Tsunami construction risks in the Mediterranean – outlining Malta's scenario

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Abstract

Purpose – To provide data on the tsunami hazard of the Mediterranean region, to outline the Maltese Islands specific tsunami risks.

Design/methodology/approach – The physics of tsunami and the tsunami magnitude scales are first introduced. The Mediterranean tsunami characteristics are introduced by reference to sources (1962-2003). Following this the Mediterranean tsunami vulnerability assessment is undertaken. This then narrows down to assessing the Maltese tsunami hazards with reference to various newspaper articles, with finally a risk assessment for Malta tsunami exposure calculated.

Findings – Considering the high loss of life occurring in the Indian Ocean catastrophic tsunami, tsunami awareness hazards are to be kept ongoing whilst Malta should form part of an expected European Tsunami Warning System.

Practical implications – Planning is to consider various options available including tsunami barriers, evacuation paths, buildings with vertical evacuation facilities. It would be more prudent to work with nature by moving all inessential structures further into the interior and to protect the shoreline with suitable vegetation.

Originality/value – Creates a Mediterranean/Maltese awareness to tsunami hazards/risks in a highly developed tourist region.

Keywords Tidal waves, Malta, Tourism, Risk analysis

Paper type Research paper

1. Introduction

Tsunami is composed of two Japanese words, meaning Harbour Wave, although it is now known that tsunamis do not originate in harbours. Tsunamis threaten coastlines around all the oceans of the world, however, 80 per cent of all tsunamis occur in the Pacific Ocean, in an area known as the Ring of Fire (Kong, 2004). Although tsunamis in the Pacific Ocean are more frequent and devastating than in the Mediterranean, due to the vast development that has occurred around the Mediterranean shoreline over the past century, economic measures are now a must to reduce in a reasonable manner the risks from a tsunami event. In the early 1900s, tsunami information was briefly mentioned as an effect of seismic data. Owing to the growing economic importance of the Mediterranean shorelines, tsunami catalogues were compiled, covering the whole European coast, financed by the EU called GITEC (acronym for genesis and impact of tsunamis on the European Coasts).

The Mediterranean region is active with earthquakes and volcanoes, some of these generating tsunamis. Historically around 1500 BC, the eruption of the volcano Santorin, on the island of Thera, is said to have caused a tsunami, which led to the sudden decline of the Minoan civilization around the island of Crete, with many attributing the legend of Atlantis to this event, which as described by Plato, was a

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highly developed island culture which sank beneath the sea. On the other hand, what had happened to the temple people on the Maltese Islands around 5000 BC? Do alluvial deposits on the otherwise limestone rock formations indicate a tsunami of Biblical proportions? Surely, the Malta site has an edge over the Atlantis theory due to the greater antiquity involved.

2. The physics of tsunami and bathymetry data

A tsunami begins when an underwater disturbance suddenly displaces a column of ocean water. Sometimes, landslides trigger tsunamis, or a chunk of land may break off the coast and slide into the ocean. Or a volcano may erupt depositing ash and molten rock onto the seabed. Even a meteorite or asteroid falling into the sea, can set off a tsunami. However, the most destructive tsunamis of all are a result of earthquakes that occur at depths of less than 50 km, with a duration of more than 15 s, suggested as an indication of possible tsunami generation. On offshore locations, when the inland epicential distance equals the source depth, the tsunami intensity becomes four to five times less than from a source in the open ocean. With the source located under the shoreline the intensity of tsunami is approximately the same as for ocean sources (Yanovskaya *et al.*, 2003).

In the deep seas over 6,000 m, the tsunami waves propagate with a speed exceeding 800 km/h, equivalent to that of a commercial jet plane and a wave height of only a few tens of centimeters. They can move from one side of the Pacific Ocean to the other in less than a day. Tsunami waves are distinguished from ordinary ocean waves by their great length between wave crests often exceeding 100 km, and with the time between these crests ranging from ten minutes to an hour. The crest of a tsunami wave is usually indistinguishable from the rest of the wave, not being seen or felt by people aboard ships, or noticed by anyone in an airplane above (NOAA, IOC, ITIC, LDG, 2002). On the other hand, wind driven waves have a wavelength of 100-200 m, with the period between crests varying from 5 to 20 s.

Approximating the speed of propagation to $(D/L < 1/20)$:

$$V = (gD)^{1/2} \tag{1}$$

in the deep sea $(D/L > 1/2)$:

$$V = \left(\frac{gL}{2\pi}\right)^{1/2} \tag{2}$$

neglecting focusing, from conservation of energy, wave height varies with depth given by:

$$H_2 = H_1 \left(\frac{y_1}{y_2}\right)^{1/4} \tag{3}$$

waves break, approximately given by $D = 1.28H$ or $L = 7H$, where g is the gravitation of the earth – 9.81 m/s^2, D is the water depth in m, L is the wavelength in m from crest to crest of the wave, H is the depth in m of the wave from crest to trough Table I is obtained.

Table I has been calculated from the shallow water approximation, although with the rapid accelerations and decelerations associated with turbulent flow in fast moving tsunami bore and surges Keuleugen (1950) had updated the shallow water relationship to (The Tsunami Risks Project, 2000):

$$V = 2(gD)^{1/2} \tag{4}$$

The bathymetry data for the Mediterranean Sea, indicates maximum depths encountered in the Ionian Sea exceeding 4,000 m. The deepest part below the seabed at over 10,000 m is found in the Pacific. However, in the Tyrrhenium and Ligurian Sea, the depth rarely exceeds 2,000 m. In the Malta Plateau, extending between Malta and Sicily the depth rarely exceeds 200 m. The same may be said of the extensive Tunisian Plateau reaching Lampedusa, here again the depth is limited to within 200 m, as also in the Gulf of Venice at the top part of the Adriatic Sea. On the other hand, the depth between Malta and Libya, just exceeds 1,000 m on the Malta end. At the Eastern Mediterranean from Cyprus up to Israel/Lebanon the sea depth is again limited to within 2,000 m.

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

From the normal shoreline bathymetry features outlined above, as the tsunami approaches land, the wave slows down, the height of the wave increases and their wavelength decreases. Deep water close to the shore, on the other hand, hampers the build up of a very high wave. An enormous wall of water builds up and then inundates the land in a tide-like flood. The surge momentum may increase the wave height at shoreline to give a runup height being two to five times when particle velocity within 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 30 m for tsunami waves generated near the earthquake's epicentre or 15 m for tsunamis of distant origin, but even a tsunami, 3-6 m high may be very destructive.

The runup height R from conservation of energy flux equation (Chesley and Ward, 2004), for linear water waves and considering equation (3) is given by:

$$R = A^{4/5}h^{1/5} \tag{5}$$

where A is wave amplitude and h is still water depth for a shallow wave location where wave height is much smaller than water depth.

Table I.
Velocity and wavelength of tsunami wave for given ocean depth

Depth (m)	Velocity (km/h)	Wave length (km)
7,000	943	282
4,000	713	213
2,000	504	151
200	159	48
50	79	23
10	36	10.6

Source: NOAA, IOC, ITIC, LDG (2002)

A non-breaking wave unlike a breaking wave due to limited drag forces develops a larger inundation distance. The energy of a wave becomes less concentrated as the wave 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.

Offshore and coastal features can alter the size and impact of tsunami waves. Deep water close to the shore, hampers the build-up of a very high wave. A coral reef can act as a breakwater, diminishing some of a tsunami's energy. However, 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 fjords or inlets, they often form a bore, a steep rapidly advancing wave with almost a vertical face.

The force of some tsunamis is enormous. Large rocks weighing several tons, along with boats and other debris can be moved inland hundreds of meters. Boulders with masses around 200 tons (about 5 m across) can be displaced by tsunami surges only 10 m deep, whereas short period storm waves with heights of 100-150 m are required to produce the same movement. The very largest wave-displaced boulders recorded, found in the Bahamas on ridges 40 m above mean sea level, with a mass of 2,000 tons imply tsunami surges of 30-40 m depth (The Tsunami Risks Project, 2000). On the other hand, it is very improbable for wind driven waves to be higher than 12 m, with boulders up to 15 tons weight being washed over sea walls 4 m above sea level.

A train of waves travelling through still water appears to move at half the speed of the individual waves, with the energy being 1/2 potential and 1/2 kinetic.

The energy E, per unit length of wave crest/wavelength from wave theory, assuming no loss of energy is given by:

$$E = \frac{\rho g L H^2}{8} = \frac{\rho H^2 V}{8} \tag{6}$$

where ρ is the density of the sea given at 1,000 kg/m^3, with the other symbols as defined previously.

The total horizontal force is given by the addition of the hydrostatic, hydrodynamic impulsive and inertial force acting on the impinging structure. The vertical force is given by the buoyancy forces, hydrodynamic lift and weight of water inside the structure (Hinwood, 2005).

For hydrodynamic tsunami loads, due to fast moving waters, using double the velocity of the propagating tsunami wave, as per equation (4), this is calculated from:

$$E = 0.5 \rho C_d V^2 A \tag{7}$$

where C_d is a drag coefficient taken at 2 and A is the surface area of obstruction normal to the flow, with this equation being similar to those for wind loading.

Tsunamis, although with rarely breaking waves, are very destructive because of the much higher water velocities, with onshore velocities for the recent Indian Ocean disaster having ranged from 17 to 47 km/h, whilst noting that velocities of 10 km/h for a river is considered to be fast flowing. Observed flow velocities in historical tsunamis have been inferred to be of the order of 35-108 km/h (Blong *et al.*, 2005). Even considering a velocity < 5 m/s and wave height < 5 m forces exceed 5,000 kg/m^2 with windows and masonry panels expected to fail at 10-20 per cent of this level (Pomonis, 2005). Not only do tsunamis result in high lateral pressures or buildings they also lead to scour, with the worst scour sometimes occurring during backwash, undermining buildings, may cut roads, railways and pipelines and destroying marine habitats. Local scour holes provide pools of brackish water which encourage mosquitoes and other hygiene problems. Much of the scour occurs as the water returns to the sea because of the generally steeper water slope (Hinwood, 2005).

3. Tsunami magnitude scales

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

Tsunami magnitude m (IIDA *et al.*, 1967):

$$m = \log_2 H \tag{8}$$

where H is the maximum observed or measured runup (in meter).

Tsunami intensity K_0 (Soloviev, 1990), modified Sieberg seismic sea wave intensity scale: after Ambraseys (1962):

$$K_0 = \log_2 H^{1/2} \tag{9}$$

Figure 1 shows that whilst at low magnitudes, below magnitude $m6$ the commonest cause of tsunamis is earthquakes, at higher magnitudes different mechanisms are predicted to take over, in succession submarine landslides, volcano lateral collapses and at the highest magnitudes impacts. Whilst the Mediterranean is most at risk from

m	K_0	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 littering of the coast 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 II. A comparison between Iida's and Ambraseys' tsunami magnitude, defining degree of damage

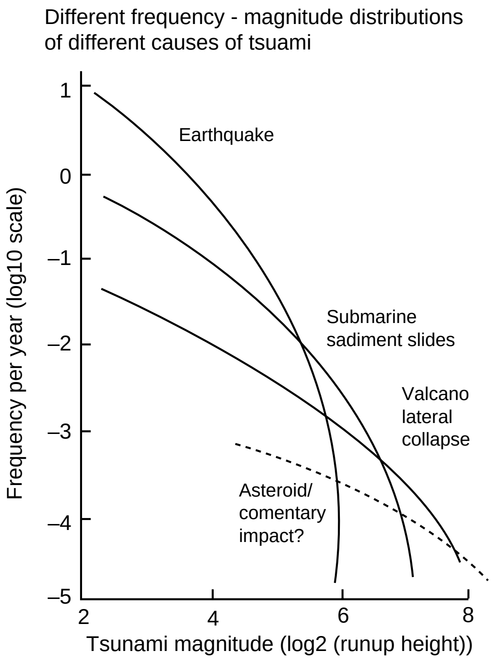

Figure 1.

the small, frequent earthquake generated tsunamis, the pattern changes for the distribution of risk from larger, less frequent tsunamis in the magnitude of $m > 7$. The level of risk from events in the high magnitude range may be as high in the Atlantic Oceans in the Pacific (The Tsunami Risks Project, 2000).

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

4. Mediterranean tsunami characteristics

The Mediterranean region is active with earthquakes and volcanoes, some of these generating tsunamis, 20 per cent of which have been damaging. In 365 AD following an M 7.7 earthquake in Crete, a tsunami caused extensive damage in Libya, Egypt, Calabria and as far as Spain. This tsunami is unique in the historical record, in that it is the only event of its kind known to have propagated across the entire Mediterranean.

Table III indicates that the Mediterranean Sea has a higher rate of occurrence than the recent Boxing Day 2004 apocalyptic tsunami disaster that occurred in the Indian Ocean, together with the probability also of a runup height of 15 m. Further to Table III, in the more exposed parts of the Mediterranean a 1.5 m high runup has a return period of 100 years, with 500 year return period for a 4.0 m high runup and a 1,000 year return period for a 7.0 m runup (Swiss Re Zurich, 1992). Most Mediterranean tsunami sources lie along mainland and island coastal regions, with tsunamis reaching local coasts soon after they have been generated, giving little time for warning, varying from 1 to 30 minutes.

Table III.
Runups in meter, with their return period in years for various seas

Runup (m)	Mediterranean	Black Sea	Indian Ocean	North America	Caribbean	South America	Hawaii	New Zealand	South West 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

Source: The Tsunami Risks Project (2000)

4.1 Eastern Mediterranean region

Historical records show that the western Mediterranean is less prone to damaging tsunamis than the east. 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 having been catalogued over the past 2,000 years (Papadopoulos, 1998). Table IV gives the wave heights recorded and return period in years for this region.

A recent tsunami (K_0-V) in the eastern Mediterranean occurred in 1956, triggered by an earthquake MM 7.8 in the Aegean Sea. The waves reached 15 m high in the epicentral region and caused boats being driven onto docks, houses flooded and three persons reported drowned. Away from the epicentral area the waves attenuated rapidly, to 2.5 m runup on the eastern coast of Crete and small amplitudes recorded on the Egyptian Coast.

On the other hand, where clear evidence for past tsunamis in Greece is preserved, geological record suggests that individual tsunamis may have been much smaller than historical, recent and even scientific accounts describe. Even for the 1956 Aegean tsunami, which was instrumentally recorded and well studied, scientific reports of the distance inland and the elevation to which flooding occurred were highly inaccurate (Dominey-Howes, 1998).

4.2 Central Mediterranean region

Amongst the Italian tsunami catalogues the first example due to Caputo and Faita (1984) is worth mentioning. This quotes that between the period 1000 AD and 1975 AD, there were 70 recorded tsunamis of intensity between II and 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 two by slumps, the frequency of occurrence of Italian tsunamis of different magnitudes is calculated from:

$$\log n = 3.00 - 0.425 K_0 \tag{10}$$

where n is the number of tsunamis of intensity K_0 per 1,000 years. This indicates that intensity VI is to be expected every 350 years, intensity V every 133 years and intensity IV once every 50 years.

Tinti and Maramai (1996) have published an updated GITEC catalogue with 70 entries, over the same above period, by critically revising the above Caputo studies.

K_0	Wave height for each tsunami grade according to Soloviev (m)	Wave height documented in Greece and the surrounding areas (m)	Return period in Greece (years)	Number of events in Greece
II	+1	(0.3)	(16)	
III	+2	+1 (2.55)	4 (40)	55
IV	+4	+5 (5.5)	26 (103)	25
V	+8	+11	170	10
VI	+16	+20	1,100	2

Note: Wave height according to Soloviev (1978) and according to the Greek records for each grade of tsunami intensity (Papathoma *et al.*, 2003), bracketed values refer to the Gulf of Corinth, Greece (Papathoma and Dominey-Howes, 2003)

Table IV.

Tinti (1991) had demonstrated that the sections of coastline most exposed to tsunamis included (Degg and Doornkamp, 1992):

I – The Messina Straits between mainland Italy and Sicily (average of ten tsunamis per 1,000 years).

II – The eastern coastline of Sicily, especially around Catania (average of ten tsunamis per 1,000 years).

III – The northern coastline of Calabria (average of 1.5 events per 1,000 years).

IV – The Gargano promotory in the Southern Adriatic Sea (>1 tsunami per 1,000 years).

The region with the highest earthquake triggered tsunami potential is the Calabrian arc, including the Straits of Messina. The Messina earthquake (MM 11-1908) caused waves (K_0-VI) of 8.5 m on the Sicilian and more than 10 m on the Calabrian Coast, with the maximum height of 11.7 m at S. Alessio. The last tsunami recorded in this region was 1954, so a high probability exists for another tsunami disaster.

Tinti (1991) has shown that besides for the localities indicated in sections I-IV above, the other regions may be classified thus. The Central Adriatic is a region of moderate tsunami hazard, whilst the Northern Adriatic, Western Sicily and the Ligurian Sea all exhibit a comparable low level of hazard exposure. For example, close to the Venice Lagoon, 0.35 tsunamis per 1,000 years are to be expected, i.e. every 2,850 years. The least tsunami hazard is along the Latium (around Rome) and Southern Tuscan coasts, with events expected once every 10,000 years.

4.3 Western Mediterranean region

Most of the tsunamis originating in the west have been triggered by North African earthquakes, with their epicentres close to the coastline, especially the Algerian coast. The Oran Algerian earthquake (1790, M-X), triggered a tsunami effecting the coast of Spain. The Algiers earthquake of 1773, triggered a tsunami that had a runup of 1.8 m at Algiers and 9.1 m at Tangier. The more recent Algerian earthquake (1954, M-X), triggered submarine slumping that broke underwater cables (Papathoma and Dominey-Howes, 2003). The updated GITEC catalogue has 24 entries, over the period 220 BC-1980 AD, modified after Reicherter (2001).

Historical data and information about tsunamis in France show that from 2000 BC to 1991 AD, the total number of events is 25, but with weak reliability value. Twenty-one of these events occurred in the nineteenth century. Most of the tsunamis occurred in the Nice-Cannes region (13 events), in Marseilles (five events), in Sete (three events) and the island of Corsica (two events). Taking into account that the first event was mentioned in 1564, the return period for the French coast is taken at 18 years for the Ligurian Sea.

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 centimeter for points far from the earthquake epicentre and of the order of a few tens of centimeter in the vicinity. The climbing of the tsunami waves on a beach increases these numbers by a factor of 2-3, 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 5-10 times less than in Nice and Cannes. Tsunami waves in Corsica do not exceed 8 cm (Pelinovsky *et al.*, 2001).

Considering the above updated data for the Mediterranean regions this is to be compared with Soloviev (1990) catalogue (IIDA *et al.*, 1967), outlined in Table V.

5. Mediterranean tsunami vulnerability assessment

Owing to changes in the style and density of occupation and utilisation of the Mediterranean coastal zones related to tourism and infrastructural 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 numbers of deaths and injuries, the need for response, recovery and rehabilitation activities (Papathoma and Dominey-Howes, 2003). This type of flooding disaster would require antidiarrhoeals and antibiotics treatment, together with splints and plaster of Paris for fractures and cuts.

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 (Soloviev, 1978). Vulnerability includes the presence of on and offshore protective barriers. These could reduce the initial crest height but have little effect on the total water volume or maximum inundation, but more time is provided for escape and impact loads reduced. Further to the vulnerability assessment is the

Coastal region	Average recurrence (years)	Intensity-I Average	Maximal	Year of last tsunami	Probability of next tsunami
N. Aegean	22	2.4	III	1978	Low
Eastern Greece	26	3.1	IV	1956	High
S. Turkey	18	2.6	III	1961	High
Aegean Sea	9	3.7	X	1968	High
Hellenic Island arc	21	3.5	VI	1948	High
Cyprus	17?	3.5	V?	1979	Low
E Mediterranean	106	3.2	V	1870	Medium
W. Greece	14	–	VI	1953	High
Corinthian Gulf	20	–	V	1981	Low
Albania	31	3.2	IV	1920	High
Yugoslavia	20	3.3	V	1979	Low
Venetian Gulf	180?	3.0	VI	1511	–
Eastern Italy	52	3.2	V	1889	High
Calabria/Sicily	12	3.8	VI	1954	High
W. Italy	46	3.5	V	1870	High
Ligurian Sea	17	2.8	IV	1914	High
Spain	100	3.0	III-IV	1860	High

Source: Soloviev (1990)

Table V. Characteristics of the principal Mediterranean tsunamigenic zones 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 (Papathoma and Dominey-Howes, 2003).

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 $< 3\text{-}5$ m above sea level or 7-10 m 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 four units: high, medium, low and very low IDZ, by subdividing the IDZ reach.

Vulnerability of the built environment to include (Papathoma *et al.*, 2003):

- *Number of stories in each floor*. Only one floor, vertical evacuation impossible, more than one floor vertical evacuation possible, leading to a lower vulnerability. This is important to disaster planners as buildings may be identified which are likely to contain large number of trapped or injured survivors, for paramedics to go directly, as there is no possibility of vertical evacuation. Even ordinary timber houses retain a degree of watertightness for short period.
- *Description of ground floor*. Open plan with movable objects (high vulnerability) open plan without movable objects (moderate vulnerability) none of the above low vulnerability.
- *Building material, age, design*. Buildings of fieldstone, crumbling and/or deserted (high vulnerability) ordinary brick/masonry (moderate vulnerability), precast/reinforced concrete (low vulnerability). A great deal of property damage caused from a tsunami is from missiles or objects thrown by the waves. Consideration must be given to room egress and avoiding risk of people trapped against a ceiling.
- *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. On the other hand, a failed structure may serve as useful role as a damaged pile of concrete, much as a damaged rubble mound breakwater may continue to provide residual protection after having failed. Sediments and even rock surfaces may be loosened with undermining of buildings and coastal defences. Fixed objects such as also fuel storage tanks may also be ripped off their foundations by buoyancy forces.
- *Movable objects*. It can cause injury to persons, damage to buildings or block evacuation routes – these include old cars, refrigerators, containers, with the damaging effect of scour occurring. Disaster managers have to make sure that access roads to the beach are not blocked, as building debris is a significant contributor to building failure and human injury. Trunk roads, telecommunication lines are to be placed above maximum flood levels, together with emergency shelters.
- *Sociological data*. Population density during the night, the day, the summer and winter. Touristic centres will have high variations during the seasons, with the

beaches vacant in mid-winter and most of the 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), on the other hand, large engineered coastal barriers could have a negative environmental impact. It appears likely that mangroves can survive and will be effective in attenuating a tsunami of height up to 3 m and possibly 5 m (Hinwood, 2005).

It is of vital importance 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 to be used as a tool for local planning and to determine post-tsunami emergency disaster response.

6. Anticipated Maltese tsunami hazards

Aguis de Soldanis in his manuscript *Gozo Antico & Moderno*, 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 (MM-VII) of 1693, when the Mdina Cathedral amongst others collapsed. From Table II this description tallies with a destructive tsunami ($K_0 - \mathrm{V}$). This most severe earthquake in Sicily (MM-XI) generated two tsunamis at Catania and Augusta, which according to reports produced three withdrawals of the sea and three major waves.

Another tsunami-like event was recorded on 28 December 1908. This was generated by a massive earthquake (MM-XI) in the Messina Straits which in turn generated a tsunami with at least three large waves, that caused serious damage and considerable drowning to 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 Grand Harbour were also recorded. A number of fishing boats were damaged or destroyed, but no deaths recorded (Savona-Ventura, 2005). The flooding in Msida was further reported to have reached Mannarino Road after water had been sucked out of Ghajn tal-Hasselin (the extent of the shoreline at that time), with many of the old Msida dwellings damaged or destroyed (Said, 2005). 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, on the day of the earthquake the sea moved out from the shore baring the seabed. It was only hours later that the sea gushed in again to shore (Cini, 2005). Although memories of these natural disasters are generally short lived, during the 1972 Malta earthquake, a mother who lived in Zejtun scurried out of her home, but on arriving close by to Torri Mamo warned others not to go closer to the shore, as at any minute the wave might strike, so impressed was she of what her father had recorded concerning the Messina disaster. Details of the La Valletta tide gauge readings, 1908

Messina Strait tsunami is portrayed on the GITEC-TWO European Tsunami Catalogue (Tinti *et al.*, 2001).

Closer to our time in 1973, it was reported that in Salina Bay a sudden recession of the sea occurred, lowering the depth by 0.6 m, followed a short while later by a wave that caused the sea level to rise 0.6 m, with the event accompanied with 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 had been reported to be very 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 (MM-VII) was noted in the Aegean Sea (Savona-Ventura, 2005). The last two events mentioned could possibly not be attributed to a tsunami, but could be waves excited by meteorological perturbations.

It would be of help, to assess further Malta's tsunami risk if careful search for data is carried out in the libraries, newspapers collections and public archives, both ecclesiastical and of the state.

If a tsunami similar to 1693, were to strike at Xlendi nowadays, the 5-7 m wave runup would encounter five to six storey high buildings on the shoreline. Loss of life would be minimised if adequate circulation routes to the upper floors are in existence at ground level. Horizontal inundation could be expected to be 300 m inland over a 10-20 min period unlike a few seconds for a normal wave, with house contents swept out by the receding waters, with sand and pebbles deposited in buildings. Fishing boats could be expected to be swept inland. Obviously, the seafront shoreline landscaping works together with trees would be totally uplifted.

The Xlendi 1693 tsunami scenario is typical for all the low lying shoreline developments, occurring mostly on the NE tilt side of Malta with 300 m high cliffs on the SW. The coastline is rather indented, with many headlands and bays, the principle being the headland containing the capital Valletta, and forming the Grand Harbour. Thus the above tsunami scenario also applies to the seaside towns of Marsalforn, the Sliema ferries, 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 varies from a gentle slope of 1.5° (1:35) along the Pembroke – Salina stretch, Marfa Ridge and Gozo's Dahlet Qorot to Marsalforn stretch. The Sliema – Marsascala stretch increases to a slope of 2.75° (1:20). Note that above stretches are all along the N-E side of the Maltese Islands. The 300 m high cliffs on the S-W side on both Malta and Gozo have a higher slope of 11.5° (1:5), except for the Ghar Lapsi area, again approximating to the Sliema-Marsascala stretch. Comino, on the other hand, approximates to a slope of 5° (1:12.5) all round. Deep waters of 18-10 m depth are encountered in the fjord type five-fingured shape of the Grand Harbour. Malta is situated in the relatively stable northernmost platform of North Africa connecting Sicily in a mostly shallow shelf, except for the Malta Basin, situated just off the SE coast.

Besides the residential damage, the touristic beach concessions, water sports facilities are at a higher risk as placed at lower lying ground closer to the shoreline, with Mellieha Bay, the Sliema Front, Qawra, Marfa, Marsascala being particularly vulnerable. The 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_0-III.

The agricultural land being 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 up in debris, together with the ensuing soil erosion and the salinity increase in the top soil layer. This 1:100 seabed gradient is also found in the Mellieha Bay graben feature, St Thomas Bay and the Marsaxlokk/Birzebbuga facilities. In most of the inundation area larger tsunamis are likely to be erosional rather than depositional events. Even quite moderate tsunamis have been found to produce up to 2 m 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 (The Tsunami Risks Project, 2000).

Although anticipated damage to touristic facilities is worrying, as tourism contributes nearly a 1/3 of Malta's GDP, the infrastructural facilities close by to the shoreline may grind Malta to a halt. The power stations at Marsaxlokk and Marsa, together with the freeport facility at Birzebbuga, the harbour works around the Valletta Grand harbour extending to Marsa, the reverse osmosis plant at Pembroke, together with the Gozo ferry terminals are cases in point. To be noted that a 3 m runup tsunami has been known to have shifted a container weighing one ton, a distance of 5 m horizontally (Papathoma *et al.*, 2003). Thus the importance of the tying down of storage facilities and mechanical lifting equipment in the low-lying port facilities. Tsunami not only involve dynamic forces acting on the risks, but also the immersion of the objects in seawater, even if, for example, gas turbines and compressors remain on their foundations, corrosion will produce a very large loss, and salvaging will be costly as well. If machinery is present, there is the certainty of heavy rusting. Values at risk in modern ports, warehousing, power stations, situated in low-lying land is enormous. Seacraft in bays or ports are at a higher risk than those out at sea.

7. Risk assessment for Malta tsunami exposure (Swiss Re Zurich, 1992)

As an example, consider a shed next to a quay storing electronic equipment. The height of the quay above the sea level is 1.5 m. 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 merchandize stored up to the level of girders and due to the spray of salt water.

The damage will be calculated for waves at 4 and 7 m high, with the return period for Malta considering the previous various Mediterranean return periods, the Malta values 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 generalizations about controls on the intensity of the impact hazard, but damage is more or less coincident with the IDZ. The damage for a 4 m high wave is assumed at 50 and 100 per cent for 7 m high.

Gross annualized damage rate for a single event:

$$X = \sum \mathrm{MDR}v/R \tag{11}$$

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

$$X = 50 \times \frac{2}{600} + 100 \times \frac{2.5}{1,500} = 0.33\,\text{per cent}$$

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

The same exercise is to be carried out for the exposed Mediterranean with respective return periods of 500-1,000 years giving:

$$X = 50 \times \frac{2}{500} + 100 \times \frac{2.5}{1,000} = 0.45\,\text{per cent}$$

8. Discussion and conclusion

The recent Indian Ocean catastrophic tsunami has made people aware of the lack of early warning systems which would save tens of thousands of lives. The cost of this tsunami has been estimated at 19 billion dollars, together with a counted dead to date at 290,000 persons.

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 human lives. The costs in million euros/life saved were applied in a "Swiss based regulation" project (Seiler and Beinz, 2001):

I – Voluntary risk exposition, e.g. dangerous sports – no compensation.

II – Direct individual benefit, e.g. car driving – 2.75 euros/life saved.

III – Individual benefit, e.g. working conditions – 6.70 euros/life saved.

IV – Involuntary no direct benefit, e.g. vicinity to dangerous installation – 13.5 euros/life saved.

Considering the ratio of the Swiss GDP, with the effected countries in the Indian Ocean, to average 1:7, a tentative figure of $2 million/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.

The repeat of a similar 1693 tsunami would be disastrous for Malta's economy, considering tourism to contribute nearly a 1/3 of Malta's GDP. As tourist facilities and part of the Island's infrastructure are placed in low-lying coastal areas, evaluations of the most important risks should be undertaken. "Low-lying areas" might be defined as those less than 3-5 m above sea level. Thus developments placed on a storey high escarpment of over 4 m height, as encountered in some seaside towns or villages, are less at risk. Planning is to consider various options 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 inessential structures further into the interior and to protect the shoreline with suitable vegetation.

As it is easy to go onto high land, being about 15 m above sea level on foot, within 20-30 minutes, it is important that besides tsunami awareness hazards to be kept ongoing, coupled with community education and evacuation drill, to instil community awareness and participation in disaster reduction programmes, Malta forms part of the expected European Tsunami Warning System, for casualties to be kept to a minimum in such an event. An aware, ten year old girl had been instrumental in saving lives via direct hotel management communication in this recent Boxing Day Indian Ocean tsunami. 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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