17 Investigations on the Possible Source of the 2002 Landslide Tsunami in Rhodes, Greece, Through Numerical Techniques

Filippo Zaniboni, Gianluca Pagnoni, Alberto Armigliato, Katharina Elsen, and Stefano Tinti

Abstract

The island of Rhodes (Aegean Sea, Greece) has been repeatedly hit by tsunamis in the past due to the numerous tsunamigenic sources present in the area, most of which are seismic. Here an investigation is made on the most recent event that occurred on March 24, 2002 in the northeast of the island: unexpected waves affected a 2 km long coastal segment, overtopping part of the sea-wall (3–4 m high) that runs along the littoral road a few km away from the city of Rhodes. Data on the tsunami are poor. Due to the lack of evidence of seismological or meteorological causes, the hypothesis of a landslide source for the tsunami is here explored by means of numerical codes implementing models both for the landslide dynamics and the tsunami propagation. The reconstructed failing mass is located at about 100 m sea depth with a volume of 30 million m^3. A sensitivity analysis is further run by varying the source volume, to evaluate the effects on the tsunami impact.

Keywords

Landslide tsunami • Numerical modeling • Coastal hazard

17.1 Introduction

During the evening of March 24th, 2002, unusual waves affected a coastal segment of about 2 km in the northeast side of the island of Rhodes (marked in yellow in Fig. 17.1). The waves overtopped the sea wall protecting the littoral road, 3–4 m high, damaging some shops and stores located on the landside of the road.

The island of Rhodes, located in the south-eastern Aegean Sea, was affected in the past by several large earthquake-generated tsunamis, as for example the events of 1303, 1481, 1609 and 1741, that caused many casualties and severe damages also in other Greek islands (Papadopoulos et al. 2007). In the case of the 2002 event, however, the seismic origin for the tsunami can be ruled out, since no shock was recorded by the Greek seismic network in the evening of March 24. Since also storms and other meteorological anomalies can be excluded from the analysis of meteorological data, the only remaining option is that a submarine failure was the cause for the observed waves. This hypothesis was soon advanced and was further supported by the statements of some local fishermen, reporting an increase of the sea depth about 1 km off the affected shoreline (Papadopoulos et al. 2007).

Also with the goal of investigating such possibility, a high-resolution bathymetric survey was carried out after the event off the northeast coast of Rhodes by the Hellenic Center of Marine Research (HCMR) in the search for evidences of underwater failures (Sakellariou et al. 2002). The most studied zone was the steep slope NW of the northern tip of the island of Rhodes (named Cape of the Mills), that was found to be characterized by several scars and headwalls at depths of about 300–400 m, (visible in Fig. 17.1).

F. Zaniboni (✉) · G. Pagnoni · A. Armigliato · K. Elsen · S. Tinti
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
e-mail: filippo.zaniboni@unibo.it

G. Lollino et al. (eds.), *Engineering Geology for Society and Territory – Volume 4*,
DOI: 10.1007/978-3-319-08660-6_17, © Springer International Publishing Switzerland 2014

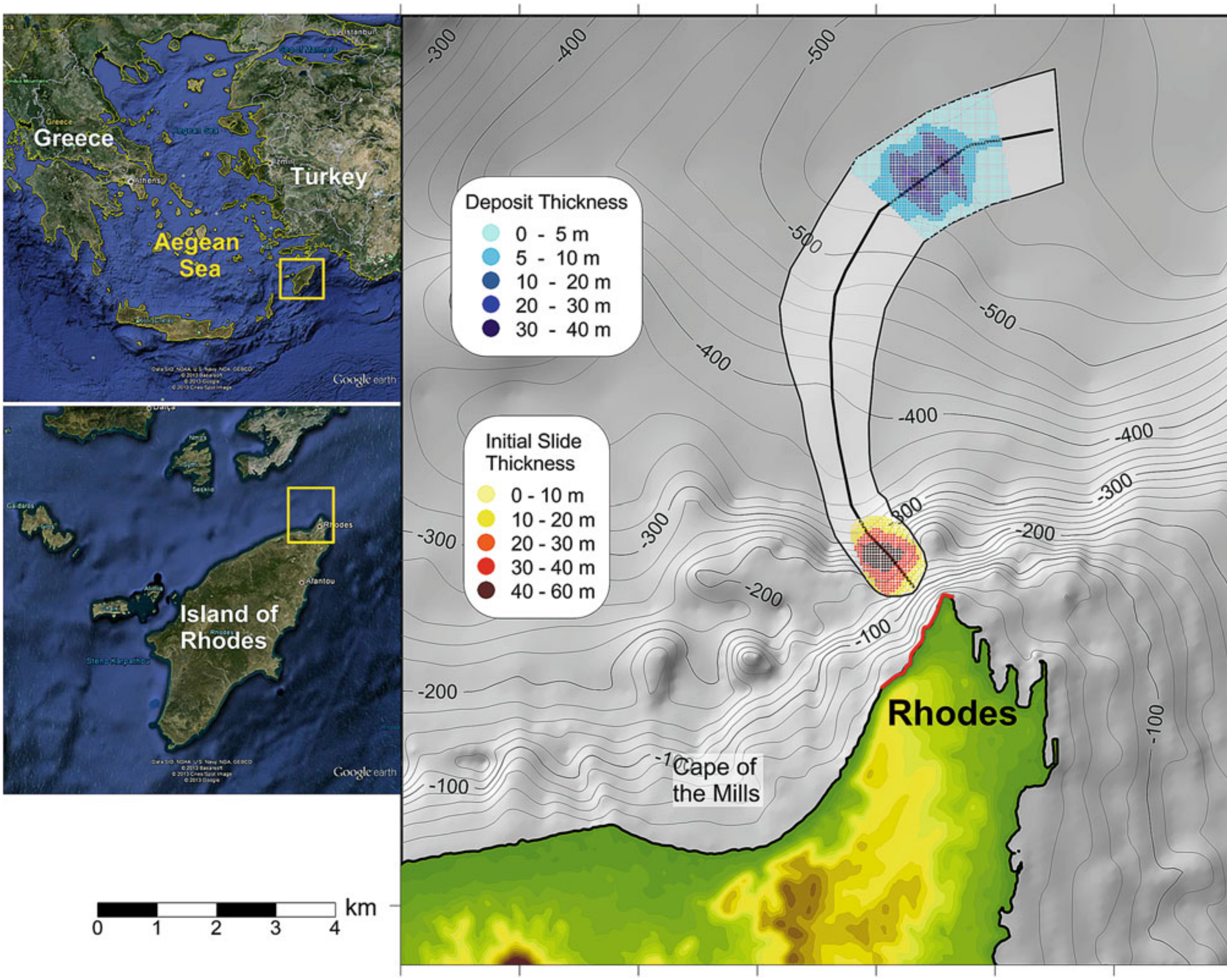

Fig. 17.1 Map of the northern tip of the island of Rhodes, with the 2002 affected coastal stretch evidenced in *red*. The sliding surface is highlighted in *light grey*, the CoM trajectory by the *black line* inside it. The *yellow-red scale area* marks the initial thickness of the landslide, the *cyan-blue* is for the final deposit

This area was seen to be the most prone to mass flows, and since it fits also with the area of sea depth changes reported by fishermen, Sakellariou et al. (2002) suggested it could be the best candidate for the 2002 tsunami generation, though they did not identify any specific scars as the source of the tsunami neither any specific depositional features.

In this work we explore the hypothesis of a landslide generation for the tsunami by studying this occurrence through numerical simulations. First we make assumption on the position of the source and reconstruct the sliding mass, on the basis of the available data. Second, we simulate the landslide motion by means of the numerical code UBO-BLOCK1, that provides the tsunamigenic impulse. Eventually, we calculate the generation and propagation of the tsunami through the numerical code UBO-TSUFD, and compare the results with the observations.

To cope with the uncertainties in the source, we conduct a sensitivity analysis by changing the source volume, more specifically the landslide thickness, which is seen to have the main effect of changing the tsunami size and the impact on the coast.

17.2 Numerical Models

The slide dynamics is simulated through the numerical code UBO-BLOCK1, developed and maintained by the University of Bologna tsunami research team. It implements a

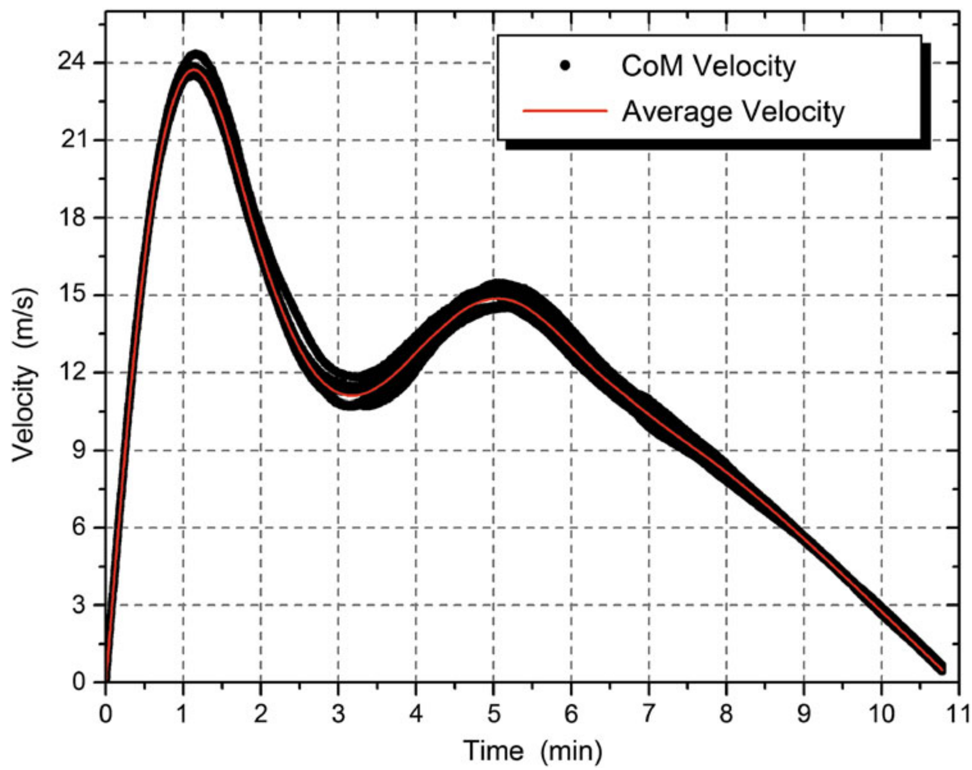

Fig. 17.2 Velocity of the individual blocks (*black dots*) and average velocity (*red line*), obtained as the mean of the CoM velocity at each time step, versus time

Lagrangian block approach, meaning that the mass is partitioned into a series of blocks and that the active forces (gravity, buoyancy, drag, block reciprocal deformation) are referred to the centre of mass (CoM hereafter) of each block. The code needs as input the specification of the sliding surface, the upper surface of the initial mass, the CoM pre-defined trajectory and the lateral boundaries confining the mass spreading during the motion (all reported in Fig. 17.1).

An intermediate software, UBO-TSUIMP, starting from the complete time-history of the slide motion computes the tsunamigenic impulse, which is related to the local changes to sea floor produced by the moving slide attenuated through a filter based on the ratio of the typical slide wavelength over the local sea-depth. It also performs the mapping of such impulse from the landslide grid, Lagrangian, to the tsunami grid, which is Eulerian.

The propagation of the tsunami is computed via the numerical code UBO-TSUFD, developed by the same research team, that solves the shallow water equations with a finite difference technique, where the impulse due to the slide is introduced as a forcing term. The software requires as input a grid with regular steps, with each node representing the local sea depth or topography.

Detailed examples of applications of such models can be found in Tinti et al. (2006, 2011), Tonini et al. (2011), Zaniboni et al. (2013).

17.3 The Simulation of the Submarine Slide

The landslide scenario is determined starting from some considerations in Sakellariou et al. (2002). The mobilized volume is hypothesized in the range of 32 million m^3, and is obtained considering one of the scars along the underwater slope NW of the city of Rhodes, between 120 and 320 m depth, and simply filling it considering the surrounding morphology (Fig. 17.1). The initial mass thickness (in yellow-red scale in Fig. 17.1) that reaches the maximum value of 60 m, and is on average around 27 m, is distributed over an area of 1.2 km^2. The undisturbed sliding surface (in pale grey in Fig. 17.1), is defined on the basis of the bathymetry and is delimited laterally by boundaries that control the mass spreading during the motion; the CoM track (black inner line) is specified following the line of maximum local gradient, and is found to bend north-eastward in deeper sea. The slide motion is then computed by inputting the above elements in the UBO-BLOCK1 code.

Figure 17.1 contains also the location of the final simulated deposit (cyan-blue area). The hypothesized landslide stops at more than 500 m sea depth, at a distance of 8 km from the source. The thickness lowers to an average value of 8 m, the area covered by the slide growing to 4 km^2. As visible in the velocity graph (Fig. 17.2), a strong acceleration phase brings the mass to the speed of 24 m/s and is followed by a fast deceleration when the mass reaches the sub-horizontal foot of

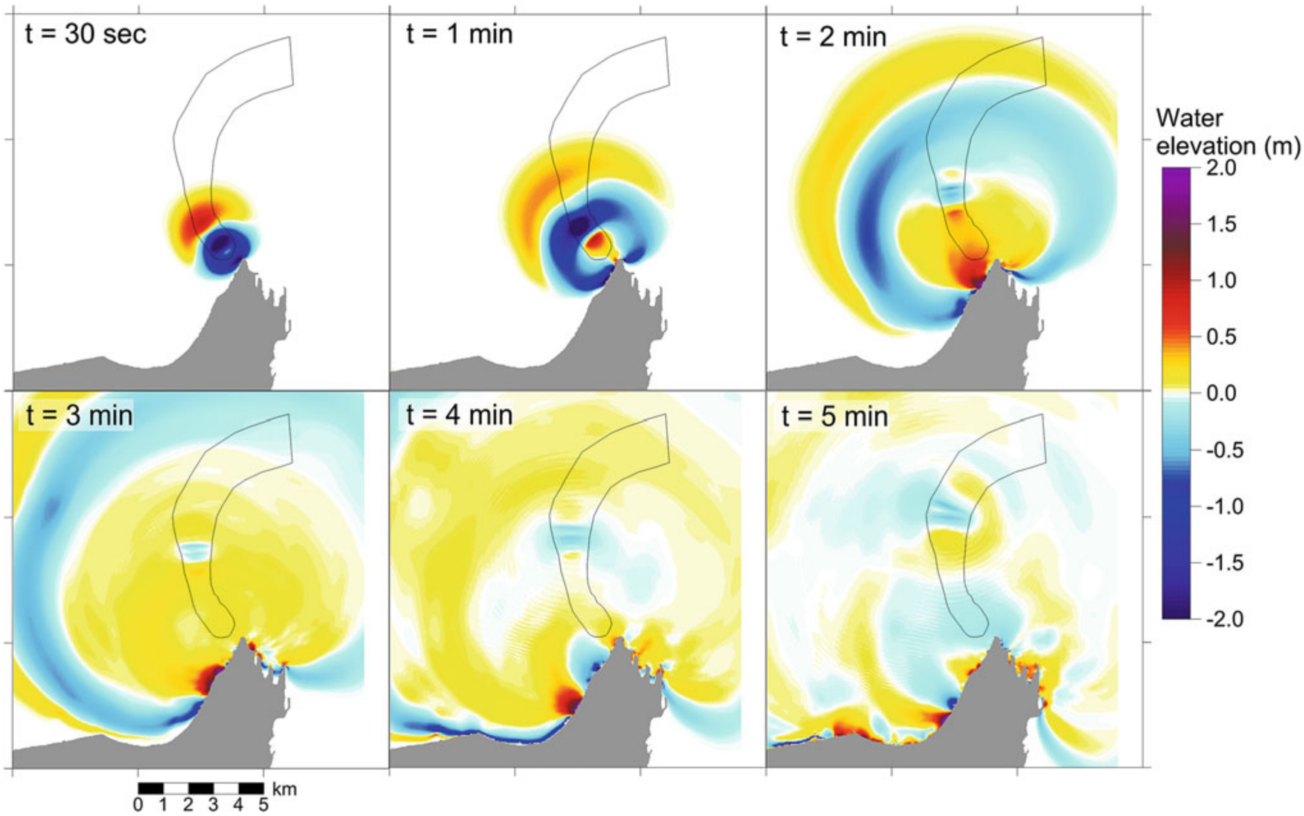

Fig. 17.3 Tsunami propagation over the computational domain, covering the northern part of the island of Rhodes. Positive signal, corresponding to sea level increase, are marked in *yellow-red*, negative (corresponding to water lowering) in *cyan-blue*. The sliding surface boundary is marked in *black* in each sketch

the escarpment, between 300 and 400 m depth. After this, the slope steepens again, and a new acceleration rises the velocity up to values of 15 m/s. The motion stops after about 11 min. Black dots in Fig. 17.2 represent the velocities of the individual CoMs. Since all speeds happen to be quite similar to one another and close to the average value (red line), one can infer that the mass remains rather compact while sliding. The first part of the motion, with the strongest acceleration and highest velocity reached, is the most tsunamigenic, considering also that afterwards the mass moves in deeper water, and therefore its capability of generating perturbation on the sea surface is reduced.

17.4 Tsunami Propagation Modeling

The computational grid of the tsunami model is made of over 160,000 regularly spaced nodes, 40 m apart, covering the northern part of the island of Rhodes (the most affected by the 2002 event) and the bathymetry north of it.

The model output of Fig. 17.3 shows an initial radial propagation for the tsunami, centered in the source zone (southern part of the black contour, Fig. 17.3). The sea surface perturbation exhibits a negative front (marked in cyan-blue) propagating southward, opposite to the landslide motion towards the coast of Rhodes, and a positive signal moving northward, towards the open sea. After about 30 s the tsunami reaches the coast where the 2002 event was observed, first manifesting with a negative signal, i.e. a sea withdrawal, of more than 2 m. The same area is affected by a positive signal, meaning sea inundation, about 2 min after the slide initiation. In all the panels of Fig. 17.3 one can also observe the propagation of a train of waves along the coast, which means that the coastal bathymetry favours the trapping of wave energy along the near-shore zone. The tsunami crosses Cape of the Mills after 2 min, hitting the eastern coast with a front almost parallel to the coast. The same happens along the coast to the west of the source (see the t = 4 min sketch), where before the main sea retreat one can observe a small positive signal, that is part of the fast circular front travelling offshore.

The synthetic marigrams, reported in Fig. 17.4, confirm some features already mentioned above. The first negative arrival, over 2 m deep, in the coastal segment in front of the source area (marigrams 1, 2 and 3), is followed by sea level rise almost equivalent to the withdrawal (in nodes 2 and 3).

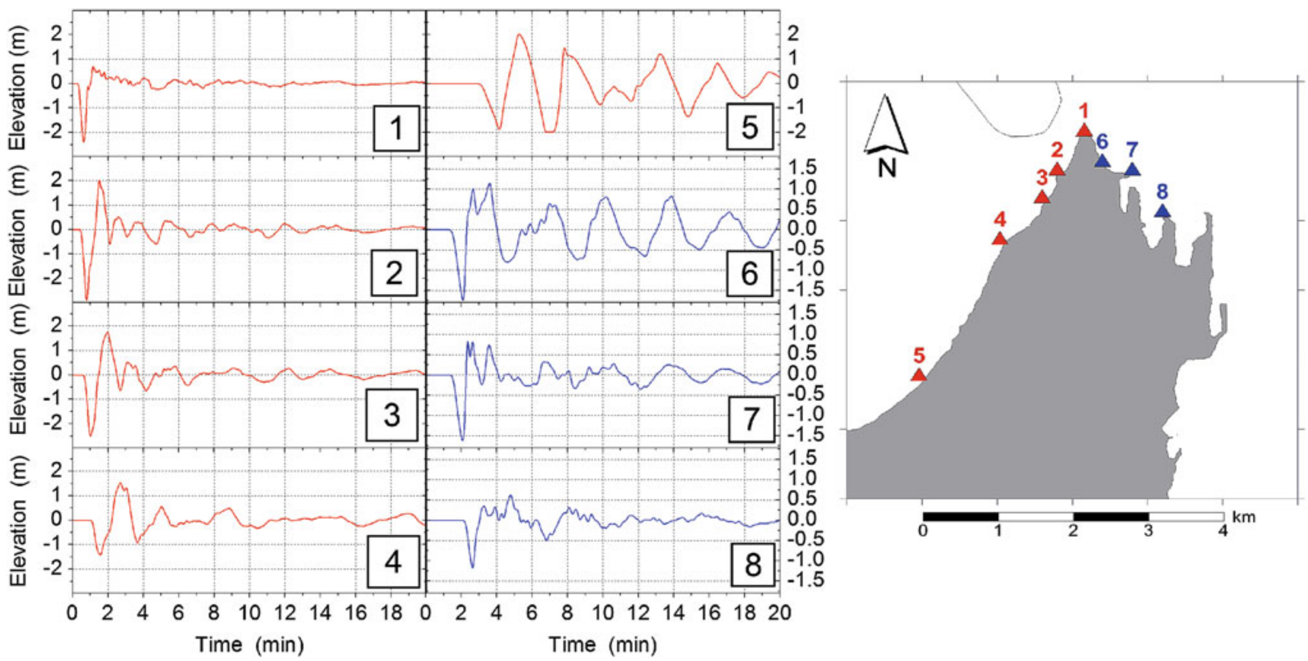

Fig. 17.4 Virtual tide gauges located west (in *red*) and east (in *blue*) of Cape of the Mills

This seems compatible with the observations, reporting that the 3–4 m seawall was overtopped by the waves. The tsunami shows a 2 min dominant period, and affects the coast with a series of crests and troughs with decreasing amplitude. Moving westward the tsunami weakens, but still remains not negligible: node 4 (2 km far from the source) and node 5 (around 4 km away) record a first peak-to-peak perturbation of over 3 m, with sizeable oscillations lasting for more than 20 min. Marigrams 6, 7 and 8 corresponding to nodes beyond Cape of the Mills (reported in blue in Fig. 17.4) exhibit and initial sea retreat and waves of smaller amplitude (−1.5/+1 m) but still capable to produce damages to the harbor structures.

17.5 Sensitivity Analysis and Discussion

The scenario presented here is based on conjectures on the landslide that do not have direct evidence or validation. An accurate geophysical characterization of the initial sliding mass (volume, thickness, shape) does not exist, and likewise also a sound estimate of its initial position is missing. Moreover no observations of the final deposit, that could provide strong constraints on the dynamics modeling, have been made yet. Moreover, as concerns the tsunami only the qualitative effects of the waves on a short segment of coast are known through eyewitnesses accounts (overtopping of the sea wall and watering of the shops on the road), since the tide gauge in the harbor of Rhodes did not work in the evening of the tsunami.

A first attempt to constrain the characteristics of the source and to estimate its influence on the generated tsunami has been made, by reducing the initial thickness of the above illustrated scenario (hereafter denoted as case A) to 75 and 50 %: this produces the same decrease also in the volume of the sliding mass, that turns out to be 24 million (case B) and 16 million m^3 (case C) respectively. Scenarios B and C are computed through the same numerical codes as case A and results are compared in Fig. 17.5, by the respective maximum water elevation produced along the northern coast of the island of Rhodes. A first very interesting observation is that there is an almost linear correlation between the sliding mass thickness and the wave height on the coast, especially along the coast west of Cape of the Mills, where the tsunami propagation is faster and direct. Moving to the east of the Cape, on the other hand, this direct dependence seems to fail, or at least to weaken, due probably to the non-linear effects rising from the tsunami interaction with the small harbors and basins in this zone. Along the coastal segment most affected by the 2002 tsunami, one can notice 2–5 m wave elevation for case A, 1.5–4 m for case B and 1–3 m for case C. If case A seems to slightly overestimate the observations (consisting mainly of the overtopping of the sea-wall, 3–4 m high), case C seems to represent the lower bound for such an occurrence. These two cases can be then interpreted as the maximum and minimum limits for the mass generating a tsunami compatible with the observations.

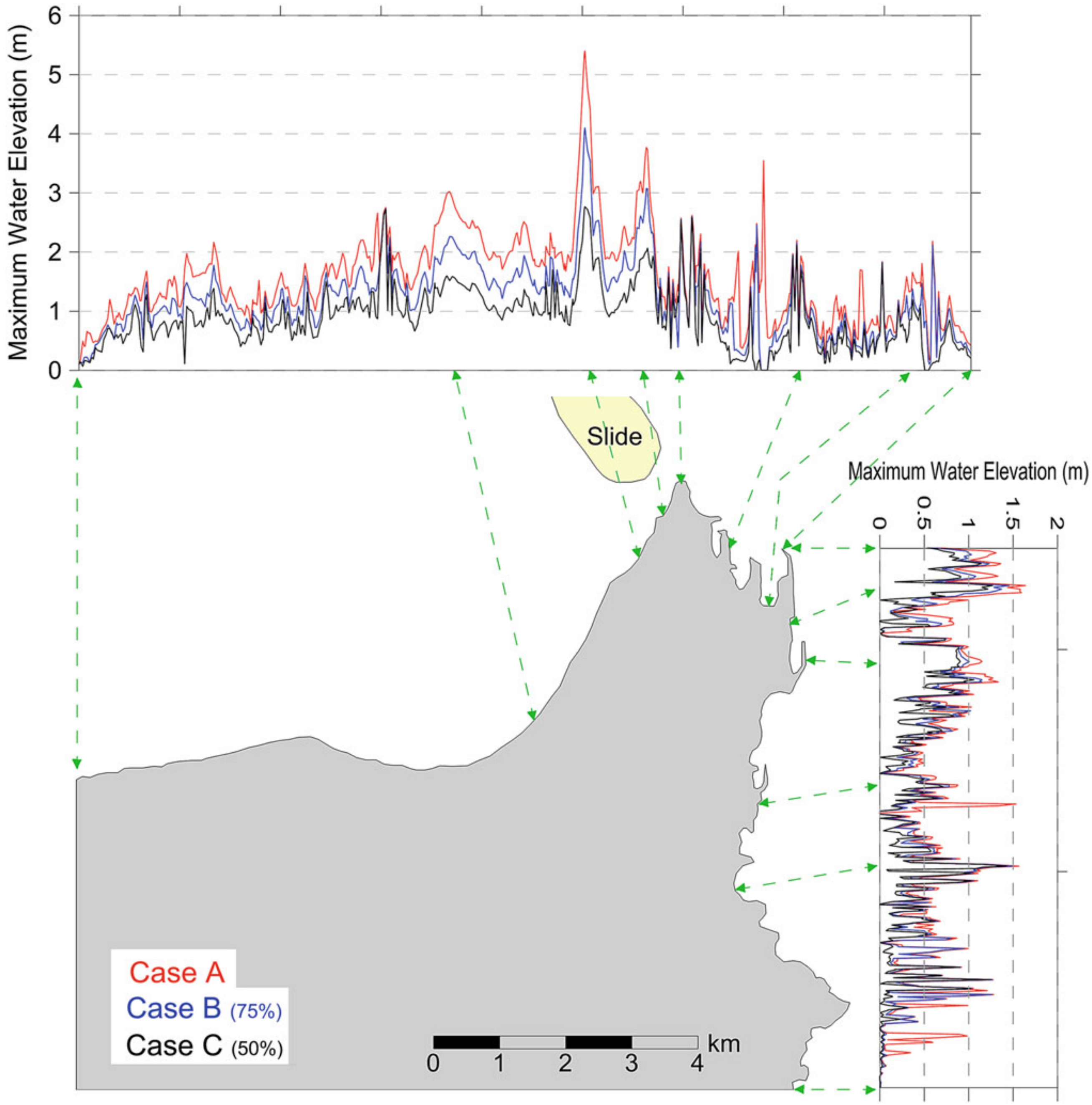

Fig. 17.5 Maximum water elevations along the coast for the three scenarios of slide: the reference case, *A* in *red*; the 75 % reduced thickness case, *B* in *blue*; the halved-thickness case, *C* in *black*

17.6 Conclusions

The 2002 non-seismic tsunami affecting the northern tip of the island of Rhodes is here investigated through numerical techniques. A rough initial mass reconstruction has been performed, basing on some indications coming from bathymetric surveys carried out offshore the NW coast of the city of Rhodes by the HCMR, especially focused along the steep slope located between 100 and 300 m depth. A volume of more than 30 million m^3 has been estimated, detaching from about 120 m sea depth: the slide reached a maximum velocity of about 24 m/s, before slowing down and reaching deeper water, at 500 depth, 8 km far from the source.

The simulated tsunami hits the coast within 1 min, with a leading negative wave, corresponding to a sea withdrawal, followed by an almost equivalent water rise, and continues for tens of minutes to affect the coast with 2 min wave period. Moving east of Cape of the Mills the tsunami loses strength, remaining however in the range between −1 and 1 m oscillations.

Due to the scarce availability of observations, it is difficult to constrain the parameters governing the model. An attempt is here made by reducing the initial mass thickness and evaluating its effects on the generated tsunami, comparing them with the evidences. The main result is that the reference case A and the halved-thickness scenario (case C) represent respectively the upper and lower extremes of the range of possible volumes for the 2002 tsunami source.

As a general comment, it is worth to underline the hazard posed by events like this: small-volume slides can mobilize suddenly along steep slopes, not far from densely populated and industrialized coasts, causing waves that can cause casualties and huge damages on local scale.

Acknowledgments This work has been carried out in the framework of EU-FP7 project ASTARTE, contract no. 603839.

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