Reconstruction and Tsunami Modeling of a Submarine Landslide on the Ionian Margin of Calabria (Mediterranean Sea)

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Abstract

The Ionian margins of Calabria are affected by repeated sediment failures, recorded by slide scars at seabed and stacked slide deposits. We present a reconstruction of the geometry and dynamics of one of the largest seabed features, the Assi failure on the relatively steep slope off southern Calabria, and use it as input to numerical modeling to evaluate the potential tsunamigenic hazard. The Assi failure is up to 6 km wide and at least 18 km long, and involved the displacement of ca. 2 km^3 of sediment, inferred to have taken place within the last 4,000 years in two main phases. The first and larger phase is used as input to the tsunami modeling, on the assumption that the slide moved in a single step as a coherent mass of 1.85 km^3, in order to evaluate the most disruptive possible consequences. The results indicate that within 8 minutes, waves just over 1 m in height affect the southern Calabrian coast between Monasterace and Roccella Jonica, where their capacity to cause damage could be amplified in small harbours. This shows that tsunamis represent a hazard for Ionian coastal areas, and calls for accurate monitoring and further study.

Keywords

Ionian Sea • Calabrian margin • Morpho-bathymetry • Sub-bottom profiles • Submarine failure • Tsunami modeling

Introduction

Submarine landslides are important agents for downslope sediment transport and seafloor geomorphic change, and potential tsunamigenic events that represent geohazards for coastal communities. The tectonically-active Ionian Margins of Calabria (IMC, Fig. 1) provide an interesting natural laboratory to study such processes. The seabed dynamics of the IMC are being examined in the context of the Italian projects MaGIC (Marine Geohazards along the Italian Coasts) and RITMARE (La Ricerca Italiana per il Mare). Integrated seabed mapping during MaGIC has shown the margins to be characterized by numerous slide scars, interpreted as the sign of recurrent slope failures (Morelli et al. 2011; Ceramicola et al. 2014). One of the largest geomorphic features is the Assi slide, located within 10 km of the coast (Fig. 1). Information on this feature is available from both swath bathymetric data and high-resolution sub-bottom profiles. The objective of this study is to present a reconstruction of the geometry, volume and dynamics of the Assi slide and its environs, and use it as input to a model of tsunami generation and propagation.

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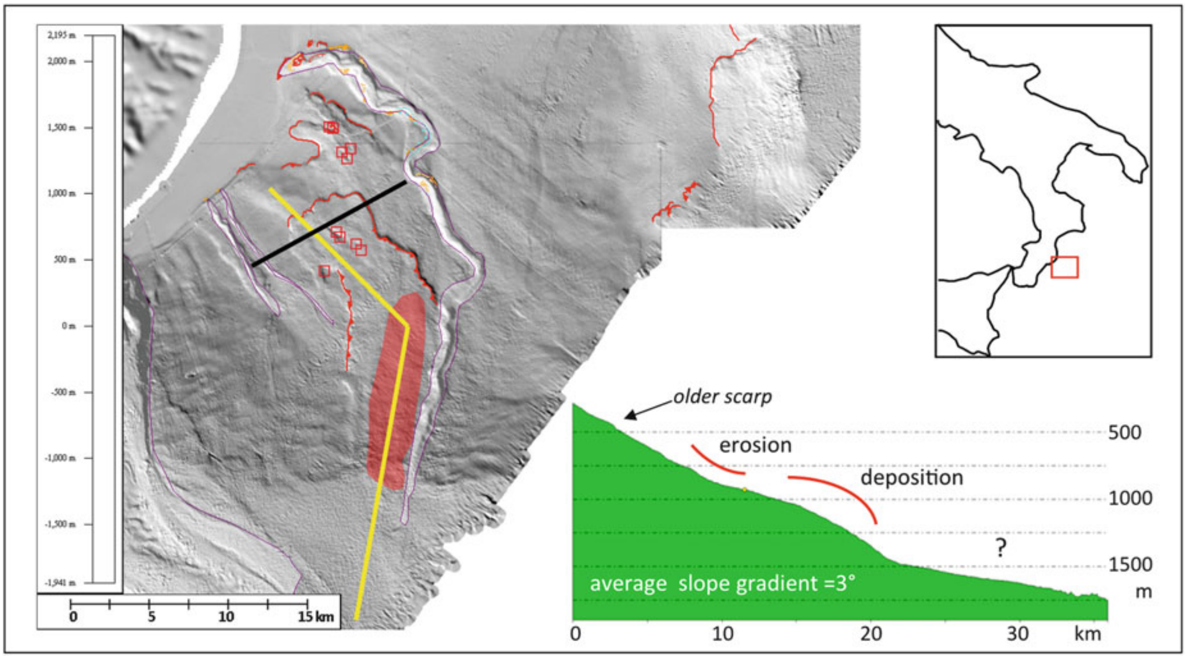

Fig. 1 Study area location on the Ionian margin of Calabria. Main figure: *shaded* relief from DEM of multibeam data acquired by OGS; submarine canyons are indicated in *white*, *red lines* denote seabed scarps, the elongated *red* area indicates deposited material. *Inset* shows a bathymetric profile along the axis of the Assi slide (*yellow line*). *Black line* shows location of Fig. 2

Regional Setting

The IMC forms part of a broader accretionary prism that records the NW subduction of Ionian lithosphere beneath the Tyrrhenian Sea (Sartori 2003), a process associated with historical seismic activity (DISS Working Group 2010). The SE advance of the accretionary prism over the last ~10 Ma has slowed or ceased since 0.8–0.5 Ma (Mattei et al. 2007), coincident with a km-scale differential uplift of onshore areas (Westway 1993). Uplift has contributed to the steep (3–8°) bathymetric slope offshore southern Calabria, which is incised by canyon systems that reflect sediment transport into the deep-water Spartivento and Crotone fore-arc basins (Sartori 2003). The open slopes between the canyons are marked by scarps (<50 m) interpreted to indicate recurrent failures (Fig. 1).

Methods and Data

High-resolution geophysical data were acquired by the R/V OGS Explora during campaigns in 2005 and 2009. Swath bathymetric data were acquired over an area of about 30,000 km^2 using Reson 8150 (12 kHz) and 8111 (100 kHz) multibeam systems, to obtain DEMs of variable cell size (5–50 m). Sub-bottom profiles consist of about 10,000 line-km of Chirp data (2–7 kHz). Our interpretive method consists of integrating seabed morpho-bathymetric elements with acoustic facies identified on the sub-bottom profiles, in order to identify the principal sedimentary features of the margin and reconstruct their dynamics.

Calculations of the slide dynamics, of the resulting tsunamigenic impulse and of tsunami propagation are performed using three numerical codes developed and maintained by the University of Bologna Tsunami Research Team. Code UBO-BLOCK1 solves equations of motion accounting for gravity, buoyancy and all interactions between the sliding mass (discretized into a chain of interacting, volume-conserving blocks) and the environment, to obtain the slide acceleration, velocity, position and shape at each time step. These elements are used to compute the tsunamigenic impulse via code UBO-TSUIMP, which filters the perturbation provided by the slide motion through the sea depth (cutting the higher frequencies), and computes the forcing term used as input for the tsunami model. The tsunami propagation is simulated by code UBO-TSUFD, implementing the non-dispersive Navier-Stokes equations with the shallow water (SW) approximation. For a more detailed description of the codes, see Tinti et al. (1997), for applications see Tinti et al. (2006, 2011) and Zaniboni et al. (2013).

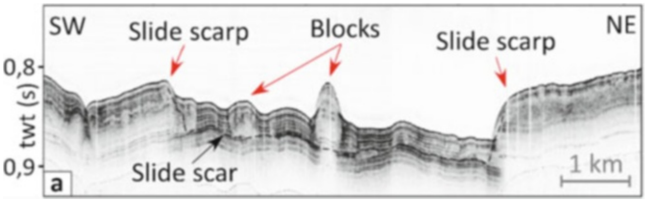

Fig. 2 Chirp sub-bottom profile across the upper part of the Assi slide (location in Fig. 1). *Black dashed line* marks the low-angle unconformity at the base of the slide deposits

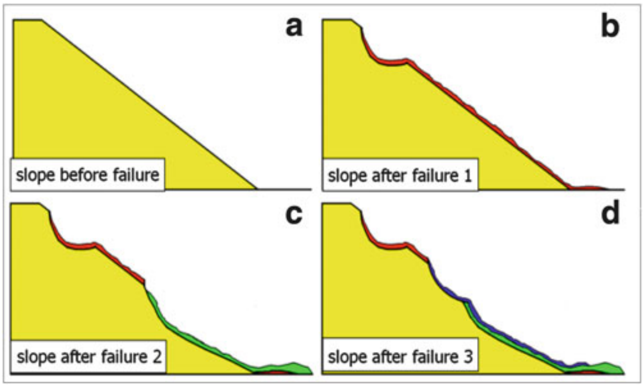

Fig. 3 Reconstruction of failure dynamics along the Calabrian Ionian margin

Results and Discussion

Seabed Mapping

The Assi failure lies off southern Calabria on an open slope between the large Siderno canyon system to the west and the smaller Assi canyon to the east (Fig. 1). Morpho-bathymetric data reveal a number of arcuate scarps indicative of sediment failure, including several on the upper slope in water depths of 150–500 m (Fig. 1). Downslope, the Assi slide is apparent as a seabed scarp up to 50 m high, defining an elongated slide scar up to 6 km wide and at least 18 km long, extending across water depths of 500–1,400 m (Fig. 1). The slide scar has a minimum width of 3.1 km in water depths of 730 m; above this narrowing, its axis is of NW-SE orientation, whereas below it is of N-S orientation (both parts are perpendicular to the regional slope). Bathymetric profiles along the slide show concave upper and convex lower profile (Fig. 1). The lowest parts of the slide intersect the Assi canyon, and the slide has no apparent expression on the adjacent floor of the Spartivento basin (Fig. 1).

Sub-bottom profiles across the Assi slide show it to contain both stratified and unstratified deposits, above a low-angle basal unconformity (Fig. 2). The upper part of the slide consists mainly of stratified deposits and unstratified blocks that have seabed expression (Fig. 2), while the lower part contains more mixed acoustic facies. The slide is observed to truncate sediments that include unstratified layers interpreted as older debris flow deposits (Fig. 2), including near-seabed layers seen to be linked to the seabed scarps observed upslope (Fig. 1).

Reconstruction of Failure Dynamics

We interpret this part of the slope to have been affected by at least three phases of failure (Fig. 3). The oldest phase (SLIDE 1) is associated with scarps on the upper slope (Fig. 1) and unstratified deposits on the slope below that are truncated by the younger Assi slide (Fig. 2). The Assi slide itself provides evidence of two phases of failure: the N-S oriented lower slide (SLIDE 2), which we infer to be older, and the NW-SE oriented upper slide (SLIDE 3). The Assi slide extends over an area of ca. 90 km^2 and we estimate that it mobilised a total ca. 2 km^3 of sediment during the two events (Fig. 3).

The age of the three slide events (Fig. 3) has been estimated from the thickness of a layer of sediment observed on sub-bottom profiles to overlie the slide deposits across the slope (e.g. Fig. 2). On the upper slope above SLIDE 1, this deposit is 6 m thick, whereas downslope above both SLIDES 2 and 3 it is 4 m thick. Post-LGM sedimentation rates for this area are taken from Zecchin et al. (2011) to be about 1.4 mm/year. This yields an estimated age of ca. 4300 year for SLIDE 1 and an age of ca 2850 year for SLIDES 2 and 3. The comparable thickness of this deposit across SLIDES 2 and 3 supports an interpretation of them as linked events, SLIDE 3 having formed by retrogressive failure after the larger SLIDE 2 (Fig. 3).

The first phase of the Assi slide (SLIDE 2, Fig. 3c) is the largest of all the failures to have affected this steep open slope. In the following, we focus on SLIDE 2 (hereafter simply referred to as the Assi slide) to model the failure dynamics and evaluate its tsunamigenic potential.

Numerical Modeling of the Assi Slide

The material mobilised during SLIDE 2 was used for the tsunami modeling, assuming that the material failed in a single step and remained a coherent mass. This represents a ‘worst-case’ scenario, chosen in order to evaluate the strongest possible consequences.

The calculation of the slide dynamics is performed using the numerical code UBO-BLOCK1: the sliding mass is discretized into a chain of interacting, volume-conserving blocks, whose centre of mass move along a predefined

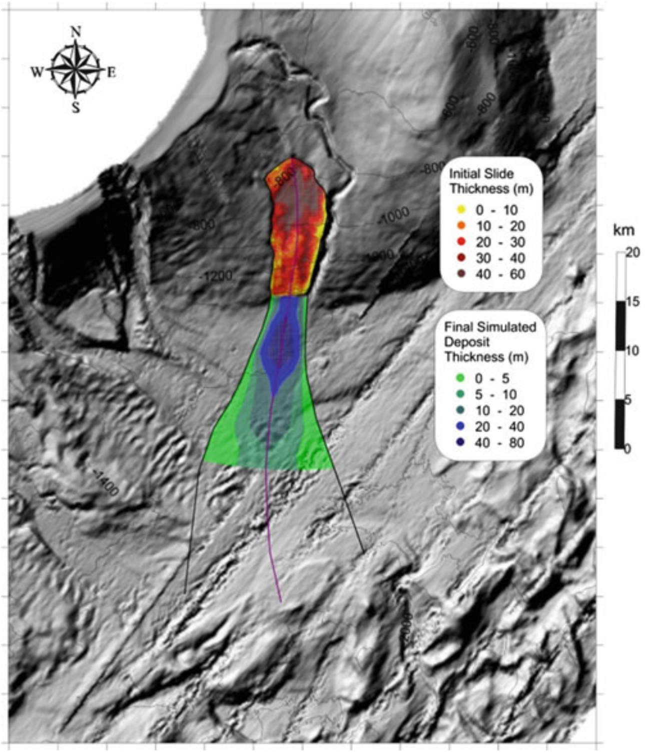

Fig. 4 Reconstruction of the initial thickness (*yellow-red-brown colour scale*) of the Assi slide and computed final deposit (*green-blue scale*). The *purple line* marks the trajectory of the centres of mass, while the two *black* side-boundaries account for lateral spreading

trajectory (Fig. 4, purple line). The inputs required by the numerical code are: the undisturbed sliding surface; the initial thickness of the mass; the trajectory of the centres of mass of the partition blocks (mostly based on the maximum local slope); and the lateral boundaries governing the spreading of the slide. Initial slide thickness was reconstructed by filling the present sea-bottom scar (Fig. 4). The sliding surface was deduced from the present bathymetry, neglecting the presence of possible deposits at the base of the slope.

The result is a mass of 1.85 km^3 volume, mainly concentrated upslope between 800–900 m water depths (see major thickness marked by the brown area in Fig. 4). The area covered by the initial mass ranges about 66 km^2, for a mean thickness of 28 m. Most of the deposit remains at the toe of the margin, where the slope reduces, at about 1,500 m water depth (Fig. 4), while the frontal part reaches deeper sea down to 1,700 m, for a runout of more than 20 km.

As concerns dynamics, the Assi slide is characterized by a slipping time of over 18 min. In the acceleration phase, the mass seems to move not coherently, as testified by the spreading of the velocities of individual blocks (black dots in Fig. 5). The mean velocity reaches a peak of about 23 m/s after more than 11 min. A fast deceleration phase follows, due to the mass reaching gentler slopes. The Froude number

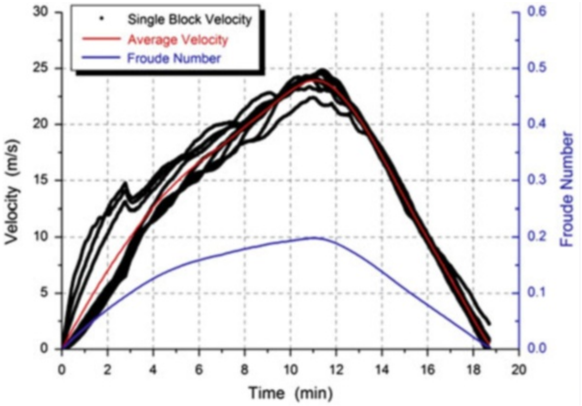

Fig. 5 Average velocity (*red line*) and individual centre of mass velocities (*black dots*) vs. time. The Froude number value is marked in *blue*

is also given in Fig. 5: this parameter is obtained as the ratio between the horizontal component of the sliding velocity and the phase velocity of the generated water wave: when it is close to the resonance condition, (i.e. the value 1), the energy transferred from the slide to the waves is maximum. The highest Froude number is relatively low, 0.2, far from the critical value, and is attained in correspondence of the velocity peak, after around 11 min. Afterwards, the Froude number decreases rapidly as the result of a double effect: the slide slows down (hence, the numerator of the ratio decreases), and the water becomes deeper (hence, the denominator of ratio increases).

Simulation of the Tsunami Propagation

The computational domain is composed of a regularly-spaced grid, 200 m step, focused on the Ionian Calabrian coast and visible in Fig. 6

Figure 6 reports the propagation of the Assi landslide tsunami at different time steps over the smaller computational domain. Initially the wave propagates almost radially from the source (t = 3 min sketch in Fig. 6), with a negative leading front moving northward, and a leading crest moving southward, in the direction of the sliding motion. Between 6 and 8 min, the tsunami hits the Calabrian coast and begins to deform, and the wave front orients almost parallel to the coast. The coastal stretch between Monasterace and Roccella Jonica is the first one attacked by the tsunami (a sea withdrawal of about 1 m). South of this area, in direction of Siderno, a first positive arrival (meaning sea invasion) is observed, while moving northward the tsunami first manifests as a negative signal.

Such features are confirmed by the virtual marigrams, reported in Fig. 7: the maximum peak-to-peak water elevation,

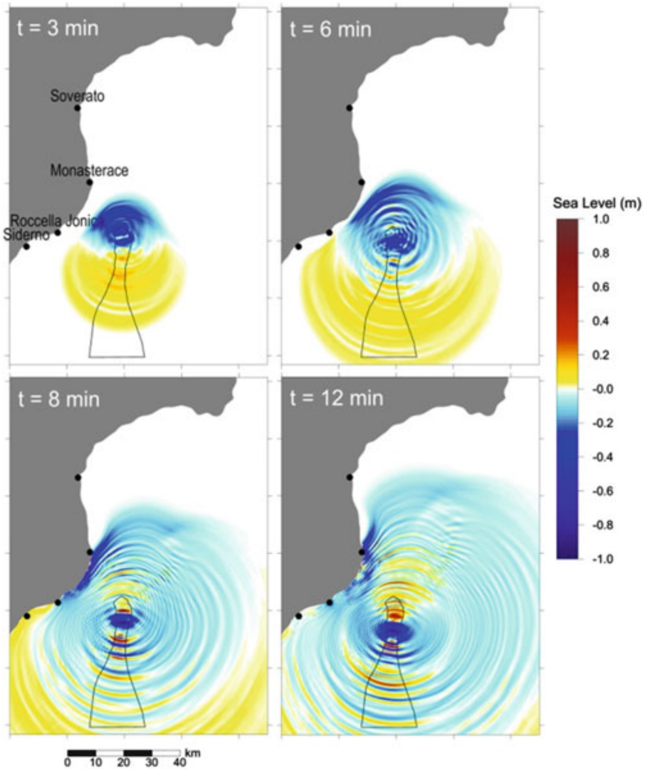

Fig. 6 Propagation of the tsunami over the smaller computational grid at different time steps. *Cyan-blue* scale stands for sea withdrawal, *yellow-red-brown* for sea level increasing. The *black line* marks the slide motion boundary

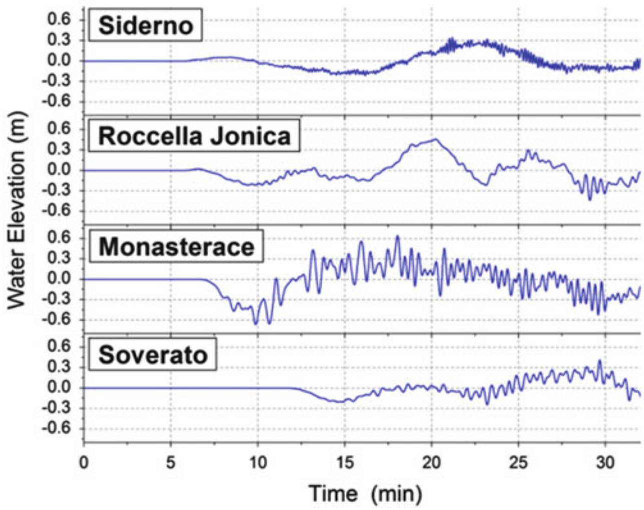

Fig. 7 Virtual tide gauge records (geographical locations in Fig. 6)

about 1.2 m, is found in Monasterace, where a first sea withdrawal of about 60 cm occurs 10 min after the landslide beginning and is followed by an equivalent maximum 7–8 min later.

The marigrams show also two more relevant features that are typical of the landslide-induced tsunamis: (1) the high-frequency signals (associated to the short wavelength waves in the fields of Fig. 6, t = 8 min and t = 12 min) overlapping the main wave; (2) the rapid amplitude decay with the distance from the source. In general the main perturbation shows a periodicity of about 8 min, and the first tsunami signal takes at least 7 min after the beginning of the landslide motion to affect the closer coast.

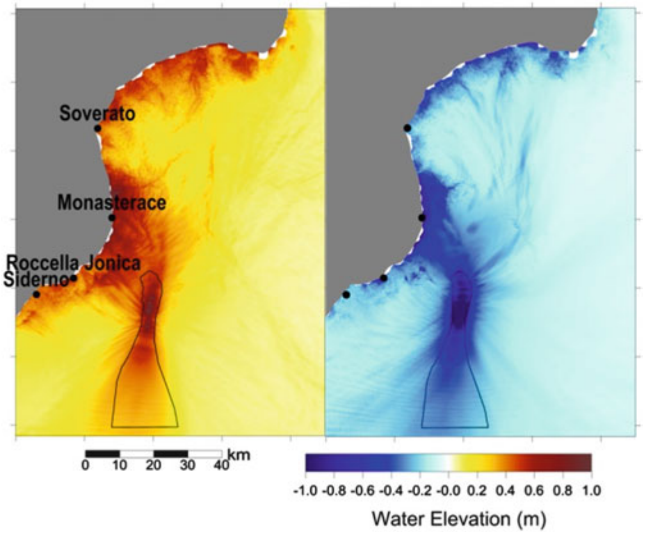

Fig. 8 Maximum and minimum water elevation over each node of the smaller computational grid

The maximum and minimum water elevation over each point of the computational domain (Fig. 8) provides a good description of how the tsunami energy distributes: in general, velocity and height of the wave is governed mainly by the sea depth, meaning that bathymetry plays the key role in driving the tsunami propagation.

In the case of Assi landslide, the main signals are clearly deviated north-westward, towards Monasterace and Roccella Jonica, while a small part of the energy departs north-eastward, as evidenced by the beam in that direction. This kind of maps can have immediate and important applications in the study of hazard along the coast.

Conclusions

This study presents the first attempt to evaluate the potential tsunamigenic hazard associated to submarine mass movements along the Ionian margins of the Mediterranean Sea, using a combination of seabed mapping and tsunami modeling. Seabed mapping shows the Assi slide to be the most recent and largest failure to have affected the steep open slope south of Calabria. The Assi slide is inferred to have taken place in two retrogressive phases, of which the first and larger was used to estimate the volume of mobilised material (~1.85 km^3), as input to modeling the failure dynamics and tsunamogenic potential.

The coastal areas along the southern part of the margin between Monasterace and Roccella Jonica, including the village of Riace Marina, are found to be the most susceptible to tsunamis generated by the Assi slide: within 8 minutes they are affected by waves with maximum peak-to-peak elevations just over 1 m in height. Such waves are not catastrophic, but would be able to cause damage, especially within the small harbors characteristic of the coast, where wave effects can be amplified by resonance and multiple. Moreover, the wave could pose threat to coastal populations, especially if occurring during the season of major tourism flow.

More generally, the unpredictability of the sliding phenomena, their proximity to the coast and the corresponding shortness of the lead time (in this case about 7 minutes), the large number of possible tsunami sources related to evidence of repeated episodes of failure along the margin, suggest that tsunamis represent a recurrent hazard for Ionian coastal areas and thus need accurate monitoring and further study.

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