like the one presented here is not very simple since the ground truth for SPLAL cannot be really accessed. In fact, the only trustworthy ground information available is the GCP set for the INAG 2002 flight. All subsequent results lay on this set. Due to the nature of the study, control areas or volumes are difficult or even impossible to access. Nevertheless a simplified model was built for estimating the least uncertainty of the final results: areas of moved material and respective volumes.

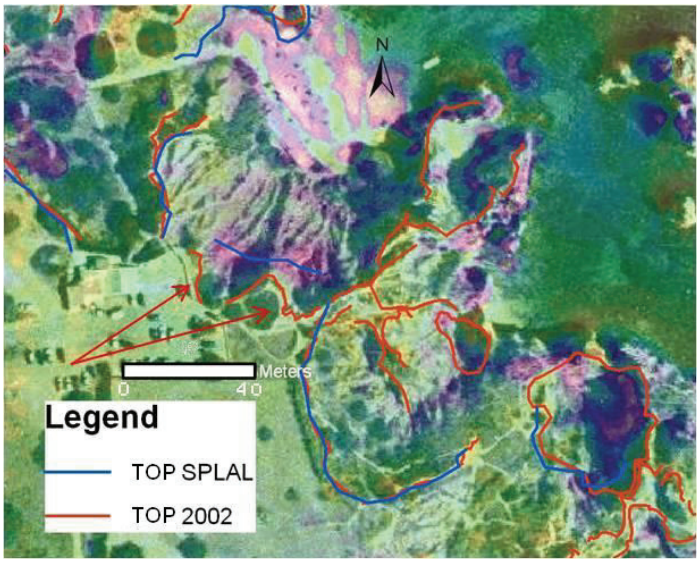

Figure 13: Praia do Camilo: Orthophoto overlaid with difference DEM and breaklines. Lost area at the cliff top is approx. 565 m².

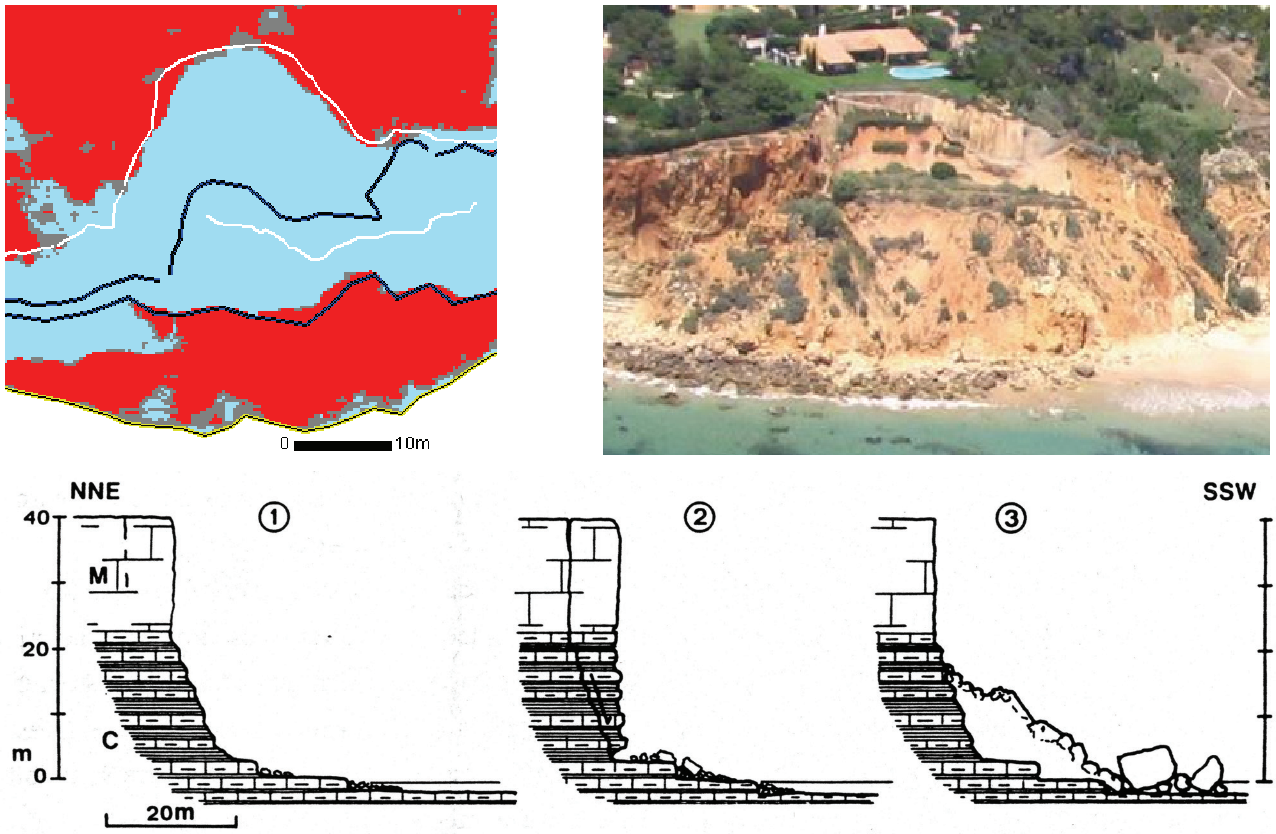

Figure 14: Praia do Canavial – Upper left: Top (white line) and base (yellow line) of cliff 2002 and of SPLAL (dark blue lines). Areas of lost (light blue) and gained (red) volumes. Lost area at the cliff top is approx. 1519 m². Upper right: Oblique photo (21 June 2006, courtesy S. B. Teixeira, CCDRA). Below: Schematic presentation of cliff evolution (10).

Assuming that the uncertainty of the DEM is approximately the uncertainty in height resulting from the aerotriangulation, and considering the limited dimensions of each event under study and the support of stereo plotted break lines in the neighbourhood, we conclude that the difference DEM (DDEM) bears an uncertainty of

$$\sigma_{ZDDEM} \approx \pm 1.4 \text{ m}$$

As for the volume of moved mass in an area of n pixels of dimension (*a* x *a*) on the ground, it results from the sum of *n* elementary volumes. Therefore it bears the uncertainty

$$\sigma_V = \sqrt{\sum^{n} a^4 \sigma_{ZDDEM}{}^2}$$

The uncertainty for the volume grows with the area as the formula reveals. As an example, for a typical area of 50 pixels with 0.5 m x 0.5 m on the ground, the formula yields

$$\sigma_V \approx \pm 2.5 \text{ m}^3$$

The uncertainty for the areas depends on the accuracy of their delimitation according to the specifications of geologists. Important for this study are special areas of cliff top retreat delimited by cliff top lines in different epochs which are not coincident with areas of lost material as shown in Figure 14. Uniform criteria for the delimitation of the areas of interest for geologists are under discussion. Polygons are easy to define when the cliff top lines of different epochs intersect each other. Problems arise if this is not the case.

The results are organised in a geographical database for coastal management in order to validate and update the 1947-1991 inventory for the region Burgau – Lagos (Figure 15). The coordinates of the inventoried landslides materialised through the centroid of the respective polygon (Portuguese Datum 73) are also corrected.

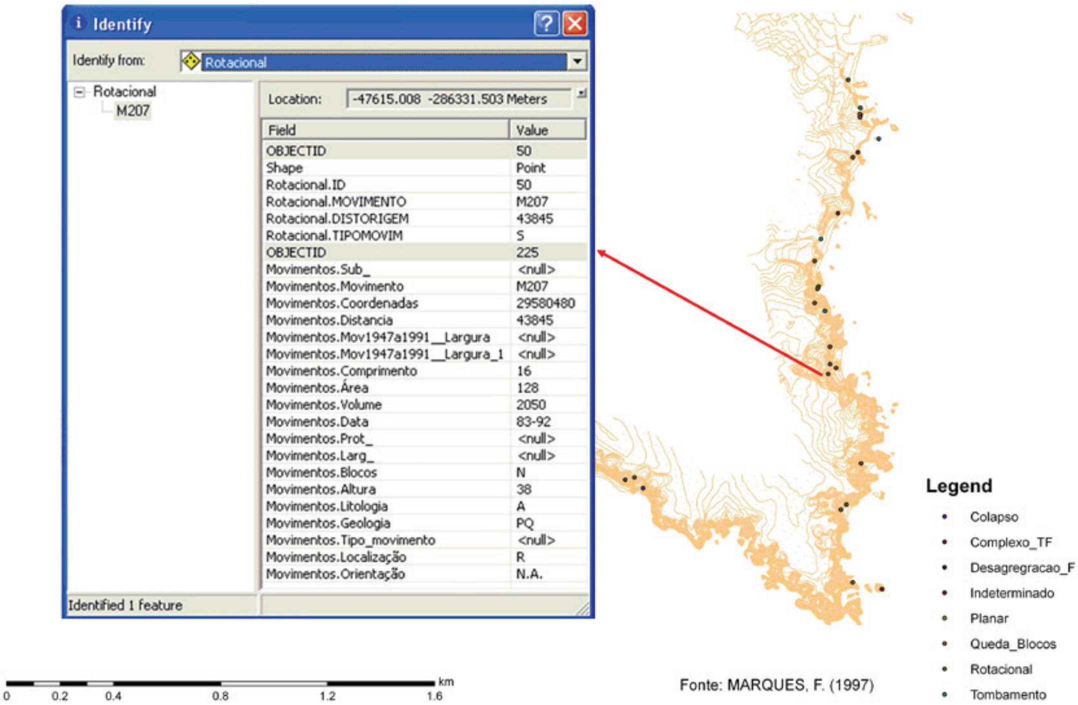

Figure 15: Example of the geographical database showing the information related to one event.

CONCLUSIONS

The photogrammetric approach by means of multitemporal DEM generation turned out to be suitable for the detection of cliff failure events in the coast of Algarve. The spatial orientation of an old aerial survey (1938-1948) could successfully be achieved and a 0.50 m² resolution DEM could be generated. The difference between two DEMs of the same region with a time gap of six decades (2002 and 1938-1948) revealed approximately 90% of the events already inventoried until 1991 and also a considerable number of new ones. Lost areas on the cliff top could be determined as well as displaced volumes for each event.

It is intended to apply the developed strategy to the entire cliff dominated coast of the Algarve covered by the available aerial surveys. A recent digital coverage of the region with suitable GSD is being acquired and will be integrated soon into the project enlarging the temporal window of the study to 6 to 7 decades. The numeric results of this study will be used to refine the existing geological models for cliff retreat behaviour in the Algarve. The 1947-1991 inventory is integrated in a Geographic Information System and shall be updated with the new acquired data for the events, enabling the redefinition of hazard and risk zones, in order to prevent severe accidents and to refine existing planning regulations.

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REFERENCES

1 Dikau,R, D Brundsen, L Schrott & M Ibsen (Editors), 1996. Landslide Recognition: Identification, Movement and Causes (Wiley) 251 pp.

2 Varnes D J, 1984. Landslide Hazard Zonation: a Review of Principles and Practice. (UNESCO Press, Paris) 63pp.

3 Guzzetti F, A Carrara, M Cardinali, P Reichenbach, M Galli & F Ardizzone, 1999. Landslide hazard evaluation: an aid to a sustainable development. Geomorphology, 31: 181-216

4 Guzzetti F, P Reichenbach, M Cardinali, M Galli & F Ardizzone, 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology, 72: 272-299

5 Teixeira S B, 2006. Slope mass movements on rocky sea-cliffs: A power-law distributed natural hazard on the Barlavento Coast, Algarve, Portugal. Continental Shelf Research, 26: 1077-1091

6 Marques F M S F, 2003. Landslide activity in Upper Paleozoic shale sea cliffs: a case study along the western coast of the Algarve (Portugal). Bulletin of Engineering Geology and the Environment, 62 (4): 299-313

7 Marques F M S F, 2006. Rates, patterns and timing of cliff retreat. A case study on the west coast of Portugal. Zeitschrift für Geomorphologie - Supplementbände, 144: 231-257

8 Marques F M S F ,1994. Sea cliff evolution and related hazards in miocene terranes of Algarve (Portugal). 7th. Int. Cong. of the I.A.E.G., 5-9 Sept. 1994, Lisbon. Proc., v. 4, p. 3109-3118 (Balkema, Rotterdam)

9 Marques F M S F, 1997. The sea cliffs of the coast of Algarve. Dynamics, processes and mechanisms. PhD thesis, University of Lisbon (unpublished, in Portuguese) 556 pp.

10 Marques F M S F, 2006. A simple method for the measurement of cliff retreat from aerial photographs. Zeitschrift für Geomorphologie - Supplementbände, 144: 39-59

11 McCurdy P G, L A Woodward, J I Davidson, R M Wilson & R E Ask (Editors), 1944. Manual of Photogrammetry, Preliminary Edition, American Society of Photogrammetry (Pitman Publishing Corporation)

12 Baeschlin C F & M Zeller, 1936. Traité de Stereophotogrammétrie (Imprimérie Berger-Levrault)