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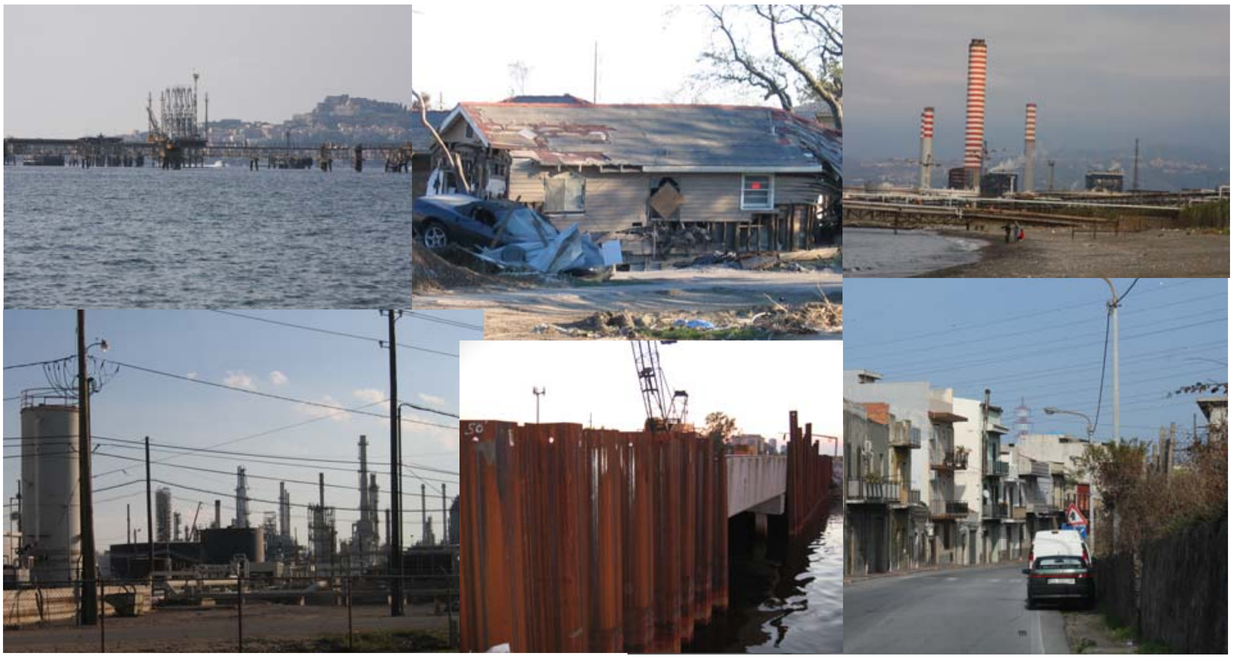
Assessment of Tsunami Risk to an Oil Refinery in Southern Italy

Ana Maria Cruz, Giovanni Franchello, Elisabeth Krausmann



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Tsunami Risk ANd Strategies For the European Region

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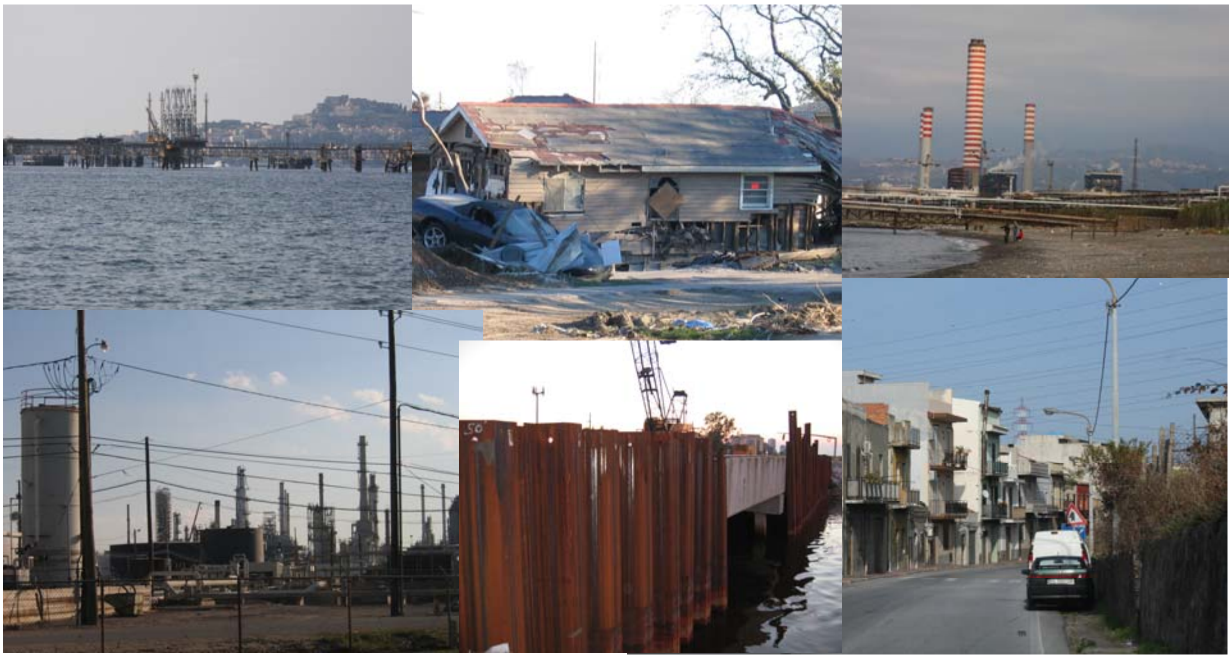

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ASSESSMENT OF TSUNAMI RISK TO AN OIL REFINERY IN SOUTHERN ITALY

ABSTRACT

Industrial facilities located in coastal areas subject to tsunami hazards may be at risk of tsunami impact and damage. Furthermore, if hazardous materials are present these can be accidentally released impacting nearby residents and dispersing into the environment. In this report we present the results of a study which analyzed the potential impact of two tsunamis originating in the Tyrrhenian Sea and their consequences at an industrial facility located on the coast in north-eastern Sicily. The results of the tsunami simulations indicate that in both scenarios there would be eighteen storage tanks (of 43 located within 400 m from the shoreline) at the industrial facility subject to flooding, with tanks closer to the shoreline suffering up to 0.8 m inundation. Flow velocities in most areas are less than 1 m/s. This indicates that any damage would occur due to hydrostatic uplift forces due to buoyancy particularly in the western part of the facility where inundation levels are higher and storage tanks are less protected. Potential damage caused by impact of floating debris may be a problem in an area near the shoreline just west of a pumping station and warehouse (central section of the refinery near the shoreline) due to high flow velocities (3-4 m/s) in both tsunami scenarios. Foundation soils and foundation systems could also be at risk from shear- and liquefaction-induced scour in this section of the plant. The likelihood for hazardous materials releases from inundated storage tanks is low but could occur due to breakage of connected pipelines and flanges due to buoyancy, or due to floating off of almost empty storage tanks and connected pipelines. Flooding of electrical equipment, such as control panels, pumps, and motors not raised above the inundation level could result in salt water intrusion leading to possible short circuit, hampering of safety and mitigation systems, process upsets and possible hazardous materials releases. We conclude however that in the two scenarios studied, the consequences of potential hazardous materials releases, fires or explosions triggered by the tsunamis on nearby residents and neighbouring facilities are likely to be small. Nevertheless, we make recommendations for preventive and preparedness measures that can be taken to reduce the risk of tsunami-triggered Natech accidents and to mitigate their consequences if they do occur.

1. INTRODUCTION

Industrial facilities located in coastal areas subject to tsunami hazards may be at risk of tsunami impact and damage. Furthermore, if hazardous materials are present these can be accidentally released and dispersed into the environment. The oil refinery fires triggered by the 1964 Niigata earthquake and tsunami in Japan serve as an example of the potentially catastrophic effects of a tsunami when it affects a highly industrialized and urbanized area. During this event, a 4 m tsunami was triggered by the 7.5 magnitude earthquake which initially caused fires in five storage tanks and oil spills in hundreds more at two oil refineries in Niigata (Iwabuchi *et al.* 2006). The tsunami hit the already earthquake stricken facility resulting in:

- additional damage to storage tanks and plant processing equipment by collision with tsunami-driven objects and by the hydrodynamic forces of the tsunami (Iwabuchi *et al.* 2006).
- the spread of leaked oil by the tsunami current into the harbor and on inundated land (Iwabuchi *et al.* 2006).
- the spread of burning crude oil carried by the flood waters causing the fires to extend to other parts of the plant including the heating furnace, the heat recovery boiler, the reactor of the catalytic conversion process, the hydrolysis treatment equipment, and the bottom of the hydrolysis reactor for the desulphurization process (Akatsuka and Kobayashi 2008).
- the spread of ignited crude oil carried by the flood waters into residential areas and the destruction of 286 houses by the fire (Iwabuchi *et al.* 2006, Akatsuka and Kobayashi 2008).

The recent Indian Ocean Tsunami of 26 December 2004 illustrates the vulnerability of industrial plants when located in coastal areas; although fortunately most of the areas affected by the tsunami were not heavily industrialized. Nevertheless, the few manufacturing sites that were impacted were severely damaged and hazardous-materials releases did occur. For example, in the city of Banda Aceh, where flood heights reached 9 m (Borrero 2005), two depots of fertilizer and pesticide and an oil retail facility located at the harbour were completely destroyed by the tsunami. Spilled oils and other materials from the damaged facilities dispersed completely into the environment (Van Dijk 2007). Similar tsunami effects were documented at Krueng Raya Harbour and Meuloboh. In Krueng Raya Harbour, where water flood heights were observed at 5 m (Borrero 2005), three of eight oil storage tanks were displaced and their contents lost at an oil storage depot. One of the tanks was found empty at a nearby village. At another oil storage facility at Meulaboh, three of four tanks were moved and the contents of the tanks dispersed. At both locations, Van Dijk (2007) reports the contents of the tanks were washed away and diluted into the sea with little trace. The author documented however a substantial number of filled barrels and some oil slicks at several places in Krueng Raya and as far as 2 km from the harbour.

The Indian Ocean tsunami of 26 December 2004, the third largest natural disaster in recorded human history and the largest to be caused by sea waves (Levy and Gopalakrishnan, 2005), caught many countries by surprise, particularly those that considered their territories tsunami risk free. Following the tragic event, many resources and efforts around the world have been spent on improved tsunami hazard identification and mapping, tsunami vulnerability assessment, tsunami risk assessment and management, and introduction of tsunami hazard reduction methods including improved warning systems (Dareinzo et al. 2005; Jonientz-Triesler et al. 2005; Lorito et al. 2008).

Within this framework the Tsunami Risk and Strategies for the European Region (TRANSFER) project, co-funded under the European Commission's 6th Framework Programme, researches the tsunami risk in Europe by focusing on several geographically different tsunami-prone regions. In the frame of and funded by the TRANSFER project, the Major Accident Hazards Bureau at the Joint Research Centre of the European Commission in Ispra, Italy, has analyzed the potential consequences of tsunami impact on an industrial facility which houses and processes hazardous materials. The work focused on the north eastern coast of Sicily, which has been identified as a tsunami-prone region under the TRANSFER project. Two credible tsunami source scenarios were selected and modelled, and the potential for damage and hazardous-materials releases resulting from the tsunami impacts to an industrial facility located in this area were assessed. Moreover, recommendations for tsunami risk reduction are made. This report describes the results of our study and constitutes part of Deliverable 8.4 of the TRANSFER project.

2. TSUNAMIS

A tsunami is a sea wave of local or distant origin that results from large-scale water-body displacements associated with large earthquakes, major submarine slides, or large volcanic eruptions. It is characterized as a shallow-water wave and differs from wind-generated waves in its period and wavelength. A tsunami can have a period of 5 minutes to 2 hours, and a wavelength in excess of 500km. Wind-generated waves usually have periods of 5-20 seconds, and a wavelength of 100-200 meters (Anderson 2007).

Tsunami waves travel across deep waters at very high speed and are almost imperceptible, but slow down as they reach the coast growing in size. The speed of a shallow-water wave is equal to the square-root of the product of the acceleration of gravity and the depth of the water. The rate at which a wave loses its energy is inversely related to its wavelength. Therefore, because a tsunami has a large wavelength, it will lose little energy as it propagates. Thus, in deep water a tsunami will travel at high speeds propagating across long distances with little energy loss. When it enters more shallow waters near the coast, it undergoes a transformation. Since the speed of the tsunami is related to the water depth, as the depth of the water decreases, so does the speed. However, the total energy remains almost constant. This results in the growing of the height of the wave as it approaches the coastline (Anderson 2007). Because of this "shoaling" effect, a tsunami may grow to be a meter or more in height.

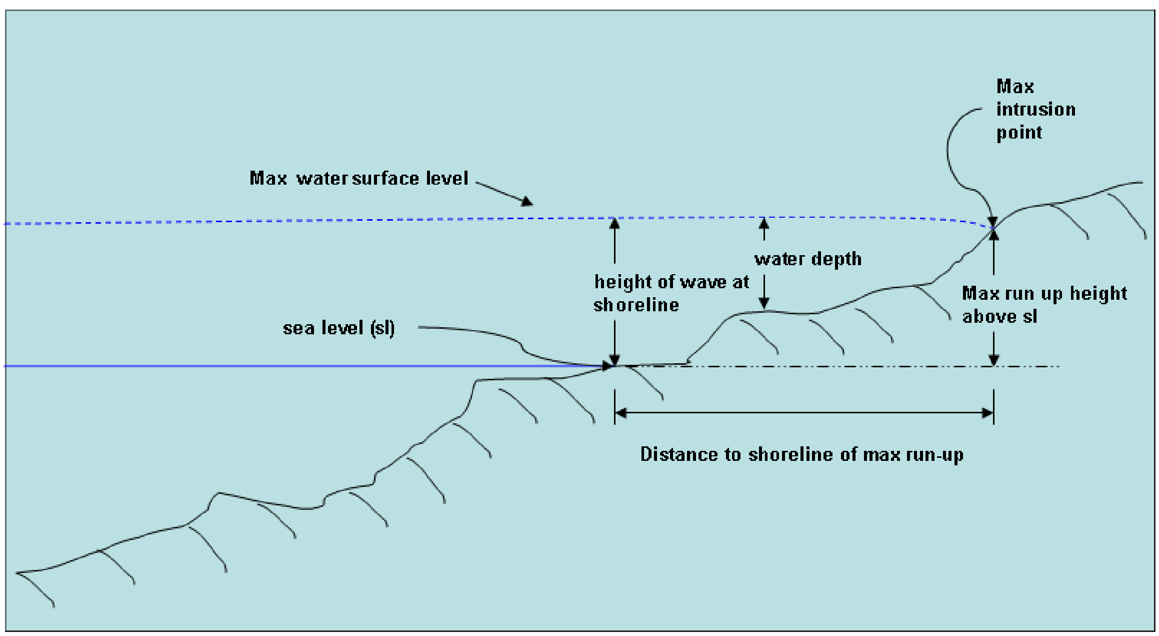

Figure 1. Definition of tsunami inundation terms (adapted from Anderson 2007).

Local bathymetry, undersea features, and the slope at the beach modify the tsunami as it approaches the shore and the effects at the shoreline can change considerably within very short distances. Thus, tsunami characteristics and behaviour at the shore are very difficult to predict (Yen, Robertson, and Preuss 2005). See figure 1 for a definition of tsunami inundation terms. Generally, run-up heights tend to be greatest near where the offshore bathymetry is steeper. Furthermore, if a tsunami approaches the coast during astronomical high tides the run-up heights may be even greater.

3. TSUNAMI HAZARDS IN THE MEDITERRANEAN SEA AFFECTING SOUTHERN ITALY

Tsunamis in the Mediterranean Sea are associated to earthquakes, volcanic eruptions and landslides. The Mediterranean Sea basin is characterized by high seismicity and volcanic activity due to the active lithospheric plate convergence. Furthermore, due to its steep terrain, coastal and submarine landslides are frequent (Papadopoulos and Fokaefs 2005).

Tsunamis in the Mediterranean Sea, although less frequent than those in the Pacific or Indian oceans, have caused extensive damage and loss of life (Lorito *et al*. 2008). There are historical accounts of major tsunamis following large earthquakes such as the M>8 near Crete in 365 AD and 1303; and M>7 in 1222 near Cyprus (Lorito *et al*. 2008). Devastating tsunamis occurred following earthquakes of M=6.9 and M=7.2 in 1783 and 1908, respectively, in the Messina Straights in Italy (Papadopoulos and Fokaefs 2005).

Catalogues of tsunamis affecting European seas have been put together since the 1960s. The most updated tsunami catalogues for the Mediterranean Sea are those of Papadopoulos (2002, 2003) for Greece and surrounding regions, including the Marmara Sea, and Tinti et al. (2004) for the Italian region and the Côte d'Azur (Papadopoulos and Fokaefs 2005).

The updated Italian tsunami catalogue by Tinti et al. (2004) covers the period between 79 AD and the present. It incorporates a detailed revision and evaluation of the original sources of data, integrating and updating a tsunami catalogue published by Tinti and Maramai in 1996. The updated catalogue contains data for 67 tsunamis affecting the Italian seas. More than 50% of these affected Southern Italy.

3.1 Earthquake associated tsunamis

Lorito *et al.* (2008) studied earthquake-related tsunami hazards in Southern Italy. The authors focused on three tsunamigenic source zones: the Tell system in the Algeria-Tunisia offshore capable of generating earthquakes up to magnitude 7.0, the southern Tyrrhenian Sea thrust system capable of triggering earthquakes of magnitude 7.0 and higher, and the Hellenic Arc proven to be capable of generating frequent and occasionally very large earthquakes of magnitude >8.0, respectively located at short, intermediate and large distances from the coasts of southern Italy (see figure 2 from Lorito *et al*. (2008)).

For each zone, Lorito *et al.* identified possible earthquake-related scenarios leading to tsunami. For each scenario they determined the maximum wave heights expected, the average and standard deviation estimates of the maximum wave height due to the set of scenarios pertaining to each zone, and the tsunami travel time maps for each of the investigated tsunamigenic source zones.

The results of Lorito *et al.* indicate that the greatest threat to southern Italy would come from earthquakes along the Hellenic Arc source zone. Waves with average maximum height of 1 m or higher are expected along most of southern and eastern Sicily (from Trapani to Messina) and the south-eastern coasts of the southern Italy peninsula (from Reggio Calabria to Cantanzaro, Taranto, Brindisi and almost Bari). Furthermore, Lorito et al. found that extreme wave height values of 4 m are very common all along the south-eastern coast of peninsular southern Italy. Travel time for waves reaching southern Italy and the south-eastern coasts of Sicily would be between 60-70 min.

Lorito *et al.* determined that earthquakes along the southern Tyrrhenian source zone could produce low energy tsunamis. They estimated the average maximum wave height is around 0.2 m. Waves of 0.5 m and higher would affect only few localities around the northern coast of Sicily such as Palermo, Trapani, and Milazzo. Their results indicated that average wave travel times to these locations would vary between 5-10 min.

The Algeria-Tunisia offshore source zone can generate tsunamis that would have a greater impact on the coasts of Sardinia. Nevertheless, Lorito *et al.* found that the western coast of Sicily (from Cinisi to Sciacca, and between Trapani and Marsala) would be affected by maximum wave heights in the order of 0.5 m. Wave travel times are in the order of 40-50 min.

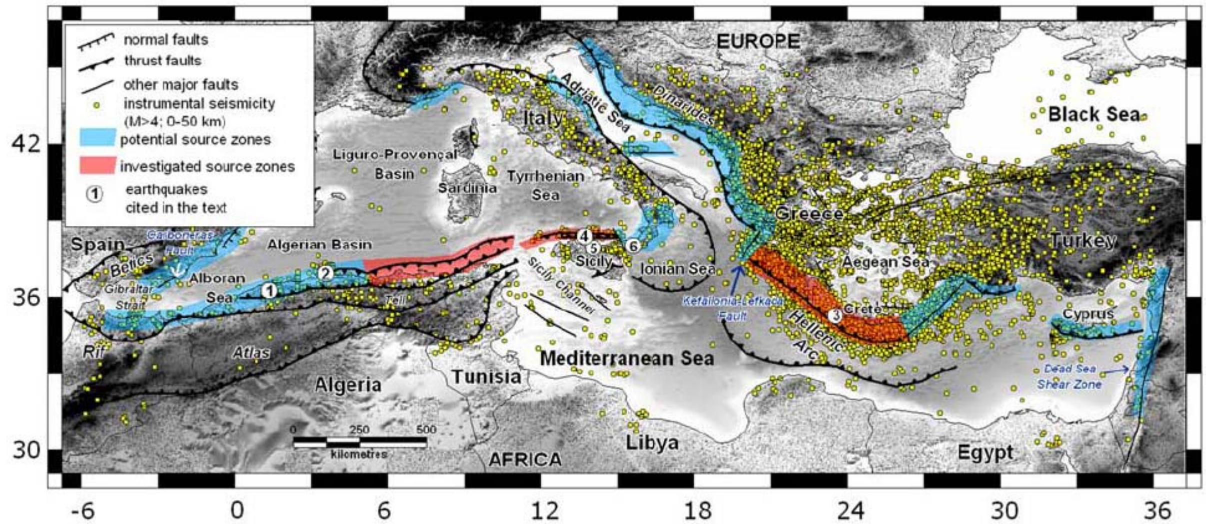

Figure 2. Tectonic sketch map of the Mediterranean basin. Instrumental seismicity (yellow dots; m>4; depth 0-50 km) is taken from the ISC Catalogue (ISC 2004). Color-shaded ribbons highlight the main structures capable of generating tsunamis that pose significant hazard to Mediterranean shore-facing settlements (shown in blue or red. Those shown in red have been investigated in this work). Selected earthquakes are shown with circles: 1) el Asnam, 1980; 2) Boumerdes, 2003; 3) Crete, 365 AD; 4) Palermo, 2002; 5) Northern Sicily, 1823; 6) Messina Straits, 1908.

3.2 Volcano, submarine and land slide associated tsunamis

Tsunami waves resulting from volcanic eruptions, volcano-associated submarine slides and landslides, and mass failure (submarine and land slides) have historically affected the coasts of Italy. These have originated mainly in the Campagna and the Aeolian Islands regions of the country. Approximately, 18 % percent of the tsunamis in the new catalogue of Italian tsunamis (Tinti *et al.* 2004) are volcano associated; less than 3 % are due to mass failure.

Interestingly, the first tsunami in the new Italian tsunami catalogue was generated by the large Plinian eruption of Vesuvius (in Campagna, Italy) in 79 AD, and resulted in the destruction of Pompei and other Roman villages (Tinti et al. 2004). One recent example occurred in December 2002 following a phase of explosive activity of the Stromboli volcano. The tsunami was caused by a massive submarine landslide followed by a subaerial landslide from an elevation of 650 m above sea level on the northwest slope of Stromboli Island (Maramai *et al.* 2005). Tsunami waves as high as 8-10 m were recorded in Stromboli, and smaller waves were observed as far as 170 km at Mondello, northern Sicily and on the island of Ustica.

4. VULNERABILITY OF INDUSTRIAL FACILITIES TO TSUNAMI IMPACT

Tsunami and consequent floodwaters can impose different loads on industrial facility buildings and equipment. These include (Yeh, Robertson, and Preuss 2005):

- Hydrostatic loads, which occur when standing or slowly moving water encounters buildings or a building component. Hydrostatic loads act laterally on an object and always act perpendicular to the surface to which it is applied. It is caused by an imbalance of pressure due to a differential water depth on opposite sides of a structure. Hydrostatic loads increase as the depth of water increases.
- Buoyant loads or vertical hydrostatic loads, which act vertically through the centre of mass of a displaced volume on partially or totally submerged components.
- Hydrodynamic loads, which result from moving water. These loads are a function of water flow velocity and structure geometry. They are induced by the flow of water moving at moderate to high velocity.
- Surge loads, which are caused by the leading edge of a surge of water impinging on a structure
- Breaking wave loads, particularly waves breaking on small-diameter vertical elements (e.g., piles, columns in the foundation of a building or a storage tank), and waves breaking against walls (e.g., breakaway wall, sea wall).
- Impact loading, which results from floating debris such as wood, small boats, portions of houses, vehicles, containers, etc. striking a building, a building component, or equipment.

However, there is little guidance on how industrial facilities can prevent or mitigate tsunami effects. Current structural design codes focus on loadings due to riverine floods and storm waves; providing little guidance for loads specifically induced by tsunami effects on coastal structures (Yeh, Robertson, and Preuss 2005).

This is in part because there is scant empirical data that relates the various damage states (light, moderate, severe, complete) of industrial equipment versus flood water depths and water flow velocities. Furthermore, there are no specific methodologies available to carry out vulnerability and risk assessments of tsunami impact to industrial facilities (Campedel, Antonioni, and Cozzani 2008).

5. METHODOLOGY AND ASSUMPTIONS

Based on tsunami source data for two credible tsunami scenarios provided by the TRANSFER project partners at the University of Bolognia, tsunami flow velocities and run-up heights along the north eastern Sicily coast were modelled by the JRC with the in-house model HyFlux2 (Franchello 2008a, Franchello 2008b, Franchello and Krausmann, 2008). The numerical model was run with a nested grid system: running with a grid size of 400m x 400m in the abyssal plain, 100mx100m in the continental shelf, a smaller grid size (20m x 20m) near the shore, and a fine grid size (5m x 5m) in the run-up zone. The two scenarios were a) an earthquake along the Capo Vaticano fault in Calabria and b) a land-slide at Stromboli. For the scenario a) the source data provided by the partners were the velocity and water surface elevation fields at 100 s, calculated by a finite element model while for the scenario b) the water surface elevation at 0 sec was provided by the University of Bologna.

Data collected for the simulations included digital elevation model (DEM) data at a 100m x 100m grid level (SRTM DTED, 3 arc sec), bathymetry data in the far field at a 1000m x 1000m grid level (SRTM30_plus, 30 arc sec), and in the near field vector data corresponding to isolines - digitalized from a nautical map - for the north eastern coast of Sicily. Isolines were also digitalized for the specific area where a refinery is located, assuming a constant upward slope from the shoreline (0 m) to the railroad tracks that cross the refinery from west to east. Figure 3 presents a map of the digital elevation model used (DEM) for the study region in the near field. ArcGIS was used to store, retrieve and analyze data and maps.

Data about the industrial facility[1] located in the study area was obtained from previous work carried out by Giardina (2000) and through review of safety reports and other pertinent documents. Data on location of processing units, warehouses, and storage tanks including substances stored in them were taken from Giardina. This data was compared with recent satellite images of the industrial facility obtained from Google-Earth. Storage tank dimensions and maximum storage quantities were estimated based on measurements taken from the Google-Earth

[1]The names of the refinery and other neighbouring facilities, as well as the name of the town where they are located, are not disclosed to protect their identities.

satellite image of the refinery using typical height to diameter ratios for large atmospheric storage tanks, and assuming tanks were filled to 75% capacity (Austin 1988; Sinnott 1989). The refinery's official website was also reviewed. Data on total number of storage tanks and quantity of chemicals stored and processed reported on the refinery's website was used to check the accuracy of the estimated tank dimensions.

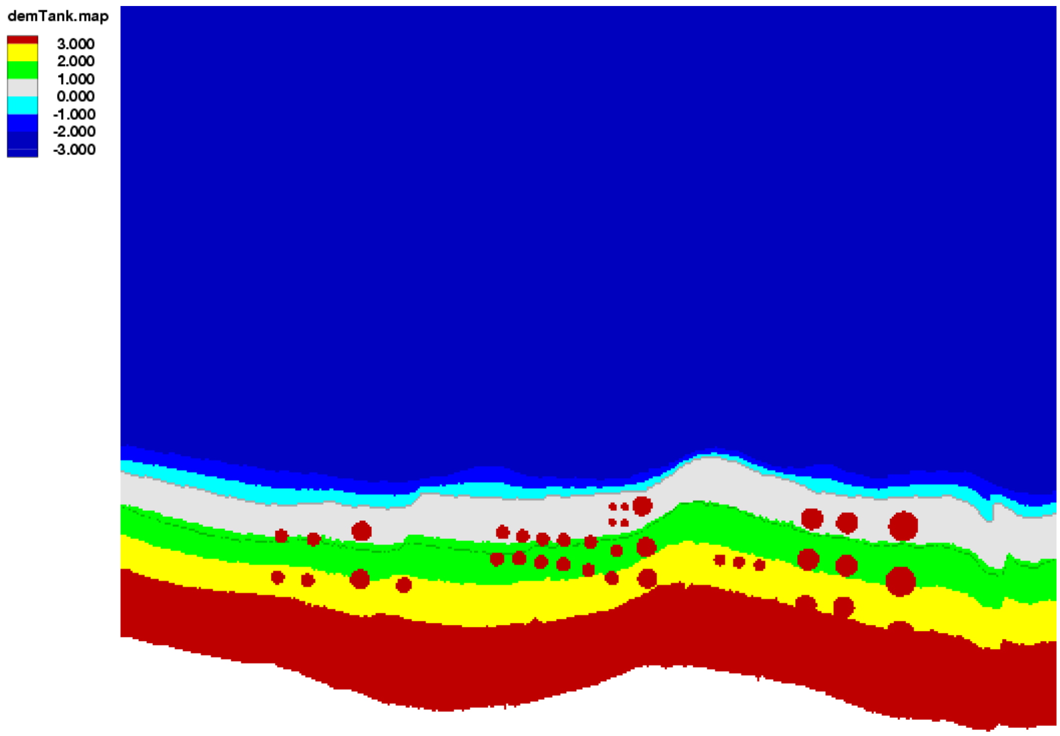

Figure 3. Map of DEM data for the study region. Red dots indicate the location of storage tanks within 400 m from the shoreline.

The weight of each tank was estimated in order to determine buoyancy of empty tanks subject to flooding. In general, weight loads considered for design purposes include vessel shell, vessel fittings (e.g., manways and nozzles), internal fittings (e.g., plates, heating and cooling coils), external fittings (e.g., ladders, platforms), auxiliary equipment which is not self supported (e.g., condensers, agitators), insulation, and the weight of the liquid to fill the vessel (Sinnott 1989). In this particular case we were interested in the total weight of the shell and fittings excluding the contents. The total weight of a steel cylindrical vessel with domed ends, and uniform wall thickness excluding internal fittings such as plates can be calculated with equation (1) (Sinnott 1989):

$$W_v = 240C_vD_m(H_v + 0.8D_m)t \qquad \text{Eq. (1)}$$

where

C_v = a factor to account for the weight of nozzles, manways, etc.

D_m = mean diameter of vessel, m

H_v = height, or length, m

t = wall thickness, mm

The tank wall thickness, t, required at depth H_L of liquid can be estimated with equation (2) (Sinnott 1989):

$$t = \rho_L*H_L*g*D_t/(2*f_t*J*1000) \qquad \text{Eq. (2)}$$

where

H_L = liquid depth, m

ρ_L = liquid density, kg/m^3 (should assume 1000 kg/m^3)

J = joint factor (if applicable)

g = gravitational acceleration, 9.81 m/s^2

f_t = design stress for tank material, N/mm (for carbon steel/ stainless steel the values range from 135 to 165)

D_t = tank diameter, m

Eq. (1) provides a good estimate of the weight of the tank. For the calculations the liquid depth was assumed to equal the tank height (estimated height from GoogleEarth). The mean diameter of the vessel was assumed to equal the estimated tank diameter (estimated diameter from GoogleEarth). In general when refinery specific data was not available, typical generic data for this type of facility was used for the calculations.

Interviews with the industrial facility's managers and engineers were requested. However, at the writing of this report, the interviews had not been granted. A field visit to the refinery was performed by colleagues from the JRC. The field visit was carried out in order to collect data on altitudes (elevation above sea level) and latitude/longitude coordinates (with a hand held GPS) at various reference points to compare and validate topographic (DEM) data used for the tsunami inundation modelling. Furthermore, features that might influence tsunami wave propagation and inundation were documented. The field visit included data collection offsite and did not include an onsite visit as the refinery did not reply to our written request.

The risk assessment methodology included hazard identification and characterization for the two tsunami scenarios proposed, determining exposure and vulnerability of the industrial facility components (mostly storage tanks near the shoreline) to the tsunamis.

6. SCENARIO DEVELOPMENT AND ANALYSIS

Two credible tsunami scenarios were developed and its impacts analyzed. Initial tsunami conditions for both scenarios were provided by the TRANSFER partners at the University of Bologna. The first scenario is a tsunami triggered by an M_w 7.0 earthquake along the Capo Vaticano fault near Calabria studied by Piatanesi and Tinti (2002). This fault line is believed to be the source of an earthquake and tsunami in Calabria on 8 September 1905 which devastated many towns and villages and resulted in more than 500 victims. The tsunami source conditions were provided in the form of an ANSI file containing data on longitude, latitude and wave amplitude in meters. The wave amplitudes were input into the in-house HyFlux2 model for the tsunami simulation.

The second scenario is a tsunami triggered by a landslide at the Stromboli Volcano as studied by Tinti et al. (2003). Initial conditions were provided as an ANSI file containing 5 columns including longitude, latitude, x-component of the velocity, y-component of the velocity, and wave amplitude. The information provided by the University of Bologna was computed by means of a numerical model based on a Lagrangian approach (see Tinti et al. 2003 for a full description).

The data provided was not indeed a pure initial condition, because the generation of a tsunami by a landslide is not an instantaneous process, but the forcing takes place over a finite time interval. The data provided represent the tsunami field at a time (100 s) after which it is reasonable to assume that the forcing due to the landslide is over and that what remains is the pure tsunami propagation.

The wave amplitude and velocity components were input into the HyFlux2 model for the tsunami propagation and run-up simulations. Note that for the landslide scenario not only the wave amplitude but also the velocity components were input to the model.

There are several large oil refineries located along the northern and southern coasts of Sicily, as well as in the southern peninsula of Italy, and they are therefore subject to tsunami hazards as was described in section 2. In this study we are interested in assessing the risk of tsunami impact to a refinery located in north-eastern Sicily as it would be exposed to tsunamis from these two scenarios.

In the following sections we briefly describe the oil refinery and the critical target equipment. We discuss the development of each tsunami scenario, and for each scenario we analyze the tsunami wave propagation and its potential impact at an oil refinery along the north-eastern coast of Sicily. Based on the tsunami modelling results, we assess the potential damage and hazardous materials release that could result at the refinery.

6.1 Description of the oil refinery

The refinery of interest processes about 10 million tons of crude oil per year. The refinery produces gasoline and naphtha fuels, kerosene, propylene, gas and fuel oils, liquefied petroleum gas (LPG), and other hydrocarbons which serve as a prime materials for the petrochemical industry.

The refinery consists of the following sections (see figure 4a and 4b):

- Processing: atmospheric and vacuum distillation units, and catalytic reforming unit, hydrocracking unit and hydrodesulfurisation unit, among others.
- Storage farm: 127 storage tanks with capacity of over 3.75 million m^3 for prime materials, intermediate products and finished products. Figure 4c shows the main storage tanks at the refinery indicating a tank identification (ID) number.
- Port terminals: Two jetties used for loading and unloading tankers of up to 420,000 DWT (Dead Weight Tonnage). The port terminals have a maximum crude oil reception rate capacity of 15,000 tons per hour. It moves about 570 ships per year (max. capacity is 900

ships/yr). Through the two port terminals it moves approximately 12 million tons per year of crude oil and other products.

- Utilities: such as boilers, cooling towers, and process air.
- Mitigation systems: for atmospheric and marine pollution.

6.1.1 Topography

The refinery occupies an area of about 2 km^2. It is located along a stretch of coast line about 1.5-1.7 km from west to east along the eastern part of a bay. It is bounded by residential areas on its western end and along the western and south western edges. The distance from the shoreline to the refinery fence line in the western most tip of the refinery is about 80 m at an elevation of 1-1.5 m. The western end of the refinery on the shoreline is flat, and in fact the storage tanks and other equipment that are visible across the fence line are slightly below this level. See figures 5 and 6.

The eastern end of the refinery on the shoreline and the eastern sides are bounded by a power plant. The south-eastern corner is bounded by a small road and a highway. The southern part of the refinery is bounded by a small road, becoming residential towards the west. The distance between the shoreline and the refinery fence line at the eastern end is about 20 m, at an elevation of 2-2.5 m. Some soil erosion and scouring along the refinery fence line was noted on the eastern end (see figures 7 and 8). At the south eastern corner (point inland) of the refinery we estimated the elevation to be about 12-18 m. At the area where the railroad tracks cross over to the neighbouring power plant we estimated the altitude to be about 8-15 m. Figure 9 summarizes the observed distances and elevations at various points around the refinery.

The field observations from outside the fence line of the refinery indicated that the DEM data used for the tsunami modelling sufficiently approximates the elevations near the rail road tracks but was less accurate in representing elevations near the shoreline. This undoubtedly adds uncertainty to the tsunami modelling results. Nonetheless, the DEM data used was the best data available for the simulations.

6.1.2 Storage tanks and tsunami protection measures

There are over 30 large storage tanks less than 200 m from the coastline at the refinery. Other features located on or near the coastline include the refinery's two port terminals (see item no. 10 in figure 9), a warehouse, pumping station and 3 water storage tanks (item no. 9 in figure 9), and parts of the distillation unit (item no. 11 in figure 9).

The storage tanks on the eastern side (both near the shoreline and towards the southern end) of the refinery (tank ID 52-58), used for crude oil storage, all have earthen containment dikes of 3-4 m in height (see figures 10 and 11). Storage tanks on the western side of the plant (tank ID 0, 1, 6, 7, 10, 11, 15, 18, 120, 121 and 31), used for storage of intermediates and finished product, appear to have 0.8-1m high brick and concrete walls. During the field visit, containment walls or dikes were only partially visible from our vintage point outside the refinery. We assume that the walls are present around all storage tanks as this is general practice (see figures 12 and 13).

At the shoreline there are no visible tsunami protection measures such as break walls, or other type of barriers. On the eastern end there is a natural earthen barrier about 4-5 m in height, 2-3 m in width, and about 30-40 m in length. However, it has been dug into to allow for placement of piping and other equipment. Thus it would provide little flood protection. It could however provide some protection from debris impact to the exposed pipelines. The earthen barrier has been subject to soil erosion (see figures 14 and 15). The fence surrounds the entire refinery. On the shoreline, the fence is supported by a small brick and concrete wall (0.5m x 0.15m, see figures 15 and 16), designed to keep intruders out, but not water. The support wall for the fence is no longer visible in some areas (due to sand dunning, see figures 15 and 16). The fence support wall on the southern and eastern sides of the refinery (inland) stands high, about 2m in height.

6.1.3 Port terminals

There are two port terminals that go into the sea to a distance of about 350-400 m. There were two large ships moored at each one at the time of the site visit. Loading arms were visible from the shoreline (figures 17 to 19). The port terminal area is open, without any break-walls, or natural features to protect the ships from wave action.


Stoccaggi prodotti finiti
Stoccaggi prodotti finiti
Magazzini
Magazzini
Tap
Merox Kerosene
Stoccaggi prodotti finiti
Topping 4
Stoccaggio gasolio
Topping 3
Topping 3
Desolforazione
Stoccaggi prodotti finiti
Stoccaggio gasolio
Stoccaggio gasolio
Reforming catalitico
Recupero gas
FCC
Stoccaggi vari
Stoccaggi GPL
Stoccaggi prodotti finiti
Vacuum
Vacuum
Stoccaggi GPL
Stoccaggi GPL
Stoccaggi vari
Stoccaggi vari
Recupero Zolfo
Uffici
Laboratorio
Serbatoi stoccaggio
Stoccaggio oli
Sala pompe
TAZ
Magazzini
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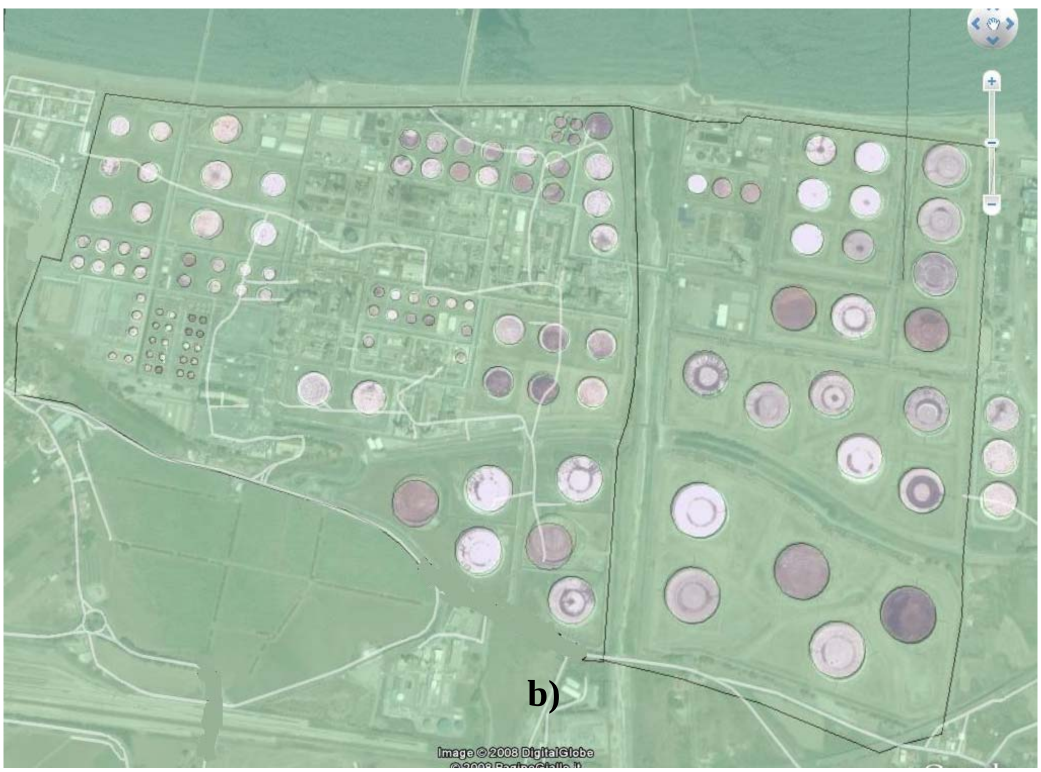
a)


b)
Image © 2008 DigitalGlobe

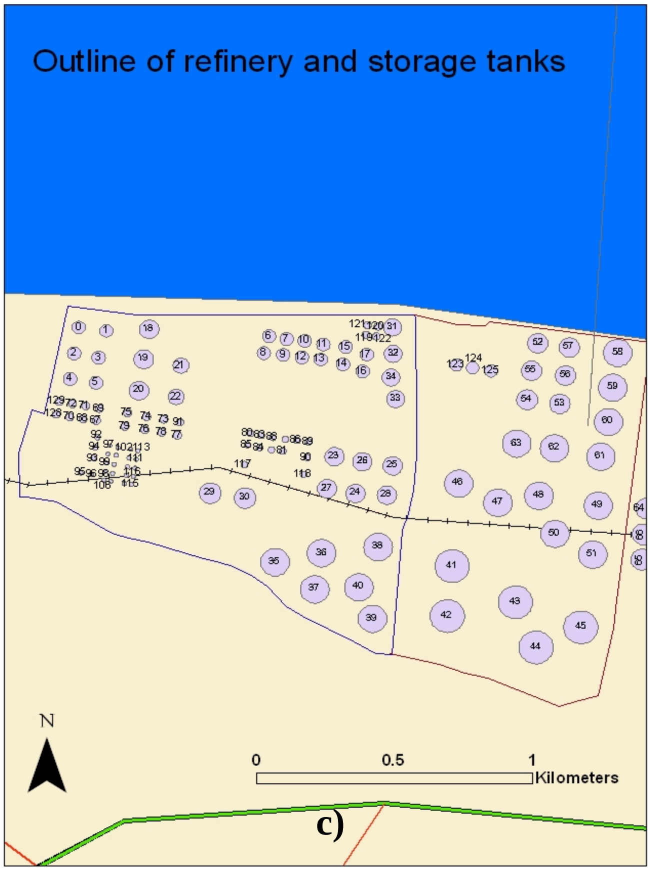


Figure 4. a) Floor plan of the refinery (Giardina 2000); b) satellite image showing distribution of storage tanks; and c) storage tank identification (ID) numbers.

6.1.4 Residential areas and other facilities

There are residential areas neighbouring with the refinery on its western and south western sides. Any oil spills on the shoreline during a tsunami would likely be transported by wave action (water inundation) into a nearby port area and inundated residential areas to the west of the refinery (figures 20 to 23). On its eastern side the refinery is bordered by a power plant. The power plant is located about 30-40 m from the shoreline at an elevation of about 2-2.5m. However, it appears that several buildings and equipment at the power plant are below the 2m level. The land around the power plant was flat, with an increase in elevation to about 5-8 m at its southern end. There are no visible tsunami (or wave action) protection measures (see figures 24 and 25).

Figure 5. View of the refinery shoreline at the western end. The refinery starts where the people are fishing. Distance between shoreline and refinery at this point is about 60-80 m.

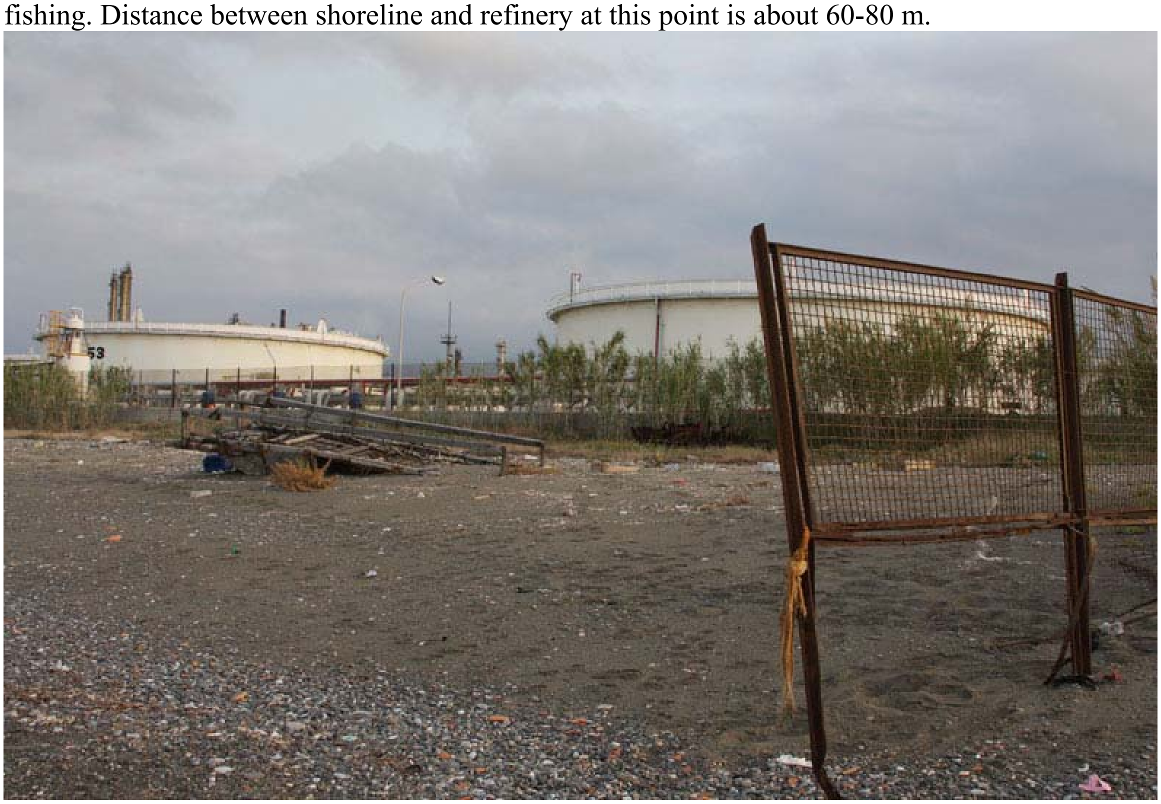


Figure 6. Fence at the shoreline indicating where the refinery shoreline begins. Elevation above sea level at horizontal fence line along the shoreline of the refinery is about 1-1.5 m.

Figure 7. View of the refinery along the eastern side facing the power plant. Distance from the shoreline to the refinery at this point is about 20 m, and elevation above sea level about 2-2.5 m. Some soil erosion and scouring along the refinery fence line was noted.

Figure 8. View of shoreline from eastern tip of refinery looking towards the west. Notice distance from refinery fence line to shoreline contracts to about 10m.

Figure 9. Satellite photo of the refinery. 1- Western end of the refinery at the shoreline, distance between water line and refinery fence line is approximately 60-80 m, elevation is 1-1.5 m. 2- Eastern end of the refinery at the shoreline, distance between water line and refinery fence line is approx. 20m, elevation is 2-2.5 m. 3- Distance between water line and refinery fence line at this point is approximately 5-10 m, elevation is 1m. 4. Eastern side of the refinery neighbouring with the power plant, elevation is 5-8 m. 5- Eastern-south part of the refinery neighbouring with the power plant, elevation is 12-18 m.6- Warehouses and other small buildings neighbouring the refinery on the north western edge. Distance to the shoreline is approx 60-80 m and elevation 1-1.5 m. 7- Shoreline area in front of the power plant, distance to the shoreline is approx. 30-40 m, and elevation is 2-2.5 m. 8- Southern end of the refinery at the open canal. Elevation at this point is approx. 15-18 m. 9- Warehouse, pumping station, and 3 water storage tanks. 10. Refinery port terminals. 11- Distillation unit.

Figure 10. Earthen dikes around these four storage tanks (in the background) located at the south eastern corner of the refinery.

Figure 11. Refinery fence line along the eastern side of the refinery (neighboring with the power plant), and the 4m high earthen wall around a storage tank.

Figure 12. Storage tank for finished product on western end of the refinery near the shore line. No earthen dikes around this tank.

Figure 13. Storage tanks for finished product on western end of the refinery. Concrete containment dike is visible around tank no. 53 in this photo, and appears to be about 0.8-1 m in height.

Figure 14. Front view of natural earthen barrier (approx. 4 -5m in height) at the eastern edge of the refinery at the shoreline. Some soil erosion is evident.

Figure 15. Side view of the natural earthen barrier shown in figure 6. Soil erosion is evident from this photo as well as sand dunning over fence line.

Figure 16. Refinery fence line along the shoreline. Notice that in some areas the fence support wall is no longer visible as it has been partly covered by sand.

Figure 17. A ship docked at one of the port terminals (west) at the refinery.

Figure 18. A ship docked at one of the port terminals (east) at the refinery.

Figure 19. Loading arms are visible in this photograph at the port terminals of the refinery.

Figure 20. Residential area on south-western side of the refinery.

Figure 21. Beach and residential areas neighboring refinery on its western side.

Figure 22. View of port area to the west of the refinery.

Figure 23. Residential area (beach front property) near the western side of the refinery. Notice that road is at a slightly higher elevation than the homes in the background. Elevation here is about 1.5 m.

Figure 24. View of neighbouring power plant to the east of the refinery. Distance from water line to power plant fence line is approximately 30-40 m, elevation is 2-2.5m.

Figure 25. Beach front part of the power plant neighbouring with the refinery.

6.2 Earthquake-triggered tsunami

The first scenario constructed for the study corresponds to a tsunami triggered by an M_w 7.0 earthquake along the Capo Vaticano fault in the Bay of Saint Eufemia, Calabria, according to a study by Piatanesi and Tinti (2002) (figure 26).

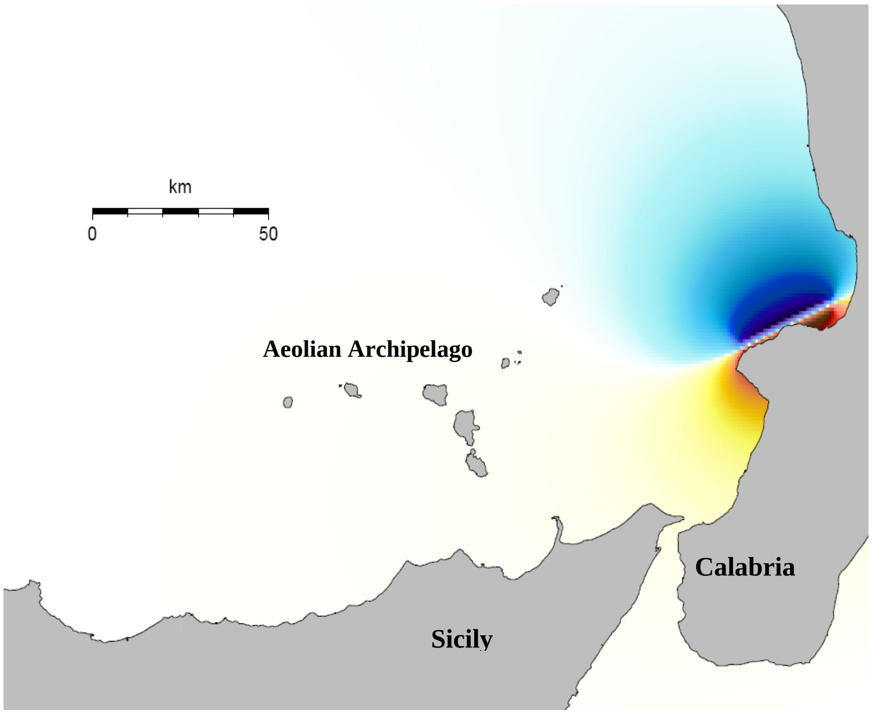


Figure 26. Initial conditions of the earthquake-triggered tsunami along the Capo Vaticano fault. Courtesy of the University of Bologna. Blue indicates water surface level below sea level, red indicates water surface level above sea level.

Although the Capo Vaticano fault is about 75 km from the area of interest, the earthquake would be felt at in the north-eastern part of Sicily. Modified Mercalli Intensity (MMI) values in this area for the earthquake were estimated at VI-VII (Guidoboni et al. 2007) based on historical records of a similar earthquake in Calabria on 8 September 1905. Previous earthquake experience shows that the likelihood of moderate damage (e.g., failure of some connected pipelines, repairable damage to tank support systems; moderate likelihood of release of tank contents) at these MMI levels would be low, less than 5% according to tables published by Seligson et al. (1996). Thus, the facility would most likely experience no damage or just light damage such as slight movement of tanks from tank supports due to the earthquake forces. No hazardous materials releases would be expected from this earthquake.

Using the initial conditions provided by University of Bologna, the results of our tsunami propagation modelling show that the earthquake would produce a large tsunami wave which would propagate across the South-eastern Tyrrhenian region affecting Calabria, the Aeolian archipelago, and northern Sicily. The first positive wave would arrive the area of interest approximately after 27 min. The tsunami wave would be approaching the coastline laterally from east to west, impacting the port terminals perpendicularly. The maximum wave height at the port terminals would be about 1.2 m above normal tide; with about a 2-2.5 m differential between the wave crest and trough.

The maximum water surface level at the shoreline of the refinery would vary between 1m and 1.2 m (see figure 28a). The water flow velocity at the shoreline would vary between 0.5 m/s to 4 m/s. The area immediately to the west of the warehouse and pump station would experience the highest water flow velocities (see figure 29a). In general the western half of the refinery experiences higher water flow velocities than the eastern half.

The distance to the sea of the maximum water run-up is estimated at about 140m; the area between the two port terminals would be inundated the greatest distance inland (see figure 30a). This area would also suffer the highest water run-up (see figure 31a). In general the western half of the refinery would experience greater run up heights, between 1.2m - 1.30m, than the eastern end, which would be subject to maximum run up heights of 1m - 1.2m.

There would be eighteen large storage tanks subject to flooding. Figure 32a) maps the storage tanks and the maximum water run-up. Figure 33a) shows the storage tanks and the maximum water flow velocities, and figure 34a) shows the storage tanks and maximum loads. As indicated above, the western half of the refinery is subject to higher water run-up heights and higher water flow velocities than the eastern half. For this scenario maximum water loads appear uniform along the coast. However, loads near the shoreline are higher than further inland. Thus, the storage tanks closer to the shoreline (ID. 18, 120 and 121) would experience higher loads.

6.3 Landslide-triggered tsunami

As was described in section 3, recent research has demonstrated that the Stromboli Volcano has the potential to produce large catastrophic tsunamis and that its effects would be felt along the northern coast of Sicily (Tinti et al. 2003). Based on the initial tsunami conditions provided by the University of Bologna, a landslide-triggered tsunami at Stromboli was modelled. Figure 27 shows the location and initial conditions of the landslide-triggered tsunami.

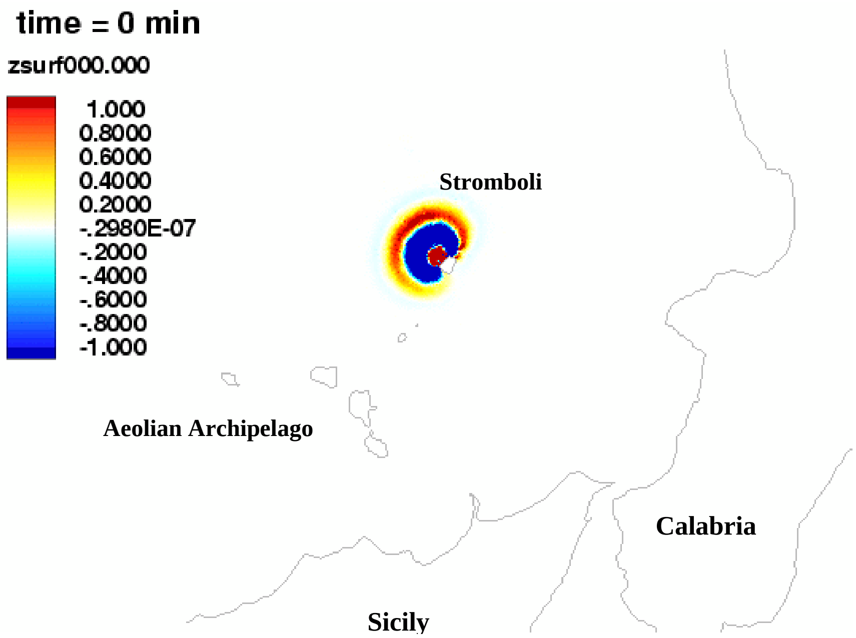


Figure 27. Initial conditions of the landslide-triggered tsunami at Stromboli input into the HyFlux2 tsunami model. Note: Time = 0 for our tsunami modelling with HyFlux2. However, the input data used for the modelling represents the tsunami field at a time = 100 s after which it is reasonable to assume that the forcing due to the landslide is over and that what remains is the pure tsunami propagation.

The results show that the modelled landslide at Stromboli would generate a large tsunami wave which propagates towards the south-eastern Tyrrhenian region affecting Calabria, the Aeolian archipelago, and northern Sicily. The first positive wave would impact the refinery after about 17 minutes. The tsunami wave would approach northern Sicily from north to south, thus impacting the coastline at the refinery perpendicularly. The maximum wave height at the port terminals would be between 0.5-0.8 m above normal tide with about a 1.2-1.8 m differential between the wave crest and trough.

The maximum calculated water surface level at the shoreline at the refinery would be lower than for the Capo Vaticano scenario, varying between 0.4m and 1.0m (see figure 28b). However, the maximum water flow velocity is generally higher, varying between 1.0 m/s to about 4 m/s. Peak water flow velocities are higher in the area immediately to the west of the warehouse and pump station (see figure 29b). The distance to the sea of the maximum water run-up varies between about 80m to a little over 160m. The area between the two port terminals would be inundated the greatest distance inland (see figure 30b), experiencing also the highest maximum water run-up (see figure 31b). In general, and similar to the Capo Vaticano scenario, the western half of the refinery would experience higher water run-up, between 1.20m - 1.60m, while the eastern half is subject to water run up heights of 0.8m - 1.0m.

In this scenario there would also be eighteen storage tanks exposed to flooding. Storage tanks near the shoreline and the maximum water run-up are shown in Figure 32b. The storage tanks located on the western half of the refinery, particularly the area between the two port terminals are subject to higher run-up heights. The area beyond the eastern side of the refinery, where the power plant begins, would be subject to water run-up of about 1.4m.

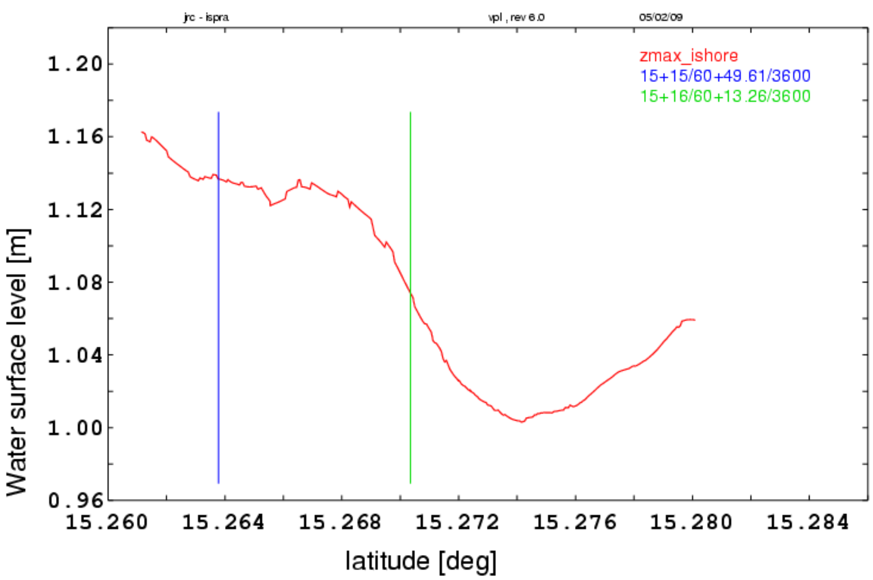
Figure 33b shows the storage tanks and the maximum water flow velocities. The areas subject to the highest run-up heights are also subject to the highest water flow velocities, as in the Capo Vaticano tsunami scenario. However, in this case, the highest water loads (hydrostatic + hydrodynamic) are not evenly distributed, but would be higher in the western half of the refinery and the eastern end beyond the refinery fence line (see Figure 34b).

7. DISCUSSION

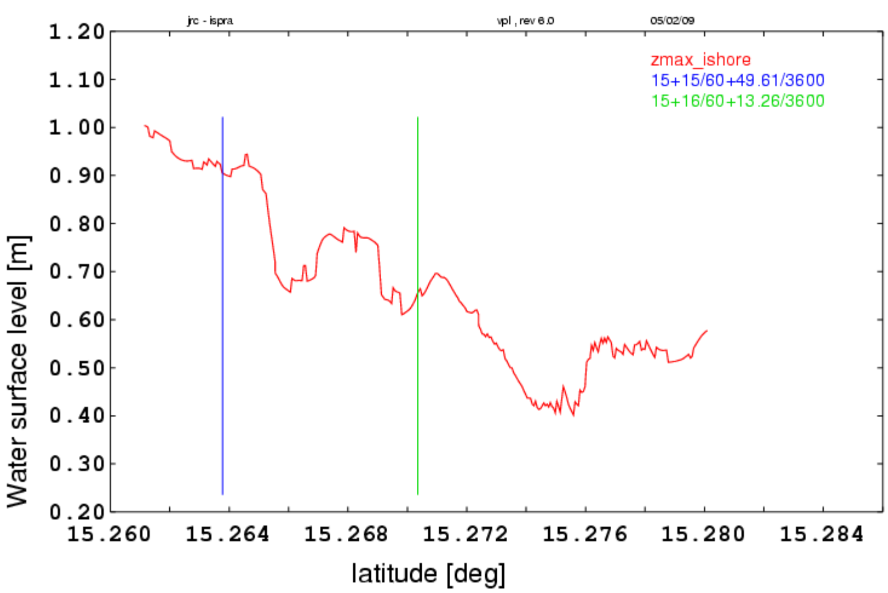
In these two hypothetical, but probable, tsunami scenarios there could be up to 18 storage tanks affected by flooding. Both tsunami scenarios are consistent in that they indicate higher exposure to flooding of the western half of the refinery, and in particular the area between the two port terminals. Over all, the Stromboli tsunami produces slightly higher water flow velocities, while the Capo Vaticano tsunami results in greater water depths at the exposed tanks (see Table 1).

In order to understand the potential impact of the modelled tsunami scenarios at the refinery the vulnerability of the exposed equipment needs to be assessed. However, there are only scarce simplified equipment damage models available in the literature to assess damage probabilities of industrial equipment due to tsunami impact or flooding. Campedel et al. (2008) have proposed flood vulnerability curves for industrial equipment. The equipment vulnerability curves were developed based on past flood events correlating different damage states for different types of industrial equipment (e.g., anchored and unanchored atmospheric storage tanks, pressure vessels) with the maximum water depth and the square of the water flow velocity. Thus, the computed maximum water depth and the maximum water flow velocities for both simulations were used to determine an equipment vulnerability index (ranging from 0 – low probability of damage to 5 –

high probability of damage). The values were read off the vulnerability curves published by Campedel et al. (2008) which are presented in figure 35. The results are shown in table 1.

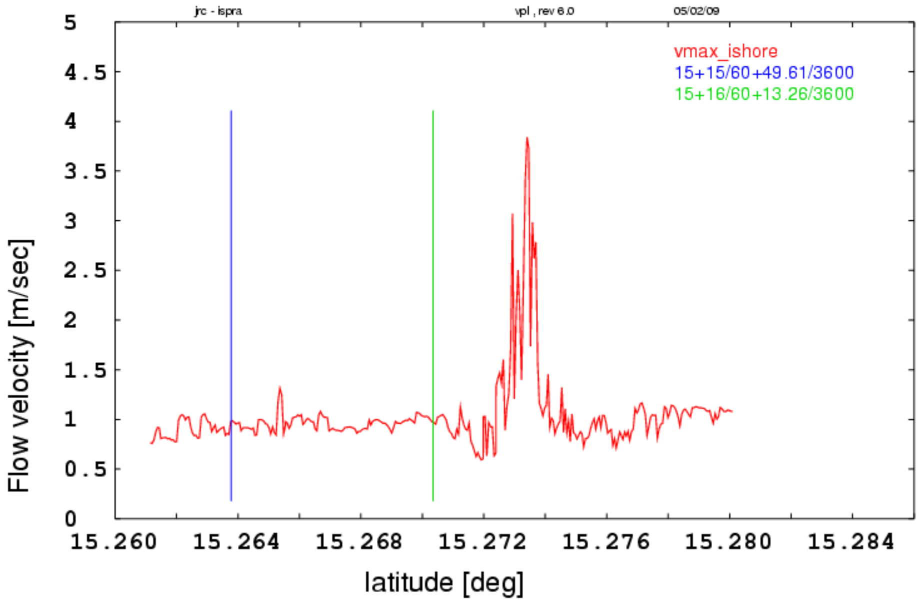


a) Maximum water surface level in the shoreline

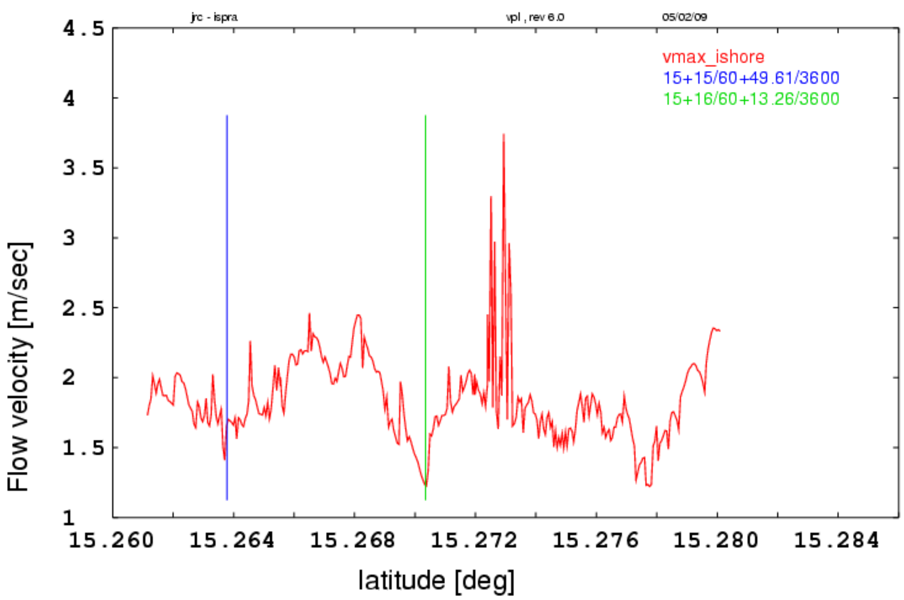


b) Maximum water surface level in the shoreline

Figure 28. Maximum water surface level (water run-up) at the shoreline of the refinery for a) Capo Vaticano and b) Stromboli tsunamis. The blue and green lines mark the location of the two port terminals.

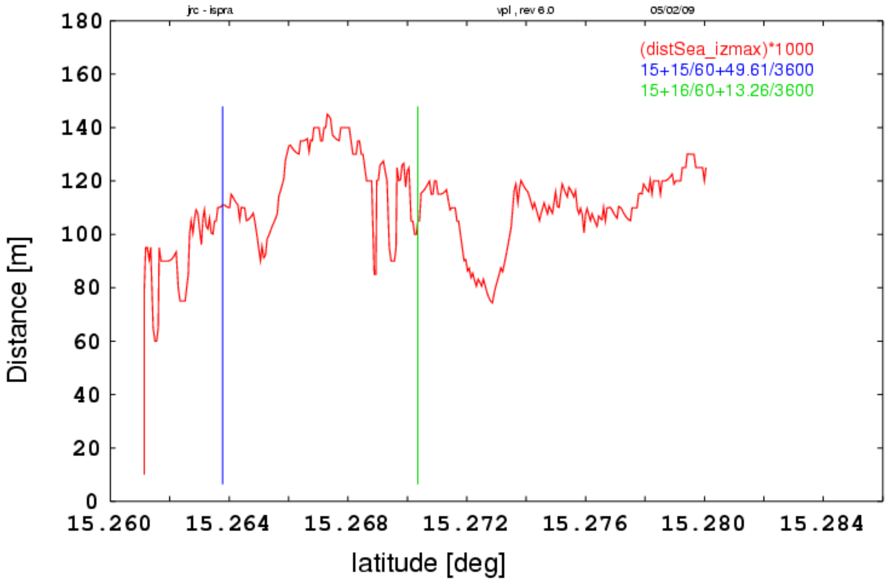


a) Maximum water velocity in the shoreline

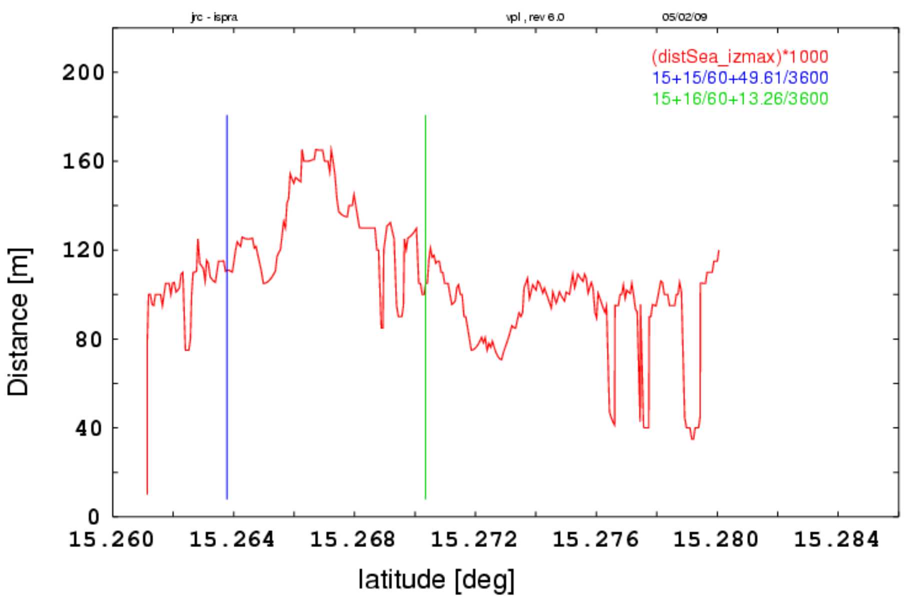


b) Maximum water velocity in the shoreline

Figure 29. Maximum water flow velocity at the shoreline of the refinery for a) Capo Vaticano and b) Stromboli tsunamis. The blue and green lines indicate the location of the two port terminals.

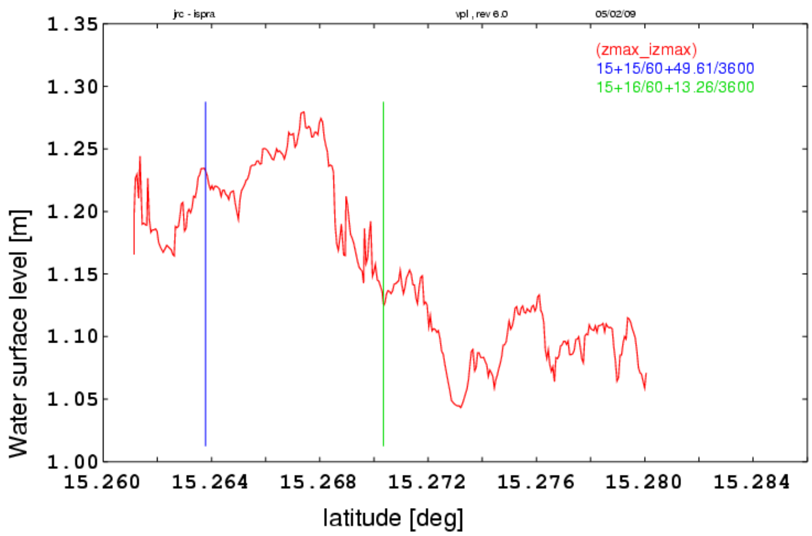


a) Distance to the sea of the maximum water runup

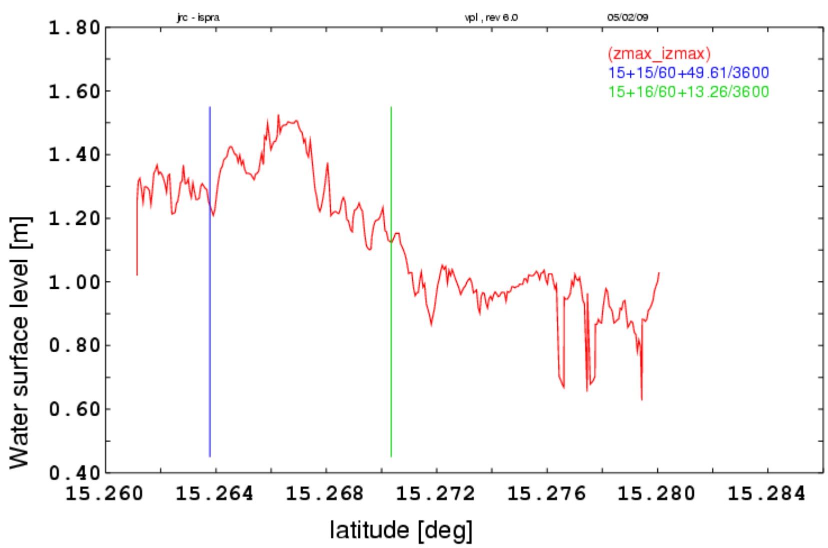


b) Distance to the sea of the maximum water runup

Figure 30. Distance to the sea of the maximum water run-up along the refinery for a) Capo Vaticano and b) Stromboli tsunamis. The blue and green lines indicate the location of the two port terminals.

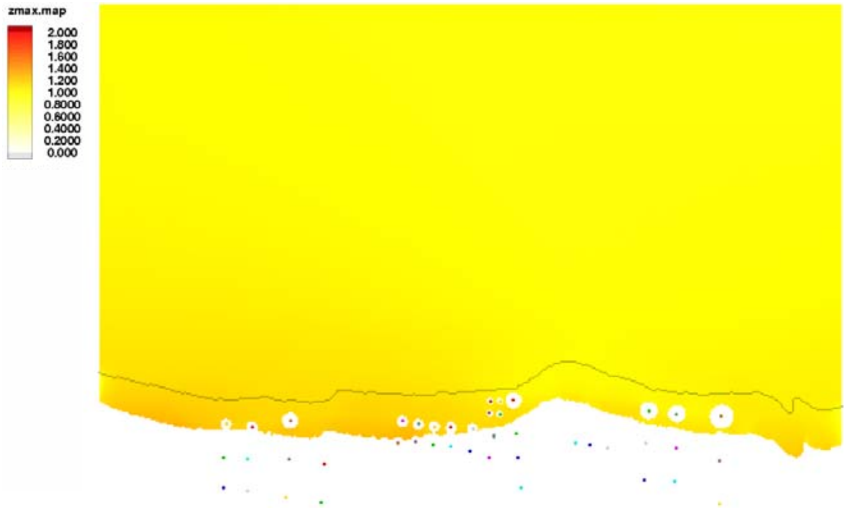


a) Maximum water runup

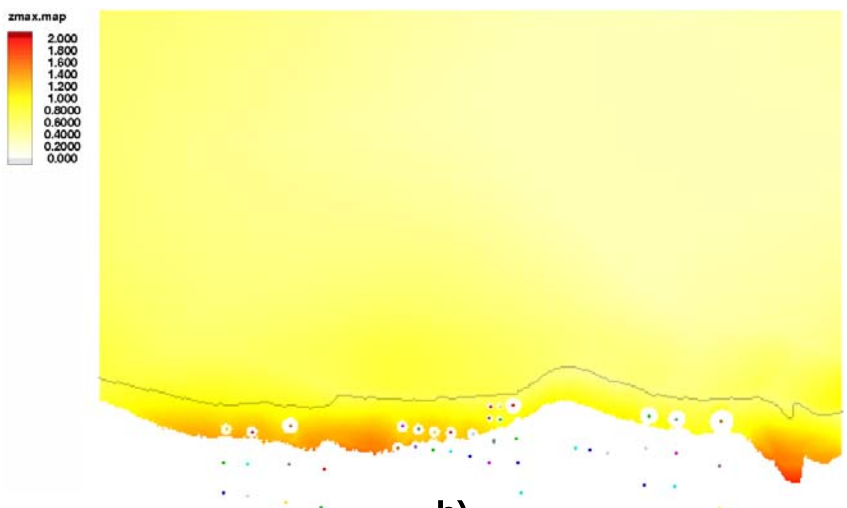


b) Maximum water runup

Figure 31. Maximum water run-up along the refinery for a) Capo Vaticano and b) Stromboli tsunamis. The blue and green lines indicate the location of the two port terminals.

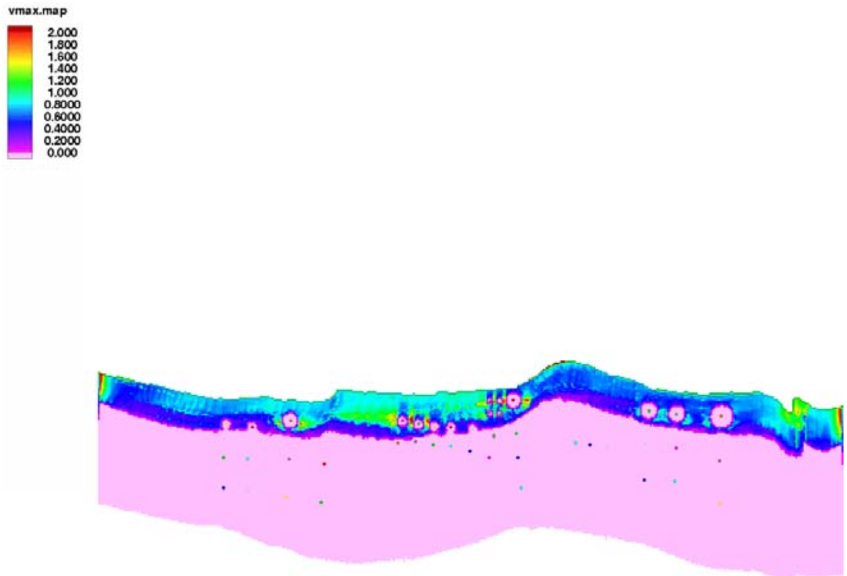


a)

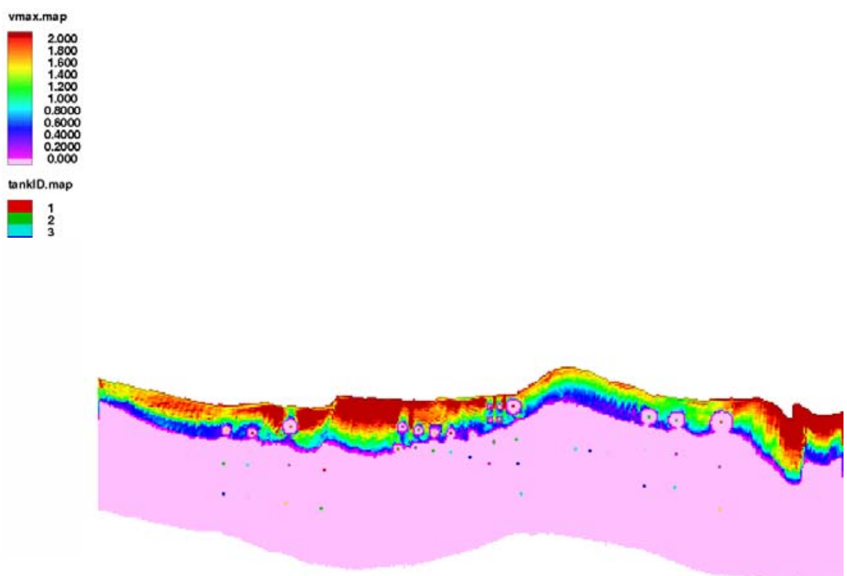


b)

Figure 32. Map of storage tanks near the shoreline showing the maximum water run-up (maximum water surface level a.s.l.) for a) Capo Vaticano and b) Stromboli tsunamis.

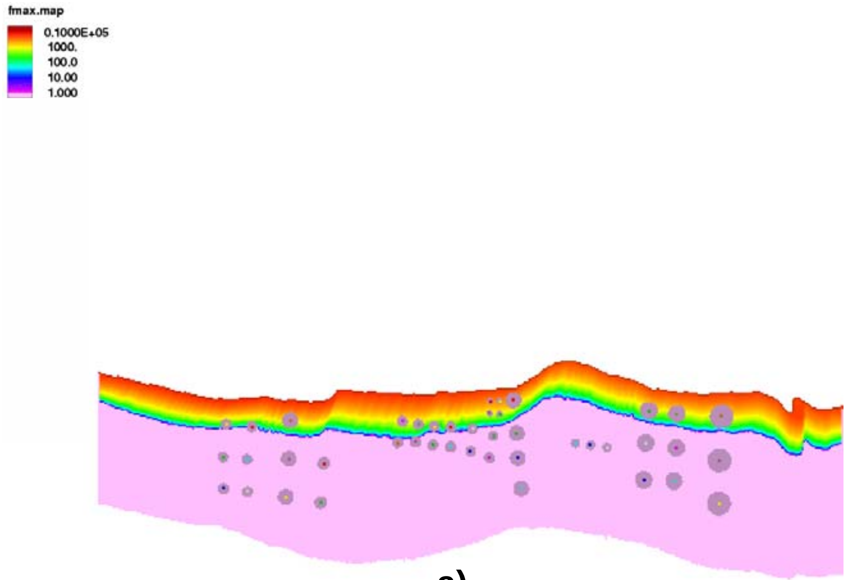


a)

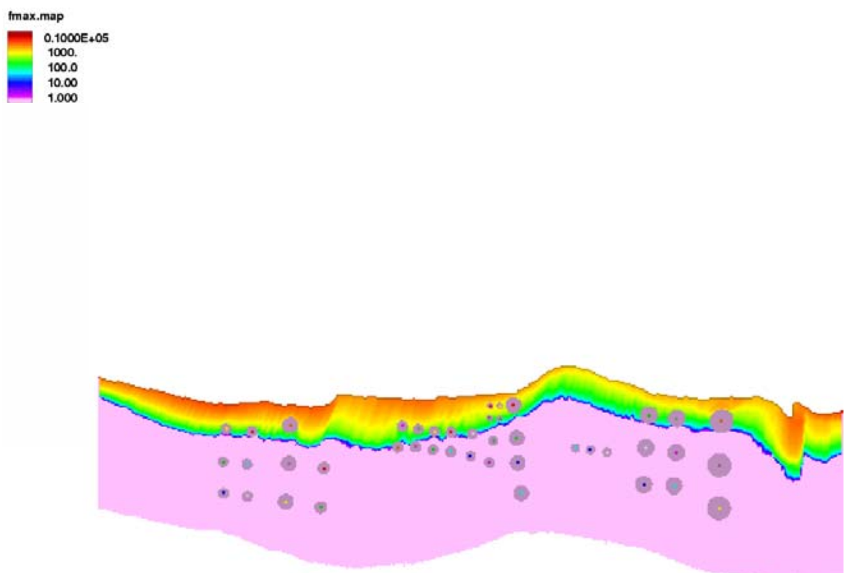


b)

Figure 33. Map of storage tanks near the shoreline showing the maximum water flow velocities for a) Capo Vaticano and b) Stromboli tsunamis.



a)



b)

Figure 34. Storage tanks near the shore and maximum loads (hydrostatic + hydrodynamic) for a) Capo Vaticano and b) Stromboli tsunamis.

Because the equipment vulnerability curves produced by Campedel et al. were developed based on limited empirical data (mostly from riverine and hurricane related flood events), the values presented here provide only an indication of potential consequences, and should not be considered definitive. The vulnerability index is zero for almost all tanks for both tsunami scenarios. Based on empirical data, Campedel et al. note that an index = 0 indicates that there is a

0-5% probability of damage. Only two storage tanks, ID 120 and 121, have an index value of 1 for the Stromboli tsunami, which translates to a probability of damage higher than 5%.

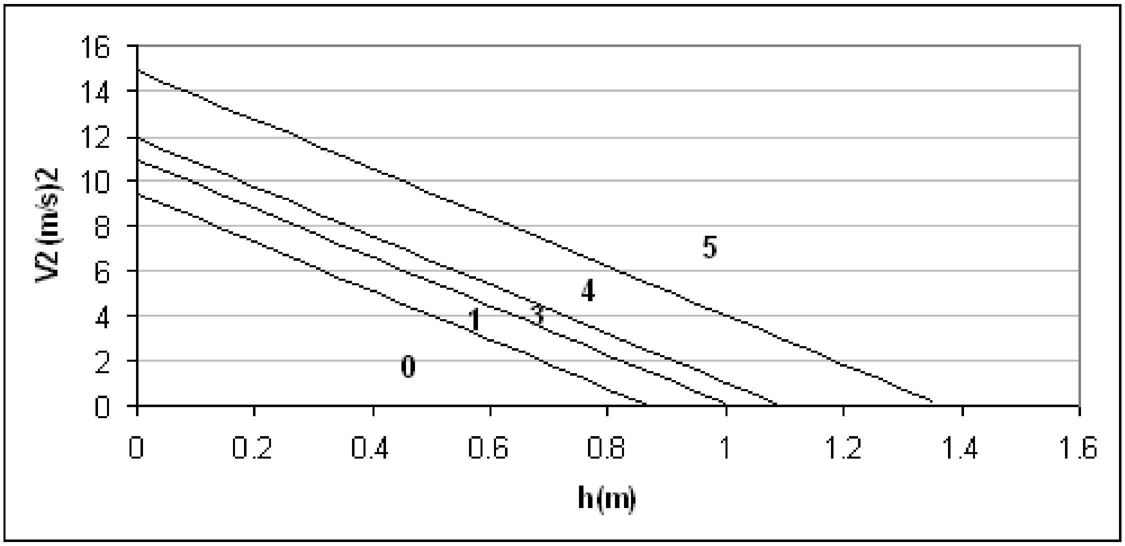


Figure 35. Plot for the calculation of the equipment vulnerability in the case of floods. V2: square of water flow velocity; h: maximum water depth. The vulnerability zones indicate the equipment vulnerability index (0 - low probability to 5 - high probability) (Courtesy of Campedel *et al.* 2008).

Water flow velocities are generally small for the Capo Vaticano scenario, but may reach values of 1 m/s or higher at some tanks for the Stromboli tsunami. According to Campedel et al. (2008), under slow submersion (water flow velocities < 1m/s) damage would be restricted to failure of flanges and connections mostly due to floating off of unanchored empty or almost empty storage tanks and attached appurtenances and pipelines.

Campedel et al. (2008) summarized the following damage threshold limit values for structural damage with loss of containment and with consequent release of hazardous materials:

- High water level condition: water level, h > 1 m and minimum velocity, v, required v=0.25 m/s
- High flow condition: v > 2 m/s and h=0.5 m
- High risk condition: h ≥ 1 m and v ≥ 1 m/s

Under high water level conditions and low water velocity buoyant loads are mostly responsible for any damage and consequent release of hazardous materials. Thus, an estimate of the forces exerted on each tank by the flood waters, and the resulting buoyant force was estimated assuming that the flood waters have overtopped the concrete containment walls around tanks. It is important to point out that while these barriers serve the purpose of retaining accidental releases from the tanks, they have not been designed to keep flood waters out. It could be assumed that they would provide some level of flood protection to the individual tanks as long as the walls are not damaged or overtopped. Tanks on the far eastern side of the refinery have earthen containment walls. These we believe would provide sufficient protection against flood damage. Thus the estimates provided here are conservative. The ratio, r, of the buoyant force to the weight (fmaxZ/W_v) of the tank has been calculated for both tsunami conditions. The results are shown in table 2.

Empty tanks with an $r > 1$ could float off if not properly anchored. Table 2 also provides information about each storage tank indicating the type of tank, tank diameter (D), height (H), tank shell thickness (t), the weight of the tank (W_v), the maximum[2] water depth, the resulting maximum force from the x and y directions (fmaxXY) and the resulting maximum buoyant force (fmaxZ) at each tank for each tsunami scenario.

In both scenarios, some damage to empty or almost empty storage tanks could occur if these are not properly anchored to overcome buoyancy loads (at those tanks where $r > 1$) in the case that concrete containment walls are overtopped or damaged. Buoyancy loads could also affect low lying pipelines, particularly those located at the pump station which lie only 10-20 meters from the shoreline where water depths are greater than 1 m. Floating off of pipelines could result in pipeline breaks and consequent release of hazardous materials if these are in operation or if they have not been properly de-inventoried before the tsunami.

Flood waters run inland as far as 140 m in both scenarios. Thus, inundation is likely to result in salt-water intrusion on low-lying equipment such as pumps and motors, electrical panels, and electronic control equipment, particularly at and near the pump station and warehouse, as well as at the western half of the refinery where water depths are greater. Damage to electric and/or electronic control equipment could result in process upsets and possible accidental releases of hazardous materials. The inundation may furthermore overcome the internal plant drainage

[2] The maximum is evaluated by considering the values at each tank at each time step. Values of hmax, vmax, fmaxZ at each time step are an average of the pixel data around the tank, while values of fmaxXY at each time step are an integral of the normal component to the tank surface of the forces in the pixels around the tank.

system, possibly causing waste oil to be lifted by the floodwaters which may spark fires and explosions upon contact with an ignition source (e.g hot refinery parts).

Water flow velocities reach 3-4 m/s at the shoreline just to the west of the pump station and warehouse in both scenarios. Any debris (e.g., drift wood, small boats, lumber) being transported by the tsunami wave in this area close to the shoreline could result in damage to the refinery fence-line along the beach front, and if it were overturned or overtopped (easily overturned by large debris as the fence is made of thin wire), possibly to building structures, storage containers, pipelines or other exposed elements in this area.

Debris impact can be the dominant cause for building damage (Yeh *et al.* 2005). However, it is difficult to estimate debris loads accurately. In general debris load are a function of the weight of the waterborne object and its velocity, and inversely related to the duration of impact. Furthermore, the impact loads are influenced by where a building or exposed element is located in the potential debris stream (FEMA 2006):

- Immediately adjacent to or downstream from another building
- Downstream from large floatable objects (e.g., exposed or minimally covered storage tanks)
- Among closely spaced buildings

Several equations have been proposed to estimate debris impact loads (Matsutomi 1999, Haehnel and Daly 2002, ASCE 2003, FEMA 2002, FEMA 2006). A detailed discussion of the topic is, however, beyond the scope of this work.

In the Stromboli scenario, high water flow velocities (2-4 m/s) and water depths > 1m, combined with possible turbulence near the shoreline could result in soil erosion and localized scour particularly around the area just to the west of the warehouse and pump station, up to the second port terminal, and at the far eastern side of the refinery where some soil erosion and scouring is already present; although in the latter case no damage to the refinery would be expected. The refinery fence-line support wall could also be subject to scouring in this area. Weakening of the support wall would increase the likelihood of the fence-line being overturned.

Table 1. Tank flood vulnerability index (index) for the Capo Vaticano and Stromboli tsunamis. Also shown are maximum water depth (hmax) (maximum water run-up height minus the digital elevation), maximum velocity (vmax), and the square of vmax used to read the flood vulnerability index (from 0 – none to low likelihood of damage to 5 – high likelihood of damage) from the equipment vulnerability curves published by Campedel et al. (2008).

	Capo Vaticano				Stromboli			
ID	hmax [m]	vmax [m/s]	vmax2	index	hmax [m]	vmax [m/s]	vmax2	index
0	0.17	0.22	0.05	0.00	0.19	0.30	0.09	0.00
1	0.12	0.13	0.02	0.00	0.17	0.25	0.06	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.44	0.58	0.34	0.00	0.35	0.96	0.92	0.00
7	0.34	0.68	0.47	0.00	0.30	0.95	0.90	0.00
8	0.01	0.10	0.01	0.00	0.03	0.28	0.08	0.00
9	0.02	0.08	0.01	0.00	0.02	0.16	0.03	0.00
10	0.19	0.51	0.26	0.00	0.21	0.51	0.26	0.00
11	0.17	0.25	0.06	0.00	0.17	0.46	0.21	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.06	0.14	0.02	0.00	0.08	0.17	0.03	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.50	0.40	0.16	0.00	0.40	1.02	1.03	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.63	0.50	0.25	0.00	0.33	0.78	0.60	0.00
32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52	0.38	0.32	0.10	0.00	0.18	0.36	0.13	0.00
53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
57	0.40	0.31	0.10	0.00	0.16	0.36	0.13	0.00
58	0.44	0.28	0.08	0.00	0.19	0.42	0.18	0.00
59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
119	0.44	0.60	0.36	0.00	0.27	0.78	0.60	0.00
120	0.75	0.69	0.48	1.00	0.41	1.27	1.62	0.00
121	0.78	0.71	0.50	1.00	0.46	1.20	1.43	0.00
122	0.39	0.56	0.31	0.00	0.17	0.69	0.48	0.00

Table 2. Ratio of buoyant force to weight of tank indicating buoyancy of empty tanks for the Capo Vaticano and Stromboli tsunamis. In addition to the ratio, the table columns show the tank identification number (ID), tank type, diameter (D), height (H), tank wall thickness (*t*), tank weight (W_v), maximum force component in the X and Y direction (fmaxXY), and maximum force component in the Z direction (fmaxZ) (buoyant force).

						Capo Vaticano			Stromboli		
ID	TANK_TYPE	D [m]	H [m]	t	Wv	fmaxXY [N]	fmaxZ [N]	r	fmaxXY [N]	fmaxZ [N]	r
0	FLOATING_ROOF	40	15	4.79	2334601	37961	2134885	0.9	37691	2348407	1.0
1	FLOATING_ROOF	40	15	4.79	2334601	18388	1457025	0.6	31427	2042664	0.9
2	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
3	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
4	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
5	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
6	FLOATING_ROOF	40	15	4.79	2334601	125331	5404784	2.3	86860	4263878	1.8
7	FLOATING_ROOF	40	15	4.79	2334601	81537	4246295	1.8	71628	3756736	1.6
8	FLOATING_ROOF	40	15	4.79	2334601	635	169146	0.1	4589	415376	0.2
9	FLOATING_ROOF	40	15	4.79	2334601	1585	278309	0.1	2133	287791	0.1
10	FLOATING_ROOF	40	15	4.79	2334601	33919	2302747	1.0	37153	2526443	1.1
11	FLOATING_ROOF	40	15	4.79	2334601	29229	2039980	0.9	27165	2047403	0.9
12	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
13	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
14	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
15	FLOATING_ROOF	40	15	4.79	2334601	6520	735296	0.3	8531	925306	0.4
16	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
17	FLOATING_ROOF	40	15	4.79	2334601	0	12	0.0	0	12	0.0
18	FLOATING_ROOF	55	16	7.03	6010356	255356	11726238	2.0	180164	9396131	1.6
19	FLOATING_ROOF	55	16	7.03	6010356	0	23	0.0	0	23	0.0
20	FLOATING_ROOF	55	16	7.03	6010356	0	23	0.0	0	23	0.0
21	FLOATING_ROOF	45	17	6.11	3776186	0	16	0.0	0	16	0.0
22	FLOATING_ROOF	45	17	6.11	3776186	0	16	0.0	0	16	0.0
31	FLOATING_ROOF	55	16	7.03	6010356	367327	14590528	2.4	104122	7617769	1.3
32	FLOATING_ROOF	55	16	7.03	6010356	0	23	0.0	0	23	0.0
33	FLOATING_ROOF	55	16	7.03	6010356	0	23	0.0	0	23	0.0
34	FLOATING_ROOF	55	16	7.03	6010356	0	23	0.0	0	23	0.0
52	FLOATING_ROOF	60	15	7.19	7041058	168681	10507788	1.5	44769	5000728	0.7
53	FLOATING_ROOF	60	15	7.19	7041058	0	28	0.0	0	28	0.0
54	FLOATING_ROOF	60	15	7.19	7041058	0	28	0.0	0	28	0.0
55	FLOATING_ROOF	60	15	7.19	7041058	0	28	0.0	0	28	0.0
56	FLOATING_ROOF	60	15	7.19	7041058	0	28	0.0	0	28	0.0
57	FLOATING_ROOF	60	15	7.19	7041058	176971	11012109	1.6	43271	4502663	0.6
58	FLOATING_ROOF	80	15	9.58	15696467	328578	21813942	1.4	127509	9144607	0.6
59	FLOATING_ROOF	80	15	9.58	15696467	0	49	0.0	0	49	0.0
60	FLOATING_ROOF	80	15	9.58	15696467	0	49	0.0	0	49	0.0
119	FLOATING_ROOF	25	8	2.00	362880	77375	2108028	5.8	33946	1296717	3.6
120	FLOATING_ROOF	25	8	2.00	362880	219253	3591919	9.9	68716	1971737	5.4
121	FLOATING_ROOF	25	8	2.00	362880	240165	3765960	10.4	84857	2204376	6.1
122	FLOATING_ROOF	25	8	2.00	362880	61665	1858218	5.1	16471	803986	2.2

In general, erosion and localized scour can aggravate the effects of flooding by lowering the ground surface around foundations leading to loss of load-bearing capacity and resistance to lateral and buoyant loads. Erosion and scour could also increase flood depths and, therefore, increase depth dependent flood loads (FEMA 2006). Localized scour determinations require detailed knowledge of the water depth, flow velocity, soil characteristics, and foundation type (FEMA 2006). Much of the evidence gathered suggests that localized scour depths around piles and other thin vertical members are approximately equal to 1.0 to 1.5 times the pile diameter (FEMA 2006). Overall, erosion and scour would most likely not represent a large threat to storage tanks at the refinery, but would mainly undermine protection barriers such as the natural protection barrier (figures 14 and 15), and the refinery fence-line that could serve to filter small debris, as well as a some equipment foundations near the shoreline (figures 15 and 16).

The above analysis indicates that the likelihood of major hazardous materials releases from damage to storage tanks is low. However, small leaks from damaged flange connections and broken pipelines due to floating off of empty or almost empty storage tanks are possible in both tsunami scenarios. Damage from debris impact, erosion and scour appears not to be a major issue in terms of potential releases, or at least not as a direct result.

Hazardous materials releases in the form of oil spills could result from broken loading/unloading arms and pipeline breaks at the port terminals, particularly during the Capo Vaticano tsunami. Since the Capo Vaticano tsunami impacts the coastline laterally, the two port terminals would receive the wave impact perpendicularly. Thus, any ships docked on the east side of the port terminals could have a forcing effect on the pier structures and could cause some damage while a ship moored on the west side would be pushed away from the pier possibly tearing pipe connections and leading to oil spills. Spills from loading and unloading arms at jetties following tsunamis have been documented. In fact an oil spill at this refinery was observed following the Stromboli tsunami of December 2002. Two oil tankers moored at the wharfs were at risk of having their mooring lines broken. The tankers moved away about 10m. A small oil spill was reported as a result of the single tsunami wave observed (Maramai *et al.* 2005). It is not clear if the spill was caused because the moored tankers were still in the process of (un)loading or if transfer was stopped but they were still connected to the wharf via the transfer arms. Steinberg and Cruz (2004) reported hazardous materials releases at the jetty of an oil refinery in Turkey following a tsunami triggered by the Kocaeli earthquake of August 1999. The authors write:

At the refinery's port terminal, which partially collapsed, a ship at the loading/unloading naphtha terminal tore loose during the earthquake- triggered tsunami, breaking pipe connections and causing a leakage of 50 tons of naphtha directly into the sea. In addition, approximately 35 tons of LPG were released at the jetty during the tsunami when an LPG loading/unloading arm broke.

8. CONSEQUENCE ANALYSIS

The consequences of potential hazardous materials releases, fires or explosions triggered by any of the two tsunamis on nearby residents and neighbouring facilities are likely to be negligible because the amounts of chemical that might be released are expected to be small. Nonetheless, even small amounts of oil can form a thin film over flood waters and can be dispersed and transported quickly throughout large areas. Any damage in this case will be restricted to coating of surfaces with oil; although oil spills have been reported to disperse completely leaving almost no trace. This would be the case if high turbulence occurs; for example during the Indian Ocean tsunami (Van Dijk 2007). If floating oil catches fire (e.g., due to contact with very hot surfaces or other ignition source), the fire could be spread over large areas very quickly. In this case the refinery itself and its workers would be at risk.

Releases of flammable gases such as LPG due to damaged flanges or broken pipe connections may occur. In the case of LPG the port terminals are particularly vulnerable. Any release could lead to the formation of a vapour cloud and possibly vapour cloud explosion (VCE). According to an accident scenario taken from Giardina (2000) involving a break of the transfer and the resulting overpressure nearby residents would probably not be affected unless the vapour cloud is carried far enough as the nearest residences are more than 700 m away. An explosion however could cause damage to the port terminals and other ships, as well as trigger domino effects.

9. TSUNAMI RISK REDUCTION MEASURES

Numerous studies have demonstrated that engineered structures in coastal regions exposed to tsunami (or storm-surge) inundation can be subject to a variety of concomitant damaging phenomena (Rossetto 2007, Robertson 2007). These include uplifting due to submersion of structures, overturning and displacement due to wave loading, debris impact, or foundation failure caused by liquefaction-induced scour in sandy subsurface deposits. The impact of a tsunami on a low-lying coastal industrial area could therefore result in damage to or collapse of industrial buildings, tanks and other equipment storing or processing hazardous materials and consequently to a Natech accident with the release of dangerous chemicals and potentially devastating consequences on the population and the environment. Since tsunami inundation usually affects a wide swath of land the risk of a domino effect[3] in a densely industrialised area is elevated. Industrial facilities need to prepare for such an event, and measures to prevent a tsunami-triggered Natech accident and/or to mitigate its consequences need to be put into place to ensure effective risk reduction.

Land-use planning is the obvious way to avoid the impact of a tsunami, and limiting industrial development along tsunami-prone coasts minimises the hazard associated with the inundation. Land-use restrictions are, however, difficult to impose as many hazardous areas are already heavily industrialised and it may be decided to accept certain risks from infrequently occurring hazards as long as they do not outweigh the benefits derived from an industrial activity. In this case supplementary measures are required to protect hazardous facilities. This means that static and hydrodynamic wave action on structures, as well as on the protective measures needs to be considered during the design and operation of an industrial plant.

Tsunami protection measures such as offshore breakwalls or other types of external barriers onshore have proven to be efficient in reducing the tsunami force (Ergin 2006, Jayappa 2008, Maheshwari). Experience from storm-surge mitigation after Hurricane Katrina also highlights the potential of barriers for flood protection, such as earthen berms, sheet-pile walls, or concrete foundation and walls (Harris 2008). These barriers could also keep tsunami-driven debris from washing into the plant where collision of debris with tanks or equipment containing hazardous materials could lead to releases of toxic, flammable or explosive substances. The studied refinery does not have any breakwalls leaving the two port terminals fully exposed to potential tsunami wave action. In the eastern part of the refinery there is a stretch of earthen barrier that would

[3] For the purpose of this work and in accordance with the Seveso Directive a scenario where a chemical accident in one industrial establishment triggers an accident in one or more neighbouring facilities off-site is called domino effect (European Union 1997). In the chemical-engineering community domino effect can also refer to an accident triggering other accidents within the same establishment.

protect any piping and equipment lying behind it from the full force of the incoming waves. It does, however, not run along the full length of the refinery and would therefore provide little protection from inundation.

In the absence of external barriers all structures and components that contain hazardous materials and all systems critical for the safety of the installation need to be protected from wave-load damage and water intrusion. This can be achieved by e.g. the creation of artificial hills on which to situate sensitive equipment or the installation of retaining dikes, as well as waterproofing and appropriate design of safety systems. Water entering buildings and other structures will cause anything that is not properly anchored to float, thereby increasing the debris load that can cause further damage. Of particular concern are storage tanks that may float off their foundations due to submersion and subsequent buoyancy, thereby tearing pipe connections and resulting in the release of possibly flammable and/or toxic materials. These materials would then be dispersed by the floodwaters over vast areas and possibly catch fire upon contact with an ignition source. Adequately designed anchoring with bolts or other types of restraint systems should keep tanks and other equipment from floating off under most conditions. As an additional protection measure a minimum quantity of material could be stored in these tanks at all times to ensure that they would not suffer buoyancy in the case of flooding. Since it was not possible to visit the studied refinery we could not determine the type of anchoring or restraint systems utilised on-site. We noticed, however, earthen containment dikes and brick or concrete walls around the storage tanks visible from the plant's perimeter. While these barriers serve the purpose of retaining accidental releases from the tanks rather than keeping flood waters out, it can be assumed that they would provide some level of flood protection to the individual tanks as long as the walls are not overtopped.

It is also necessary to assess the potential of soil for liquefaction-induced scour as it may result in foundation failures and damage to or collapse of engineered structures. Therefore, the siting of tanks and equipment on soil that is susceptible to liquefaction and scouring should be avoided. If this is not feasible foundations need to be reinforced and remedial action needs to be taken to stabilise the soil, e.g. using methods such as jet grouting, vibroflotation, etc.

Tsunami monitoring and warning systems can allow sufficient lead time for preventive measures to be taken to reduce exposure or vulnerability of equipment and processes. Emergency shutdown of processes that depend on pumps, motors or materials located in areas close to the shoreline would reduce their vulnerability to process upset due to flooding, short circuit, power outages, etc. that might be triggered by the tsunami. Warning would also provide some time, if adequate emergency procedures are established beforehand, to move materials and portable equipment out of harms way to avoid water damage or water intrusion, or to secure any objects, equipment, etc. that could become water borne and inflict debris damage on other equipment. In the case of the refinery studied in this work warning times would be rather short. Our calculations indicate that the first wave would arrive at the refinery after 17 minutes in the Stromboli scenario while it would take 27 minutes for the first wave to arrive from Capo Vaticano. The warning lead time is therefore only sufficient for emergency shutdown and possibly securing of loose objects and portable equipment if the refinery has planned for such an event. The same applies to tankers moored at the refinery's two oil terminals that would be exposed to the full wave impact. After a tsunami warning with a lead time of a few hours moored tankers would ordinarily cease loading or unloading and move into deep water to reduce the risk of a major oil spill (Eskijian 2006). Since in our study the tsunami is generated in the near field with the corresponding short warning times there would not be sufficient time to move the tankers. They could only terminate the transfer, disconnect hoses and wait for the waves to hit. As already indicated before of the two scenarios modelled in this study a tsunami created by the Capo Vaticano fault would probably be of higher concern for the oil terminals as the incoming tsunami waves would hit laterally. Any tanker moored at the terminals would not only suffer vertical but possibly also significant lateral displacement. This highlights the importance of stopping transfer and disconnecting the loading arms to minimise the risk of an oil spill during a tsunami.

In order for the above measures to effectively prevent damage and hazardous-materials releases by a tsunami it is important that affected structures are able to withstand the ground motion of a possibly preceding earthquake with limited structural damage. This is applicable to both shore protection systems and industrial facilities which when weakened would have less resistance to an impacting tsunami wave. Moreover, releases from tanks and pipes triggered by the earthquake would be spread by the incoming flood waters, possibly exacerbating the consequences of the event. An analysis of empirical damage data at the MMI levels to be expected at the study area from the modelled earthquake in the Capo Vaticano fault shows that the likelihood for anything more than light earthquake damage in the refinery is low.

The discussed structural tsunami risk reduction measures need to be supported by organisational measures to be effective in minimising the risk of a tsunami impact on a chemical facility. This includes the drawing up of a tsunami hazard management plan both at plant and community level that incorporates organisational tsunami response procedures and the emergency evacuation of workers and residents in view of possible inundation, as well as hazardous-materials triggered by it. Moreover, compliance with building codes that limit land use and building construction practices needs to be monitored. Where necessary the lawmaker is called upon to intervene with targeted legislation to ensure a high level of safety in and around hazardous facilities with respect to a possible tsunami impact.

10. STUDY LIMITATIONS

This study has provided valuable information on the potential impact of two credible tsunami scenarios on an oil refinery in northern Sicily. Nevertheless, the study has a number of limitations which are due to the assumptions made and the uncertainties in the input data (such as e.g. DEM, bathymetry, refinery schematics, etc.), as well as in the tsunami propagation and inundation model used.

The source data for the tsunami simulations for both scenarios provided by the University of Bologna, is based on simulations using historical data. While these results are certainly subject to parameter and modeling uncertainties we assume them to be negligible. The uncertainty in the utilized model for simulating the tsunami propagation and inundation, HyFlux2, derives from the fact that it is a 2D model, and it is therefore unable to capture small 3D wave effects, such as turbulence on the beach. However, the model has been tested against experimental tsunami wave run-up output showing satisfactory results (Franchello 2009).

The most important limitation concerns the accuracy of the bathymetry and DEM data used in the simulations. In the open sea a bathymetry of 1 km x 1km resolution was used, and in the near field vector data corresponding to isolines for the refinery area were input. The DEM data resolution was 100m x 100m, and vector data corresponding to isolines assuming a constant upward slope from the shoreline (0 m) to the railroad tracks that cross the refinery were used. As was discussed in section 6.1.1 the DEM data accurately predicts the elevations near the rail road tracks but is less accurate in representing elevations near the shoreline. Thus, uncertainty results in the modelled tsunami run-up heights. The present study results could be improved by using very fine grid size bathymetry and DEM data at the refinery, and re-running the simulation model with a very fine grid size in the run-up zone. Even very small changes in local bathymetry and the slope at the beach can result in very different effects at the shoreline within short distances. These inaccuracies in the bathymetry and DEM data will undoubtedly result in uncertainty in the observed effects from the two tsunami scenarios on the refinery.

In fact, uncertainty in the DEM data, and the assumption of a constant slope introduces an error in the estimation of tsunami loads which uses the computed water depth at each tank. Due to the constant slope assumption, the maximum water depth around a tank will vary depending on which part of the tank is being considered as the tank diameters are relatively large ranging from 25-80 m. For example, in the Capo Vaticano scenario, tank ID 18 (D=55 m) is subject to 0.85 m inundation on the north side (closer to the shoreline) and to 0.25m on the south side (farthest from the shoreline). Nonetheless, it is correct to assume that the tanks are on completely horizontal support foundations and that the water depth for a submerged tank at any point of the tank should be the same.

Finally, there is uncertainty in the present study due to uncertainty concerning the exposed elements (location, dimensions, distances, etc.) at the refinery such as storage tanks, pipelines, processing equipment, building structures, and other plant features. Estimates on equipment distribution and storage tank dimensions were based on an outdated floor plan of the refinery, corroborated by a satellite image from Google Earth and data from the refinery's website. An accurate floor plan of the refinery including accurate DEM data at each tank and major process equipment would provide more reliable results on the vulnerability assessment.

11. CONCLUSIONS

In this report we have presented the results of a study which analyzes the potential impacts of two tsunami scenarios originating in the Tyrrhenian Sea and their consequences at an industrial facility located on the coast in north-eastern Sicily. The results of the tsunami simulations indicate that in both scenarios there would be 18 storage tanks at the industrial facility subject to flooding, with tanks closer to the beach suffering up to 0.8 m inundation.

The above results indicate that there is low likelihood of damage to storage tanks due to hydrodynamic loads in either scenario. Water flow velocities in most areas are less than 1 m/s. This indicates that any damage would likely occur due to hydrostatic uplift forces due to buoyancy particularly in the western part of the facility where inundation levels are higher and storage tanks are less protected. Nevertheless, storage tanks in this part of the refinery do have concrete containment dikes and these may provide some flood protection. Thus, damage due to buoyancy loads would occur only if the containment dikes are damaged by flood waters or if they are overtopped.

Damage due to impact of floating debris may be a problem particularly to the west of the pump station and warehouse in both scenarios where water flow velocities reach 3-4 m/s. Any debris being transported by the tsunami wave in this area could result in some damage to building structures, storage containers, pipelines or other exposed elements. Foundation soils and foundation systems could also be at risk from shear- and liquefaction-induced scour in this section of the plant.

The refinery port terminals would be at risk of tsunami wave damage, particularly during the Capo Vaticano tsunami because the wave would impact the piers perpendicularly. Thus, any ships docked at the port terminals could have a forcing effect on the pier structures possibly causing some damage. Furthermore, ships moored on the west side would be pushed away from the pier possibly tearing pipe connections and leading to oil spills.

The likelihood of hazardous materials releases from inundated storage tanks is low. However, small releases could occur due to breakage of connected pipelines and flanges due to buoyancy loads. Flooding of electrical equipment, such as control panels, pumps, and motors, not raised above the inundation level could result in salt water intrusion leading to possible short circuit, hampering of safety and mitigation systems, process upsets and possible hazardous materials releases.

We conclude however that in the two scenarios studied, the consequences of potential hazardous materials releases, fires or explosions triggered by the tsunamis on nearby residents and neighbouring facilities are likely to be small. Nonetheless, small changes in the accuracy of the data used in the simulations, particularly bathymetry and DEM could result in higher or lower inundation values than those obtained for the present study. Thus, we recommend that preventive and preparedness measures be taken to reduce the risk of tsunami-triggered Natech accidents and to mitigate their consequences if Natech events do occur.

REFERENCES

Akatsuka, Hirotaka; and Hideo Kobayashi (2008). Fire of Petroleum Tank, etc. by Niigata Earthquake. Failure Knowledge Database, Japan Science and Technology Agency. <Retrieved April 2008> http://shippai.jst.go.jp/en/Detail?fn=0&id=CB1012035&kw=Environment

Anderson, Cheryl (2007). *State of Hawai'i Multi-Hazard Mitigation Plan Update 2007*. Hazards, Climate & Environment Program, University of Hawai'I with the Hawai'i State Hazard Mitigation Forum, the Hawaii State Earthquake Advisory Committee, the Hawaii State Hurricane Advisory Committee, and the four county planning efforts, including the County of Kauai, the County of Maui, the County of Hawaii, and the City and County of Honolulu. (16 December 2008)<http://www.scd.state.hi.us/2007_hmp.html>

ASCE Standard (2003). *Minimum Design Loads for Buildings and other Structures*. ASCE 7-02, American Society of Civil Engineers, pp. 376.

Austin, George T. (1988). *Shreve's Chemical Process Industries.* Fifth Edition. McGraw-Hill International Editions, Chemical Engineering Series: Singapore, pp.859.

Borrero, Jose C. (2005). *Field Survey Northern Sumatra and Banda Aceh, Indonesia, after the Tsunami and Earthquake of 26 December 2004*. Preliminary report. Earthquake Engineering Research Institute, February 9.

Cochard, R., Senaratne L. Ranamukhaarachchi, Ganesh P. Shivakoti, Oleg V. Shipin, Peter J. Edwards, and Klaus T. Seeland (2008). The 2004 tsunami in Aceh and Southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability. *Perspectives in Plant Ecology, Evolution and Systematics*, 10, 3–40.

Cozzani, V., M. Campedel, N. Buratti, B. Ferracuti, M. Savoia (2007). Development of a Framework for the QRA of Risk Related to Na-Tech Accidents Induced by Seismic Events. Presented at the 7th IIASA-DPRI Forum on Disaster Risk Management Coping with Disasters: Challenges for the 21st Century and Beyond, Stresa, Italy , 19-21 September.

Cruz, A. M., 2003. Joint natural and technological disasters: assessment of natural disaster impacts on industrial facilities in highly urbanized areas, Dissertation, Graduate School, Tulane University, New Orleans, LA., pp. 212.

Cruz, A. M. and L. J. Steinberg (2005). "Industry Preparedness for Earthquakes and Earthquake-Triggered Hazmat Accidents During the Kocaeli Earthquake in 1999: A Survey." *Earthquake Spectra*, 21(2), 258-303.

Cruz, A. M.; L. J. Steinberg; and R. Luna (2001). Identifying Hurricane-Induced Hazardous Materials Releases in an Oil Refinery. *Natural Hazards Review*, 2(4), 203-210.

Darienzo, M. et al. (2005). Local tsunami warning in the Pacific coastal United States. *Natural Hazards*, 35 (1), 111-119.

Erdik, Mustafa (2000). *Report on 1999 Kocaeli and Duzce (Turkey) Earthquakes.* Kandilli Observatory & Earthquake Research Institute, Bogazici University, Istanbul. Webpage: http://www.koeri.boun.edu.tr/earthqk/Kocaelireport.pdf

Ergin, A., and Balas, C. E. (2006). Damage risk assessment of breakwaters under tsunami attack. *Natural Hazards* 39, 231-243.

Eskijian, M. L. (2006). Mitigation of seismic and meteorological hazards to marine oil terminals and other pier and wharf structures in California. *Natural Hazards* 39, 343-351.

European Union (1997). Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances. Official Journal of the Eruopean Communities L10.

FEMA (2002). Coastal Construction Manual. FEMA 55. Federal Emergency Management Agency.

FEMA (2006). Recommended Residential Construction for the Gulf Coast: Building on Strong and Safe Foundations. Mitigation Assessment Team (MAT) Program, US Department of Homeland Security, April. <16 February 2009> Webpage: http://www.fema.gov/library/viewRecord.do?id=1853

Franchello, Giovanni (2008a). Shoreline tracking and implicit source terms for a well balanced inundation model. submitted to Int. J. Num. Meth. Fluids.

Franchello, Giovanni (2008b). Modelling Shallow Water Flows by a High Resolution Riemann Solver. EUR 23307 EN, European Communities.

Franchello, Giovanni and Krausmann, Elisabeth (2008). HyFlux2: a numerical model for the impact assessment of severe inundation scenario to chemical facilities and downstream environment. EUR 23354 EN, European Communities.

Giardina, Gesualda (2000). Applicazione della metodologia HARIA2 alla pianificazione di emergenza nell'area di Milazzo. Master thesis, University of Pisa.

Guidoboni E., G. Ferrari, D.Mariotti, A.Comastri, G.Tarabusi and G.Valensise (2007). Catalogue of Strong Earthquakes in Italy (461 B.C.-1997) and Mediterranean Area (760 B.C.-1500). CFTI4Med, INGV-SGA. Available from http://storing.ingv.it/cfti4med/.

Haehnel, R. B., and S. F. Daly (2002). Maximum impact force of woody debris on floodplain structures. *Technical Report: ERDC/CRREL TR-02-2*, US Army Corps of Engineers, 40pp.

Harris, S. P. and Wilson, D. O. (2008). Mitigating hurricane storm surge perils at the DeLisle plant. *Process Safety Progress* 27(3), 177-184.

Iwabuchi, Yoko; Shunichi koshimura, and Fumihiko Imamura (2006). Study on Oil Spread Caused by the 1964 Niigata Earthquake Tsunami. *Journal of Disaster Research*, **1**(1), 157-168.

Jayappa, K. S. (2008). Coastal problems and mitigation measures including the effects of tsunami. *Current Science* 94(1), 14-15.

Jonientz-Trisler, C. et al. (2005). Planning for tsunami-resilient communities. *Natural Hazards*, 35 (1), 121-139.

Levy and Gopalakrishnan (2005). Promoting disaster-resilient communities: The Great Sumatra-Andaman Earthquake of 26 December 2004 and the resulting Indian Ocean Tsunami. *Water Resources Development*, 21 (4), 543-559.

Lorito, S.; M. M. Tiberti; R. Basili; A. Piatanesi; and G. Valensise (2008). Earthquake-generated tsunamis in the Mediterranean Sea: Scenarios of potential threats to Southern Italy. *Journal of Geophysical Research*, 113, B01301, doi:10.1029/2007JB004943.

Maheshwari, B. K., Sharma, M. L. and Narayan, J. P. (2005). Structural damages on the coast of Tamil Nadu due to tsunami caused by December 26, 2004 Sumatra earthquake. *ISET J. of Earthquake Technology* 42(2-3), 63-78.

Maramai, A.; L. Graziani, G Alessio, P. Burrato, L Colini, L. Cucci, R. Nappi, A. Nardi, and G. Vilardo (2005). Near- and far- field survey report of the 30 December 2002 Stromboli (Southern Italy) tsunami. *Marine Geology*, 215, 93-106.

Matsutomi, H., and N. Shuto (1994). *Tsunami Engineering Technical Report No. 11*, DCRC, Tohoku University, 29-32.

Morita, M; and J. Mori (2005). Fault Plane Determination for the 1964 Niigata Earthquake Using Tsunami Simulations. *American Geophysical Union,* Meeting Abstracts, Fall.

Papadopoulos, G. A. (2002). Tsunamis in the East Mediterranean: A catalogue for the area of Greece and adjacent seas. *Proceedings of the International Workshop on Tsunami Risk assessment beyond 2000: Theory, Practice and Plans*, Moscow, Russia, 34-42.

Papadopoulos, G. A. (2003). Tsunami hazard in the Eastern Mediterranean: Strong earthquakes and tsunamis in the Corinth Gulf, Central Greece. *Natural Hazards*, 29(3), 437-464.

Papadopoulos, G. A.; and A. Fokaefs (2005). Strong tsunamis in the Mediterranean Sea: A re-evaluation. *ISET Journal of Earthquake Technology*, Paper No. 463, 42(4), 159-170.

Piatanesi e Tinti (2002). Numerical modelling of the September 8, 1905 Calabrian (southern Italy) tsunami. *Geophysical Journal International*, 150(1), 271-284.

Robertson, I. N., Riggs, H. R., Yim, S. C. S., and Young, Y. L. (2007). Lessons from Hurricane Katrina storm surge on bridges and buildings. *J. Waterway, Port, Coastal, and Ocean Eng*., November/December 2007, 463-483.

Rossetto, T. et al (2007). The Indian Ocean tsunami of December 26, 2004: observations in Sri Lanka and Thailan. *Natural Hazards* 42, 105-124.

Sinnott, R. K. (1989). Chemical Engineering Volume 6 (in SI units): An introduction to chemical engineering design. Volumes in the Chemical Engineering Series by J. M. Coulson & J. F. Richardson. Pergamon Press: Oxford, pp 838.

Steinberg, L. J., and Cruz, A. M. (2004). When natural and technological disasters collide: lessons from the Turkey earthquake of August 17, 1999. *Natural Hazards Review*, **5**(3): 121-130.

Tinti, S., and Maramai, A. (1996). Catalogue of tsunami generated in Italy and in Côte d'Azur, France: a step towards a unified catalogue of tsunamis in Europe. *Ann. Geofis*., 39, 1253-1299.

Tinti, S., Maramai, A. and Graziani, L. (2004). The New Catalogue of Italian Tsunamis. *Natural Hazards*, 33(3), 439-465.

Tinti S., Pagnoni G., Zaniboni, F., Bortolucci (2003). Tsunami generation in Stromboli Island and impact on the south-east Tyrrhenian coasts. *Natural Hazards and Earth System Sciences*, 3, 299-309.

Tsunami Research Group (1999). *Izmit Bay Tsunami Survey, August 22-26, 1999.* Tsunami Research Group at the University of Southern California, Los Angeles.

Van Dijk, Sander (2008). *Environmental Impact Assessment: Tsunami Indonesia.* United Nations, Office for the Coordination of Humanitarian Affaires, Banda Aceh, Aceh, Indonesia. <Retrieved March 2008>. http://humanitarianinfo.org/sumatra/reference/assessments/doc/other/report_def_draft_send_2601.pdf

Yeh, Harry, Robertson, Ian, and Preuss, Jane (2005). Development of design guidelines for structures that serve as tsunami vertical evacuation sites. Washington State Department of Natural Resources, Washington Division of Geology and Earth Resources, Open File Report 2005-4, November

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Abstract
Industrial facilities located in coastal areas subject to tsunami hazards may be at risk of tsunami impact and damage. Furthermore, if hazardous materials are present these can be accidentally released impacting nearby residents and dispersing into the environment. In this report we present the results of a study which analyzed the potential impact of two tsunamis originating in the Tyrrhenian Sea and their consequences at an industrial facility located on the coast in north-eastern Sicily. The results of the tsunami simulations indicate that in both scenarios there would be eighteen storage tanks (of 43 located within 400 m from the shoreline) at the industrial facility subject to flooding, with tanks closer to the shoreline suffering up to 0.8 m inundation. Flow velocities in most areas are less than 1 m/s. This indicates that any damage would occur due to hydrostatic uplift forces due to buoyancy particularly in the western part of the facility where inundation levels are higher and storage tanks are less protected. Potential damage caused by impact of floating debris may be a problem in an area near the shoreline just west of a pumping station and warehouse (central section of the refinery near the shoreline) due to high flow velocities (3-4 m/s) in both tsunami scenarios. Foundation soils and foundation systems could also be at risk from shear- and liquefaction-induced scour in this section of the plant. The likelihood for hazardous materials releases from inundated storage tanks is low but could occur due to breakage of connected pipelines and flanges due to buoyancy, or due to floating off of almost empty storage tanks and connected pipelines. Flooding of electrical equipment, such as control panels, pumps, and motors not raised above the inundation level could result in salt water intrusion leading to possible short circuit, hampering of safety and mitigation systems, process upsets and possible hazardous materials releases. We conclude however that in the two scenarios studied, the consequences of potential hazardous materials releases, fires or explosions triggered by the tsunamis on nearby residents and neighbouring facilities are likely to be small. Nevertheless, we make recommendations for preventive and preparedness measures that can be taken to reduce the risk of tsunami-triggered Natech accidents and to mitigate their consequences if they do occur.

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