Natech risk analysis in "Seveso" plants

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Abstract. All companies covered by "Seveso" regulation provisions need to develop a risk analysis system for the safety of people and the integrity of the environment, taking into account the various factors leading to relevant accidents, including natural events, such as earthquakes, tornados, flooding, tsunamis, etc. The risk analysis method regarding risks due to natural causes (also known as "NaTech", i.e. Natural Hazard Triggering Technological Disasters), described in this paper and focusing in particular on risks associated with tornados and tsunamis, is based on careful and well-structured research work as regards historical data on natural events occurring in the region where a "Seveso" plant is located, for the purpose of then conducting a probabilistic assessment of consequences. The information sources are research institutions and public databases, at national and international as well as regional/local level, and specialized scientific journals. Based on the regional data collected and on possible types of damage to the industrial facilities under examination, it is possible to assess the potential risk of relevant accidents caused by extreme natural or meteo-climatic events, then plan the necessary actions, including the ability to withstand the said natural event and the possible need for any adjustment work.
Key Words: regulation, safety, environment integrity, meteo-climatic events, tornado, tsunami.

Introduction

Tornados. According to the glossary of the American Meteorological Society (http://glossary.ametsoc.org/wiki/Tornado), a tornado is "... a rotating column of air, in contact with the surface, pendant from a cumuliform cloud, and often visible as a funnel cloud ...". In order for a vortex to be classified as a tornado, it needs to be in contact both with the ground and with the basis of the cumuliform cloud. It has the following specific characteristics:

- a vortex diameter ranging from a few dozen meters to ground diameters ground exceeding 2.5 km;
- translational speeds between 50 and 100 km/h;
- high-speed vortex winds, from over 100 to more than 320 km/h, exercising dynamic pressures on the affected surfaces which, in the case of the maximum speed may be as high as one ton per square meter (about 0.1 bar);
- a high vertical wind component (the upward currents can be reach up to 300 km/h);
- pressure drop which accompanies these events, an actual baric collapse whose estimated value is around 0.1 bar;
- creation of "wind-borne missiles", i.e. objects thrown at great speed and distances.
- The damage which a tornado may cause are a result of three main types of effects:
- Forces due to atmospheric pressure gradients.
- Forces caused by the wind on the exposed structure surfaces (positive pressures in the case of upwind surfaces, negative pressures for downwind pressures, localized negative pressures with a suction effect).
- Impacts of the debris scattered by the wind.

Generally speaking, the most widespread consequences of a tornado include blowing away the roof in buildings and sheds, breaking windowpanes, tearing off doors and windows, damaging vertical metal structures such as towers, trellises and power lines. The highest energy levels, however, have even more destructive consequences.

The intensity of a tornado and its potential to cause damage, also of a destructive nature, is typically associated with the speed of the winds generated in the vortex. Almost all of the information about the characteristics of a tornado is still based on the degree of damage, as opposed to direct physical assessments. The estimate of a tornado's intensity is based on the Enhanced Fujita Scale, according to the 2007 review, which consists of six levels (EF0/EF5).

Table 1

Enhanced Fujita Scale (http://www.spc.noaa.gov/faq/tornado/ef-ttu.pdf)

Degree	*Wind speed in km/h*	*Potential damage*
EF0	105–137	Limited damage: damage to chimneys; breaks tree boughs; causes trees with superficial roots to fall; damage to roadside posters and signs.
EF1	138–175	Moderate damage: detaches the roof surfaces; motorhomes moved from their foundations or overturned; moving cars pushed off the roads; garages might be destroyed.
EF2	176–220	Considerable damage: roofs blown away from houses; motorhomes destroyed; garages destroyed; large trees broken; lightweight objects thrown like missiles by the wind.
EF3	221–269	Roofs and some walls blown away from solidly built houses; trains derailed; most of the trees in woodland areas are uprooted; cars lifted from the ground and blown away.
EF4	270–320	Solidly-built houses razed to the ground; structures with weak foundation blown a short distance away; cars violently blown away; large missiles are generated.
EF5	>320	Houses with a strong framework lifted from their foundations and blown at considerable distances, then disintegrating; missiles the size of cars flying through the air at distances of more than 100 meters; trees are debarked.

Tsunami. Unlike traditional sea waves, caused by the wind and by currents, a Tsunami has the effect of an intense submarine perturbation which affects the whole water column, from the seabed to the surface. The waves produced by such sudden forces can reach a length of 240 km. In deep water, generally speaking, they are only 30-60 centimeters high and characterized by a very high propagation speed: their propagation speed is actually a rather complex function of sea depth and wave length whose impact, to a smaller extent, can be approximated as follows:

$$V = \sqrt{gh}, \quad (1)$$

Where: V – velocity of wave propagation (m/s); g – gravity acceleration (m/s^{2}); h – sea depth (m).

When a Tsunami starts approaching the coast, the seabed – as it becomes increasingly shallow – causes an attrition with the submarine perturbation, leading it to suddenly slowing down its high propagation speed. Due to the energy conservation principle, the height of the wave then increases massively, until an actual wall of water is formed; because there are no substantial refraction phenomena, the wave surges like a very high tide, invading the mainland. If the wave cable is the first to reach the coastline, there will be what is known as a "draw-down" effect (lowering of the sea level), followed by the so-called "run-up" effect (sudden rising of the sea level). The main characteristics of a tsunami wave are outlined in the Figure 1.

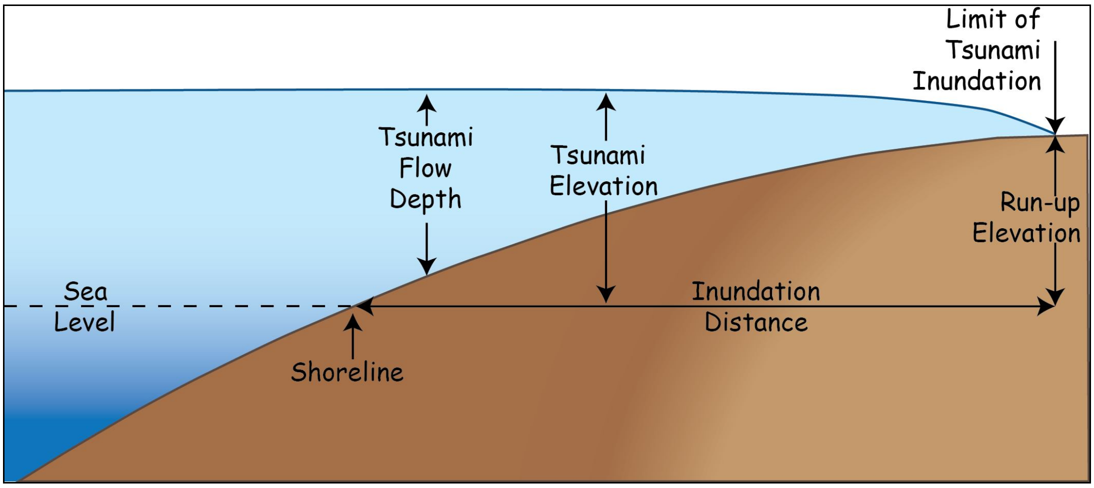

Figure 1. Main characteristics of tsunamis (www.ds.iris.edu).

The possible causes of a tsunami include earthquakes, underwater landslides and volcano eruptions. The magnitude threshold for a tsunami-generating earthquake, which is used by the alert system currently in force in the Pacific region (Pacific Tsunami Warning System PTWS), is 6.5 on the Richter Scale.

Based on some historical reviews published with regard to extreme natural events causing accidents in industrial installations, it is possible to assess both the incidence of these events on the total accidents and which of these natural events appear to have occurred most frequently. The historical analysis carried out on the main international databases available (Mars, U.S. CSB, Sozogaku, Aria and Midhas), out of a total of 16,543 accidents occurring between 1916 and 2016, showed that 236 of them were caused by extreme natural events, accounting for 1.42% of the total. Out of the total incidents, 62% were caused by lightning, while the second cause of accidents appeared to be flooding, which accounted for 22% (Figure 2).

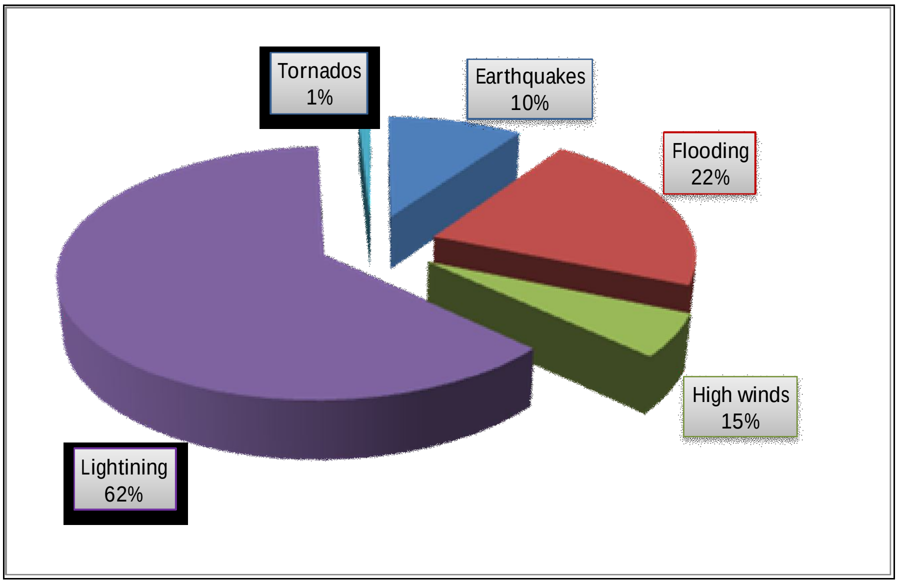

Figure 2. Accidents caused by natural events.

It is clear that both tornados and tsunamis are events which – in terms of frequency – seldom appear to cause relevant accidents. Nevertheless, the amounts of energy involved and the climatic changes underway make it necessary to carefully consider the industrial risks associated with their occurring.

Material and Method

Tornados. In order to assess the tornado risk concerning a plant where relevant accidents could potentially occur and located in the Puglia region, the diagram outline presented in Figure 3 has been followed.

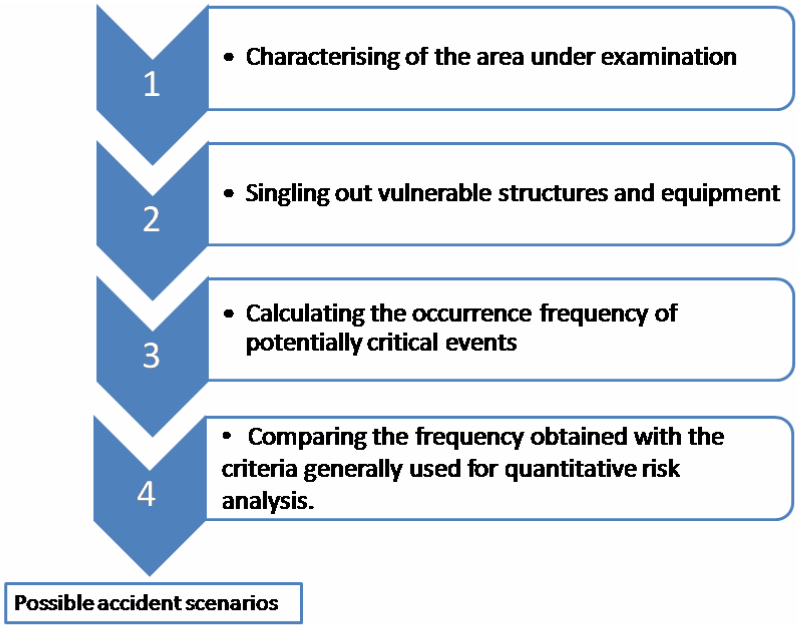

Figure 3. Tornado risk assessment pattern.

Tsunami. In order to assess the tsunami risk for a plant covered by the provisions of Directive 2012/18/UE "Seveso" and located in the Sicily region, the following pattern presented in Figure 4 was followed:

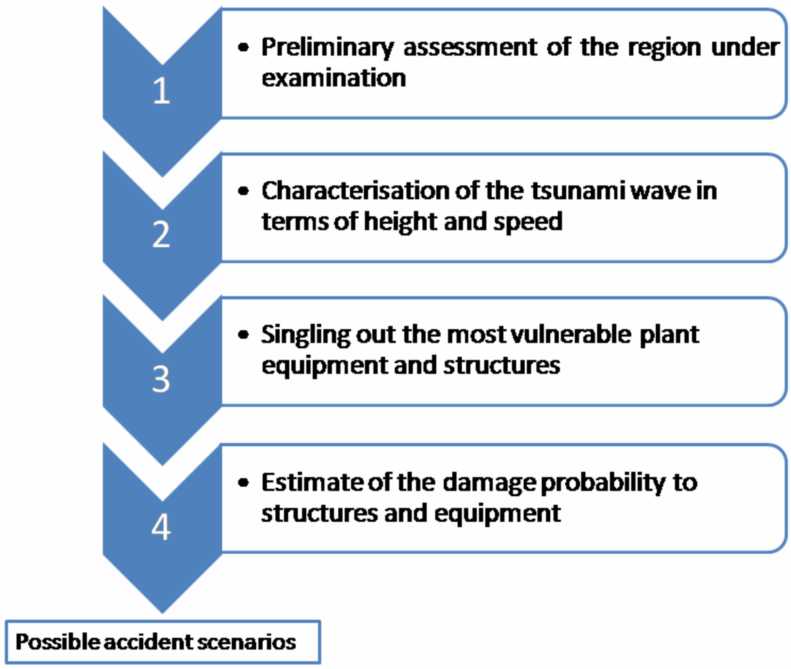

Figure 4. Tsunami risk assessment pattern.

Results and Discussion

Tornado

<u>Characterizing the region</u>. In order to characterize the region under examination, based on the number of tornado events occurring over the years, reference was made to a specialized bibliography on the subject, covering the region under examination (Gianfreda et al 2006), and to the European Severe Weather Database (www.eswd.eu), a database collecting reports of weather events occurring all over Europe, divided by type with indications – though not always available – of the intensity (Fujita Scale), length of the path/width of the tornado, its duration, as well as number of people injured and fatalities caused, an abstract of the available data is provided in Table 2.

Table 2

Abstract from the European Sever Weather Database (www.eswd.eu)

Torre Annunziata Campania Italy (40.75 N, 14,46 E) 03-03-2016 (Thusday) 16:00 UTC (+/- 1 hrs.)	**Based on information from**: photo or video of the event, a television or radio broadcast, photograph(s) and7or video footage of the inflicted damage, a report on a website. **Occurring over**: landwater **Intensity and characteristics**: **F1** The intensity raitni was based on photograph(s) and/or video footage of the inflicted damage Suction vortices were not observed. The funnel cloud was not observed. *Waterspout with landfall; source: "Torre Annunziata, tromba d'aria nel porto e vento forte a Rovigliano", Source: "Tromba d'aria nel Golfo di Napoli: spettacolare video del fenomeno" INMETEO, 03 MAR 2016; http://www.lostrillone.tv/index.php?pag=video&id=449 http://www.inmeteo.net/blog/2016/03/03/tromba-daria-nel-gofo-napoli-spèettacolare-video-del-fenomeno/* **Report Status**: **Report confirmed** (QC1)

It has thus been possible to single out the tornado events affecting the Puglia region, highlighting their time distribution and relevant estimated intensity level, to study the event from a regional perspective by highlighting the areas which have been hardest hit in the past.

In the Puglia region, according to the database, starting from the year 1832, there have been 54 events in total, with a maximum estimated intensity amounting to degree EF3.

Based on information available in the bibliography (Figure 5) and on the database - only with regard to the past ten years, during which period these reports have been available on a more regular basis - four events are reported with the said degree of intensity.

The Puglia region, during the summer, is affected by very strong supercell storms, associated with cool and dry air descending from the Balkans which meets the hot and humid air from the Gulf of Taranto; this leads to the formation of tornados, most of which have originated in the Salento peninsula and followed a SW-NE direction. The month during which the most intense events generally occurred is September, with almost all of the events being concentrated between May and early December.

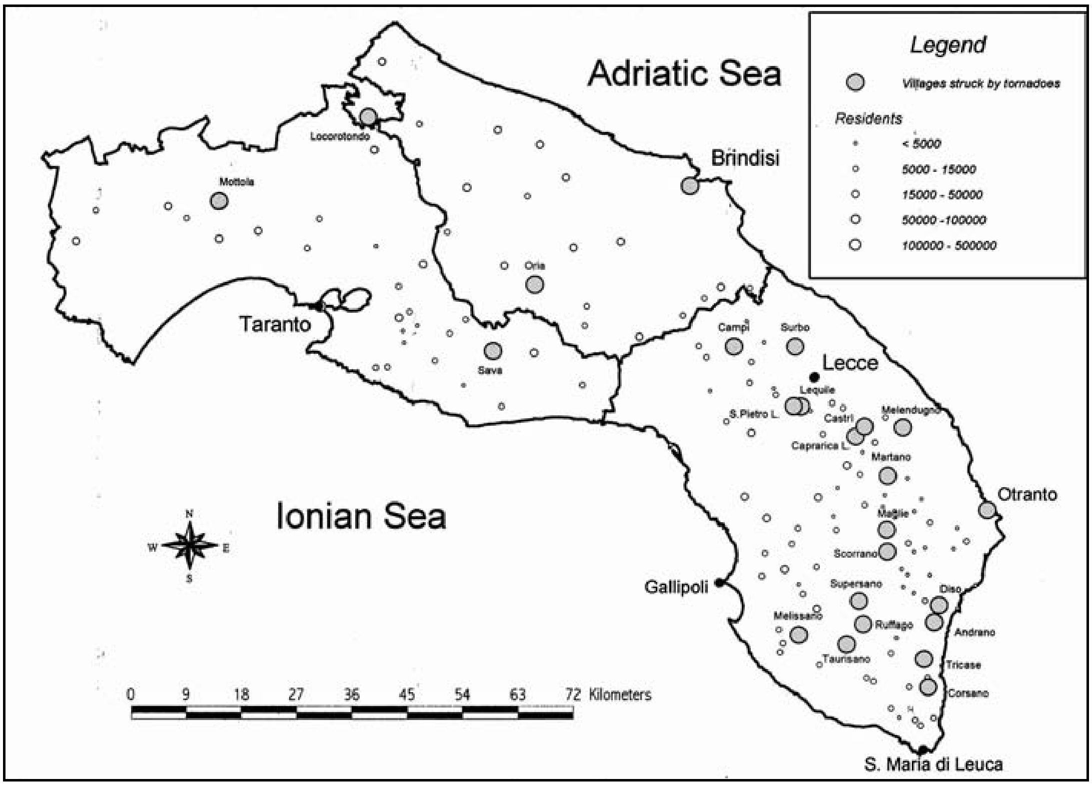

Figure 5. Distribution of tornadoes in the Puglia region (Gianfreda et al 2006).

Singling out vulnerable structures and equipment. Due to the complex mechanisms triggered by a tornado, it is difficult to quantify the combined results of applied forces, and thus to forecast the subsequent damage to equipment and other structures in a plant, which makes it even more susceptible to causing relevant accidents. In the Fujita Scale classification no reference is made to industrial facilities, therefore the general vulnerability of these structures can be assessed only on an estimated basis, by similarity approximations which do not apply to all cases. The dynamic pressure and wind speed variations are one of the main threats posed by a tornado (the other one being object and fragments being thrown about), the indicative points of reference as regards the vulnerability of equipment and structures also included the degree of damage associated with dynamic overpressure (following explosions), as listed in the bibliography (Van Geel 2005). The dynamic pressure on a wall hit by the wind at a speed v (m/s) can be calculated as follows:

$$q=\frac{1}{2}\rho v \quad \text{(Van Geel 2005)}$$

Where: q - dynamic pressure Pa (N/m^2), p - air density (kg/m^3) considered equal to 1.225 kg/m^3 (sea level), v - wind speed (m/s).

As for the equipment most sensitive to dynamic pressures, mention should be made of raised structures in industrial plants (for example distillation columns), in which case also much lower degrees of damage (light-moderate) are associated with very high dynamic overpressure peaks (≥20 kPa) (Van Geel 2005) corresponding to wind speeds higher than those estimated for Degree EF5 (Table 3).

Table 3

Maximum wind speed dynamic overpressure degree of damage

Degree	*Max wind speed (km/h)*	*Dynamic overpressure (kPa)*	*Potential damage*
EF1	175	1.5	Moderate damage: Detaches the roof surfaces; motorhomes moved from their foundations or overturned; moving cars pushed off the roads; garages might be destroyed.
EF2	220	2.3	Considerable damage. Roofs blown away from houses; motorhomes destroyed; garages destroyed; large trees broken; lightweight objects thrown like missiles by the wind.
EF3	269	3.41	Roofs and some walls blown away from solidly built houses; trains derailed; most of the trees in woodland areas are uprooted; cars lifted from the ground and blown away.
EF4	320	4.85	Solidly-built houses razed to the ground; structures with weak foundation blown a short distance away; cars violently blown away; large missiles are generated.
EF5	>320	>4.85	Houses with a strong framework lifted from their foundations and blown at considerable distances, then disintegrating; missiles the size of cars flying through the air at distances of more than 100 meters; trees are debarked.

For other types of structures present in a plant, on the other hand, it has been possible to make a more realistic comparison using damage indicators from the EF Scale, most notably as regards sheds and warehouses with a metal structure and high trellises, structures which are included among the 21 Damage indicators, an example of which is given below (Figure 6 & Table 4).

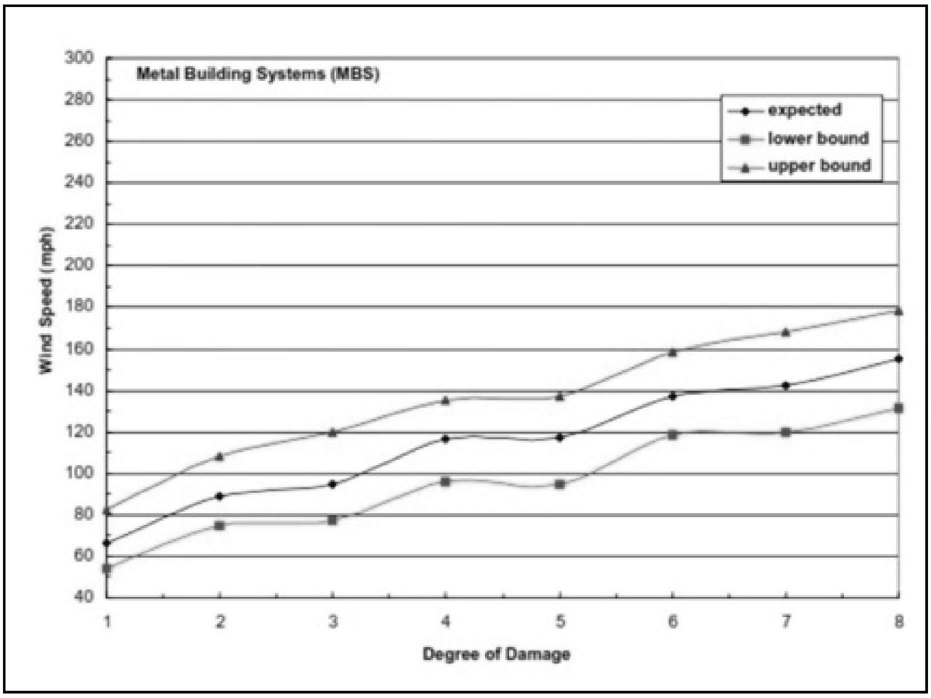

Figure 6. Degree of damage and wind speed associated with metal building systems (http://www.spc.noaa.gov/faq/tornado/ef-ttu.pdf).

Table 4

Degree of damage and wind speed associated with metal building systems

*DOD**	*Damage description*	*EXP*	*LB*	*UB*
1	Threshold of visible damage	67	54	83
2	Inward of outward collapsed of overhead doors	89	75	108
3	Metal roof or wall panels pulled from the building	95	78	120
4	Column anchorage failed	117	96	135
5	Buckling of roof purlins	118	95	138
6	Failure of X-braces in the lateral load resisting system	138	118	158
7	Progressive collapse of rigid frames	143	120	168
8	Total destruction of building	155	132	178

* - Degree of damage, EXP – expected, LB- lower bund, UB – upper bund.

The assessments have been made in greater detail in with regard to any equipment found in a plant which could be the source of relevant accidents, such as columns, reactors, tanks. Without other bibliographical data to provide reliable indications or points of reference as to the possible damage caused by tornados of different intensity to plant equipment, a few estimates have been made to assess general vulnerability based on:

- exposed resistance surfaces and weight;
- strong foundations and anchoring.

In the case under examination, the empty and full weights of the structures, as well as the anchoring method to the ground through heavy foundations, meant that they could be expected to prove more stable than sheds, warehouses and high trellises previously analyzed, and thus able to counteract more successfully the dynamic components to which they would be subject in the worst case scenario assumed with regard to the Puglia region, that is to say a tornado with EF3 intensity.

As regards upward currents alone, which can reach 300 km/h, considering their impact – for simplicity purposes – on a surface placed orthogonally, it is possible to reach a dynamic pressure in excess of 1,100 kg for each square meter.

As regards the plant equipment under consideration, listed in Table 5, whose indicative weight by surface unit on the plan can be even expected to greatly exceed 1,100 kg/m^2, apart from their being solidly anchored to the ground (additional strength), they are unlikely to be lifted and carried away as a consequence of an upward current.

Table 5

Characteristics of some typical plant equipment

Item	*Empty weight (kg)*	*Full operating weight (kg)*	*Empty weight / external surface ratio (kg/m^2)*	*Full operating weight / external surface ratio (kg/m^2)*	*Empty weight / plan surface ratio (kg/m^2)*
Reactor	346,075	446,075	478	616	7,863
Purge Bins	131,500	331,500	185	467	4,109
Column 1	323,000	1,504,706	303	1,412	21,250
Column 2	145,000	418,000	166	480	9,530
Tank	450,000	30,450,000	66	4,492	142

The data in this study showed that the structures which seemed to be most critical, in terms of weight/exposed surface ratio, were empty tanks; the latter, even though they are more vulnerable, in terms of the actions produced by a tornado (but not subject to upward currents, because of their resting on the ground and being anchored), were nevertheless in a less critical position as regards possible accidental spills.

<u>Occurrence frequency of critical events</u>. The study conducted, in relation to the characteristics of the region, identified as critical events, i.e. possible events which could lead to relevant accidents in terms of dynamic pressures generated, tornados with an intensity level equal to EF3. Based on the available statistics it is possible to complete a preliminary estimate of historically ascertained frequency as regards tornados of class EF 3 (F3), both at national level and in the region where the plant under examination is located, expressed as occurrences/year. This frequency applies to the whole reference regional surface (A3) for which historical occurrences of tornados have been taken into account.

As regards the damage area, it should be noted that the wind speed generated, with the subsequent dynamic pressure, varies within a tornado; the most damaged area in the case of a class EF3 tornado (listed among damage indicators) can be expected to be 150 m wide (Brooks 2004). In order to assess the hardest hit area within the plant, a conservative estimate was made on the basis of a pathway crossing the plant with a width of 150 m, thus affecting the largest possible surface (AS3).

The frequency with which a tornado with intensity level equal to EF3 could thus be expected to cause damage in the plant under examination is thus estimated as F3 x AS3/ A3, which – in this case – produced an extremely conservative estimate amounting to 7.56 x 10-7 occ/year.

Tsunami

<u>Preliminary assessment of the area under examination</u>. A preliminary assessment of the area to verify its having been subject to historically recorded tsunami events was made possible by referring to the Catalogue of Euro-Mediterranean Tsunamis, where more than 290 of them are listed, based on both their intensity, according to the Ambraseys-Sieberg scale which includes six degrees of damage based on the effects of the tidal wave (from 1 - very light, instrumental to 6 - disastrous) (http://roma2. rm.ingv .it/it/risorse/banche_dati/52/catalogo_degli_tsunami_euro-mediterranei). To sum up, apart from the historical data included in the Catalogue, a region within the Mediterranean area can be generically regarded as subject to a tsunami risk in the following cases:

- a distance from the coastline of less than 1,000 m (the greatest water ingression was recorded during the tsunami of 30/07/1627 in the Gargano area, when the water, through the mouth of the river Fortore, reached about 3,000 metres inland),
- a high risk of earthquake (Areas classified as 1 and 2 according to Italian Seismic Legislative, as subsequently amended and integrated), or which is close to areas at high risk of earthquake,
- having active volcanic areas, either above sea level or underwater (e.g. Tsunami in Stromboli on 30 December 2002).

<u>Characterisation of the tsunami wave</u>. Based on the events which have occurred in the Mediterranean region, some studies included in the references (Cruz et al 2009; Tiberti et al 2009; Lorito et al 2008), using mathematical models, have provided useful indications for an estimate of the maximum intensity level, specifically in terms of wave height, expected along the Mediterranean coastline, taking as tsunami sources those which have proved most relevant, based on physical characteristics and historical evidence, for example the Hellenic Arc and the Ibleo-Maltese Fault. As regards the coast of Sicily, for instance, measured in kilometers starting from a point chosen at random, the source (Lorito et al 2008) shows the following wave heights caused by a hypothetical tsunami caused by a an earthquake in the Hellenic Arc (Figure 7).

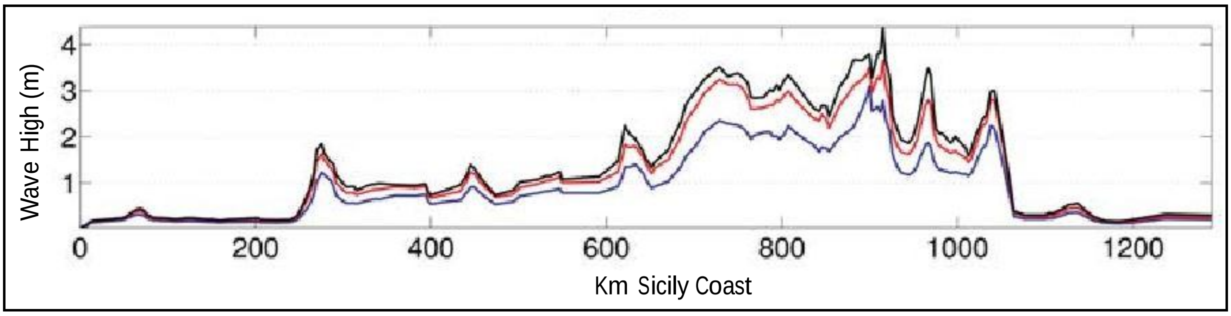

Figure 7. Expected wave height profiles along the Sicilian coastline (Lorito et al 2008).

The next step was to forecast at what distance and up to what height the expected wave could hit the mainland. The two main propagation modes for a tsunami wave along the mainland are outlined in Figure 8.

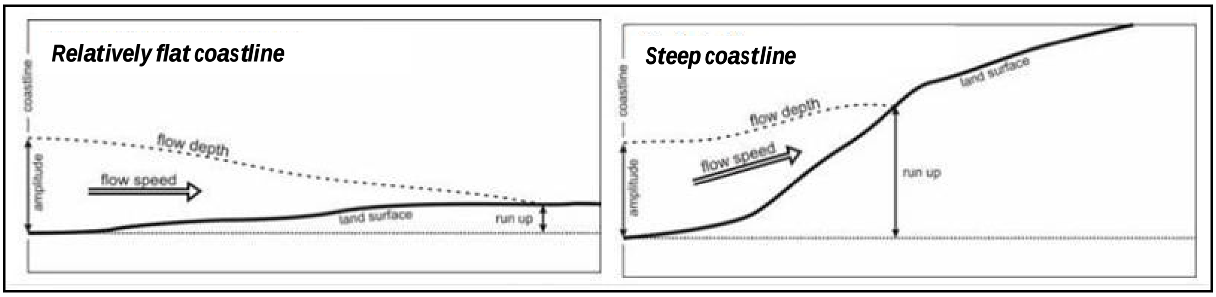

Figure 8. Propagation of a wave on the mainland (Saunders et al 2001).

If the slopes are steep (box on the right) the wave moves up the coastline, rapidly losing energy in terms of height and speed, still reaching considerable run-up levels, sometimes even significantly higher than those of the initial wave. Along a relatively flat coastline (box on the left) the diagram shows a steady decrease in terms of wave height all along its propagation path through the mainland. As regards these specific types of coastline, there appears to be a specific correlation between the maximum potential run-up of a wave and the ingression distance on the mainland, which makes it possible to calculate the decrease in terms of energy during this phase. Generally speaking, the decrease in terms of run-up can be estimated at about 1 m for every 200 m of ingression through the mainland (Fraser & Power 2013), as shown in the Figure 9. This assumption, for instance, is used as a benchmark to establish evacuation zones in several countries at risk of tsunami events (e.g. New Zealand, Samoa Islands).

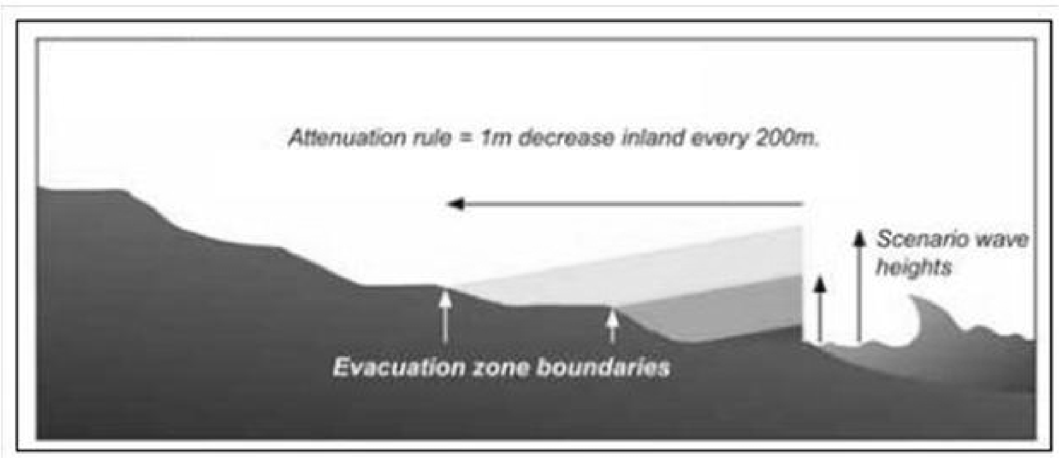

Figure 9. Attenuation rule (Fraser & Power 2013).

Considering that, in the open sea, the speed of the wave is a function of its height, it is thus possible to predict, in general, that - as the wave moves further inland- there will be a decrease in its speed which is directly proportional to that of its height (Matsutomi et al 2010).

Selecting vulnerable structures and equipment. Tsunamis and the subsequent flooding can cause different types of additional loads on the structures and equipment of industrial plants. The following are the most significant (Table 10):

- hydrostatic loads exercised by the water, when it is either still or moving slowly, on each surface with which it comes into contact, acting laterally and perpendicularly and caused by a pressure unbalance due to different water heights on both sides of the structure;
- hydrostatic loads with a vertical impact on structures and equipment partially or totally submerged by water;
- hydrodynamic loads resulting from the movement of water, as a function of the flow speed and geometry of the structure;
- loads due to the impact of debris carried by the water.

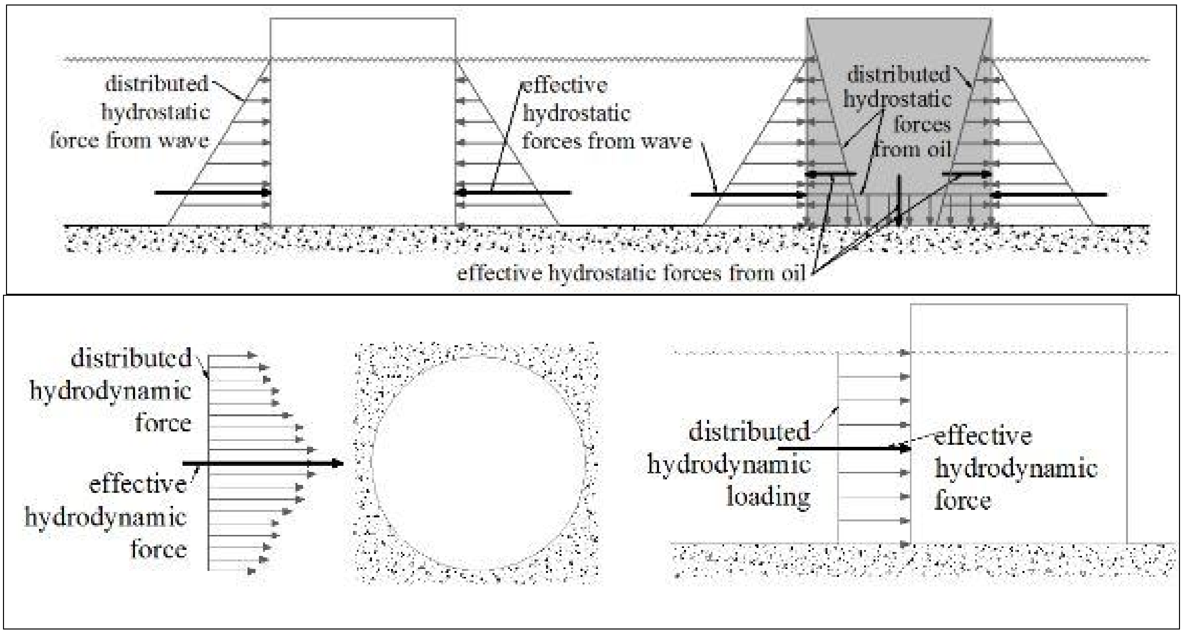

Figure 10. Hydrostatic and hydrodynamic loads (Brooker 2011).

As regards the additional loads caused by tsunamis, it has been possible to perform a qualitative analysis allowing for a selection of plant equipment which appeared to be most critical in the event of flooding. This analysis was based on research results from the reference source (Campedel 2008) with regard to industrial accidents caused by flooding on plants containing dangerous substances, carried out on the main European and US databases. Out of a total 272 cases, it was concluded that atmospheric and floating roof storage tanks appear to be most frequently involved in this kind of accidents, thus most vulnerable (Figure 11).

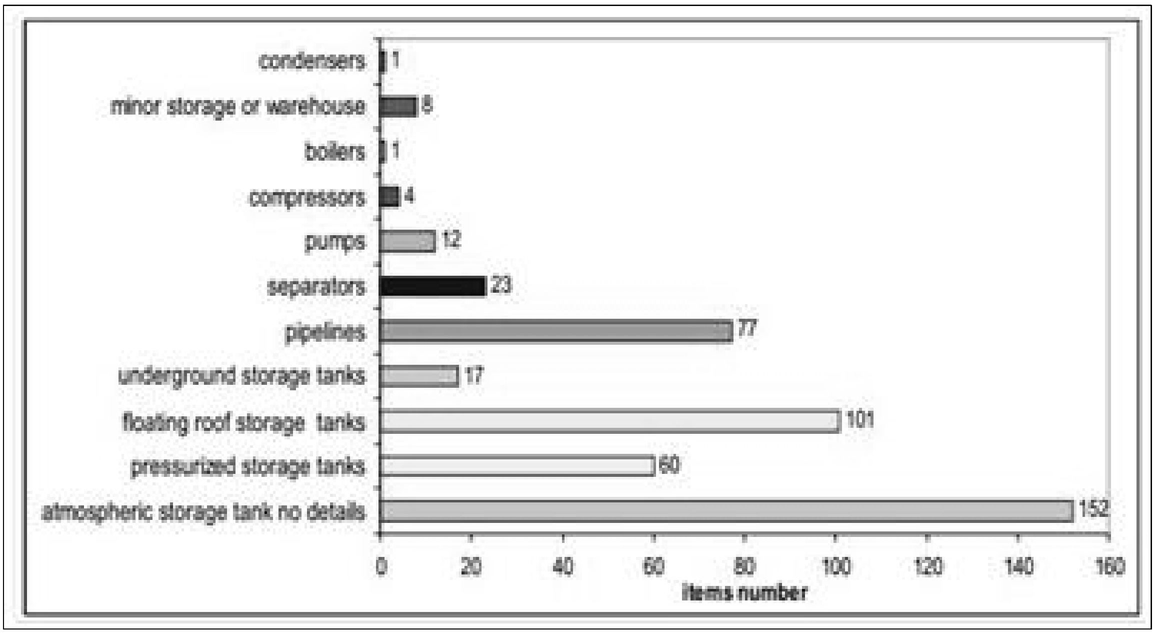

Figure 11. Equipment involved in accidents caused by flooding (Campedel 2008).

Generally speaking, 74% of the equipment involved in accidents caused by flooding, according to the study (Campedel 2008), consists in storage tanks, especially because of the amount of hazardous substances they contain (Figure 12).

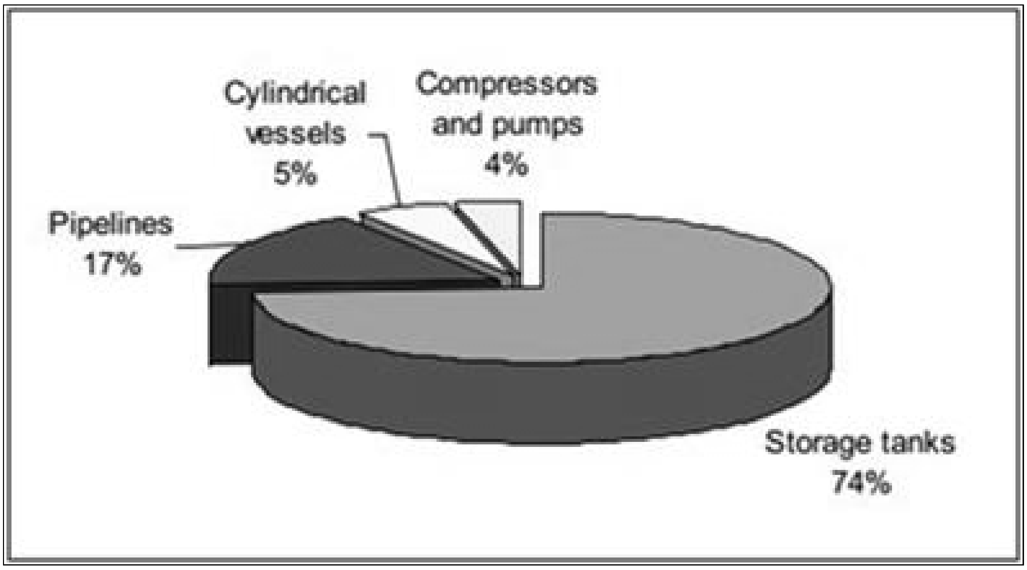

Figure 12. Percentages of types of equipment involved in accidents caused by flooding (Campedel 2008).

Estimate of the damage probability. More specifically, in the case of storage tanks, the definition of a vulnerability index is associated with the exceeding of specific damage probability thresholds as a consequence of the tsunami, defined in terms of height and speed of the wave. These correlations are also known as frailty curves; they are derived from processing based on historical data, related to damage sustained by different types of tanks (e.g. of the anchored or non-anchored type, pressurized tanks, etc.), an instance of which is outlined in Figure 13.

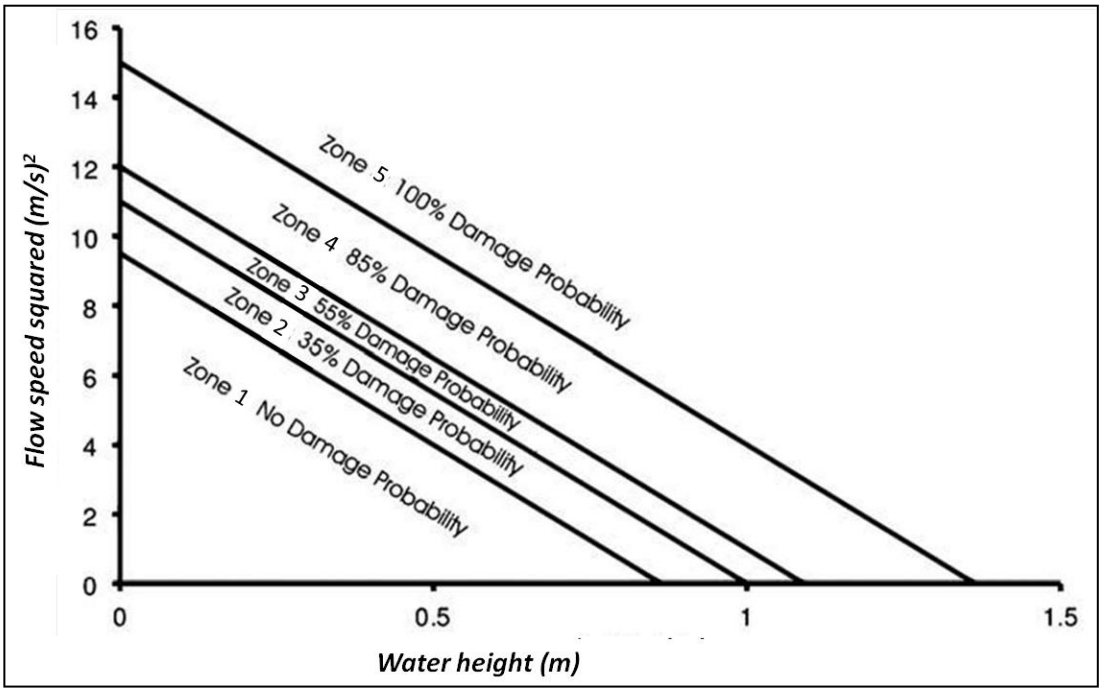

Figure 13. Fragility curves (Cruz et al 2009).

What appears to be especially significant is the filling level of the equipment which is hit by a tsunami wave. The Figure 14 shows the correlation between tank resistance, expressed as percentage of tanks which remain intact after a flooding event, and their respective filling level. It should be noted that, as the filling value of a tanks approaches 10%, there are considerable increases – eventually reaching the totality – as regards the percentage of tanks which are able to withstand a flooding event without incurring any damage. In the case under examination, the content density could prove to be slightly lower than the value in the Table 5.

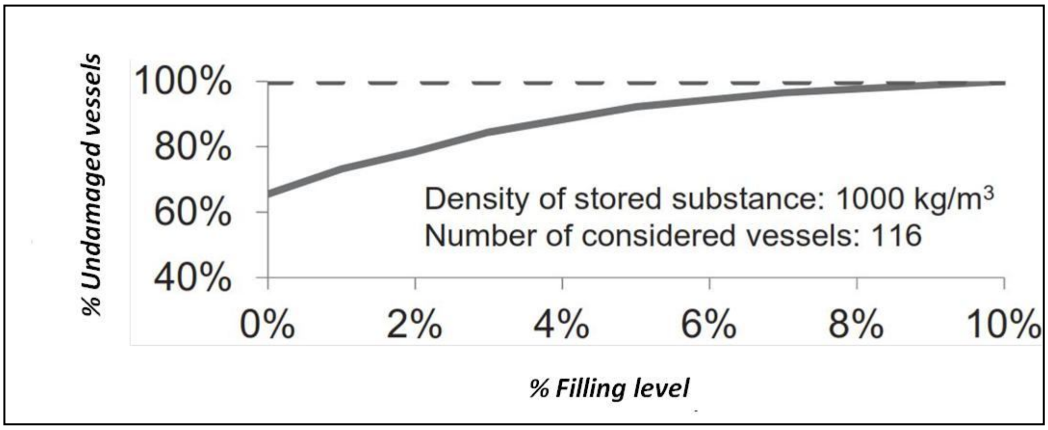

Figure 14. Relationship between filling level and tank resistance (Landucci et al 2013).

Finally it will be possible to estimate the maximum run-up value which could be reached by that wave along the coast in front of the Plant under examination, and then to calculate the expected height levels for the more vulnerable equipment (as storage tanks) potentially hit by the wave in respect of the maximum estimated ingression distance, using a merely cautionary approach which also takes into account the possibility of the wave propagating without any attenuation (Figure 15).

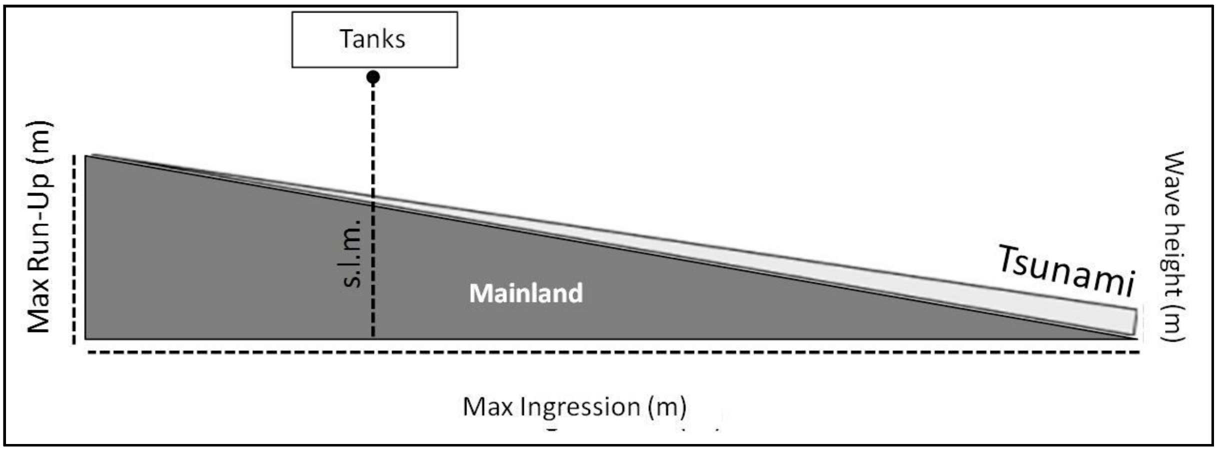

Figure 15. Simplified diagram of propagation without attenuation.

Conclusions

Final assessment of the tornado risk. The occurrence frequency of a tornado whose intensity level is EF3, able to produce substantial damage to facilities such as warehouses and raised metal structures inside the plant, seems to be extremely low; as a consequence the accident scenario, supposing that due care is taken and considering the necessary probability assumptions in respect of its development, could be expected to show even lower occurrence frequencies. The foreseeable damage to vulnerable structures has been taken into account, however it seems reasonable to exclude the likelihood of believable relevant accident scenarios, given the extremely remote possibility of equipment containing hazardous substances becoming involved in a tornado of sufficient intensity to result in a catastrophic collapse. The likelihood of objects with a substantial mass being thrown about also appears to be extremely remote, given the maximum expected intensity of a tornado event in this area.

Tsunami risk assessment. According to the wave height values listed in the studies which have been taken as reference and, based on a historical analysis, considering storage tanks as the most critical equipment in the event of flooding, it has been possible to apply the attenuation rule (Figure 9), thus estimating the maximum run-up value which could be reached by that wave along the coast in front of the Plant under examination, and then to calculate the expected height levels for the storage tanks potentially hit by the wave in respect of the maximum estimated ingression distance, using a merely cautionary approach which also takes into account the possibility of the wave propagating without any attenuation (Figure 15).

The values obtained as regard the wave height were then compared with the frailty curves available in literature, to estimate the probability of damage to the equipment; also taking into account the relative density, this figure is close to zero for all items under consideration.

The analyses have been complemented with a subsequent assessment of the natural and artificial protection measures in the plant, which ought to counteract the possible effects caused by flooding; these include offshore structures such as the seawall and detached breakwater, as well as plant facilities such as containment basins.

Finally, considering the influence of the filling level on the probability of damage in the event of flooding (Figure 14) it has been concluded that tanks which are filled to low levels or empty, even though they are more vulnerable to possible damage, appear to be in a less critical position as regards possible massive spills, potential sources of relevant accidents.

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