Tsunami Risks in the Mediterranean – Part 1

Excerpts from a paper by Perit Denis Camilleri to be presented at the Lisbon IASBE September conference. Part 2 of this paper will be published in the next issue of tA. Perit Camilleri represents the KTP on the MFSA Catastrophe Insurance Committee.

"Tsunami" is composed of two Japanese words, meaning Harbour Wave, though it is now known that tsunamis do not originate in harbours. Tsunamis threaten coastlines around all the oceans of the world, but 80% of them occur in the Pacific Ocean. The vast development that has occurred around the Mediterranean shoreline over the past century necessitates that economic measures are taken to reasonably reduce the risks from a tsunami.

The Mediterranean region is active with earthquakes and volcanoes, some generating tsunamis. Around 1500BC, the eruption of the volcano Santorin on Thera is said to have caused a tsunami, leading to the sudden decline of the Minoan civilization around Crete. And what happened to the temple people of Malta around 5,000BC? Do alluvial deposits on the otherwise limestone rock formations indicate a tsunami of Biblical proportions?

Physics of Tsunami

A tsunami begins when an underwater disturbance suddenly displaces a column of ocean water. This can be triggered by landslides, a chunk of land breaking off the coast, or a volcano erupting and depositing material onto the sea bed. The most destructive tsunamis result from earthquakes that occur at depths less than 50km.

In deep seas over 6,000m tsunami waves propagate with speeds exceeding 800km/hr and a wave height of a few tens of centimetres. Tsunami waves differ from ordinary ocean waves by the great length between wave crests, often exceeding 100km, and the time between crests, ranging from 10-60 minutes.

Approximating the speed of propagation to :

(D/L < 1/20) $\mathbf{V = (gD)^{1/2}}$

in the deep sea (D/L > ½) $\mathbf{V = (gL/2\pi)^{1/2}}$ (1)

waves break, approximately given by D = 1.28H or L = 7H, where **g** is the gravitation of the earth (9.81 m/s2); **D** is the water depth in m; **L** is the wavelength in m; **H** is the depth in m of the wave from crest to trough

Table 1 has been calculated from the shallow water approximation.

The bathymetry data for the Mediterranean indicates maximum depths in the Ionian Sea exceeding 4,000m. In the Tyrrhenium and Ligurian Sea, the depth rarely exceeds 2,000m. In the Malta Plateau, extending between Malta and Sicily, the depth rarely exceeds 200m, as also in the Tunisian Plateau reaching Lampedusa and in the Gulf of Venice at the top part of the Adriatic Sea. The depth between Malta and Libya just exceeds 1,000m on the Malta end. At the Eastern Mediterranean from Cyprus up to Israel/Lebanon the sea depth is again limited to within 2,000m.

D(m)	V(km/h)	L(km)
7,000	943	282
4,000	713	213
2,000	504	151
200	159	48
50	79	23
10	36	10.6

Table 1 – Velocity & Wavelength of Tsunami wave for given Ocean Depth [2]

Normally all continents and lands bordering the sea are surrounded by a 1°(1:55) gently sloping submerged plain, being an underwater extension of the coastal plain, called the continental shelf. The 130m deep water normally extends for 78km leading onto the continental shelf break, characterised by a marked increase in slope. The abyssal zone below 1,800m extends downwards to great depths.

Normal shoreline bathymetry features cause tsunami waves to slow down, the height of the waves increases and their wavelength decreases. Deep water close to the shore hampers the build up of a very high wave. The surge momentum may increase wave height at the shoreline to give a runup height being 2 to 5 times higher when particle velocity within the wave exceeds wave velocity for a breaking wave, whilst a non-breaking wave does not amplify the runup height. This build-up may be higher than 30m for tsunami waves generated near an earthquake's epicentre or 15m for tsunamis of distant origin. A non-breaking wave develops a larger inundation distance, its energy becomes less concentrated as it spreads. Thus, a tsunami has more energy when it strikes a shoreline that is relatively close to its point of origin, than it does when it reaches a distant coast.

Other features can alter the size and impact of tsunami waves. A coral reef can act as a breakwater, diminishing some of a tsunami's energy. A V-shaped bay can act as a funnel, concentrating the energy of the tsunami into a smaller area. When tsunami waves hit the mouth of a river, harbour, fjord or inlet, they often form a bore, a steep rapidly advancing wave with an almost vertical face.

The force of some tsunamis is enormous. Large rocks weighing several tons can be moved inland hundreds of metres. Boulders with masses around 200 tons can be displaced by tsunami surges only 10m deep, whereas short period storm waves with heights of 100-150m are required to produce the same movement. The largest wave-displaced boulders recorded, found in the Bahamas on ridges 40m above mean sea level, with a mass of 2,000 tons imply tsunami surges of 30-40m depth[2]. It is improbable for wind driven waves to be higher than 12m, with boulders up to 15 tons being washed over sea walls 4m above sea level.

Tsunami Magnitude Scales

Most scales are derived from measurements of runup, the maximum on-shore wave height measured above the normal height of the sea. Two widely used measures as per the following equations, are compared in Table 2.

Iida[3]: Tsunami magnitude $m = \log_2 H$, where **H** is the maximum observed or measured runup in m (2)

Ambraseys[4]: Tsunami intensity $K_o = \log_2 H^{1/2}$ (3)

The most common cause of tsunamis of magnitudes below m6 is earthquakes, while at higher magnitudes different mechanisms are predicted to take over, such as submarine landslides and volcano lateral collapses.

The occurrence of various runup heights in the different global regions is outlined in Table 3.

Mediterranean Tsunami Characteristics

The Mediterranean region is active with earthquakes and volcanoes, some generating tsunamis, 20% of which have been damaging. In 365 A.D. following an MM7.7 earthquake in Crete, a tsunami caused extensive damage in Libya, Egypt, Calabria and as far as Spain. This tsunami is unique in historical record as it is the only event of its kind known to have propagated across the entire Mediterranean.

Table 3 shows that the Mediterranean has a higher rate of occurrence than the recent tsunami in the Indian Ocean, along with the probability of a runup height of 15m. In the more exposed parts of this region a 1.5m high runup has a return period of 100 years, a 500 year return period for a 4m runup and a 1,000 year return period for a 7m runup[5]. Most Mediterranean tsunami sources lie along mainland and island coastal regions, with tsunamis reaching local coasts quickly, giving little time for warning (1-30 minutes).

Eastern Mediterranean: Records show that this area is more prone to damaging tsunamis than the West. The strongest tsunamis are excited in the Aegean Sea and the Hellenic and Calabrian arcs. Greece and the surrounding regions have long been affected, with more than 160 events catalogued over the past 2000 years[6]. A recent tsunami (K_oV) in the Eastern Mediterranean occurred in 1956, triggered by an MM7.8 earthquake in the Aegean Sea. The wave heights reached 15m in the epicentre region and drove boats onto docks. Away from the epicentre the waves attenuated rapidly to 2.5m runup on the eastern coast of Crete and small amplitudes recorded on the Egyptian Coast.

Central Mediterranean: Amongst the Italian tsunami catalogues the first example by Caputo and Faita[7] is worth mentioning. This quotes that between 1000 and 1975AD, there were 70 recorded tsunamis of intensity between II-III, 20 of intensity IV, 7 of intensity V and 3 of intensity VI.

From this catalogue of 100 events, of which 78 were triggered by earthquakes, 20 by volcanic eruptions and 2 by slumps, the frequency of occurrence of Italian tsunamis of different magnitudes is calculated from:

Log n = 3.00 – 0.425 K_o (4) where **n** is the number of tsunamis of intensity Ko per thousand years. This indicates that intensity VI is to be expected once every 350 years, intensity V every 133 years and intensity IV every 50 years.

Tinti and Maramai[8] published an updated GITEC catalogue with 70 entries, over the same period, critically revising the Caputo studies. Tinti (1991) demonstrated that the sections of coastline most exposed to tsunamis included [9] the Messina Straits between mainland Italy and Sicily (avg. 10 tsunamis per 1,000 years), the eastern coastline of Sicily, especially around Catania (avg. 10 tsuamis per 1,000 years), the northern coastline of Calabria (avg. 1.5 events per 1,000 years), and the Gargano promotory in the southern Adriatic Sea (>1 tsunami per 1,000 years).

The Messina earthquake (MM11 of 1908) caused waves (K_oVI) of 8.5m on the Sicilian and more than 10m on the Calabrian Coast, with the maximum height of 11.7m at S.Alessio. The last tsunami recorded in this region was in 1954, so a high probability exists for another tsunami disaster.

Western Mediterranean: Most tsunamis originating in the west are triggered by North African earthquakes, with epicentres close to the coastline, especially the Algerian coast. The Oran Algerian earthquake (MM10 of 1790), triggered a tsunami affecting the coast of Spain. The Algiers earthquake of 1773 triggered a tsunami with a runup of 1.8m at Algiers and 9.1m at Tangier. The more recent Algerian earthquake (1954, M-X) triggered submarine slumping that broke underwater cables [10].

There is a relatively high tsunami activity zone, starting at Marseilles, passing along the western Italian coasts, ending at the north of the Sicilian coasts. The western part of the Mediterranean French coast is protected from tsunamis generated in the northern part of the Ligurian Sea by the southern part of the French Rivera. Wave heights on the tsunami records are of the order of a few cm for points far from the earthquake epicentre and of the order of a few tens of cm in the vicinity. The climbing of the tsunami waves on a beach increases these numbers by a factor of 2 to 3, based on real information of the tsunami tide gauges and observed wave heights on the beach during the 1887 Ligurian and 1979 Nice tsunamis. The amplification factor can reach 1 at selected points. At Marseilles, Toulon, Sete and Perpignan the wave amplitudes are 5 to 10 times less than in Nice and Cannes. Tsunami waves in Corsica do not exceed 8cm [11].

Damage caused to the Banda Aceh Shore by the December Tsunami

m	Ko	Runup(m)	Comments
-2	I	0.25	Very light – smallest tsunami perceptible only on very sensitive tide gauges.
0	II	1.00	Light – noticed by those living along the flat shore & familiar with the sea.
1	III	2.00	Rather strong – generally noticed due to flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coast. In estuaries reversal of the river flow for some distance upstream.
2	IV	4.00	Strong – flooding of the shore to some depth. Light scouring on man-made ground. Embankments and dykes damaged. Light structures near the coast damaged. Solid structures on the coast injured. Big sailing vessels and small ships drifted inland or carried out to sea. Coasts littered with floating debris.
4	V	16.00	Very strong – general flooding of the shore to some depth. Quay walls and solid structures near the sea damaged. Light structures damaged. Severe scouring of cultivated land and coast littered with floating items and sea animals. With the exception of big ships all other types of vessel carried inland or out to sea. Big bores in estuary rivers. Harbour works damaged. People drowned. Wave accompanied by strong roar.
6	VI	64.00	Disastrous – partial or complete destruction of man-made structures for some distance from the shore. Flooding of coasts to great depth. Big ships severely damaged. Tress uprooted or broken. Many casualties.
8	-	256.00	Catastrophic damage on transoceanic scales -typical oceanic island collapse, generated tsunami.
10	-	1,000.00+	Large asteroid impact – generated tsunami?

Table 2 – a comparison between Iida's and Ambraseys' tsunami magnitude, defining degree of damage

Runup(m)	Mediter-ranean	Black Sea	Indian Ocean	North America	Caribbean	South America	Hawaii	New Zealand	SW Pacific
10	250	1,000	1,000	1,000	1,000	200	200	250	200
15	1,000	-	-	-	-	750	-	1,000	-
20	-	-	-	-	-	1,000	1,000	-	1,000

Table 3- runup in metres, with a return period in years for various seas [2]

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Tsunami Risks in the Mediterranean – Part 2

Excerpts from a paper by Perit Denis Camilleri presented at the Lisbon IASBE September conference. Part 1 of this paper was published in the Summer issue of tA.

Due to changes in the style and density of occupation, utilisation of the Mediterranean coastal zones for tourism and infrastructure developments over the past 40 years, the potential impacts of future tsunamis are likely to be much greater than in the past. Disaster and emergency planners will be interested in determining maximum wave runups, horizontal inundation and their effect on wave flooding in terms of number of deaths and injuries, the need for response, recovery and rehabilitation activities[10].

To date, tsunami hazard studies have concentrated on a uniform vulnerability of population, infrastructure and business. New vulnerability assessments are to incorporate parameters relating to the natural and built environments together with socio-economics[11]. Vulnerability includes the presence of on and off-shore protective barriers, distance from the shore, depth of flood water, building construction standards, preparedness activities, socio-economic status and amount of warning and ability to move away from the flood zone[10].

Site specific evaluations to tsunami hazard should be drawn up for large and important risks situated in low-lying coastal areas. These might be defined as those <3-5m above sea-level or 7-10m in the case of the most hazardous regions. Once the hazard of the wave runup has been defined, the potential inundation zone (IDZ) is defined as the area between the coastline and the contour of the highest recorded tsunami. The IDZ is further subdivided into 4 units: high, medium, low and very low IDZ, by subdividing the IDZ reach. Onshore velocities for the December Indian Ocean disaster ranged from 17 to 47km/hr, whilst noting that velocities of 10km/hr for a river is considered as fast flowing[12]. Observed flow velocities in historical tsunamis have been inferred to be of the order of 35 to 108km/hr[2].

Vulnerability of the built environment to include [11]:

Number of storeys: one floor, vertical evacuation impossible; more floors, vertical evacuation possible. Buildings which are likely to contain trapped or injured survivors to be identified.

Description of ground floor: open plan with movable objects, high vulnerability; open plan without movable objects, moderate vulnerability.

Building material, age, design: buildings of fieldstone, crumbling and/or deserted, high vulnerability; ordinary brick/masonry, moderate vulnerability; precast/reinforced concrete, low vulnerability.

Building surroundings: no barrier, high vulnerability; low/narrow earth embankment, high vulnerability; low/narrow masonry wall, moderate vulnerability; high concrete wall, low vulnerability. The rapid rise/fall of water on either side of obstacles creates imbalance of forces between one side of a raised embankment or wall, with the resulting pulling over or displacing off its foundations. Sediments and even rock surfaces may be loosened with undermining of buildings and coastal defences. Fixed objects such as fuel storage tanks may also be ripped off their foundations by buoyancy forces.

Movable objects: can cause injury to persons, damage to buildings or block evacuation routes. These include old cars, refrigerators, containers. Disaster managers to make sure that access roads to the beach are not blocked. Trunk roads, telecommunication lines to be placed above maximum flood levels, together with emergency shelters.

Sociological data: population density during the night, day, summer and winter. Tourist centres will have high variations between seasons, with the beaches vacant in mid-winter and most people keeping inland. The number of people per building is also of importance. Schools are densely populated in winter and the density changes in hospitals to be noted.

Economic land use data: business (shops, restaurants, hotels), residential, services (schools, hospitals, power stations, marine works). This data is important for insurance companies, as premium levels may be set for buildings, considering contents loss and business interruption loss.

Land vegetation cover: no cover, high vulnerability; scrub cover, moderate vulnerability; trees, low vulnerability; large engineered coastal barriers could have a negative environmental impact.

It is vital that disaster managers have detailed information on which buildings, infrastructural works and groups of people are particularly vulnerable to tsunami impacts. When such data is available, cost effective mitigation measures may be developed and applied. This is to be used as a tool for local planning and to determine post-tsunami emergency disaster response.

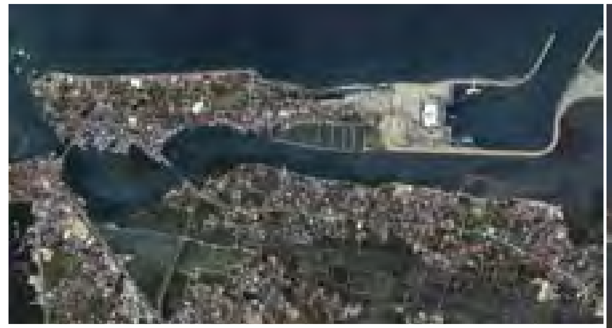
ANTICIPATED MALTESE TSUNAMI HAZARDS

In "Gozo Antico e Moderno", Aguis de Soldanis recounts how the sea at Xlendi rolled out to about one mile and swept back a little later "con grande impeto e mormorio", in the earthquake (MMVII) of 1693. This description tallies with a destructive tsunami (K_oV).

Another tsunami-like event was recorded in December 1908. This was generated by a massive earthquake (MMXI) in the Messina Straits, which in turn generated a tsunami with at least three large waves causing serious damage and considerable drowning on the eastern coast of Sicily. The waves of this tsunami reached the shores of Malta an hour later causing flooding in Msida and Marsaxlokk, while unusually high sea levels in the Grand Harbour were also recorded. A number of fishing boats were damaged or destroyed, but no deaths recorded[13]. The flooding in Msida was further reported to have reached Mannarino Road after water had been sucked out of Għajn tal-Ħasselin (the extent of the shoreline at that time), with many of the old Msida dwellings damaged or destroyed [14]. As a result of the same earthquake, the sea at Marsaxlokk turned into a foaming wave that rushed half way up the main road leading to the fishing village next to St. Peter's church. In Sliema at the Ferries, the sea moved out from the shore baring the seabed. It was only hours later that the sea gushed in again to shore [15]. Details of the La Valletta tide gauge readings, 1908 Messina Strait tsunami are portrayed on the GITEC-TWO European Tsunami Catalogue [16].

In 1973, it was reported that in Salina Bay a sudden recession of the sea occurred, lowering the depth by 0.6m, followed a short while later by a wave that caused the sea level to rise 0.6m, the event accompanied by a rumbling noise. Boats anchored in shallow water were noted to rest on the seabed. A normally dry stretch of land remained covered in seawater for a few days. Mount Etna was reported to have been active a few days earlier. In 1983, the sea in front of the Msida parish church seemed to rise in spite of calm waters, flooding the road. An earthquake (MMVII) was noted in the Aegean Sea [13]. The latter two events could possibly not be attributed to a tsunami, but could be waves excited by meteorological perturbations.

Careful search for data is carried out in libraries, newspapers collections and public archives, both ecclesiastic and of the state, would help to further assess Malta's tsunami risk. If a tsunami similar to 1693 were to strike Xlendi today, the 5-7m wave runup would meet 5 to 6 storey high buildings on the shoreline. Loss of life would be minimised if adequate circulation routes to the upper floors are in place. Horizontal inundation could be expected to be 300m inland over a 10 to 20 minute period, with house contents swept out by the receding waters. Fishing boats could be expected to be swept inland. The Xlendi 1693 tsunami scenario is typical for all the low lying shoreline developments, occurring mostly on the NE tilt side of Malta with 300m high cliffs on the SW. The coastline is rather indented, with many headlands and bays. Thus this scenario also applies to the seaside towns of Marsalforn, Sliema, Msida, Marsaxlokk, Marsascala, Birzebbuga, St Julians and the St Paul's Bay area.



The bathymetry features of the 72,850 km^2 continental shelf of Malta vary from a gentle slope of 1.50 (1:35) along the Pembroke–Salina stretch, Marfa Ridge and Gozo's Dahlet Qorrot to Marsalforn stretch. The Sliema–Marsascala stretch increases to a slope of 2.750(1:20). Note that above stretches are all along the NE Side of the Maltese Islands. The 300m high cliffs on the SW side on both Malta and Gozo have a higher slope of 11.50 (1:5), except for the Għar Lapsi area. Comino approximates to a slope of 50 (1:12.5) all round. Deep waters of 18-10m depth are encountered in the fjord type 5-fingered shape of the Grand Harbour.

Besides damage to residences, beach concessions and water sports facilities are at a higher risk, with Mellieħa Bay, the Sliema Front, Qawra, Marfa, Marsascala being particularly vulnerable. Yacht marinas are considered the most vulnerable as the floating pontoons and moored yachts will suffer the full brunt from a minimum intensity tsunami of K_oII.

The agricultural land most exposed to tsunami damage includes the low lying Pwales and Burmarrad valleys with a shoreline bathymetry slope of 1:100, which would be covered in debris, with ensuing soil erosion and salinity increase in the top soil layer. This gradient is also found in the Mellieħa Bay graben feature, St Thomas Bay and the Marsaxlokk/Birżebbuga facilities. In most of the inundation area larger tsunamis are likely to be erosive rather than depositional events. Even quite moderate tsunamis have been found to produce up to 2m of erosion of beaches and soils. Identification of larger tsunamis in geological record is thus more likely to be difficult to predict than smaller tsunamis that produce highly characteristic sheet sand deposits[2].

Infrastructural facilities close to the shoreline may grind Malta to a halt. The power stations at Marsaxlokk and Marsa, together with the freeport facility at Birżebbuga, the harbour works around the Grand Harbour extending to Marsa, the reverse osmosis plant at Pembroke, and the Gozo ferry terminals are cases in point. Storage facilities and mechanical lifting equipment in the low lying port facilities must be tied down. Immersion of objects in sea-water is also a risk: for example gas turbines and compressors may remain on their foundations, but corrosion will produce a large loss and salvaging will be costly. If machinery is present, there is the certainty of heavy rusting.

RISK ASSESSMENT FOR MALTA TSUNAMI EXPOSURE[5]

As an example, consider a shed storing electronic equipment next to a quay. The height of the quay above the sea level is 1.5m. It is assumed the shed will resist the impact, but the sea water will enter and cause damage which is practically total because of overturned piles of merchandise stored up to the level of girders and due to the spray of salt water.

The damage will be calculated for waves at 4m and 7m high. Taking note of the previous various Mediterranean return periods, the Malta return periods are estimated at 600 and 1,500 years respectively. Owing to the widely varying nature and abundance of potential debris, it is not possible to make generalisations about controls on the intensity of the impact hazard, but damage is more or less coincident with the inundation zone. The damage for a 4m high wave is assumed at 50%, and 100% for 7m high.

Gross annualised damage rate for a single event $X = \sum MDR.v/R$ (5)

where MDR is the mean damage ratio as assumed above, v is the variance factor (safety factor) covering the uncertainty in the determination of the return period R/expected loss combination.

$X = 50*2/600 + 100*2.5/1,500 = 0.33\%$.

This alarming rate shows that sensitive goods should be stored outside tsunami reach.

CONCLUSION

The cost of the December tsunami has been estimated at $19 billion, together with a 290,000 person death toll. The value of a human life is to be treated with caution, as it is claimed to be difficult, unethical and even impossible to make a valuation of such. The costs in million Euros/life saved were applied in a "Swiss based regulation" project[13].

- Voluntary risk exposition, e.g. dangerous sports – no compensation
- Direct individual benefit, e.g. car driving – 2.75Euros/life saved
- Individual benefit, e.g. working conditions – 6.70 Euros/life saved
- Involuntary no direct benefit, e.g. vicinity to dangerous installation – 13.5 Euros/life saved

Considering the ratio of the Swiss GDP to that of the affected countries to average 1:7, a tentative figure of $2million/life is being assumed. With total casualties assumed at treble the number of deaths, the societal cost of this natural disaster works out at $600 billion, paling out the material damage at $19 million.

A 1693 tsunami repeat scenario would be disastrous for Malta's economy. As tourist facilities and part of the Island's infrastructure are in low-lying coastal areas (less than 3-5m above sea-level), evaluations of the most important risks should be undertaken. Thus developments placed on a storey high escarpment of over 4m height, as encountered in some seaside towns or villages, are less at risk. Various options are available including tsunami barriers, evacuation paths, buildings with vertical evacuation facilities and warning systems. Finally it would be more prudent to work with nature by moving all unessential structures further inland and protecting the shoreline with suitable vegetation.

As it is easy to reach high land (15m above sea-level) on foot within 20 to 30 minutes, it is important that besides ongoing tsunami hazards awareness, Malta forms part of the forthcoming European Tsunami Warning System, for casualties to be kept to a minimum in such an event. Now that global tsunami risk awareness is real, communication should be easier in the event of a similar tsunami disaster, although humans are well known for their short memories.

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