A SOLUTION FOR MODELING TSUNAMI-STRUCTURE INTERACTION AND SUBSEQUENT FLOODING TO ASSESS THE SAFETY OF SEASHORE NPP AND INDUSTRIAL STRUCTURES

TECHNICAL PAPER

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Abstract: The 2011 events in Japan when the Fukushima Daiichi NPP suffered a major accident have focus the attention on the risks associated with major tsunamis. After recalling these events and the associated safety requirements, the paper outlines the underlying physics of the tsunami events and proposes an innovative modeling method to capture the phenomena and provide the means for a rational engineering of the NPP and industrial structures subject to tsunamis. Some validation cases, both quantitative and qualitative are presented to justify using such approach in documenting the safety of these installations.

1. Introduction

The tsunami that occurred in Japan in 2011 has produced massive damages to the infrastructure along the coast. Beyond the unexpected intensity of the event, engineers have found that the methodologies used to design structures against the effects of a tsunami and subsequent flooding were inadequate [1][10].

The methods used to simulate the impact of a tsunami wave on the coast were limited to predict the characteristics of the incoming wave and the spreading of water over the coast with all the structures modeled as rigid obstacles. The interaction with these structures were, at best, considered by retrieving the transient pressures applicable to the external walls of the building for a subsequent verification of the capacity of these structures to withstand such load, evidently with insufficient accuracy [13]. While the safety codes identify the tsunami events as critical for the safety of the installation, very little is defined in these codes about the modeling approaches to apply. The design processes recommended by some design standards are rather primitive for the strength of the structures [11][12] and they do not provide any recommendation for assessing the effects of flooding [7].

The need for a mode accurate modeling of the physics of tsunami-structure interaction enabling to predict accurately the damages produced by such events and, hence, to enhance the structural design was identified. Based on modeling techniques used in other industrial segments, an innovative approach has been proposed. Such method relying on a meshless modeling of the wave has been demonstrated to provide the means to capture the physics of the interaction. Its accuracy has been demonstrated quantitatively against test results carried out on scaled down mock-ups [9] and qualitatively against observations retrieved from inspections in Japan.

This paper recalls the basic physics involved in such interaction. It summarizes the main safety requirements and presents the innovative modeling method. The results of the validations tasks are described to justify its application on industrial cases.

2. Tsunami Phenomenology

The combination of the earthquake and tsunami that occurred in March 2011 in Japan caused considerable damage to the coast. Almost half a million residential buildings were damaged or destroyed. There was considerable damage to roads, railways, and public and industrial utilities. The

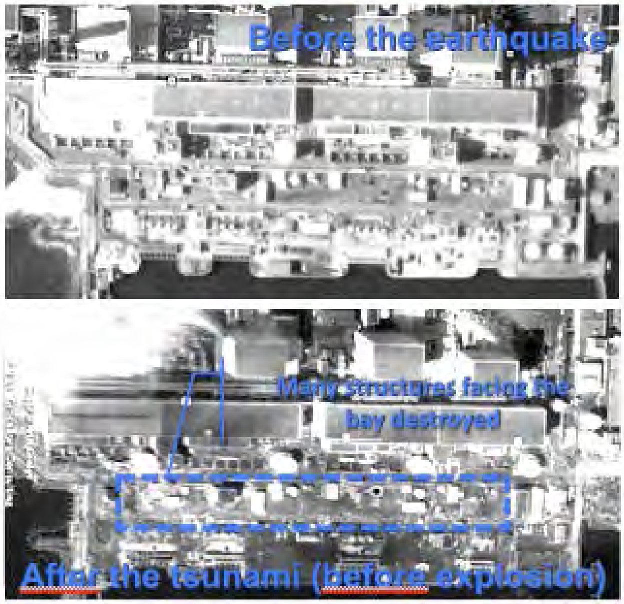


Fig. 1 – Damages caused by the tsunami at Fukushima NPP

total area inundated by the tsunami was about 561 square km. Among these damages, the most talked about are the ones relative to the Fukushima NPP.

The earthquake reaching 9.0 on the Richter scale occurred 180 km off the coast of the Fukushima Daiichi NPP with a hypocenter 24 km under the seabed. The peak accelerations recorded on the site was 0.561 g in the horizontal direction, exceeding the design base acceleration of 0.447 g. This caused all the operating units to automatically scram on reactor protection system trips.

The earthquake damaged electrical equipment, causing a loss of off-site power sources. The emergency diesel generators automatically started and provided AC power to the emergency systems in full conformance with the emergency safety plan. Few minutes after the earthquake, a tsunami warning was issued, indicating the risk of a tsunami at least 3 meters high.

Less than one hour after the earthquake, the first of a series of seven tsunamis arrived at the site. The maximum tsunami height was estimated to be 14 to 15 meters. This exceeded the design basis tsunami height of 5.7 meters and was above the site grade levels of 10 meters.

The emergency power was lost when a tsunami ran up the site and flooded the emergency diesel generators and switchgear rooms. The seawater intake structure was severely damaged and was rendered nonfunctional, hence disabling most means to cool the reactor core and the spent fuel pools.

With no cooling to remove decay heat from the core, damage has begun to develop on the day of the event. Steam-driven injection pumps were used to provide some cooling water to the reactors, but these pumps eventually stopped working; and all cooling water to the reactors was lost.

Hydrogen generated from the damaged fuel in the reactors accumulated in the reactor buildings, producing explosions in several reactor buildings. The loss of primary and secondary containment integrity resulted in ground-level releases of radioactive material.

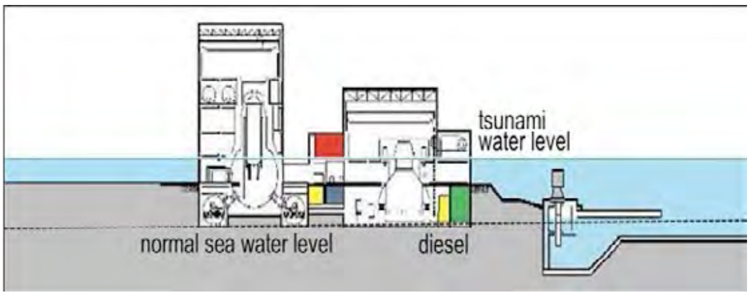


Fig. 2 –Inundation Level at Fukushima [1]

In the 1960's, when TEPCO applied for the construction permit, it was common practice to refer to historical records in order to define the design basis tsunami height. Numerical simulation of tsunamis based on tsunami generation methods (earthquakes) did not begin until the mid-1970s. The original design basis tsunami for Fukushima Daiichi was based on the Chilean tsunami of 1960, which resulted in a historic high water level of 3.12 m at the Onahama port, just north of the plant.

Based on this, 3.12 m was the design basis for Fukushima NPP when the construction permit was issued.

The tsunami design basis for Fukushima NPP considered only the inundation and static water pressures, and not the impact force of the wave or the impact of debris associated with the wave. The design included a breakwater, which ranged in height from 5.5 m to as high as 10 m, much too low to accommodate the March 2011 tsunami.

3. Tsunami Physics

Earthquakes, volcanic eruptions and other underwater explosions, landslides and other mass movements, meteorite ocean impacts or similar impact events, and other disturbances above or below water all have the potential to generate a tsunami.

A tsunami is a series of water waves (wave train) caused by the displacement of a large volume of a body of water, usually an ocean, but can occur in large lakes as well. The wavelengths of tsunami waves can reach hundreds of kilometers in deep oceans making them barely noticeable and separating the crests from five minutes to more than one hour.

While everyday wind waves have a wavelength of about 100 m and a height of roughly 2 m, a tsunami in the deep ocean has a wavelength of over 200 km. Such a wave travels at well over 800 km/h, but owing to the enormous wavelength the wave oscillation at any given point takes 20 or 30 minutes to complete a cycle and has amplitude of no more than 1 m. This makes tsunamis difficult to detect over deep water. Ships rarely notice their passage.

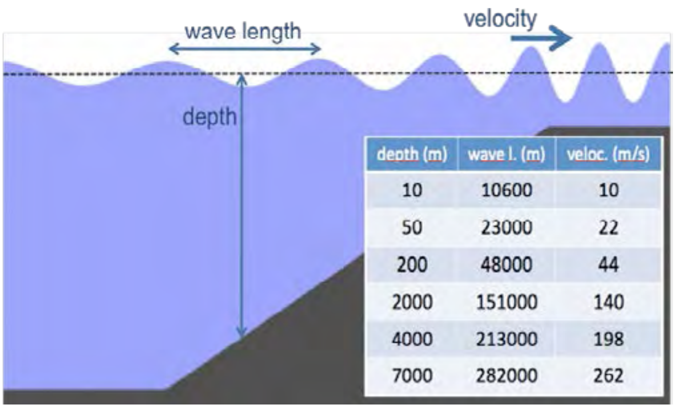


Fig. 3 – Tsunami wave typical characteristics

As the tsunami approaches the coast and shallower waters, shoaling compresses the wave and its velocity slows below 80 km/h. Its wavelength diminishes to less than 20 km and its amplitude grows enormously, producing a distinctly visible wave. Since the wave still has such a long wavelength, the tsunami may take minutes to reach full height. Except for the very largest tsunamis, the approaching wave does not break, but rather appears like a fast moving tidal bore. Open bays and coastlines adjacent to very deep water may shape the tsunami further into a step-like wave with a steep-breaking front.

When the tsunami's wave peak reaches the shore, the resulting temporary rise in sea level is termed 'run-up'. Run up is measured in meters above a reference sea level. A large tsunami may feature multiple waves arriving over a period of hours, with significant time between the wave crests.

About 80% of tsunamis occur in the Pacific Ocean, but are possible wherever there are large bodies of water, including lakes.

4. Regulatory Requirements

4.1 Philosophy of Safety

The basic approach in assessing tsunami hazards on a nuclear installation relies on a three-step approach outline as follows [5].

The first step corresponds to a regional screening. If the site region is not subject to tsunamis, no further analysis for tsunami hazards is required. A proven absence of tsunami causes in the site region may result in a determination that the site region is not subject to tsunamis. However, this should be supported by region-specific evidence. If the assessment is undetermined based on available information, an analysis of the tsunami hazard is required.

The second step corresponds to a site screening. This step insures that important safety systems are not exposed to hazards from tsunamis. It may be possible to determine that, even though the general site region is subject to tsunamis, the plant itself is sited and designed in such a way that its safety is not affected. For example, if all systems and components important to safety are located at an elevation above the maximum wave run-up due to the probable maximum tsunami (PMT), more specific tsunami-flooding assessment may not be needed for the site.

The third step is the most refined assessment, in which site-specific analyses are carried out to determine hazards posed by the PMT to the critical systems and components important to safety and to determine whether any protection is required. This step involves postulation of PMT source mechanisms, estimation of PMT source characteristics, initiation of the PMT wave, propagation of the PMT wave from the source toward the site, and estimation of tsunami hazards at the site, i.e. tsunami-structure interaction assessment.

The scope of this paper covers this third and more refined safety assessment.

4.2 Tsunami Effects on Safety

A number of effects, mainly from hydrodynamic forces, can cause severe damage to structures and their foundations. If any of these are safety-related, they must be able to withstand these effects or be protected adequately from them to ensure the safety of the plant.

Hydrostatic and Hydrodynamic Forces

Hydrostatic force acts as a pressure proportional to the depth of water applied to all structural surfaces. The hydrostatic pressure during the passage of a crest will be higher and lower during passage of a trough.

Hydrodynamic forces result from moving water interacting with structures. On-shore structures may experience impacts on the sides facing the oncoming wave, drag forces on the sides, and suction on the downstream end of the.

Systems and components important to safety must be designed to withstand these forces without loss of operation or be protected from them with appropriate shielding.

Flooding due to run-up

Tsunami waves can inundate large areas inland from the shoreline up to a characteristic elevation (run-up). The protection from tsunami flooding can be provided in the same way as for other flooding sources: either the safety important systems and components can be located above the run-up or adequate flooding protection can be provided to ensure that safety is not in jeopardy.

Projectiles

Tsunamis can dislodge and transport a wide range of debris (automobiles, trees, boats, etc.). Debris and projectiles can impact the structures at the same elevation as the water-surface level. Adequate design criteria should be employed for safety related systems and components exposed to impacts from water-borne debris and projectiles. An alternative is to locate these systems and components so that they will not be exposed to water-borne debris and projectiles.

Sediment and debris deposition

Tsunami currents are capable of carrying debris and sediment. As the waves recede, the sediment and debris can be deposited at and near the shoreline. For a NPP, all safety related systems and components should be designed such that they are not affected by the deposition of debris and sediment.

Dry intakes during drawdown

During recession of the tsunami, water level is lowered. Depending on local bathymetry, the areal extent of recession can be quite large. NPP that depend on an intakes located offshore should ensure that the maximum lowering of the water does not result in dry intakes. Protection from receding tsunami waves can be provided either by locating away from the shoreline and in deep waters the safety-related intakes, or alternative sources of safety-related water supply can be made.

Scouring

Tsunami waves in shallow waters can create scouring at the front of obstacles that can affect the foundations of the structures. A nuclear power plant that locates any safety related structures where tsunami currents may result in scouring should ensure that the structures are adequately designed to resist the scouring forces of tsunamis.

Tidal Bores

Tidal bores propagating upstream from the mouth of a river can be caused by tsunamis and can travel upstream several tens of kilometers from the estuary. The effect of a tidal bore propagating upstream to a NPP is similar to a flood wave propagating downstream. This may result in flooding of the site depending on the height of the bore and the dykes. Site selection and protection criteria for tidal bore are similar to those for other flooding mechanisms.

4.3 Safety Demonstration

While the demonstration of safety under tsunami loading is an accepted approach, the modeling techniques recommended by the design guides are recognized to be crude and approximate. In that particular field, the numerical methods that have spread in the NPP field for a variety of situation have faced so far some critical lack of practical modeling means and validation.

5. Modeling Tsunami

5.1 Multiple Scales

As for any task of mathematical modeling, modeling tsunami depends on the objectives targeted. As tsunamis are often generated in the ocean far from the coastline of interest, the first phase is related to the generation of the wave and its propagation along the oceans. This is a far field approach that will deliver wave characteristics when approaching the region of interest.

At this stage, the wave will spread depending on the regional topography of the seabed and of the coastline. A near-field modeling will deliver the characteristics of the waves at the cost toe.

For structures located at the edge of the coast, these characteristics can be used to apprehend the interaction of the waves with the structures. Otherwise, another step is required, namely the simulation of inundation that will deliver the global flooding conditions inland.

With the characteristic of the applicable waves known, the modeling of the interaction of the tsunami with the structures and the consequent flooding of the buildings can be tackled.

5.2 Far Field Modeling

Using commonly accepted models, such as MOST (method of splitting tsunami), once the original source of tsunami is characterized, it is possible to propagate the waves on areas as large as the Pacific Ocean and to predict the tsunami characteristics far away from the location of its origin. Research institutes and government agencies usually carry out such analyses to deliver these parameters to the safety agencies and the industry.

5.3 Near Field Modeling

In near-field modeling, the scale is reduced to enable taking into account local topography and enabling to predict the characteristics of the tsunami wave reaching the shoreline. The models used are similar as for the far field simulations but with a smaller scale that enables to include more details on the seabed and coastline topography, in particular it can predict wave focalization effects.

5.4 Inundation Simulation

The purpose of the inundation simulations is to predict the run-up distance of a tsunami wave determined either with a far field or with a near field simulation. For such simulations, details about the structures (including trees) on the shoreline hit by the wave are needed in order to define the obstacles raised against the wave propagation.

Form the modeling standpoint, inundation simulations, especially in urban areas, look alike models used to tsunami-structure interaction. However, the inundation models must be of one order of magnitude larger and they do not include all details. Especially, they do not account for the structural deformations and creation of floating debris that can impinge other structures.

The main purpose of that kind of simulation is to provide the municipal authorities with maps of risks to help them planning the evacuation of the population. As a by-product, for structures not located on the shoreline, these simulations can also provide the characteristics of the incoming tsunami wave.

5.5 Tsunami-Structure Interaction

In the assessment of NPP safety in case of a tsunami, this lower scale modeling is the most important. Surprisingly, modeling methodologies have not tackled it accurately; hence vindicating the simplified approach recommended in the design guides. Currently a number of solutions are being used, albeit usually modeling the structures as being rigid.

Models of tsunami waves define the loading conditions for numerical models geared toward must analysis of fluid-structure interaction [2]. Two phases can be considered in modeling a tsunami-structure interaction. The first one covers the initial impact of the tsunami wave against the structure and any protecting dyke that has been erected, creating a wave slamming effect for which the transfer of momentum is the critical parameter. After that initial phase subdues, a more classical hydrodynamic situations develops, albeit with much lower load levels and, unless scouring is to be feared with much less severe conditions for the structure. In this second phase, however, flooding can develop with water streams penetrating the structures and potentially disabling emergency safety equipment.

A proper solution for modeling tsunami-structure interaction needs to represent in a reliable way the transfer of momentum between the water and the deformable structure and provide the means to predict the dynamics of flooding inside the buildings, including potential deformation of barriers that have been established.

5.6 Tsunami Impinging Wave

Fig. 4 – Tsunami wave by Hokusai and US tsunami hazard sign

As the transfer of momentum during initial wave slamming is a critical parameter to justify the safety of structures and buildings during a tsunami event, the corresponding loading condition is important. This is represented by the characteristics of the tsunami wave.

While the culture tends to stick to the dramatic representation of a tsunami wave illustrated by the Japanese artist Hokusai [Fig. 4] to the point that is has been selected for drafting the tsunami hazard sign in the US, it does not fully represent the actual situation required to assess the safety of NPP and industrial structures subject to such events.

The actual tsunami wave records [Fig. 5 and 6] show that even near the coastline, the wavelength remains long with periods of several minutes between the crests, which is much longer than all time constants of the physical phenomena taking place during a tsunami-structure interaction.

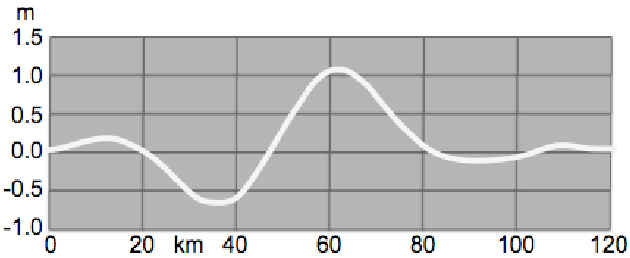


Fig. 5 – 1993 Nicaragua tsunami profile at the toe of the beach [8]

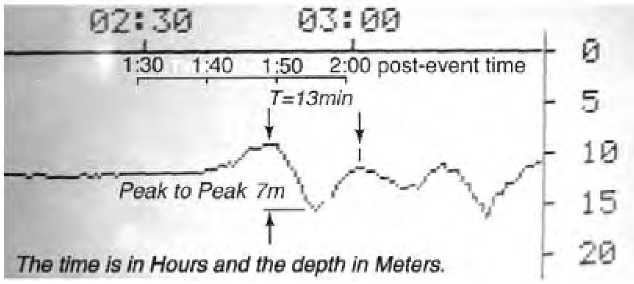
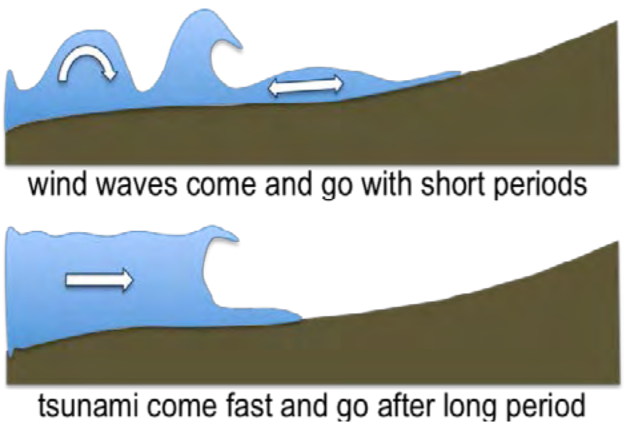


Fig. 6 – 2004 tsunami as recorded on the depth gauge of the ship Mercator anchored 1 mile off the coast of Phuket, Thailand [9]

With such long periods, the details of the wave profile can hardly be steep and assuming it to be of constant height during the whole slamming phase as well as for the subsequent flooding appears to be a reasonable and conservative approach if the height is equated to the nominal tsunami height.

The incoming tsunami wave is thus modeled as a plateau of water arriving at constant velocity to the shoreline before impacting whatever structure it encounters on its way.

Such model is actually confirmed by one of the ore recent tsunami test laboratories where a complex feeding structure has been designed to insure such wave profile.



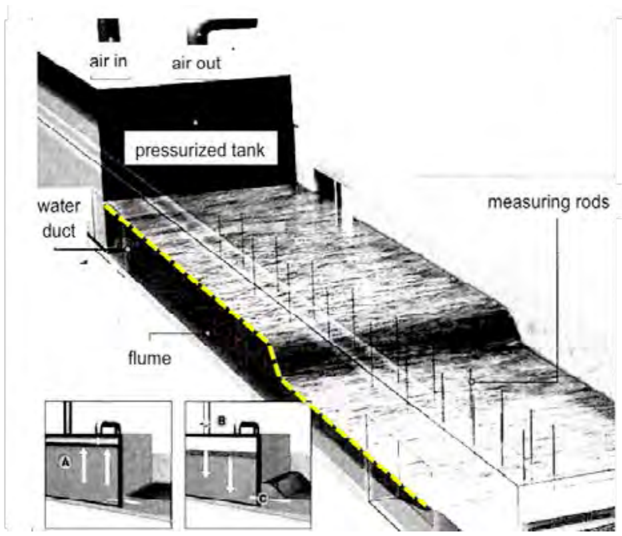


Fig. 7 – Wind and tsunami waves profiles

Fig. 8 – EPI Center's tsunami test installation at UCL to generate tsunami waves with realistic wavelengths [8]

6. Solution for Simulating Tsunami Structure Interaction and Flooding

6.1 Requirements

Any solution to model mathematically the interaction of a tsunami wave with NPP and industrial structures must be capable of capturing the essential physical phenomena that can impair the safety of the plants. This includes the capacity to predict the deformation and rupture of the structure under the wave slamming loads as well as inside the building under the flooding. It also requires, and this represent a challenge with respect to the current state-of-the-art in numerical modeling, the capacity to model the dynamic interaction of an incoming wave modeled as described here above with such deformable and breakable structure. Eventually the flooding of buildings with water running along the possible channels must also be predicted.

6.2 Water-Structure Integration

The solution selected to model the dynamic interaction between water and deformable structures is the one available in ESI product VPS in which the structure is modeled using PAM-CRASH modeling capabilities and the water with SPH (Smooth Particles Hydrodynamic) with an in-core coupling to the structural model. This product has readily been used and validated for similar configuration on other industrial sectors, most notably the aeronautics for modeling the ditching of airplanes and helicopters in water bodies [Fig. 9].

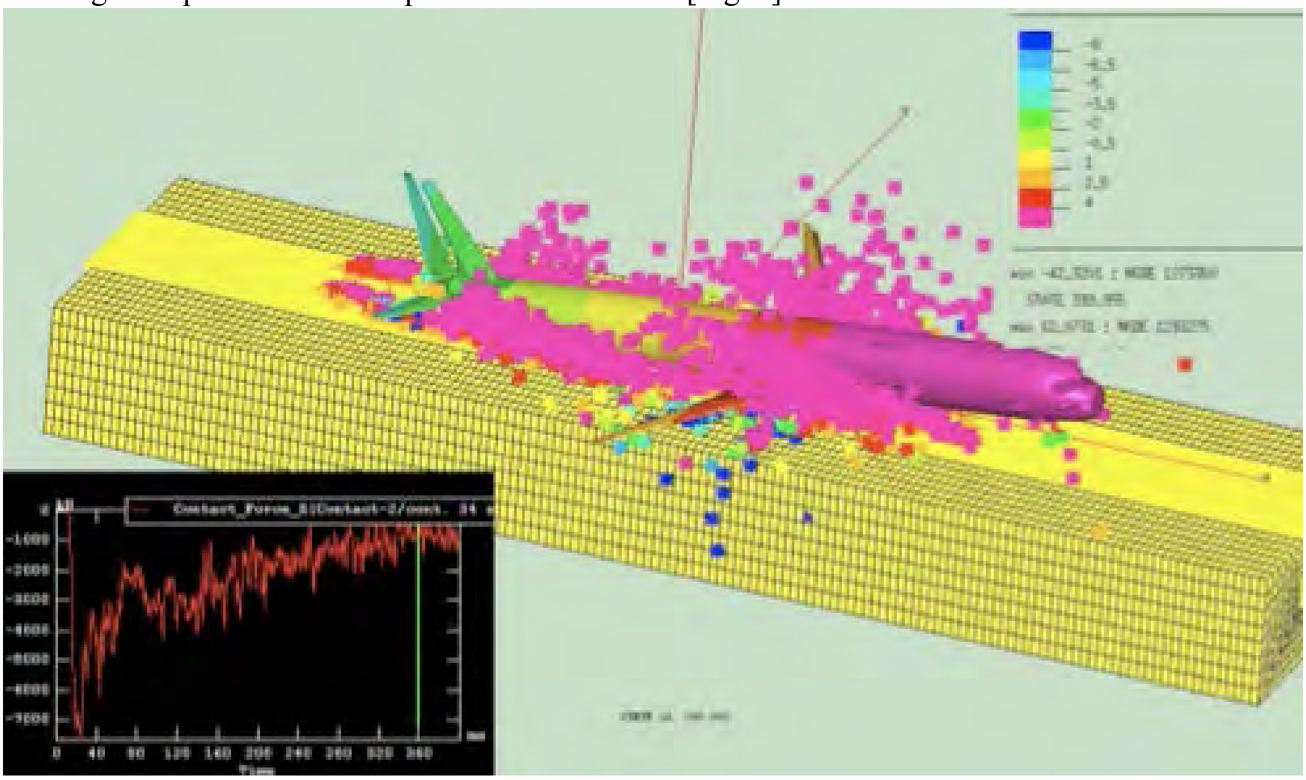


Fig. 9 – Simulation with VPS of Airbus 321 ditching in water (courtesy of DLR)

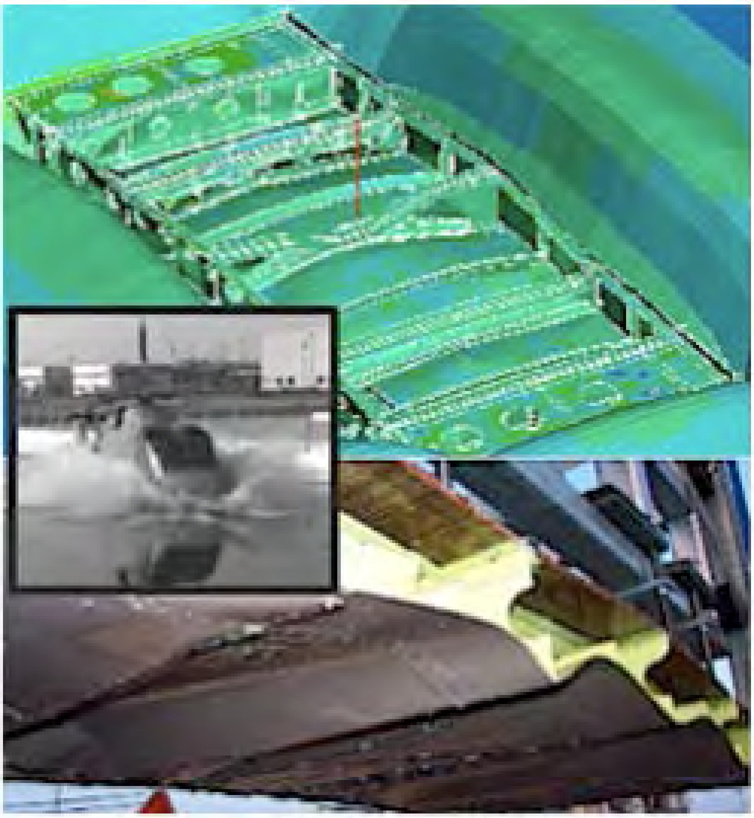


Fig. 10 – Helicopter floor deformation (simulation and test)

While in these cases, the water was still and the structures were moving, the fundamental physics is the same. These previous cases, some having been validated against full-scale physical tests [Fig. 10], confirm the validity of the solution.

7. Feasibility

7.1 Wave Slamming and Flooding

A feasibility project was carried out to illustrate the possibility of the VPS based solution to reproduce the physical features of the wave slamming and building flooding. In the test case, the building was modeled as rigid as previous projects already demonstrated the capability of accounting for deformable structures interacting dynamically with water masses.

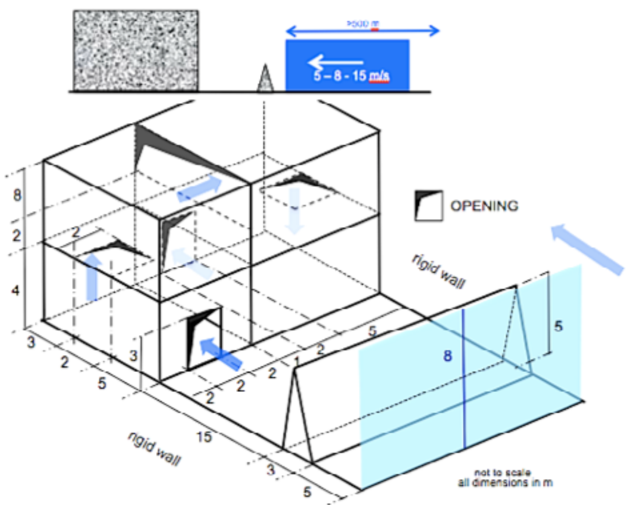


Fig. 11 – Demonstration case #1

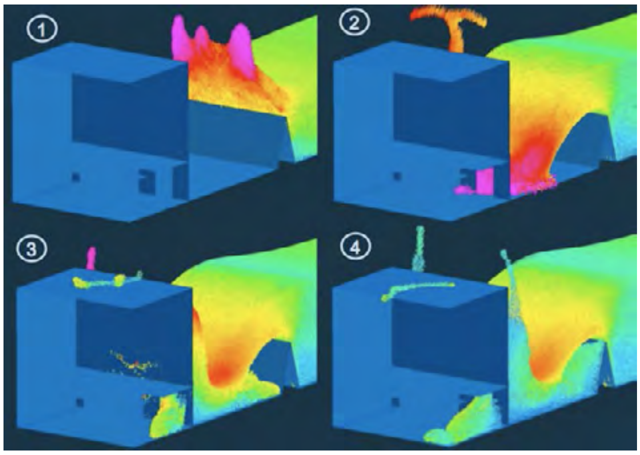


Fig. 12 – Wave slamming and initial flood

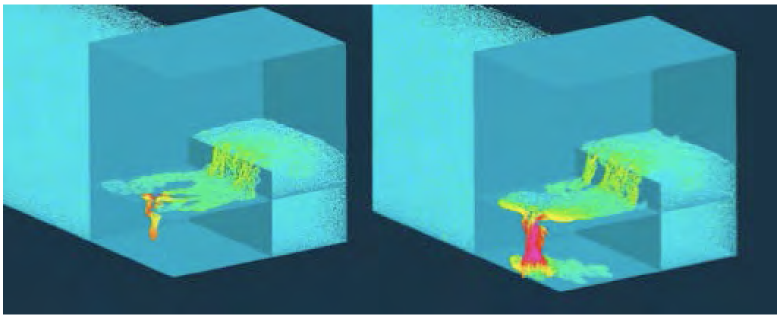


Fig. 13 – Flooding of building

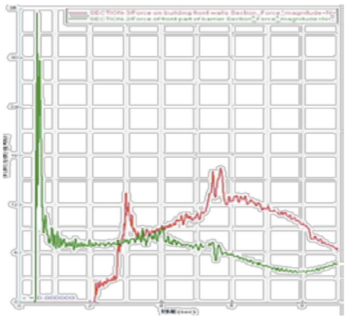


Fig. 14 – Wave slam load on structures

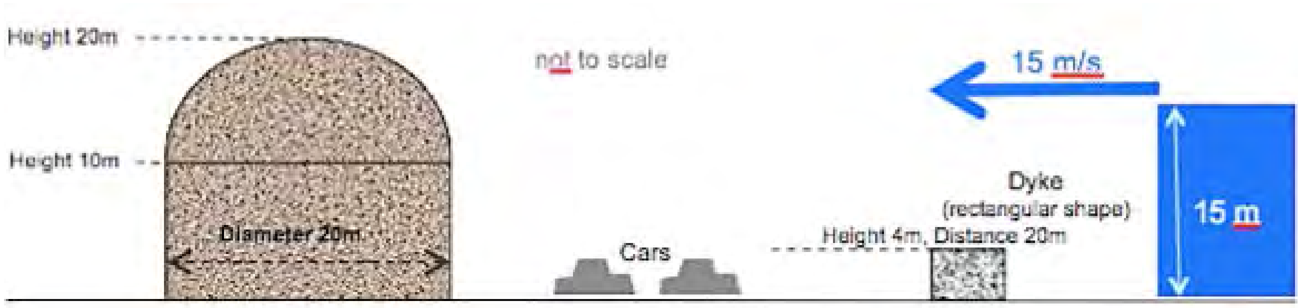


Fig. 15 – Demonstration case #2

The test case selected and the applied tsunami load case are depicted on Fig. 11. Typical results of wave slamming on the structure (including the total force applied to the building) and building flooding are depicted thereafter.

7.2 Debris and Deformable Structure

In a second test case, a typical industrial structure was selected, namely a storage tank, as depicted on Fig. 15. In this case, in addition to wave slamming and subsequent flooding, some debris (automobiles) were placed in front of the structure to demonstrate the capacity of the structure to illustrate the capacity of the model to generate projectiles, and the tank was modeled as deformable. The figures hereunder depict some results of that demonstration case.

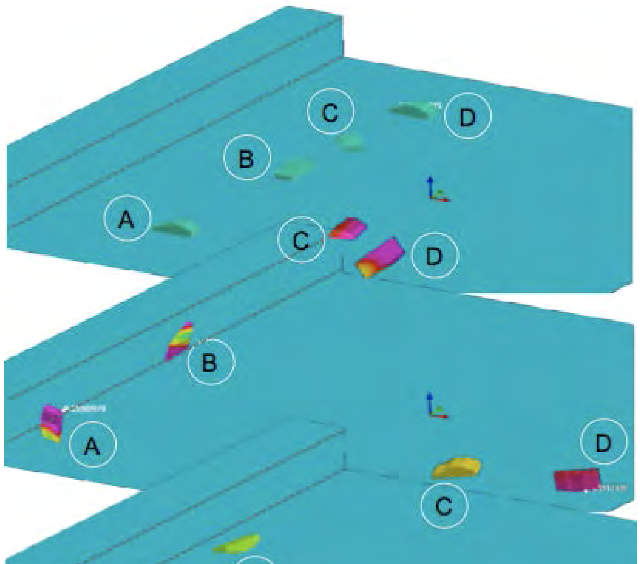


Fig. 16 – Positions of cars at different times under tsunami wave (colors represent velocity amplitude)

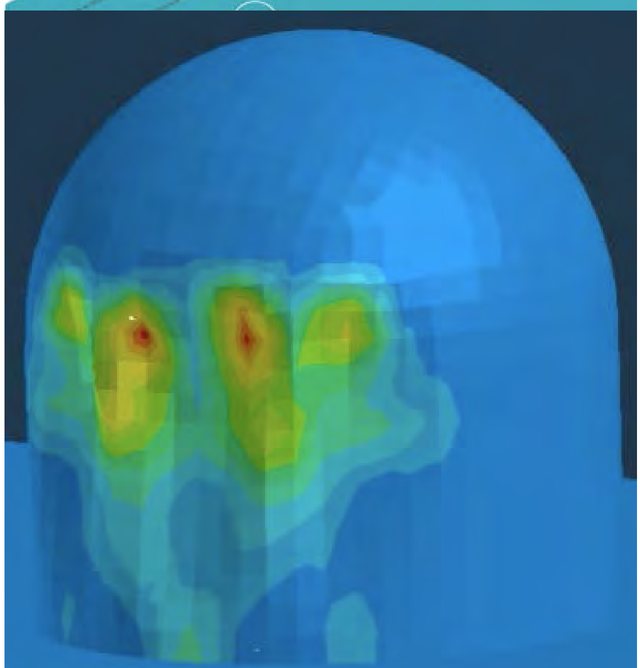


Fig. 17 – Plastic yielding of tank under wave slamming after 1 sec

8. Validation

8.1 Preamble

A critical step in any numerical approach is to validate the physical representation and modeling methodology in order to justify the reliability of the results. In the case of the VPS based method presented in this paper, two levels of validations have been carried out: the first one quantitative based on tests results in laboratory, and a the second one qualitative on a post-tsunami numerical autopsy on a real industrial structure.

8.2 Scaled Down Model

The quantitative validation of the SPH based method to model tsunami-structure interaction has been carried out on a scaled-down simple model as depicted on Fig. 18 [9]. The test was modeled using the VPS solution. The comparison of results from tests and simulations is depicted on Fig. 19. The numerical prediction (the results have not been filtered to smooth out the high frequency components resulting from the discretization) proved to be very accurate. The force applied to the column from the impinging wave (transfer of momentum) is accurately predicted. A similarly good prediction (not illustrated in this paper) was provided for the velocity time history of the water.

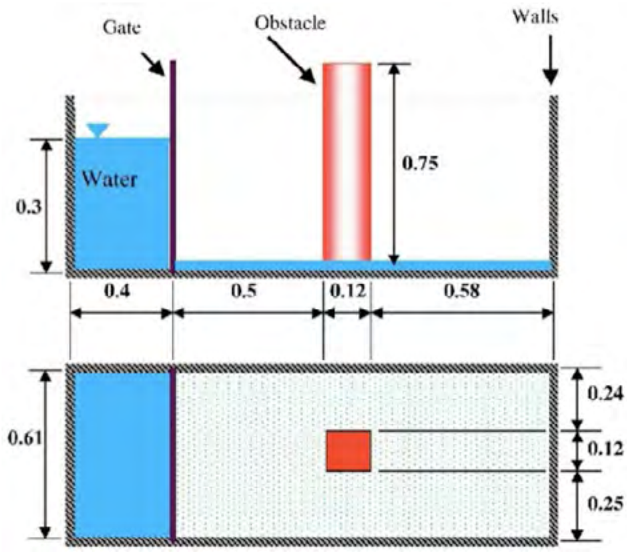


Fig. 18 – Experimental set-up for validation of wave-structure interaction

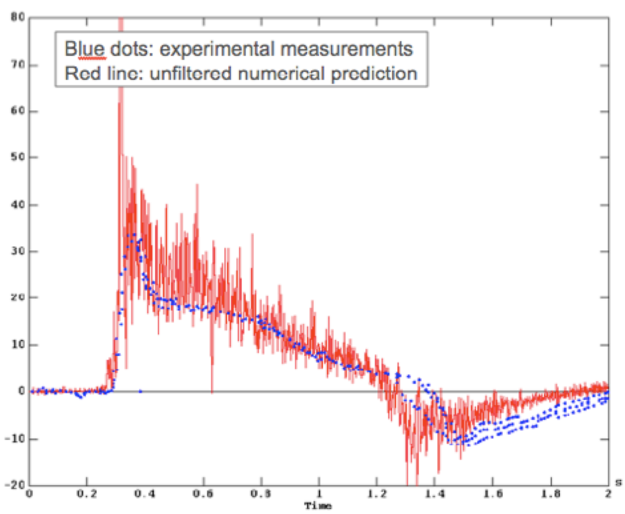


Fig. 19 – Experimental and numerical force time histories

8.3 Full Scale Autopsy

A second validation was carried out using post-tsunami observations in Japan on tank structures that have been submitted to the 2011 tsunami. In this case, no measurements were available but the inspections retrieved a number of local collapse modes [Fig. 20 and 21]. The purpose of the project was to verify that the numerical model was capable to reproduce these collapse modes on a similar structure.

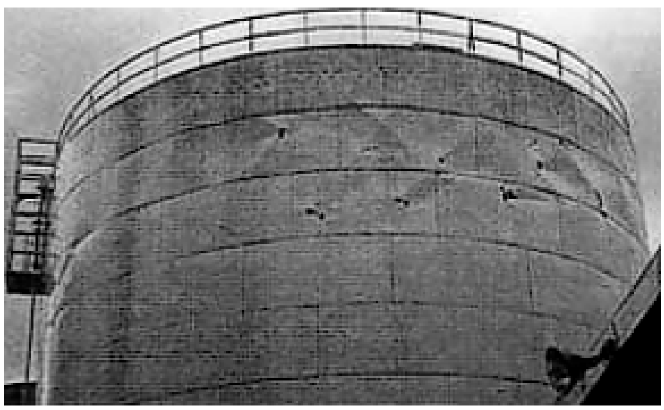


Fig. 20 – Collapse of tank side under wave slamming and lateral buckling on the lower part

Fig. 21 – 'Diamond' shape collapse mode on upper part

A typical tank structure of ca. 60 m diameter and 40 m high was modeled using VPS and submitted to a tsunami wave of 5 m impinging the structure with a velocity of 8.33 m/s.

While the numerical simulation provided numerous results (stresses, loads, moments, pressures) reported elsewhere, it also provided a picture of the deformation after the tsunami that was used to compare with the post-tsunami observations on site. Fig. 22 depicts the final collapse mode obtained.

The collapse modes predicted with the VPS model include the collapse under the wave slamming (1), the lateral buckling in the bottom part of the tank (2) and the 'diamond' shape collapse in the upper part of the tank (3). This demonstrates that the physical phenomena that have been retrieved from the on-site observations after the tsunami event were well predicted with the model.

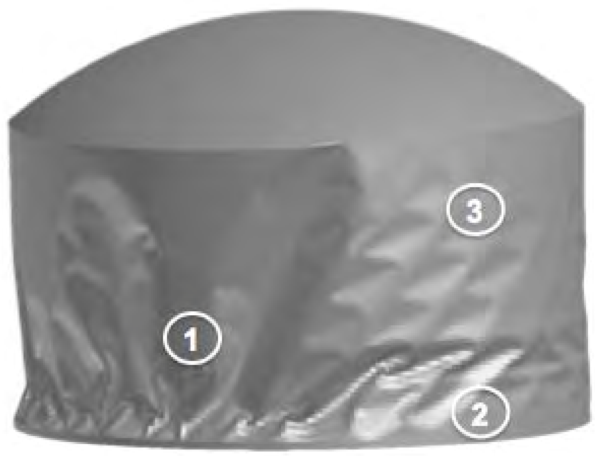


Fig. 22 – 'Diamond' shape collapse mode on upper part as predicted with numerical simulation

9. Conclusions

An innovative method for modeling the interaction between a tsunami wave and deformable and breakable structures has been presented as well as some validation cases demonstrating that it can be used reliably by engineers in charge of the safety of NPP and industrial equipments located near tsunami prone shorelines.

With such method the safety requirements stipulated in the regulations can be tackled with an improved rationale, thus leading to safer installations.

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ABOUT ESI GROUP

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