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Continental Shelf Research 26 (2006) 1077–1091

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Slope mass movements on rocky sea-cliffs: A power-law distributed natural hazard on the Barlavento Coast, Algarve, Portugal

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Available online 15 May 2006

Abstract

The coast of the Central Algarve, Portugal, is dominated by sea-cliffs, cut on Miocene calcarenites; here, the main coastal geologic hazards result from the conflict between human occupation and sea-cliff recession. The evolution of this rocky coast occurs through an intermittent and discontinuous series of slope mass movements, along a 46 km cliff front. For the last 30 years, the increase of tourism occupation has amplified the risks to both people and buildings. In the last decade we have seen several accidents caused by cliff failure, which killed or wounded people and destroyed several buildings. The definition of buffer zones limited by hazard lines parallel to the cliff edge, where land use is restricted, is a widely used and effective preventive measure for mitigating risk.

Rocky coasts typically show a slow cliff evolution. The process of gathering statistically significant field inventories of mass movements is, thus, very long. Although mass movement catalogues provide fundamental information on sea cliff evolution patterns and are an outstanding tool in hazard assessment, published data sets are still rare. In this work, we use two inventories of mass movement width, recorded on sea cliffs cut on Miocene calcarenites: a nine year long continuous field inventory (1995–2004) with 140 recorded events, and a 44 year long catalogue based on comparative analysis of aerial photographs (1947–1991), that includes 177 events. The cumulative frequency-width distributions of both data sets fit, above a critical width value corresponding to the threshold of full completeness of the inventories, to power-law distributions. The knowledge of the limits of the catalogues enabled the construction of a 53 year long record inventory over the range of mean width $\geqslant 3$ m ($n = 167$ events) and maximum width $\geqslant 4$ m ($n = 155$ events). The data assembled corresponds to a partial series and was converted to a return period-size distribution. Both return period-width distributions (mean width and maximum width) are also power-law distributions. Equations of return period-width distributions give the width of hazard lines corresponding to the width of mass movement, in which return period equals the period that hazard line is referred to.

Keywords: Coastal erosion; Rocky sea cliffs; Inventories; Power-law; Hazards; Return period; Algarve; Portugal

1. Introduction

Coastal erosion is one of the main coastal geologic risks that result from the inevitable conflict between human occupation and shoreline retreat.

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doi:10.1016/j.csr.2005.12.013

On cliffed coasts, the recession of shoreline progresses by intermittent and discontinuous series of slope mass movements, generally concentrated during phases of strong wave attack or heavy rain (Sunamura, 1992; Bird, 2000). Other mass wasting processes such as abrasion, dissolution, weathering or bioerosion, may play a role in cliff recession (Trudgill, 1985; Trenhaile, 1987; Sunamura, 1992, Bird, 2000), but have no significance in hazard genesis as they act at a microscopic to crystalline scale.

Slope mass movements on steep cliffs are instantaneous phenomena with virtually no warning. The speed of onset of a mass movement hazard is similar to the speed of onset of an earthquake (OAS, 1991); after the onset, there is virtually nothing that can be done to minimize the damages. Occasionally, preliminary warnings such as cracking noise, falling of stones or snapping of roots (Bird, 1990) can provide precious seconds or a few minutes for people to run away from the cliff. On June 1997, the fall of small blocks turned out to be the vital warning for 30 people who were dining in a beach restaurant built on the cliff toe in a beach near Lagos (Fig. 1), preceding an almost instantaneous large slope mass movement (volume $3 \times 10^4\,m^3$). Nobody was killed nor injured, but the restaurant was completely covered by the fallen debris. A single cliff failure can mobilize a wide range of volumes, up to millions of cubic meters and is a potential menace both to the cliff top buildings, and to the people standing on beaches deposited at the cliff base or to the ships that sail near the coast. Very large slope mass movements can also generate local earthquakes and tsunamis (Bolt, 2004) inducing damages that fall beyond the restricted area of the cliff collapse. Rodrigues (2002) reported a large slide on Madeira Island in a 400 m height sea cliff that produced a tsunami with a height of 8 m killing 19 people on a beach 500 m away from the cliff collapse.

Situated in the South Western limit of Europe, the Barlavento Coast, Algarve, Portugal (Fig. 1), is an important beach tourism destination. In the last 25 years the number of visitors has grown steadily and is presently higher than two million tourists a year (INE, 2002). The increase of tourism leads to intensification of urban areas in a narrow belt near the seacoast, besides the natural increase of beach occupation. About 50% of the visitors stay and bathe in the coastal zone consisting by sea cliffs cut on Miocene calcarenites. The increase of the occupation increases coastal risks, hence increasing the risks both to people and property. Over the last ten years, there has been record of several accidents caused by the collapse of sea cliffs cut on Miocene rocks. On 22 March 1998, a man was killed while fishing at the cliff edge, when a sudden rock fall dragged him down together with $2 \times 10^4\,m^3$ of falling material; on 7 October 2000, three tourists were injured by fallen material from the cliff face. Four houses on the cliff top suffered partial damages as a consequence of cliff collapse, and the debris of slope mass movements destroyed a beach restaurant and several beach facilities. Awareness of increasing risks has led regional

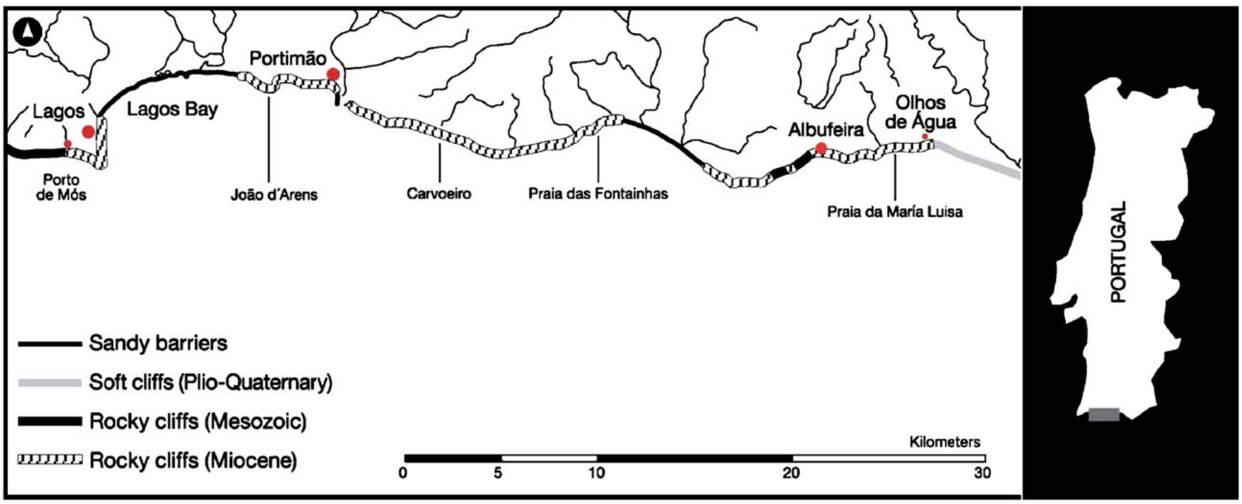

Fig. 1. Location of study area.

coastal authority (Algarve's Coordination Commission of Regional Development—CCDRA) to implement a systematic observation plan of slope mass movements on sea cliffs, which has been in place since 1995 (Teixeira, 2003) and produces a permanently updated inventory.

In this paper we present the results of slope mass movements width inventories gathered from rocky sea-cliffs. We assess the level of completeness of the inventories and show that the size-frequency distribution of mass movements fits to a power-law (fractal). Based on return period-mass movement width distributions, we propose a probabilistic power-law solution to define the width of hazard lines on the cliff top of rocky coasts prone to slope mass movements.

2. Hazard lines on rocky sea-cliffs

Prevention is the most reasonable and economical measure of decreasing the risks associated with sea-cliff failure. One of the paths to achieve this goal is the creation of hazard zones on the cliff top where land use is restricted or forbidden in order to prevent conflicts between coastal erosion and human occupation, and to avoid fatalities and property damage (Carter, 1988; NCR, 1990; Komar et al., 1999, Heinz Center, 2000; Lee and Clark, 2002). Hazard zones, limited by hazard lines, correspond to areas parallel to the shoreline where, in a pre-defined period, it is likely that effects of coastal erosion will be felt. The definition of erosion hazard lines is closely related to shoreline change, when one considers a period up to 50–100 years, which is the range of economic life expectancy for a building structure. Due to the extreme variety in coastal morphology and oceanographic conditions, no single and unique method can be defined to predict shoreline changes (NCR, 1990), and thus no single method can be applied to define erosion hazard lines on cliffed coasts.

Definition of erosion hazard lines must rely on the probable evolution of any sea cliff within the next 100 years. In defining erosion hazard lines on sea-cliffs, two related parameters have to be considered: erosion rate (E_r)—the average value of recession over a period of time -and the sea cliff life period (T_c)—the time interval between the occurrence of consecutive falls in the same cliff face, following the sequence: fall, removing of the debris cone, degradation, undermining and repetition of fall. As magnitude of erosion on sea-cliffs is greatly controlled by lithology (Sunamura, 1983; Budetta et al., 2000) and cohesiveness of cliff material (Sunamura, 1992), long-term rates and life periods of sea-cliffs are primarily dependent of type of cliff material and range over several orders of magnitude. Coasts susceptible to intense erosion such as, for instance, the coast of Krakatau, cut on unconsolidated volcanic ejecta (Bird and Rosengren, 1984), have very high long-term recession rates ($E_r \approx 10^1$ m/year) and a very short life period ($T_c \approx 10^{-1}$ year), meaning that the cliff face is renewed every year. At the opposite extreme, hard rocky coasts, such as granitic (Sunamura, 1992) or dolomitic (Marques, 1998) coasts have extremely low long-term recession rates ($E_r < 10^{-3}$ m/year) and very long life periods ($T_c > 10^3$ years).

The most widely used criteria for prediction of shoreline changes on cliffed coasts and for defining width of erosion hazard lines is based on the value of mean retreat multiplied by number of years that prevention is referred to (see, for instance NCR, 1990, that presents a wide variety of criteria used on the USA, and Hall et al., 2002 and references therein). However by considering only the mean, space and time variation of retreat values are hidden. When predicting long term shoreline changes, spatial deviation from the mean should also be considered. Variance, standard deviation of recession rates, or amplitude of spatial retreat rates (the difference between maximum and minimum retreat rates) are convenient statistics that can be used (Lee and Clark, 2002; Johnsson, 2005). Arguing that coastal erosion is a stochastic process rather than a deterministic one, Lee et al. (2001, 2002) and Hall et al. (2002) proposed a different kind of approach on soft cliffs, stating that recession should be addressed as a sum of single events, with a probability function, rather than a continuous process. They developed a probabilistic model to simulate episodic costal cliff recession where effects of changes in oceanographic conditions and extreme events, such as storm severity can be predicted. Their model fits well with historical data from soft cliffs cut on London Clay with mean recession rates of 0.3–1.1 m/yr, where renewing of cliff face is frequent.

On rocky coasts, recession rates have no practical use for defining hazard lines. In very resistant cliffs, irregularity of coastal retreat is extreme and life periods of sea cliffs ($T_c > 10^2$ year) are much longer than the century hazard line period. Hazard assessment must therefore rely on the size and frequency of single mass movements. Published criteria for defining hazard lines on rocky coasts based on inventories are very scarce. Available data shows that there is usage of two basic criteria. The first is based on single ratios between cliff height and width of hazard lines, expressed either as an angle or its tangent value. NCR (1990) describes, for the USA, sea cliffs hazard lines on the cliff top drawn as the intersection of a plane inclined at a 20° angle (1:2.75) from the horizontal passing trough the cliff toe. On Hawke's Bay, in New Zealand, Reinen-Hamill and Reynolds (2004) defined the width of cliff erosion zones as twice the cliff height measured from its toe, which means an assumed slope of 26.5° (1:2). The other criterion used on rocky coasts is a rational one and is based on historical record, widely used for flood hazards (Chow et al., 1988). It assumes that the width of hazard lines is equal to the maximum, mean or modal width of mass movements ever recorded. This type of solution was adopted in the Coastal Management Plan of Barlavento Coast where exhaustive study of sea cliff mass movements of Marques (1997) allowed the definition of reliable hazard lines based on the size of recorded mass movements over a 44 year period.

Slow evolution of rocky coasts requires long periods of data collection of mass movements, in order to obtain a representative, statistically significant inventory. Such inventories are very rare and so is experimental data. As the period of inventories is much shorter than cliff life period, it is highly improbable that there will be local field data that will include a complete cycle of sea cliff face evolution. Approaches to prevision of sea-cliff activity and forecast related hazards on rocky coasts are, therefore, conditioned to the available inherently short historical record. However, inventories can provide significant information about patterns and size-frequency distribution of single mass movements that can be used in the prediction of sea-cliff evolution.

3. Study area

The south coast of the Algarve, Portugal, located at South Western end of Europe, has a typical Mediterranean climate with hot dry summers and mild rainy winters. Average annual precipitation is 500–600 mm, 80% of which is concentrated in a wet season (October–March). Wave regime is moderate with mean annual significant height of 1 m and 85% of sea storms ($H_s \geqslant 2.5$ m) occur in the wet season (Fig. 2). Tide is semi-diurnal; mean tidal range is 2 m and spring-tide range is 3 m.

The Barlavento Coast is a rocky coast dominated by a continuous front of subvertical sea-cliffs cut in carbonate Mesozoic and Miocene rocks, interrupted by three depositional sectors, corresponding to sand barriers that enclose Holocene coastal lagoons in different infilling stages. The study area is the cliffed coast, between Porto de Mós beach and Olhos de Água beach (Fig. 1), cut in Miocene rocks, included in the Lagos-Portimão Formation (Cachão et al., 1998). Sea cliffs are composed of alternate decimetric layers of fine grained calcarenites and calcarenites with high content of macrofossils (Manupella, 1992). Carbonate content is 60–75% in fine-grained calcarenites and greater than 80% in fossiliferous calcarenites (Marques, 1997).

The total length of sea cliffs cut in Miocene was measured by Marques (1997) using detailed topographic maps (scale 1:5000 and 1:2000) and he calculated a value of 46 km. Cliff height varies from 5 to 40 m and displays a sequence of strata, horizontal or gently sloping to the South or Southeast except in the vicinity of major tectonic features of the area (the Portimão fault and Albufeira diapir; Terrinha, 1998) where the slope is greater (10–20°). A deep and well-developed karst affects the Miocene sequence, covered by Plio-Quaternary (Manupella, 1992) reddish silty-clayed sands. The expression and thickness of the reddish sands varies alongshore; in some sectors it is confined to infilling of karst depressions, in other sectors it constitutes an important part of the cliff face. In the latter case the cliff profile is composed of a lower vertical scarp cut into the sequence of

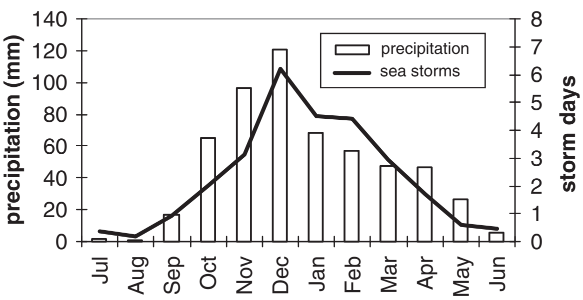

Fig. 2. Average monthly distribution (1976–2004) of precipitation at Lagos meteorological station and sea storms ($H_s \geqslant 2.5$ m) for the southern coast of Algarve. Based on INAG (2004) and the daily forecasts released by National Meteorological Institute (IM).

Miocene calcarenites and an upper sloped segment in Plio-Quaternary reddish sands (Fig. 3c).

The spatial variety of discontinuities either structural (bedding, joints and fissures) or karsic (caves, sinkholes, etc.) subjected to wave attack produces an extremely irregular and lacework cliff line, which attracts Algarve's tourists. A wide variety of morphological features of coastal erosion on rocky coasts are present, namely caves (Fig. 3b), arches and stacks (Fig. 3a,d). The irregular shape of the coast promotes the formation of dozens of small pocket beaches (Fig. 3a,b), with lengths of tens to hundred meters, and a thin sand cover about 2–4 m thick, accumulated over intertidal cut shore platforms (Fig. 3c).

Quantitative studies of the evolution of the sea cliffs on Barlavento Coast are recent. The assessment of cliff retreat rates in Miocene calcarenites was first performed by Marques (1994) based on identification and measurements of slope mass movements by comparative analysis of aerial photographs covering the period interval between 1947 and 1983. The same methodology was extended to the 1947–1991 period by the same author (Marques, 1997), identifying about 200 mass movements on a 44 year period, which affected 8% of sea front, thus permitting the evaluation of a mean period of cliff cycle of 500–600 years. This inventory is however under-sampled for mass movements with width narrower than 2–3 m, which is the detection limit of a skilled researcher in measuring local retreats using 1:30,000-scale aerial photographs (Marques, 1998, 2003). The maximum local retreat measured by Marques (1997) in sea-cliffs cut on Miocene was 45 m, in an arch collapse that occurred between 1974 and 1980. The recession rate based on values of lost area of mass movements in the 1947–1991 period is 1–2 cm/yr (Marques, 1997). Based on a seven year (1995–2002) continuous inventory of mass movements on Miocene cliffs, Teixeira (2003) calculated a mean recession rate of 1 cm/year. Observing submarine segments of cliffs on several plunging cliffs and stacks, Teixeira et al. (2004) found systematic notches, evidencing

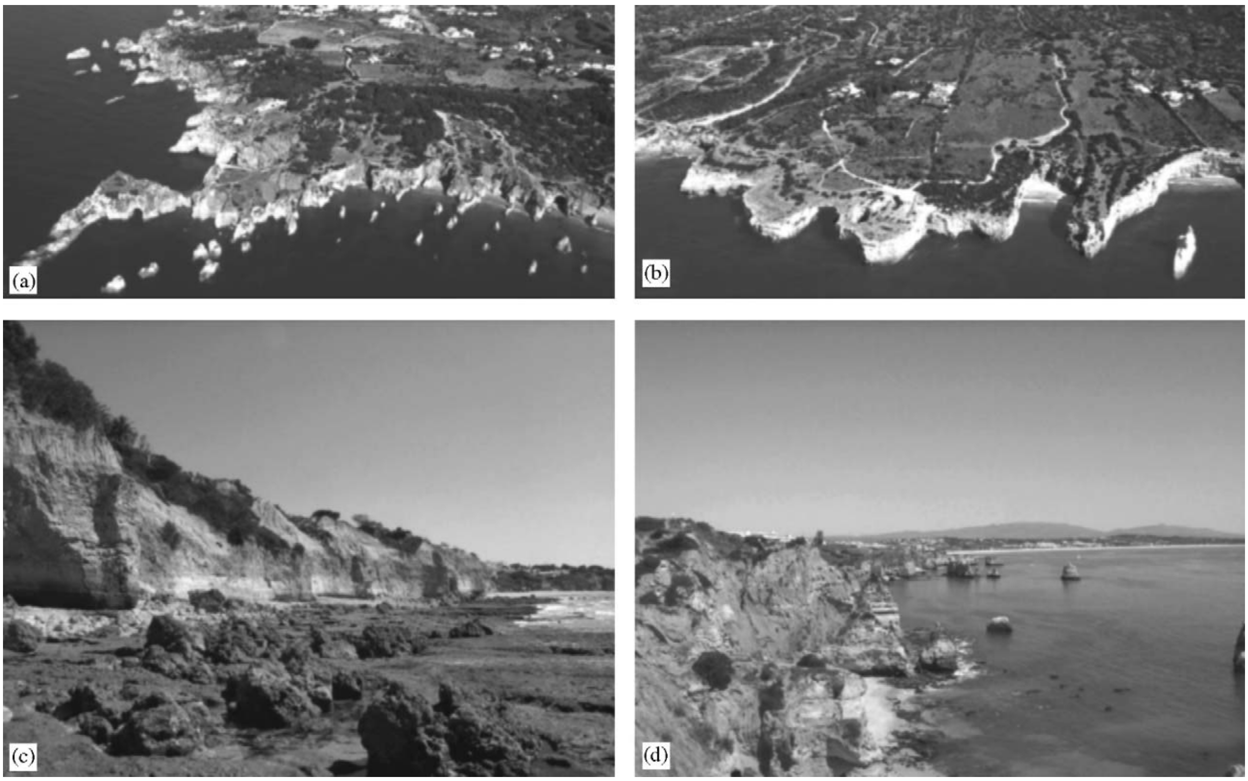

Fig. 3. Photographs of sea cliffs cut on Miocene calcarenites. (a) Oblique aerial view of João d'Arens headland, where stacks are abundant; photo R. Cunha, October 2002; (b) Close oblique photograph looking north of Fontaínhas beach, a small pocket beach confined into resistant headlands; photo R. Cunha, October 2002; (c) Maria Luísa beach, looking east, March 2004 at low neap tide; and (d) Lagos Bay looking north, in April 2004.

absence of local retreat for the last five millennia, since sea-level reached the present level (Teixeira, 2004). The systematic presence of submarine notches on stacks and promontories was interpreted as evidence that those conspicuous points are the remains of the sea cliff front, when mean sea-level stood below present level. Measuring the distance between the line defined by stacks and promontories and the present coastline, Teixeira et al. (2004) concluded that range of millennium recession rates of sea cliffs cut on Miocene rocks was 0–3 cm/yr, and maximum retreat did not exceed 300 m, in the last five millenia.

4. Methods

The regional coastal authority of Algarve (CCDRA) has been conducting a continuous observation plan since 1995, which includes the systematic recording of slope mass movements occurring on the front of rocky sea cliffs cut on Miocene calcarenites. The main source of information (80% of the recorded slope mass movements) was the reporting of occurrences by other public regional or local field authority staff, as well as by the tourism operators and fishermen who maintain a permanent observation of the coastal fringe. The network of observers proved to be very effective on reporting the mass movement events, since in about two thirds of the records, the exact day of the event is actually known.

As a complement to these hundreds of observers, a periodical observation of cliff by land and sea is conducted several times a year. The natural strong yellow colour of Miocene lithotypes, make the identification of recent mass movements easy for any sharp observer. Fresh scars on the sea cliff face, detritus cones with fine sediment content, and a yellow plume in the water, resulting from washing out of the debris, provide the most obvious signs of a recent mass movement. Periodical observation of the sea cliff front enabled the identification of a considerable amount of unreported slope mass movements (20% of the field data set). For about 85% of the records the exact month of occurrence is known. The maximum temporal uncertainty of the date of any slope mass movement is a trimester.

After each report of an occurrence or during the periodical field observation, a characterization of mass movement type and geometry (Fig. 4) was performed in situ, measuring mass movement mean and maximum linear parameters (length, height, width), directly on the cliff scar. The horizontal area of loss was computed as the product of mean length and mean width, and the volume of the mass movement was calculated as the product of horizontal area and mean mass movement height. The volume of the fresh debris produced by the mass movement provided a supplementary control of the evaluation of dimensional parameters. We found a valuable resource for the reconstitution of conditions pre-collapses on a wide variety of post cards available for the last three decades, covering different angles of the seacoast (Fig. 5a,b). Close oblique aerial photographs of partial segments of the coast taken in 1996, 1998 and 2002, as well as photographs of the cliffs taken from a boat, taken in 1996, and 2001–2004, provided useful control images of the sea front.

In this field inventory (I_f), mass movements were classified onto four types, according to the generic mass movements proposed by Sunamura

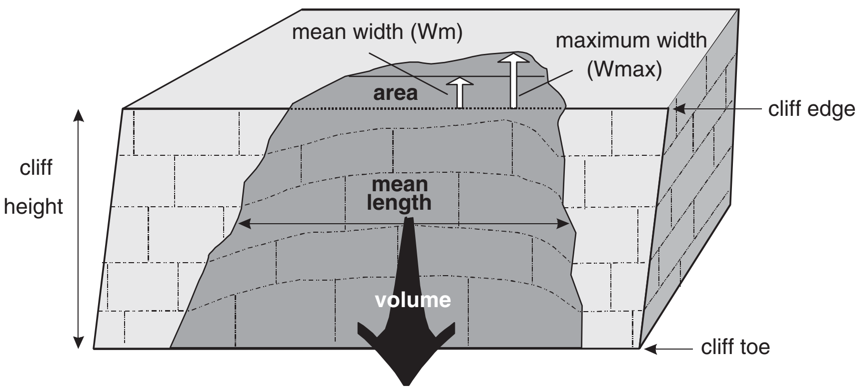

Fig. 4. Dimensional parameters of slope mass movement.

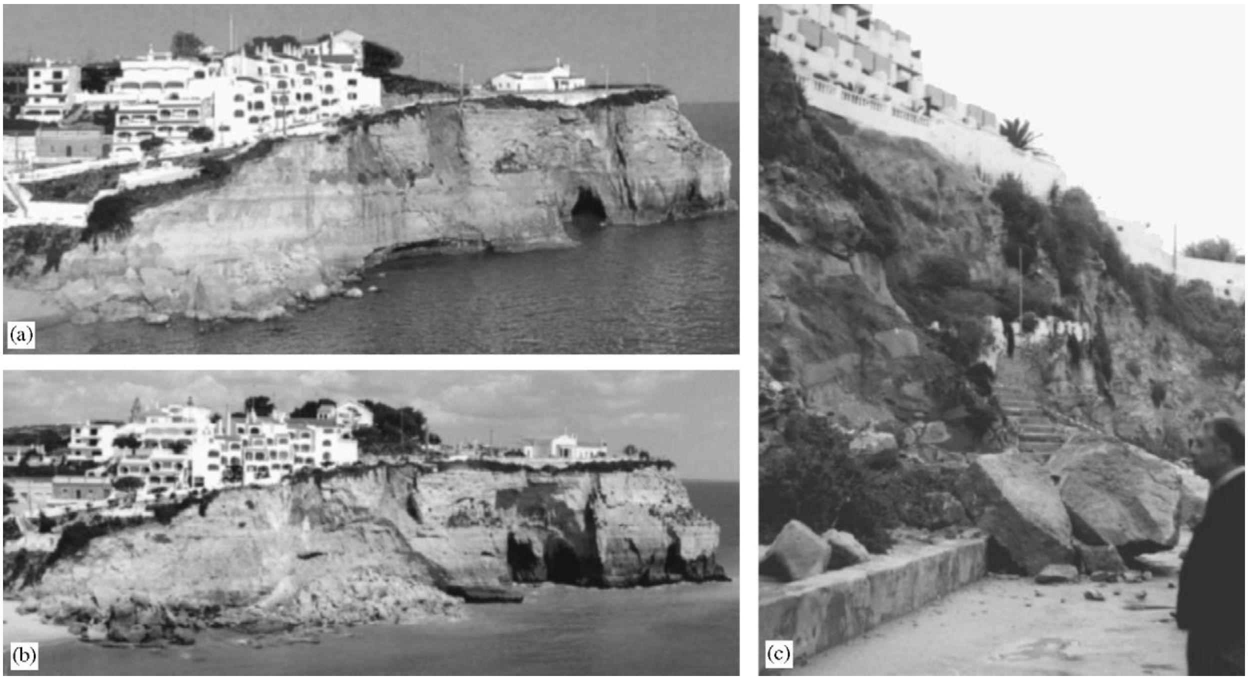

Fig. 5. (a,b) Rock fall at Praia do Carvoeiro, occurred in the 4th April 1998, with $W_{\mathrm{m}} = 3\,\mathrm{m}$ and $W_{\max} = 4\,\mathrm{m}$. Upper photo by W. Müller in 1991 (Vistal post card); lower photo taken in 5 April 1998, the day after the collapse. On the left side of both photographs in the cliff toe are the residual resistant blocks of a prior mass movement (topple) that occurred in the winter 1989/1990, with a $W_{\mathrm{m}} = 6\,\mathrm{m}$ and $W_{\max} = 10\,\mathrm{m}$, according to Marques (1997). (c) Block fall at Albufeira beach, in 17th January 1996; blocks fell into a sidewalk.

Fig. 6. (a) Roof collapse of a karsic cave in a cliff with 30 m height occurred in 1st April 2002: $W_{\mathrm{m}} = 5\,\mathrm{m}$; $W_{\max} = 8\,\mathrm{m}$. (b) Topple in sea cliff west of Olhos de Água, reported in February 2004.

(1992) and Marques (1997): rock fall (Fig. 5a,b), topples (Fig. 6b), karst collapse (Fig. 6a) and block fall (Fig. 5c).

Incompleteness is inherent to inventories based on individual mass movements (Dussauge-Peisser et al., 2002; Chau et al., 2003; Malamud et al. 2004). Some events may have been unreported whilst others may have been neglected. The smaller the movements, the more they tend to be ignored by observers, being therefore under-sampled. On the other hand, bigger mass movements are always seen and usually disclosed by several observers. Thus, the level of completeness of any data set tends to increase as the magnitude of the mass movement

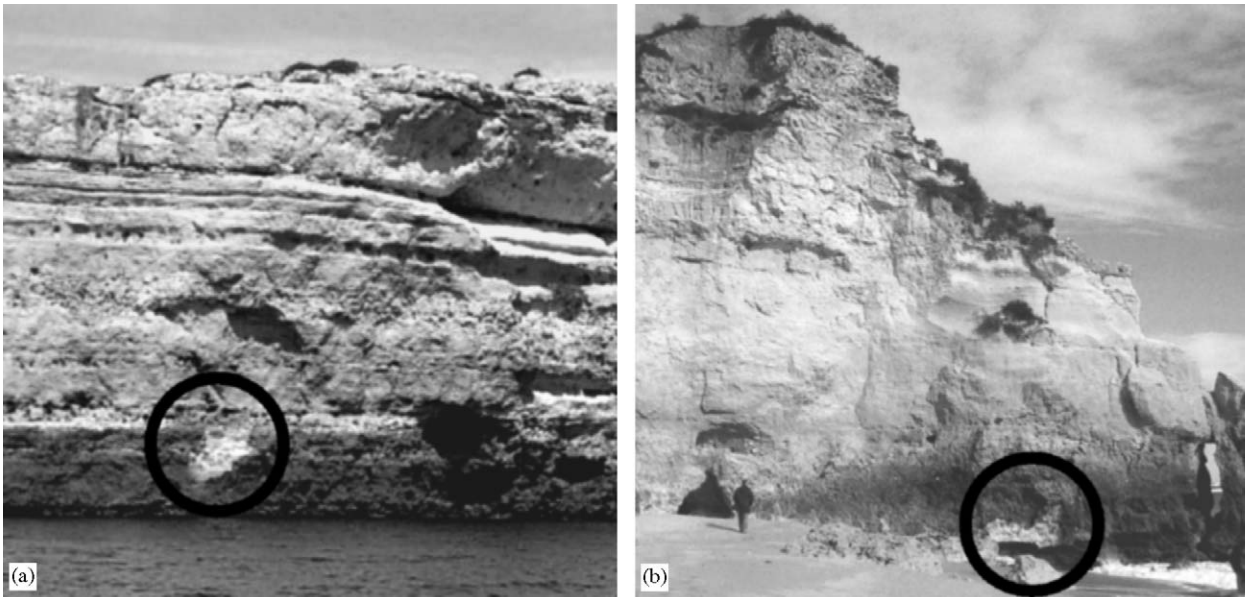

Fig. 7. Examples of recent small mass movements identified in the spray zone. Note the strong colour contrast of the fresh scars. (a) In a plunging cliff, 25 m high; (b) In a pocket beach headland, March 2004.

increases. In order to obtain a statistically reliable data set, the estimate of completeness of any mass movement inventory is crucial.

In order to test the degree of completeness of the recorded field inventory, a specific inventory of small mass movements was gathered in the spray zone, where recent falls will be most visible and more easily recognised due to strong colour contrast between fresh yellow scars and grey-brownish resulting of colonization by lichens and weathering (Fig. 7). The periodic observations of the scars showed that in the spray zone, a period of one year is sufficient to eradicate the freshness of scars, through rapid colonization by supratidal biota. Recent mass movements (occurring within a period $\leqslant 1$ year) are therefore easily identified. This inventory (I_s) is based on the counting of fresh scars of small slabs with mean width within the range 0.1–0.5 m in the spray zone, either by analysis of close photographs or directly in situ, in several sectors of the sea cliff front.

5. Results

Between July 1995 and June 2004, covering a nine years time span, 140 mass movements of sea cliffs, involving mobilization of Miocene calcarenites have been recorded and measured, spatially dispersed along the sea cliff front, which constitutes the field inventory (I_f). Rock fall were the dominant movement (64%). Topples (9%), block fall (14%) and karst collapse (13%) have approximately the same importance. During the study period one stack was destroyed and two new ones were formed.

A total of 835 m of the sea cliff front (1.8% of the total length) was altered by slope mass movements, during the nine year period of observation. The average value of the renewal of the cliff front of 0.2%/year gives an estimate for the mean life period of this cliffs of 500 years. The average loss of horizontal area was 410 m^2/year, the mean annual volume was 9760 m^3, and the average recession rate was 0.9 cm/year, which are values similar to previous estimates obtained by Marques (1997) and Teixeira (2003).

The equations that relate dimensional parameters of the recorded series of 140 events are listed in Table 1 and reveal, as expected, a strong correlation and a systematic power law best fit. It is noticeable that the maximum width is 40% bigger than the mean width. The relation between volume and area is similar to the relation found in other slope mass movements, such as rockfall (Chau et al., 2003; Hergarten, 2004) or landslides (Malamud et al., 2004), with an exponent of 1.5, suggesting a geometrical affinity between mass movements on sea cliffs and terrestrial mass movements.

The inventory of the small mass movements (mean width between 0.1 and 0.5 m), identified on the spray zone (I_s), provided a mean weighed frequency of about 100 small mass movements/year (Table 2). The 140 recorded events inventory (I_f) had a frequency of 16 movements/year, which is significantly higher than the aerial photographs inventory (I_p) of Marques (1997), with a frequency of 4 movements/year.

In terms of defining hazard lines, a linear parameter measured normal to cliff edge (the mass movement width) is the one that better relates to instantaneous retreat and therefore can be used as a convenient parameter of width of hazard zones. Fig. 8 gives the histograms of the available inventories of mass movement width reported on sea cliffs cut on Miocene calcarenites: the present inventory gathered through field observation (140 events; 1995–2004) and the inventory collected by Marques (1997) based on comparative analysis of aerial photographs (177 events; 1947–1991), with an apparent difference of distribution. Data from Marques (1997) seem to show a normal distribution whilst the distribution of field data sets show a magnitude decay pattern, i.e. the wider the mass movements are, the less frequent they are.

Table 1
relations between dimensional parameters

Equations	r^2
$V = 2.07A^{1.52}$	0.94
$V = 15W_{\mathrm{m}}^{2.57}$	0.77
$V = 6.4W_{\mathrm{max}}^{2.62}$	0.82
$A = 3.68W_{\mathrm{m}}^{1.74}$	0.86
$A = 2.09W_{\mathrm{max}}^{1.75}$	0.89
$W_{\mathrm{max}} = 1.38W_{\mathrm{m}}^{1.00}$	0.97

V—volume (m^3); A—Area (m^2); W_{m}—mean width (m); W_{max}—maximum width (m).

6. Discussion

Published data sets of frequency size associated with slope mass movements in rocky sea cliffs are very rare. The statistics of inventories gathered on purely terrestrial slope mass movements can, nevertheless, provide a reasonable approach. There is a considerable variety of slope mass movements types (Varnes, 1978; Ayala-Carcedo, 2002) but available inventories tend to consider two major types: (1) the landslide, associated with soil slope failure and, (2) the rock fall, associated with steep rocky areas (Malamud et al., 2004). This distinction presents clear affinities with the sea cliffs types, respectively, the earth or soft cliffs, and the rocky sea cliffs.

Although the number of inventories is still small, a series of recent papers (Guzzetti et al., 2002, Hergarten, 2004; Guthrie and Evans, 2004; Malamud et al., 2004; and references therein) show accumulating evidence that frequency-area or

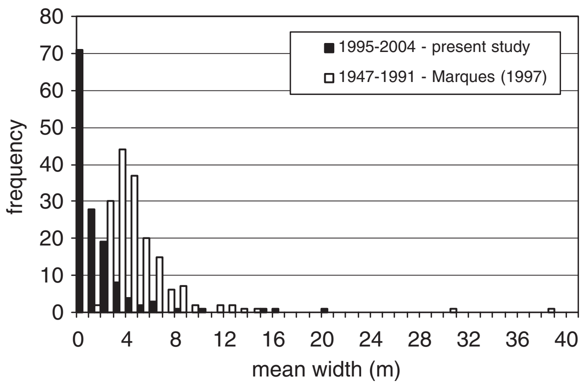

Fig. 8. Histograms of slope mass movements mean width of the available inventories.

Table 2
small mass movements frequency

Date of data collection	Source	Length of cliffs (km)	% Total cliff front (1)	Frequency (2)	Weighted frequency (3) = 2/1
4 Apr 1996	Photographs	9	20%	26	133
23 Apr 2002	Photographs	4	9%	5	58
24 Oct 2003	*In situ* observations	18	39%	54	138
28 May 2004	*In situ* observations	31	67%	43	64
Average					98

frequency-volume statistics of medium to large slope mass movements satisfy power-laws (fractal); frequency-area and frequency-volume distribution decays as an inverse power of affected area or displaced volume. Large inventories of mass movements analysed and discussed by Malamud et al. (2004) and Guzzetti et al. (2004) suggests that if small landslides are included in inventories, the frequency-area statistics show a tendency of best fit to a log-normal distribution, or a gamma distribution. In the case of inventories of rock fall the best fit distribution is still a power-law (Dussauge-Peisser et al., 2002; Chau et al., 2003), independently of the size of mass movements. If the affinity between terrestrial slope mass movements and sea cliff slope movements extends to frequency-size distributions, then one should expect that rocky sea-cliffs, such as those on the Barlavento Coast, would have power-law (fractal) frequency-size distributions, and soft cliffs would have log-normal and power-law tailed frequency-size distributions. Experimental data obtained in wave basin tests conducted by Damgaard and Peet (1999), on cliffs cut on damp sand, show that distribution of the width of slope mass movements present a best fit to a log-normal distribution.

6.1. Limits of mass movement inventories

The cumulative frequency distribution for mass movement width for both inventories, I_f and I_p, (Fig. 9), show a power-law adjustment for large mass movements, and an increasing deviation from general tendency below a critical width. The evaluation of the value of this critical point was done by means of successive linear regressions. In each step the smaller value for the previous series was removed and a best-fit equation was calculated as well as a corresponding correlation coefficient (r^2).

The highest correlation coefficient was obtained for the equation where the smallest values are $W_m = 1$ m for the field inventory and $W_m = 3$ m for the aerial photograph inventory. This critical value is interpreted as the limit value for a full level of completeness of inventories. Thus, it is assumed that any mass movement larger than $W_m = 1$ m is likely to have been recorded in the 9 year data set (I_f), and the complete series of that inventory includes 69 single events. The complete series of the inventory of mass movements collected by Marques (1997) include 166 events whilst the value of $W_m = 3$ m is

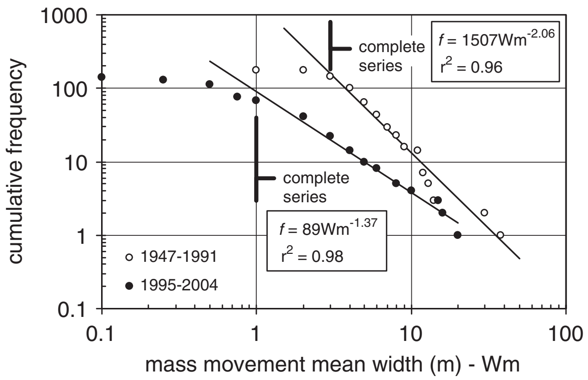

Fig. 9. Cumulative frequency-mean width relationship. The best fit equations included have the highest correlation coefficient, obtained by successive linear regressions. The limit of full completeness of the inventories correspond to $W_m = 1$ m, for the field inventory (1995–2004) and $W_m = 3$ m for the inventory based on comparative analysis of aerial photographs (1947–1991) performed by Marques (1997).

the limit of full completeness of his catalogue, consistent with the value of 2–3 m assumed by Marques (2003).

If the best fit power-law equation for mean width ($f = 89\,W_m^{-1.37}$) for the field inventory is extrapolated for smaller mass movements, i.e. if we assume a fractal or self-similar property (Mondelbrot, 1983; Turcotte, 1997), it is expected that an annual average frequency of 16 events with mean width between 0.5 and 1 m should have been reported in the study area, and 200 events with W_m within the range 0.1–0.5 m could have occurred, and so on. The mean annual frequency of 100 events provided by the small slabs inventory of the spray zone (I_s) shows that both the 140 recorded event inventory (I_f) and the aerial photograph inventory (I_p, $n = 177$ events) are incomplete for small mass movements and suggest that the self-similarity distribution extends for dimensional orders below the limits of the available inventories.

The procedure for assessment of the limit of full completeness of both inventories was extended to the maximum width parameter of mass movements and gives similar results (Fig. 10). The field inventory is complete for a maximum width equal or greater than 2 m and the inventory of Marques (1997) is complete, above the value $W_{max} = 4$ m.

The physical reason as to why the width-frequency of slope mass movements satisfy the power-law is uncertain, since it depends on the complex relation between the internal characteristics of the rock masses and the slope mass

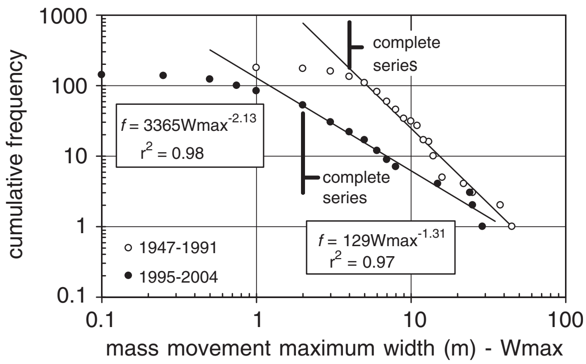

Fig. 10. Cumulative frequency-maximum width relationship.

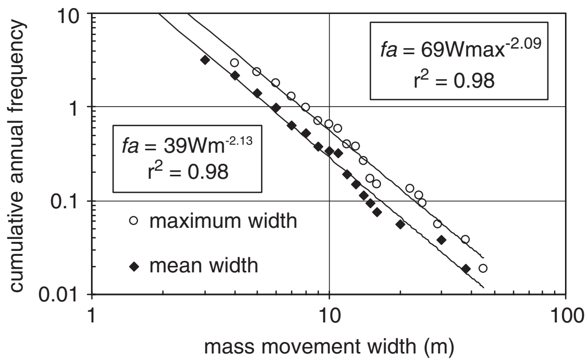

Fig. 11. Cumulative frequency-width relationship for the assembled inventories normalised for an annual frequency. Mean width series has 167 events with $W_m \geqslant 3$ m and maximum width series has 155 events with $W_{max} \geqslant 4$ m.

movements triggers. The best single explanation takes into account the relationship stated by Malamud et al. (2004) between landslide event magnitude and trigger magnitude. Retreat of cliffs or coastal bluffs is greatly dependent on the frequency of wave attack on cliff toe and on the rain intensity (May, 1978; McGreal, 1979; Wilcock et al., 1998; Benumof et al., 2000; Lee and Clark, 2002), which are triggering factors that obey, themselves, power laws. On Miocene cliffs, based on a seven year inventory, Teixeira (2003) found a linear relation between sea cliff mass movements frequency and precipitation intensity or storm frequency, both on an annual and monthly basis. A finer (daily) temporal analysis revealed that 80% of the recorded mass movements can be related to peak activity of precipitation or of sea storms, which occurred in the five day period before cliff collapse and, more commonly, in a three day period. Although the magnitude of these trigger factors increased the frequency of slope mass movement, the three largest recorded mass movements had no direct relation with the occurrence of sea storms or with the intensity of precipitation. This observation suggests that other factors, possibly internal factors, such as patterns of rock fragmentation, and geometry of karsic forms may have also a role in mass movement size distribution, hence further research is needed.

6.2. *Return period of slope mass movements*

The combination of two available inventories for mass movement width (mean and maximum) above the limit of full completeness (using the higher limit of the two inventories), produces a pair of completed inventories covering a 53 year record (44 + 9 years) above the limit value of 3 m for mean width (167 events) and 4 m for maximum width (155 events). Fig. 11 includes the cumulative frequency-size distribution for the resulting assembled inventories, normalised for an annual frequency. The results obtained show an excellent agreement between the inventories, enhancing completion of both methods of collecting data.

The complete inventory (53 years) of mass movement width can be processed as partial series—a series of data selected so that their magnitude is greater than a base value (Summer, 1987; Chow et al., 1988; Turcotte, 1997). On the Barlavento Coast, the base value is the critical value assessed in the analysis of the level of completeness of both inventories ($W_m = 3$ m; $W_{max} = 4$ m).

The complete inventories can be used as a powerful tool in hazard assessment particularly in defining width of hazard zones as a function of mass movement width, which reflects the instantaneous retreat of sea cliffs. Using an identical approach and the same definitions used in hydrologic hazards such as floods or precipitation (Summer, 1987; Chow et al., 1988; Dingman, 2002), a single hazard assessment can be achieved.

Return period (T) or recurrence interval corresponds to the time interval between occurrences of events with magnitude equal or greater than a defined value:

$T(x)$ = period of observation/number of events with magnitude equal or greater than x.

In the case of the complete inventory for mass movement mean width, the return period of events

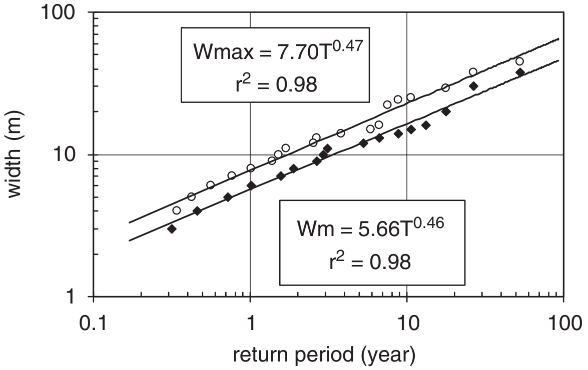

Fig. 12. Return period of slope mass movement width. Mean width series has 167 events with $W_m \geqslant 3$ m and maximum width series has 155 events with $W_{max} \geqslant 4$ m.

with width equal or greater than 3 m equals 53 years/167 events = 0.32 year, while the return period of events with width equal or greater than 10m equals 53 years/18 events = 2.9 years. If we take this single approach into consideration, cumulative frequency-size distribution can be converted to return period-size distribution (Fig. 12). Both return period-width distributions (mean width and maximum width) are power-law as for the cumulative frequency-width given by Fig. 11.

Assuming that the distribution of frequency-width is time stationary, it is possible to extrapolate it to a temporal window of 100 years, longer than the 53 years of observation. The extrapolation for larger periods implies an extension of power-law frequency-size distribution above the range of record events, thus implying the prediction that mass movements bigger than the movements recorded can occur over the interval of a century. Cliff height is a major conditioner in the width of slope mass movements. The relation between maximum width and cliff height for the 140 record mass movements in a 9-year period suggests a threshold for the ratio equal to 1. Maximum ratios are associated with movements related with karsic forms. Marques (1997) series show however that 8% of mass movements exceeded the threshold for mean width and that the value rises to 12% in maximum width series. Marques (1997) identified 4 mass movements (2% of its inventory) in which the maximum width is at least double of cliff height. This result suggests that the maximum width of mass movement can attain values higher than twice the cliff height, so in the Miocene calcarenites, values of up to 80m are realistic and possible.

Table 3
Reference values of return period of the mass movement width

Return period (year)	Hazard line	Mean width (m)	Maximum width (m)
1	H_1	6	8
5	H_5	12	16
10	H_{10}	16	23
25	H_{25}	25	35
50	H_{50}	34	48
100	H_{100}	47	67

6.3. The width of erosion hazard lines

Best fit power law equations of return period-width distributions provide a convenient tool for spatial definition of hazard lines. On cliffed coasts, erosion hazard lines limit areas (erosion hazard areas) parallel to the cliff line (the reference feature being the cliff edge), where in a defined time interval there is a probability of the area being affected by cliff retreat.

The values of mass movement width summarized in Table 3 indicate values for the width of hazard lines for defined periods and are likely to represent the width of hazardous areas for a time interval 1–100 year. Hazard lines should be measured inward from cliff edge and attempt to limit use of coastal areas prone to episodic sea cliff failure. The width of hazard lines corresponds to width of mass movement, in which the return period equals the period that the hazard line is referred to (Table 3). For instance, considering a 10 year hazard, the width of hazard line H_{10} should be at least 16 m, if we adopt the mean width of slope mass movements, or 23 m if a more restrictive criterion is chosen, i.e. if the maximum width series is elected. Using the more restricted criterion increases width of hazard lines by 40%.

This approach is considered to be very conservative, since only a small fraction of the cliff front will be affected by slope mass movements. In the sea-cliffs cut on Miocene calcarenites, with a mean life period of 500 years, we can roughly predict that in a 100 year period, only about 20% of the cliff front will be affected by slope mass movements. We can predict that events will occur but we cannot predict when or where.

By drawing hazard lines parallel to the cliff crest it is assumed that the sea-cliff front is an homogeneous population and that mass movement width is a random variable in space, that is to say that probability of occurrence of any mass movement is the same, independently of its location. This assumption can hardly hold on rocky cliffs where local variations on bedding, jointing, lithology, geomorphology, wave exposure, etc. generate a significant difference in spatial vulnerability to cliff recession. Although taking into consideration that cliff resistance is the major variable for cliffs, and that there is a considerable lithologic homogeneity in Miocene calcarenites, it can be assumed that local variations of other geologic and climatologic factors are minor and reflect the variance of a random variable.

The probabilistic solution presented here is valuable on a development plan scale and can be adjusted for a bigger scale, on partial segments of the cliff front cut on Miocene calcarenites, where mass movement inventories have sufficient number of recorded events. Policies of development hazard lines should take it into consideration and define the acceptable probability, or risk. Assuming a 100 year risk (a probability of exceedence of 1%), the results recommend that a minimum 50 m buffer zone (measured inward from the cliff edge) of non-occupation should be considered for buildings. Softer and short-lived land uses and facilities can be permitted in the buffer zone but require prior field expert judgement.

The hazard lines assessed in the present study relate only to episodic sea cliff failure. Other coastal hazards identified in the study area like hazards associated with karst evolution (Marques, 1997; Forth et al., 1999) were not considered since they are out of scope of this paper.

7. Conclusions

Frequency-size distributions of many natural hazards (earthquakes, river flood, landslides, forest fires) involving episodic events fit to power-law (fractal) distributions (Turcotte, 1997; Hergarten, 2004). Sea cliff retreat is a natural hazard which progresses as a series of discrete and single event mass movements. In this study we show that cumulative frequency-mass movement width distributions also fit to power laws. Two different inventories of slope mass movements recorded in sea cliffs cut on Miocene calcarenites, gathered by different methods, covering different time scales and different range of values show power law frequency-size distributions above a critical value, corresponding to the limit of full completeness of the data catalogues. The results show an excellent agreement between inventories, enhancing the complementary nature of both methods of collecting data.

The cumulative frequency-size distribution of linear parameters (mean width and maximum width) of sea cliff slope mass movements inventories fit to power-law distributions over the range between 1 and 45 m. Partial inventories gathered in the spray zone suggest that fractal self-similarity may extend to smaller mass movements as small as 0.1 m. The assembled width inventories covering 53 years, converted to a return period-width distribution (mean width and maximum width), are also power-law distributions and give a single solution to define width of hazard lines. The width of hazard lines corresponds to the width of mass movement where return period equals the period that hazard line is referred to. The probabilistic method introduced in the present paper can be used as a convenient management tool in rocky coasts where inventories of slope mass movements are available.

Acknowledgements

The author would like to thank Celso Pinto, Fernando Engrácia, António Contreiras, and Luís Paulino for their assistance in fieldwork. Fisherman, beach facilities owners and staff members of local authorities are gratefully acknowledged for their permanent and sharp look at the coast. Fernando Marques and César Andrade are acknowledged for their useful discussions. The author gratefully thanks Vasco Pinhol who critically reviewed the text and an anonymous reviewer for his helpful comments and suggestions that significantly improved the manuscript. Paula Gaspar and Maria Amorim assisted in figure drawing. Part of this work was co-funded by the European Union (Project RISCO- 45.03.16. FDR 00030 ProAlgarve).

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