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Abstract

Time-series bathymetric data acquired between 1991 and 2011 have been used to evaluate the recent morphological evolution of the Nice upper continental slope (SE France, Ligurian Sea). Small-scale landslides lead to a retrogressive evolution of the continental shelf/upper slope transition but their frequency, size and impact are not well known. Mapping was undertaken to identify the morphology of landslide scarps and the location of the shelfbreak. Map comparisons were performed using ArcGIS “raster calculator”. Sediment remobilization on the upper slope (up to depths of 200 m) is fast and significant; landslide scars with volumes greater than 25,000 m³ can appear with a frequency less than 8 years. Shelfbreak migration toward the coastline can reach rates of 60 m over 7–8 years where the continental shelf is over 200 m wide. Furthermore, this quantitative analysis highlights alternations between periods of strongly erosive events and sedimentation periods. On the upper slope, eroded volumes can be multiplied by 10 during periods of enhanced landslide patterns (1999–2006). Such cycle-like landslide activity raises the issue of the triggering processes. On the Nice continental slope thick poorly consolidated beds rapidly deposited on a steep slope, earthquakes and rainfall leading to fresh water circulation below the shelf were identified as potential triggers. Our 4D bathymetric study suggests that over the last 20 years the greatest impacting factor may be freshwater outflows.

Keywords

Ligurian sea • Geohazards • Bathymetry • Continental slope • Geomorphology

42.1 Introduction

Morphological changes, such as erosion of submarine continental slopes, through time are linked to sedimentary processes such as submarine landslides. At a human time-scale, low volume, high frequency landslides are largely predominant. They can be responsible for numerous hazards especially when triggered at shallow water depths. Due to the large number of submarine landslides observed on continental slope bordering the Nice coast (SE France, Ligurian Sea; Migeon et al. 2012), we decided to study the present-day mass-wasting processes remoulding the seafloor. Multibeam sonar technology provides an opportunity to

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assess morphological change on short time scale (5–8 years) and contribute to the understanding of shelf erosion throughout time. This paper presents the result of the repeated bathymetric survey of the Nice shelf/slope limit between 1991 and 2011. We propose an interpretation of the significant morphological changes observed over 20 years to provide insights on possible triggering mechanisms.

42.2 Geological Settings

Our study focused on the narrow continental shelf (~ 100 m from the coastline) and the upper slope, offshore the city of Nice. These settings are affected by a large number of submarine landslides (Migeon et al. 2012). The most recent, mobilizing approximately 8×10^6 m³, initiated during October 1979. It is responsible for the destruction of the new (in 1979) harbour-airport complex of Nice and the triggering of a 2–3 m high local tsunami (Genesseaux et al. 1980; Ioualalen et al. 2010). The Var river, which reaches the coastline just west of the airport, is impacted by a few but violent Mediterranean rainfalls. These precipitations generate floods and groundwater outflows circulating below the airport, emerging on the continental shelf (Stegmann et al. 2011). Moreover, poorly consolidated sediments deposited on steep slopes are affected by moderate seismicity (Courboulex et al. 2007) which may impact their stability.

42.3 Bathymetric Analysis

To better constrain the frequency and volumes of recent slides including their impact in terms of morphological changes, we compared four high-resolution bathymetric maps compiled from datasets acquired in 1991, 1999, 2006 and 2001 with horizontal resolutions of 10, 2, 2 and 1 m, respectively. The surveys were undergone using multibeam technology. The survey dating from 1991 used a Syledis 5 m resolution terrestrial radio positioning system. The following three used a GPS positioning system. The covered zone varies from one survey to another but portions of the dataset are common in an area extending laterally from the Var river estuary to the Paillon Canyon. The map interpretations and comparisons were performed using GIS tools. Individual scarps and shelfbreak location were identified on each bathymetric map. Then, raster comparisons were performed using the subtraction tool of ArcGIS “raster calculator” in order to calculate volume of missing deposits from slope variations through time. The precision of the calculated volumes is relative to the poorest data resolution of the two periods compared as well as the precision of xyz location. Using the coastline, optical map inspection and

excluding depth difference values rang from -2 m to $+2$ m, we assessed and greatly reduced the positioning errors.

42.4 Morphological Evolution of the Shelfbreak Over the Last 20 Years

Comparison of time-series bathymetric maps provided the specific background to locate and to quantify morphological changes over the last 20 years at shallow water depths (0–200 m). Between 1991 and 2011, an alternation between periods of low morphological changes and periods of active landsliding events or deposition/infillings involving significant volumes can be clearly discriminated.

From 1991 to 1999, due to the poor overlap between surveys, only a clear accretion of about $+6.14 \times 10^6$ m³ was detected on an area of 541×10^3 m² mainly corresponding to the 1979 scar (Fig. 42.1a). Particles were deposited on 61.2 % of the area. Erosion by small-scale landslides affected 4 % of the area, mainly on the western side of the 1979 scar.

During the 1999–2006 period, sediment remobilization on the upper slope was significant; 71 landslides with a mean volume of 1.3×10^5 m³ were initiated (Fig. 42.1b), representing a total missing volume of 9.21×10^6 m³ over a 8.3×10^5 m² area (27 % of the total area). Similar small landslides with a return frequency of 1 year or less have been described in other environments like fjords, canyon flanks or upper slope (Hill 2012; Hughes-Clarke et al. 2012; Smith et al. 2007). Our observations show that the open Nice continental slope can also be affected by fast erosional processes. During this period, parts of the shelfbreak migrated toward the coastline following the head of retrogressive scars. The shelf was reduced by 20 m along the 130-m-wide western edge of the airport (Fig. 42.1b). Map comparison can also be used to identify areas where sediment deposition prevailed. Sediment infill smoothed older scar and chute morphologies. Landslide scars representing 15×10^4 m³ of missing deposits were filled-up and disappeared from the sea floor in less than 7 years (zoom Fig. 42.1b). Biscara et al. (2012) made similar observations on the upper Gabon slope and estimated that 15–20 years were necessary to bury scars (17×10^4 m³).

During the 2006–2011 periods, only subtle morphological changes were observed (Fig. 42.1c) indicating that landslide activity significantly decreased (Fig. 42.1c). Compared to the previous period (1999–2006), the remobilized volumes are 10 times smaller. Sediment remobilization mainly corresponds to retrogressive erosion within pre-existing scars. Only one significant new landslide (about 25×10^3 m³) was triggered at 14-m water depth, leading to an instantaneous local landward migration of the

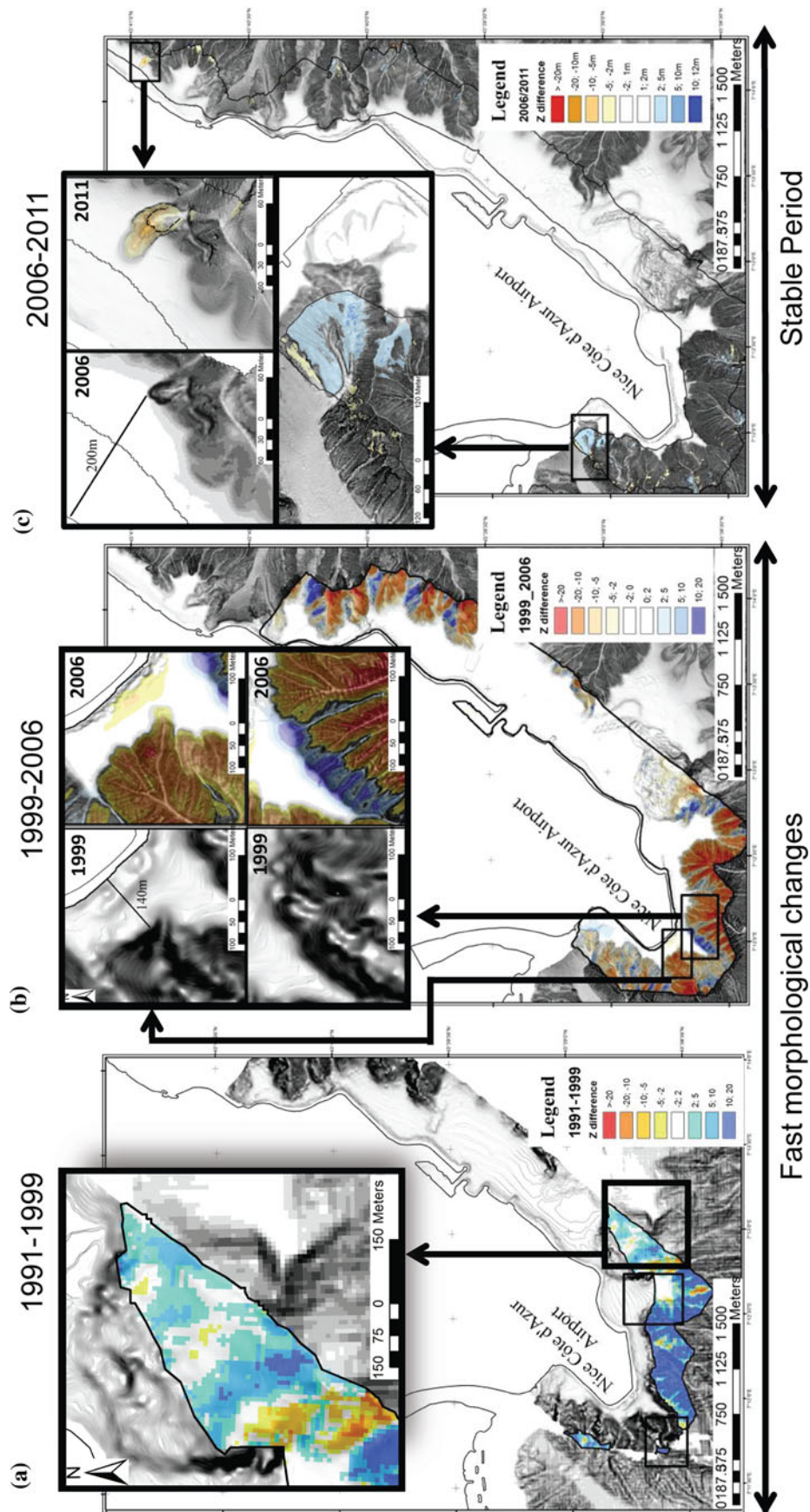
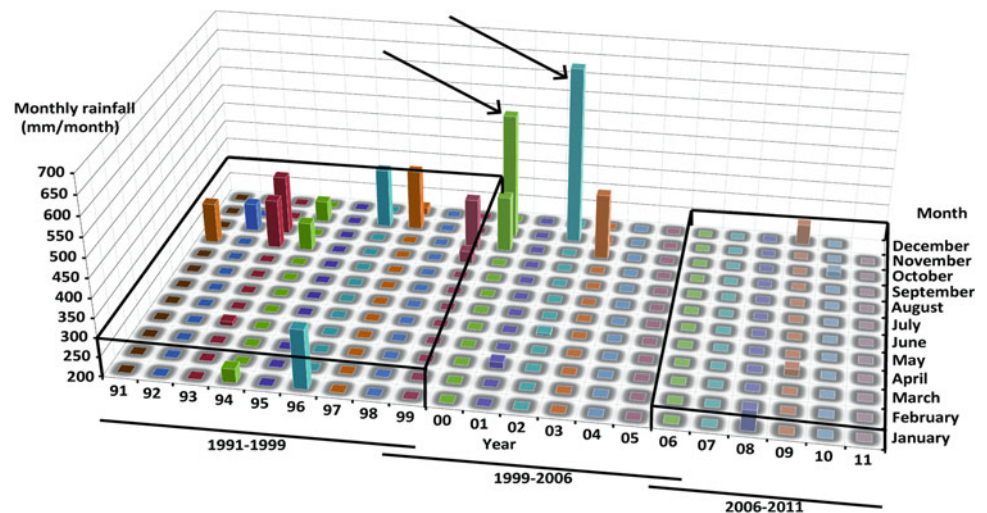


Fig. 42.1 Bathymetric comparisons of the uppermost continental slope; 1991–1999, 1999–2006, 2006–2011. Zoom on erosion/deposition areas; in B&W theoldest map and in colour the erosive area from yellow to red and the deposition area from clear to dark blue

Fig. 42.2 Monthly rainfall events in mm/month, between 1991 and 2011. *Arrows indicate the 2000 and 2002 strongest rainfall events (500 and 650 mm) of the 1999–2006 time period. Between 2006 and 2011, no significant rainfall events were recorded*



shelfbreak of 60 m, where the shelf is 200-m wide. Sediment deposition also decreased and was only identified in front of the Var-river mouth.

42.5 Possible Triggering Mechanisms

The triggering factors responsible for such rapid alternation between periods of high landslide activity and periods of relative quietness over the last 20 years are unclear. The Nice upper slope is prone to landslides due to specific local conditions such as high-sedimentation rates, overloading and critical slope angles, and presence of gas-rich layers (Migeon et al. 2012; Mulder et al. 1994; Sultan et al. 2010) but these potential factors are thought to act over longer time scales and should not be responsible for the observed high-frequency changes. We thus compared the periods of occurrence of the submarine landslides with the intensity and of external processes that are known to affect the study area: fresh-water outflow and earthquakes.

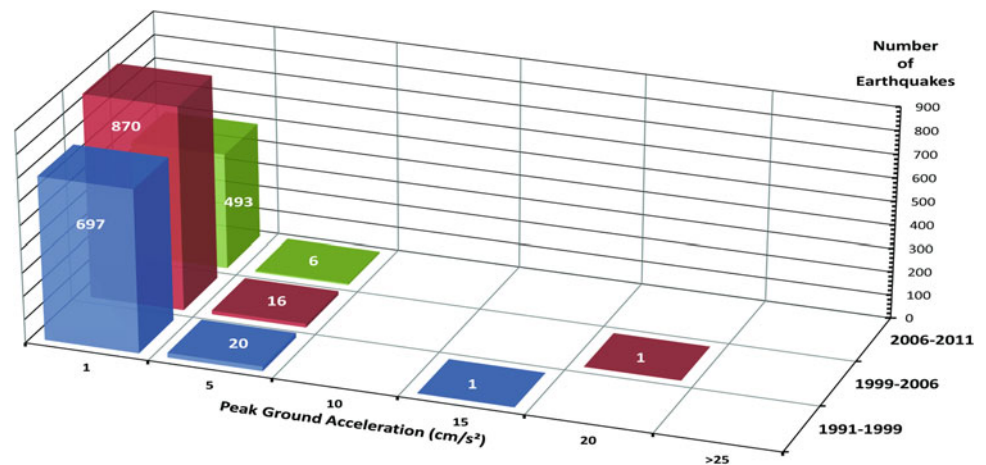
Fresh-water outflow was identified offshore the airport (Dan et al. 2007). Nowadays, the Var-river mouth is constrained by the western edge of the Nice airport. The airport was built above the aquifer of the Var delta that is known to react rapidly with rainfall affecting the Var drainage basin (Stegmann et al. 2011): outflow can generate excess pore pressure of about 10 kPa. To determine a potential relationship between rainfall, fresh-water outflow and the triggering of landslides, we examine the morphological variations identified over the last 20 years together with the monthly rainfall record (>200 mm) on the drainage basin (Fig. 42.2). During the first two periods (1991–1999 and 1999–2006) characterized by an enhanced triggering of landslides and fast

seafloor changes, strong rainfall events occurred once or several times every years. The 2000 and 2002 extreme rainfall episodes of respectively 500 and 650 mm unambiguously induced pore pressure peaks in the aquifer. In contrast, during the latest period (2006–2011), characterized by a reduced landslide activity, little morphological variations and sediment deposition, no rainfall events greater than 250 mm/month were recorded (Fig. 42.2).

Earthquakes are also classically invoked to explain the triggering of submarine landslides (Keefer 2002). Mulder et al. (1994) showed that centennial earthquakes with a Peak Ground Acceleration $PGA = 98 \text{ cm/s}^2$ can trigger submarine landslides on the Nice continental shelf. Between 1991 and 2011, the study area and the surrounding 100 km were only affected by moderate-magnitude earthquakes ($M_w \leq 3-5$). Their location and magnitude (BCSF database www.franceseisme.fr) were used in the Akkar and Bommer (2010) Ground Motion Prediction Equations models (GMPEs) to estimate the ground motions expected in the studied area.

The maximal PGA value offshore the Nice airport is estimated to be 17 cm/s^2 (Fig. 42.3) and most of the earthquakes generated PGA values lower than 5 cm/s^2 . Such values are likely too small to affect the slope stability (Keefer 2002; Mulder et al. 1994). Nevertheless the two periods of enhanced landslide triggering (1991–1999 and 1999–2006) correlate with the highest number of earthquakes and the highest estimated ground motion values. The underlying mechanism remains unclear, perhaps low-amplitude but high-frequency earthquake-related ground motion can modify slope stability and induce sediment weakening. What are the minimal ground motions parameters (PGA, PGV, PGD, duration of shaking) necessary to trigger small-size submarine landslide?

Fig. 42.3 Number of earthquakes ordered by their PGA ranges (cm/s^2) that occurred during the last 20 years. The 1991–1999 and 1999–2006 intervals underwent higher numbers of earthquakes with higher peak-ground accelerations than the 2006–2011 periods



42.6 Conclusion

Analysis of 4D bathymetric data from the Nice continental shelf reveals large variations in landslide frequency over short time periods (less than 7–8 years). Periods of enhanced landsliding can increase erosion rates by a factor of 10. Only a few previous studies (Biscara et al. 2012; Hill 2012; Hughes-Clarke et al. 2012; Smith et al. 2007) discussed the high-frequency occurrence (peri-annual) of small landslides with a $V > 100 \text{ m}^3$. The present study is a next step in the understanding submarine-slope stability and related hazard, which requires the precise identification of landslides volumes, frequency and triggering factors. Over the last 20 years, the fresh-water outflow circulating in the Var river delta deposits is likely to be the dominant factor in triggering small-size landslides. Despite previous work (Keefer 2002) indicating that earthquakes with magnitude lower than $M_w = 5$ may not trigger submarine landslides, we show that there is a correlation between number of earthquakes and frequency of mass wasting events on the continental shelf. Landslide triggering is also affected by other factors acting over longer timescales such as high-sedimentation rates and the presence of gas-rich layers.

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References

- Akkar S, Bommer JJ (2010) *Seismol Res Lett* 81:195
- Biscara L, Hanquiez V, Leynaud D, Marieu V, Mulder T, Gallissaires JM, Crespin JP, Braccini E, Garlan T (2012) *Mar Geol* 299–302:43
- Courboulex F, Larroque C, Deschamps A, Kohrs-Sansorny C, Gélis C, Got JL, Charreau J, Stéphan JF, Bethoux N, Virieux J, Brunel D, Maron C, Duval AM, Perez J-L, Mondielli P (2007) *Geophys J Int* 170:387
- Dan G, Sultan N, Savoye B (2007) *Mar Geol* 245:40
- Genesseeux M, Mauffret A, Pautot G (1980) *Comptes Rendus L'académie Des Sci. Paris* 290:959
- Hill PR (2012) *Int. Assoc. Sedimentol.* 44:47
- Hughes-Clarke JE, Brucker S, Muggah J, Hamilton T, Cartwright D, Church I, Kuus P (2012) In: Eberhardt E et al (eds.) *Landslides and engineered slopes: protecting society through improved understanding*. Taylor & Francis Group, London, pp 1091–1096
- Ioualalen M, Migeon S, Sardoux O, (2010) *Landslide tsunami vulnerability in the Ligurian sea: case study of the 1979 October 16 Nice internationalairport submarine landslide and of identified geological mass failures*. *Geophys J Int.* doi:10.1111/j.1365-246X.2010.04572.x
- Keefer DK (2002) *Investigating landslides caused by earthquakes—a historical review*. *Surv Geophys* 23:473–510
- Migeon S, Cattaneo A, Hassoun V, Dano A, Casadevant A, Ruellan E (2012) *Submar.* In: Yamada Y et al (eds.) *Mass movements their consequences*. Springer, Amsterdam, pp 451–461
- Mulder T, Tisot J-P, Cochonat P, Bourillet J-F (1994) *Mar Geol* 122:29
- Smith DP, Kvittek R, Iampietro PJ, Wong K (2007) *Mar Geol* 236:79
- Stegmann S, Sultan N, Kopf A, Apprioual R, Pelleau P (2011) *Mar Geol* 280:168
- Sultan N, Savoye B, Jouet G, Leynaud D, Cochonat P, Henry P, Stegmann S, Kopf A (2010) *Can Geotech J* 47:486