Impact on Calabria and Sicily of a large tsunamigenic scenario collapse of Stromboli volcano

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Abstract. Stromboli is a small volcanic island in the southern Tyrrhenian Sea, Italy. The volcanic cone is known to have been involved several times by lateral collapses during its geological evolution. The last episode was dated about 5000 years BP and produced a large scar in the northwestern flank of the volcano, named as Sciara del Fuoco (SdF). Here a scenario of lateral collapse is envisaged involving a material volume like the SdF case. The dynamic evolution of the collapsing rocks is studied by means of a numerical block model based on the Lagrangian concept of partitioning the mass in blocks and of computing the motion of the individual blocks. The tsunami generated by the mass entering the sea is simulated through the shallow water approximation over a computational grid embracing Stromboli and other islands of the Aeolian archipelago, and extending up to the coasts of Calabria and Sicily. The propagation of tsunami fronts and energy in the open sea and toward the Italian coasts is investigated and shows that the scenario tsunami focuses on the coasts of the southern part of Tyrrhenian Calabria from Capo Vaticano to Gioia Tauro, whilst the Sicilian coasts are comparatively much less affected.

1. Introduction

Stromboli is one of the Aeolian islands, located in the south Tyrrhenian Sea to the west of Calabria and to the north of Sicily (see Fig. 1). Its volcanic activity consists mainly in mild eruptions taking place every 10–20 min and in sporadic (almost 6 per decade) more powerful explosions. A remarkable consequence of these continuous emissions of materials is the formation of gravitationally unstable flanks along the Stromboli volcano, due to the deposition of the erupted materials. These instabilities can evolve to landslides of large amount or even to lateral large-scale collapses that can generate catastrophic tsunami waves. One such episode was identified as the flank collapse forming the Sciara del Fuoco (SdF) scar in Holocene times. This combined collapse-tsunami event was already studied in previous works (Tinti *et al.*, 1999b; Tinti *et al.*, 1999c) restricting however to near-field tsunami impact all along the coasts of Stromboli island. The aim of this work is the analysis of the wave impact on the coasts of the Aeolian islands, of Northeast Sicily and of West Calabria in order to evaluate the effect of a possible future event of similar size in these high-density population regions.

2. The Landslide Simulation

The basic collapse data to build the scenario are derived from the estimates of the Holocene collapse producing the SdF scar, that was the last lateral collapse of the Stromboli cone occurring ca. 5000 BP (Pasquaré *et al.*, 1993). Bathymetric campaigns and seismic prospecting suggest that the volume of

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volcanic rocks involved was between 0.7–1.8 km^3 (Romagnoli *et al.*, 1993; Kokelaar and Romagnoli, 1995). In the present work we assume the lower end of the estimated range. The simulation of the volcanic collapse was performed by means of the Lagrangian numerical model elaborated by Tinti *et al.* and already presented in several papers (Tinti *et al.*, 1999a; Tinti *et al.*, 1999b; Tinti *et al.*, 1999c). The model considers the landslide as a linear chain of 15 blocks that interact with each other and that are further subjected to gravity force, to bottom friction, and to the resistance of the medium in which the slide is moving (i.e., air or water). Acceleration, velocity, position and geometric variables of each block are computed at every time step (here assumed to be 1.0 s long). Figure 2 shows vertical cross-sections of the sliding body taken at different times along the main slide pathway. The landslide simulation stops when the mass reaches the deep-water region (≈2000 m depth), since its tsunamigenic potential becomes negligible here due to the filtering effect of the associated transfer function (see Tinti *et al.*, 1999a, and Tinti *et al.*, 1999b). The landslide duration exceeds 3 min, and has to be regarded as a long tsunami source, much different from seismic sources that in most cases can be taken as instantaneous tsunamigenic processes.

3. Tsunami Simulation

The tsunami triggered by the landslide was computed by solving the fluid dynamics equations under the shallow-water approximation:

$$\begin{cases} \partial_t \zeta(x,y,t) = \partial_t \eta(x,y,t) - \nabla \cdot [(h(x,y) + \zeta(x,y,t))\mathbf{u}(x,y,t)] \\ \\ \partial_t \mathbf{u}(x,y,t) = -g\nabla\zeta(x,y,t) - \mathbf{u}(x,y,t)\cdot\nabla\mathbf{u}(x,y,t) \end{cases}$$

where $\zeta(x,y,t)$ is the sea surface elevation, $h(x,y)$ is the still-sea depth, g is the vertical component of the gravity acceleration, and $\mathbf{u}(x,y,t)$ is the horizontal velocity of the fluid particles. The term $\partial_t\eta$ represents the forcing of the sea waves due to the motion of the landslide. It is related to the landslide height resulting from the landslide block model and accounts for the depth transfer function filtering the smaller wavelengths (see Tinti *et al.*, 1999a, and Tinti *et al.*, 1999b; see also Iwasaki, 1997). On the coastal boundaries the condition of pure wave reflection is imposed, while total wave transmission is allowed on the open boundaries of the domain. The above equations are solved through the finite-element method (Tinti *et al.*, 1994) on a computational grid that is formed by triangles of different size: the two basic criteria to build the grid are to optimize the isotropy and the isochrony of the constituent triangles. This means that the mesh-maker algorithm tends to create equilateral triangles with uniform crossing time (Tinti and Bortolucci, 1998). The resulting computational grid is formed by 48,367 triangular elements and 25,126 nodes. It covers the southern Tyrrhenian Sea and part of the Messina Straits separating Sicily from Calabria in the Italian mainland.

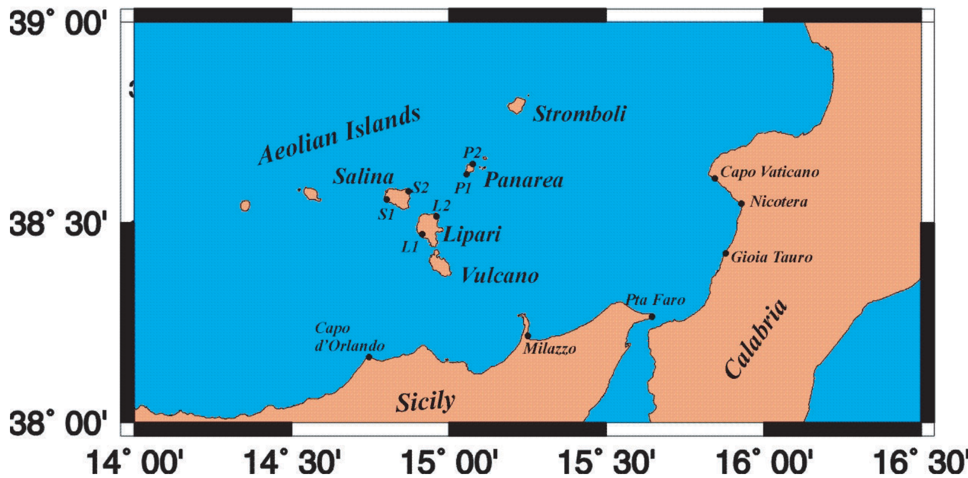

Figure 1: Map of the region involved by the tsunami induced by the lateral collapse of the northwestern flank of Stromboli.

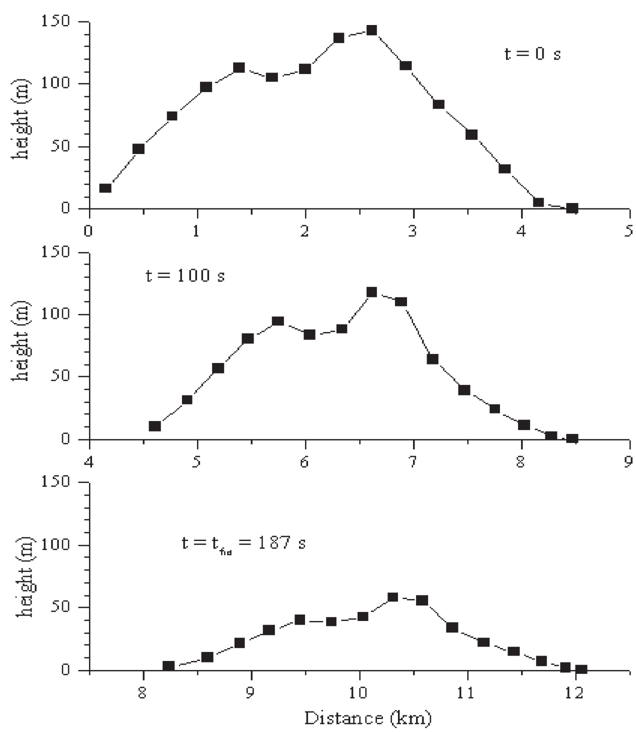

Figure 2: Profiles of the landslide taken along the slide pathway at different times. During the motion, the slide length changes slightly around the value of 4 km. Conversely, the slide height varies remarkably, lowering to about 1/3 of the initial value (from ≈150 m down to ≈60 m), since the slide basal surface becomes larger and larger offshore (see Tinti *et al.*, 1999b). The landslide simulation is stopped at the time $t = 186.5$ s.

4. Results and Conclusions

The tsunami propagation is computed at time steps of 1.0 s over an interval of 2000 s. Relevant tide-gauge records, located in the islands around Stromboli and on the more distant coasts of Sicily and Calabria, and water elevation fields are pictured respectively in Fig. 3 and 4. The most interesting feature of the radiation pattern is that, in spite of the fact that the landslide motion takes place in the northwest direction, the excited wave fronts go around Stromboli and leave the island in the form of quasi-circular waves (see fields at $t = 200$ s and $t = 400$ s of Fig. 4), suggesting that the source directivity effects are quite negligible in this case. This is mostly the effect of the morphology associated with the circular island in the source region and differs remarkably from the case of a tsunami induced by a slump on a continental shelf where directivity is manifest both in the amplitude and in the polarity of the waves: waves traveling in the same direction as the slump have a positive leading front and higher amplitude, while waves traveling in the opposite direction possess a negative leading front and are smaller (see discussion in Tinti and Bortolucci, 2000a and 2000b). Time histories in Fig. 3 confirm that all stations see positive first arrivals followed by larger negative waves. The largest waves are expectedly observed along the coasts of Stromboli. In this paper, however, we are chiefly interested in the tsunami seen outside the source region, and therefore we will neglect the waves computed in the vicinity of Stromboli in the present discussion. A few minutes from the landslide initiation the tsunami reaches the coasts of the other Aeolian islands where it is partially trapped. Time histories are shown for three islands of the Aeolian archipelago (Panarea, Salina, and Lipari), for three stations on Sicily coasts, and for three stations on Calabria coasts. As regards the Aeolian stations, we selected two stations for each island: the one facing Stromboli is directly attacked by the incoming tsunami front, the other in the island lee is hit by waves traveling around the island. It is worth observing that the two stations of the small island of Panarea show similar (5 m high) oscillations, while the lee stations of the larger islands are affected by much smaller waves than the front stations (2 m vs. 10 m for Salina and 1 m vs. 3 m for Lipari); this means that the belt formed by Salina and Lipari (and the further island of Vulcano) constitutes a substantial obstacle for the advancing tsunami, since it is able to reduce its amplitude and to modify its front. Conversely, the size of Panarea is too little compared to the main tsunami wavelength to perturb remarkably its open sea radiation. The tsunami radiates completely through the basin, reaching Calabria and the Sicily coast in almost 15 min. The gauge records calculated at the Sicily stations, and more convincingly, the field of the maximum wave depicted in Fig. 5, corroborate the idea that the Aeolian arc produces a shadow region in the southeast sector of the domain. Gauges at Capo d'Orlando, Milazzo, and Punta Faro show that in Sicily tsunami engenders slight fluctuations in the range of 1 m. The resulting picture is quite different for the tide records computed in the coasts of Calabria; here, tsunami heights are larger by a factor of 3 to 4. The justification is ready by looking at Fig. 5, from which it can be easily seen that Tyrrhenian bathymetry channels the tsunami energy

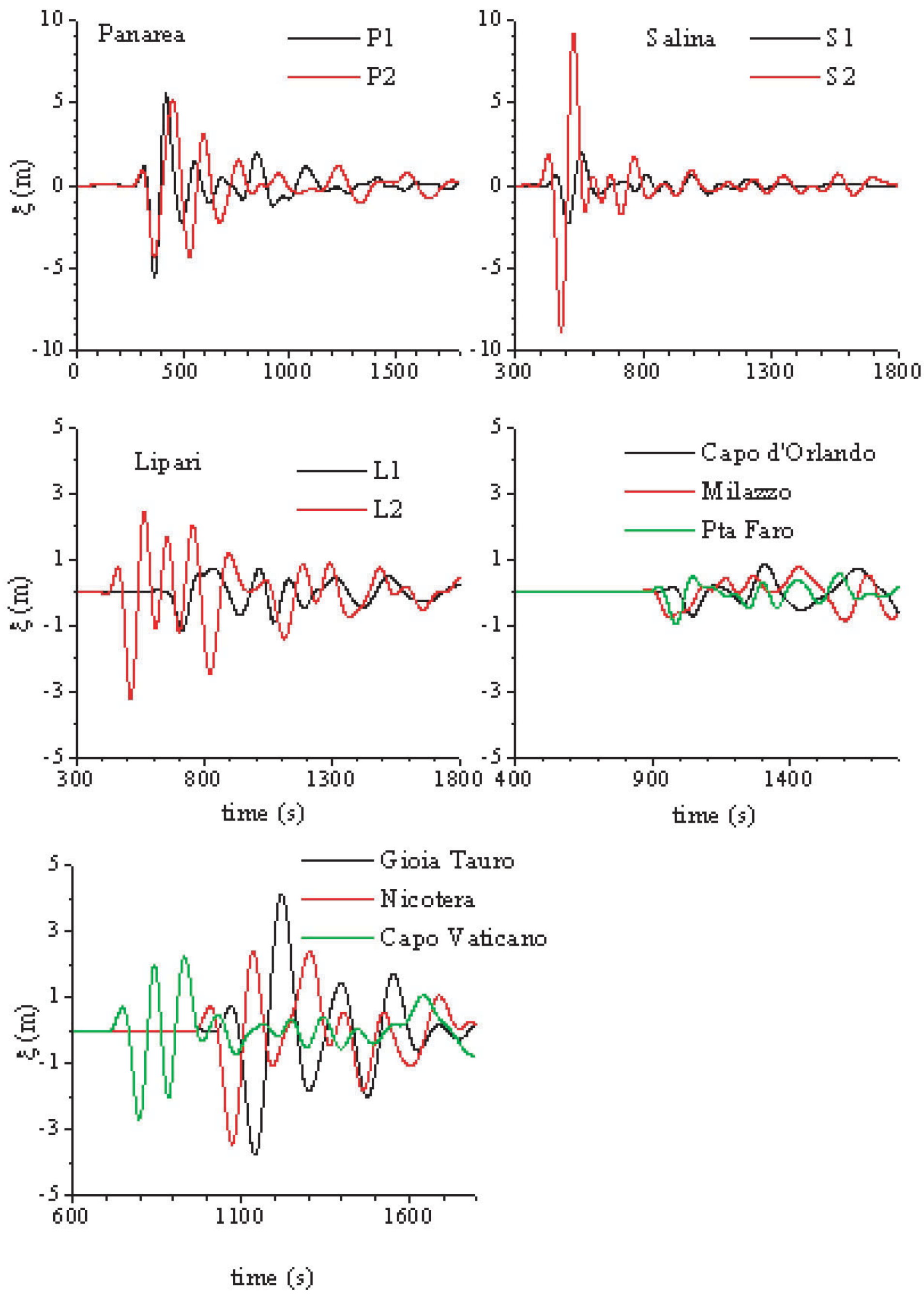

Figure 3: Computed tide-gauge records in the coastal sites shown in Fig. 1.

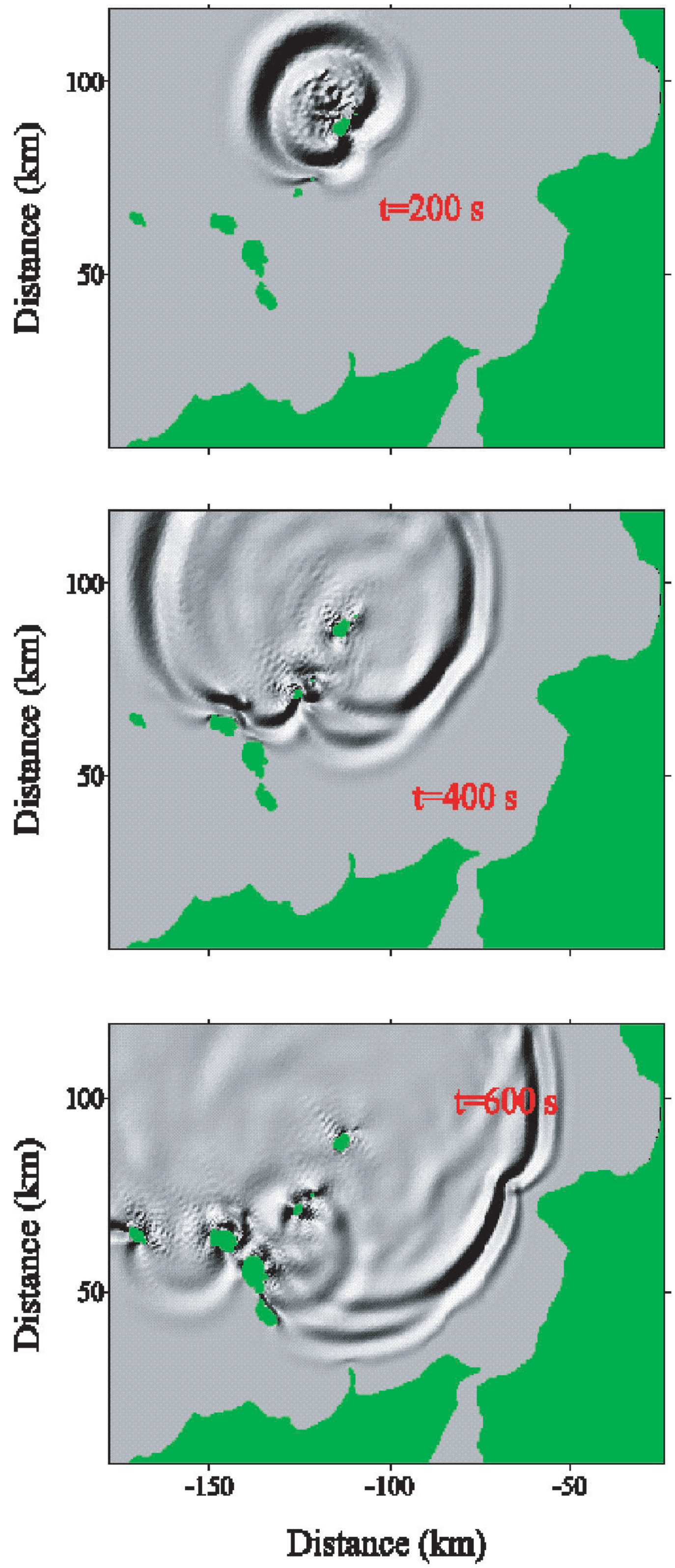

Figure 4: Elevation fields computed at times $t = 200$ s, $t = 400$ s, and $t = 600$ s after the landslide initiation. The approximate circular shape of the tsunami fronts can be observed very well on the first two pictures.

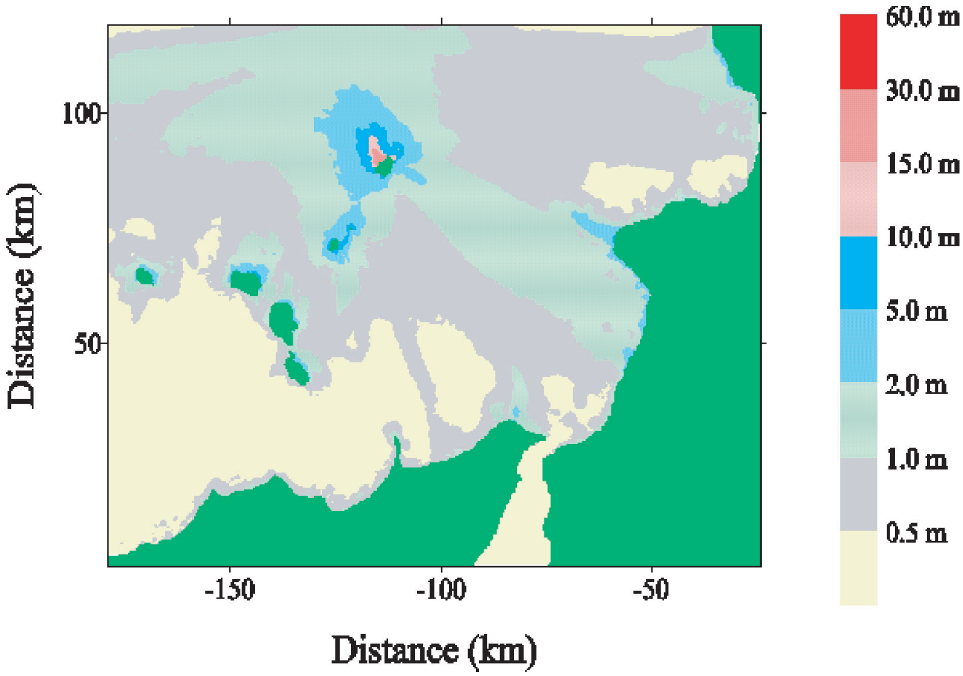

Figure 5: Field of the maximum water elevation. The highest values (several tens of meters) are observed in the source region around Stromboli. Dangerous values in the range 5–10 m are computed for many coastal sites in the Aeolian islands (e.g., Panarea and Salina). Tsunami energy is mainly conveyed toward the Calabrian coasts around, and to the south of, Capo Vaticano.

just towards those coasts of the Calabrian Gulf of Gioia that are comprehended between the northern promontory of Capo Vaticano and the harbor of Gioia Tauro.

What can be learned from the present study is that the envisaged lateral collapse of Stromboli is the source of a tsunami that constitutes a substantial threat. Previous papers have shown that the tsunami would be catastrophic for the Stromboli coasts. Here we understand that the tsunami will attack the other Aeolian islands with large, dangerous waves in the range of 5–10 m, but it will be quite smaller on the Sicilian coasts, where it will be likely to appear as a train of waves in the range of 1 m. On the other hand, hazardous waves are expected in the Calabrian coasts due to the channelling effect of the bathymetric features that are found in the open sea between Stromboli and the Gulf of Gioia.

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