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An overview on the capabilities of the TELEMACMASCARET system to deal with tsunamis: feedbacks from TANDEM project

An overview on the capabilities of the TELEMAC-MASCARET system to deal with tsunamis: feedbacks from TANDEM project

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***Abstract*— This paper gives an overview on the capabilities of the TELEMAC-MASCARET suite to simulate different steps of the tsunami phenomenon. The simulation of a full tsunami event includes generation, propagation, shoaling, run up and flooding. To deal with all these steps, a full set of benchmarks were identified with the TANDEM project [1]. Different numerical properties are required for these different steps. In this paper we summarize the final conclusions drawn from this project.**

I. Introduction

After the major tsunami events of Sumatra in 2004 and Japan in 2011, a lot of effort has been spent by the scientific community to understand phenomenon of tsunamis. Indeed, several physical aspects linked to tsunami are still under active investigation and represent open problems.

In the wake of the above tsunamis policy maker were confronted with criticisms about the readiness of their countries' defenses against major hazard. The fears on tsunami readiness are heightened in some areas where sensitive facilities could be impacted.

In this context, the French government approved the funding of a large research project dedicated to the study of tsunamis and the assessment of their risks on the French coast.

In the first part of the paper we will present the TANDEM project. The second part of this paper is dedicated to the assessment of the numerical features needed for the simulation of the tsunami generation, propagation and coastal flooding.

II. Brief presentation of Tandem project

TANDEM (Tsunamis in the Atlantic and the eNglish channel: Definition of the Effects through numerical Modeling) is a project funded by French government that includes a consortium of several research and consultancy institutions. Its main objective is the improvement of knowledge about tsunamis and the assessment of their risks on French coasts.

This project is organized in four work-packages:

- Work-package 1 (WP1): dedicated mainly to the qualification and validation of codes by handling several unitary benchmarks. These benchmarks will be described and discussed extensively in Section III.
- Work-package 2 (WP2): focuses on uncertainty quantification and propagation
- Work-package 3 (WP3): deals with simulation and lessons drawn from Tohuku event of 2011
- Work-package 4 (WP4): includes several cases linked to the French coasts

The subsequent section will not describe in detail the work-packages, however, we will cite some of their benchmarks when dealing with different steps needed to numerically describe the tsunami.

III. Assessment of numerical features needed for tsunami simulation

To reproduce a tsunami event, a numerical code has to be able to handle generation, propagation, run up, submersion and finally coastal impact and flooding. Very seldom all these features are captured with using a unique model. In a majority of past tsunami studies, the obtained results provide only few of the above-mentioned aspects. The main reason behind this is the overwhelming computation time needed to simulate all required aspects in a single numerical model run using a single mesh.

To overcome these difficulties, researches and practitioners use often different models with different mesh characteristics. In the best of cases, these meshes are nested in order to make easy chaining of models and boundary communications.

In the following we will focus on each feature of a typical tsunami and will discuss how the Telemac-Mascaret suite can represent each of them.

A. Generation

The generation of tsunamis can be the consequence of a fast movement of the earth crest (earthquakes, submarine landslides, etc) or the sudden fall of external bodies (meteorites, aerial landslide, any other body) in a mass of still or weakly moving water. Different source of tsunamis are:

1. Earthquake

The generation of tsunami source following an earthquake is an inverse problem which is far to be an easy task which explain the numerous ongoing works focusing on it.

The inversion problem recovers an initial distortion of the free surface and probably an initial velocity distribution by considering seismic and geodetic data (magnitude of the earthquake, its epicentre, slip amplitude, satellite and gauges measurements, etc.)

The most used seismic generation model in the literature is the one of Okada [2]. This latter computes the deformation of the ground using the theory of elasticity in an idealized homogenous medium. The deformation of the free surface is obtained with an instantaneous translation of the ground distortion. The initial induced velocity is assumed to be nil.

Seismic events include complex physics and can scarcely be reproduced by a single rectangular fault model (Okada). To better reproduce real scenarios, a patch of small faults (sub-faults) is preferred [3], [4], and [5].

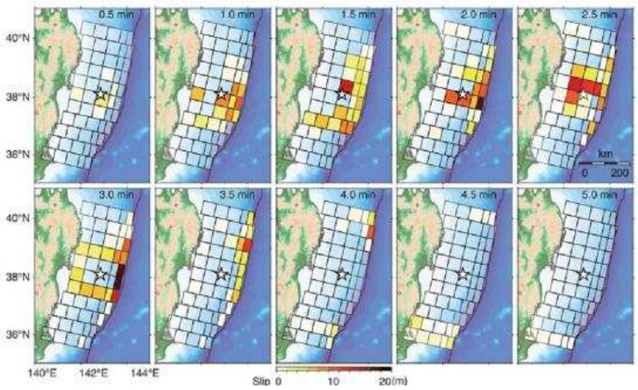


Figure 1. *Example of sub-faults used for the generation of the Tohoku event (Satake et al. [5]).*

Okada model was integrated to Teleamc-2D since version v6p2. It was widely used with in the Telemac community and overall, feedbacks are positive. However, based on the works of Hammack [7], Todorovska et al. [8] and more recently, Le Gal et al. [9], static generation (like the one of Okada) can in some cases be not sufficient to reproduce tsunami accurately. Indeed, instantaneous transmission of bed distortion can introduce non-physical behaviours that, even with heavy calibration efforts, cannot be avoided.

A more accurate generation should use "kinematic assumptions" which means to consider a finite transmission speed of the bed distortion in horizontal direction (rupture velocity Vp (Hammack[7])) and in the vertical direction (rise time tr (Todorovska [8])) or both (le Gal [9]). In the last case, the generation model reads (Fig. 2):

$$\xi(x,t) = H(L-x)H(x)\tau(t) \qquad (1)$$

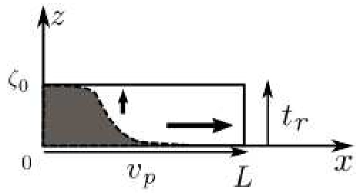


Figure 2. *Kinetic generation proposed by le Gal et al. [9]*

This new model was used to reproduce seismic generation source for the Tohoku event of 2011 and for the Gisborne-New Zealand event of March 25th, 1947. We focus in this section on the latter event.

Fig. 3 shows final free surface obtained at the end of the generation procedure of the Gisborne tsunami. For all these cases, a model with a set of 191 sub-faults. The rupture velocity Vp is considered equal to 300 m/s, which, based on seismic data, is the most probable value. Fig. 4 gives the maximum free surface obtained at the shoreline which are compared with data of Downes et al [10].

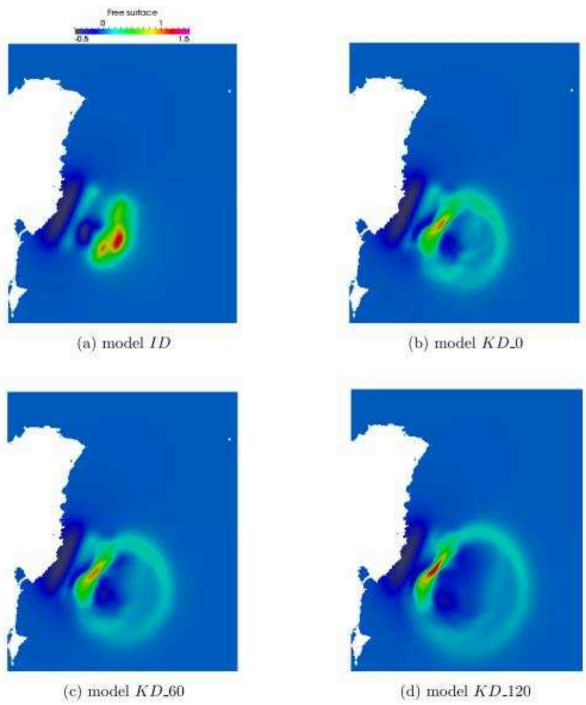


Figure 3. *the Gisborne tsunami (1947) tsunami: (a) instantenous generation, (b) kinematic generation with duration of 190s and tr=0s, (c) kinematic generation with tr=60s and (d) kinematic generation with tr=120s, by le Gal et al. [9]*

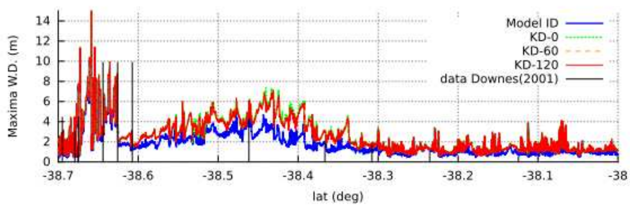


Figure 4. *maximum water elevation obtained at the shoreline. Comparison of different results with data of Downes et al. [10]*

The kinematic generation is an interesting option to be implemented in the Telemac-Mascaret suite. For more details about this topic, we refer to the PhD thesis of le Gal [9].

2. Landslides

Landslide induced tsunami is another open topic. Its complexity comes from the fact that it deals much more with soil mechanics than with hydraulics. The estimation of the volume of displaced soil and its velocity is the key point of an accurate generation of the induced tsunami. In a numerical point of view, it is safer to use a separate model to generate the initial starting state of the tsunami. Indeed, the dynamic behind a landslide is complex and the interaction between moving soil and neighbouring water is very rapid. This leads in most cases to the violation of most numerical assumptions (continuity, slow motion, homogenous media, etc.)

Within the TANDEM project, all the undertaken simulation of real case of La Palma, were based on the work of Abadie et al. [11]. This case supposes a slide of a huge volume of one mountain side due to volcanic eruption.

The nonlinear shallow water equation of Telemac-2D were used to simulate the propagation of the La Palmas event. The mesh is built using Blue Kenue using a density which varies with the bathymetry gradient. The extent of the mesh includes the major part of the North Atlantic Ocean (Fig. 5). The model consists of more 12.5 million elements and almost 6.5 million of nodes.

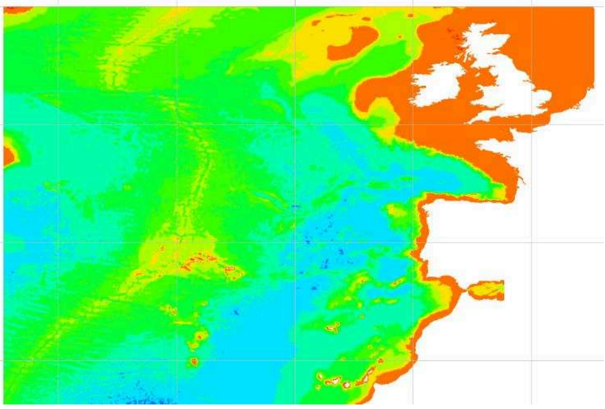


Figure 5. *mesh and bathymetry of the Canaries landslide induced tsunamis model.*

This mesh is used to reproduce four scenarios of landslide. The volume of the slide varies between 25 and 450 km^3. Fig. 6 gives snapshots of the water elevation in the case of a slide volume of 80 km^3.

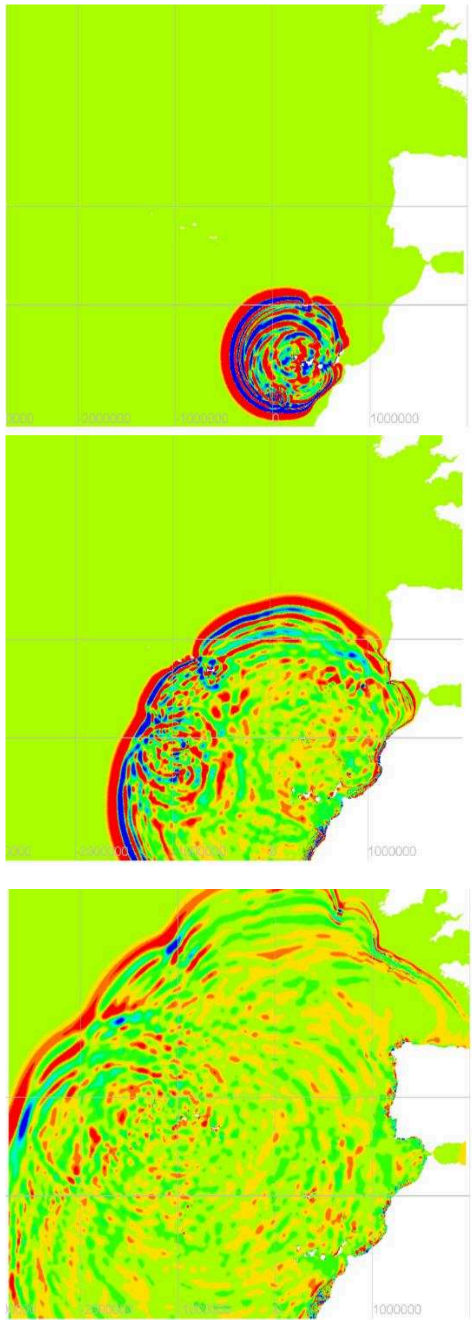


Figure 6. *Snapshots of Canaries Islands tsunami model*

Even though initial wave heights are overwhelming (around 100 m), tsunami reaches western European coasts (especially French ones) with an amplitude of several dozens of centimetres. For instance, at Brest, maximum water elevation is around 70 cm. At Bordeaux, maximum height is about 1.15 m reached by a secondary wave.

B. Propagation

To assess propagation, members of TANDEM project have identified several benchmarks with different ranges of complexity. In most of these cases, Telemac-2D with its shallow water finite elements and finite volumes versions, as well as Boussinesq one has given satisfactory results. Telemac-3D also was used for several cases and results need to be improved especially when dealing with dispersive cases.

We cannot give in this paper a full reporting about these benchmarks. However, we give here the most challenging ones in order to discuss the efforts we need to improve the code in a near future.

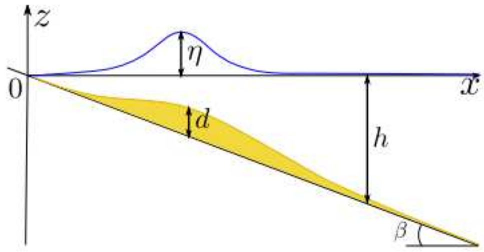


Figure 7. *Geometry and notation of analytical landslide*

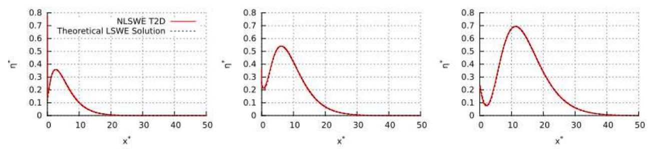
1. Case GG01: analytical landslide

This case was proposed by Liu et al.[12]. This case describes an analytical tsunami generated by landslide in 1D (Fig. 7). The solution is obtained from linearized shallow water equations. The thickness of the landslide is defined by:

$$d(x,t) = \delta exp\left[-\left(2\sqrt{\frac{x\mu^2}{\delta tan\beta}} - \sqrt{\frac{g}{\delta}}\mu t\right)^2\right]$$

Where = 1m the maximum thickness of the slide and μ=δ/L and g the gravity, t the time and x the abscissa (Fig. 7).

The introduction of the sliding bed into Telemac-2D is done by varying the bathymetry during the time loop. A very small time step is used to verify the assumption that the movement is liner. The obtained results are given in Fig. 8 and shows very good agreement between numerical and analytical results.



(a) $t^* = 0.5$ (b) $t^* = 1.0$ (c) $t^* = 1.5$

Figure 8. *Results of analytical landslide model*

2. Case P01: solitary wave

This case is one of the most challenging ones. It reproduces an analytical solution a solitary symmetrical wave. This case is very simple and the solution is the one obtained by a refined numerical discretization of Euler equations [13]. Fig. 9 describes this simple case where the wave travels with a velocity C which is the exact velocity of a solitary wave.

This case is challenging because it needs a fully dispersive model. Moreover, the non-linearity (ration of amplitude of the wave by the water height) is big which lays on the limits of the validity of Telemac-3D algorithm.

As it is known, solitary wave is not a solution of the shallow water equations. These latter tends to reshape the wave into a travelling sharp front (shock). In order to keep the original shape or the wave at least a Boussinesq model is necessary. The ideal mean should be a Navier- Stokes (Euler) model like the one of Telemac-3D.

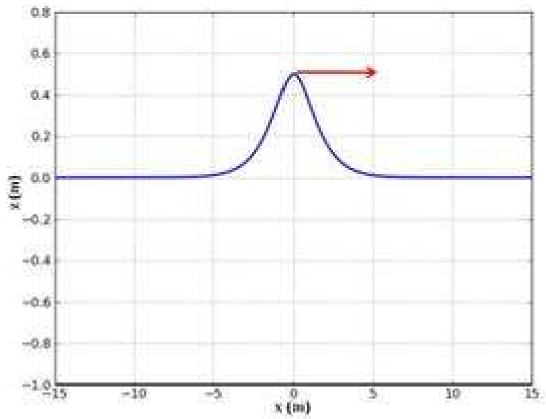


Figure 9. *Solitary wave benchmark*

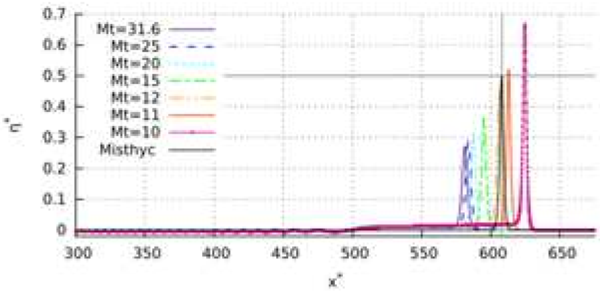


Figure 10. *Telemac-3D results for the solitary wave benchmark*

Within TANDEM project several dispersive codes were tested, among them Telemac-3D. The obtained results are shown in Fig. 10. The different curves represents different mesh refinements and different CFL values. Horizontal and vertical black lines gives the expected analytical wave height and location respectively.

The most striking conclusions from these results are:

- The extreme dependence of amplitude and location of the wave with mesh refinement and CFL values
- The shape of the solitary wave is almost conserved, however a spurious tailing wave appears and persists for most of numerical options.
- Amplitude of the wave can, for some cases, be amplified and goes over the initial value.

The question of conservation of momentum and of mechanical energy can come up.

- Compared to other codes, the results of Telemac-3D are not satisfactory. This can be explained in a major part by the fact the order in space and time of the used schemes are at best of second order. Whereas all the other codes are using very high orders
- A final explanation of the poorness of the results come from the moving mesh (Sigma transform) that introduces a non-negligible numerical diffusion but also spurious dispersion.

3. GS01: vertical movement on flat bottom [7]

This benchmark is a rectangular flume in which a wave is generated from a bed motion. The geometry and initial setting is described in Fig. 11. The bed motion is described analytically through an exponential or a sine based expression |7]. The obtained results are compared with the solution of the linear problem under an irrotational assumption. This solution can be found in [7].

This benchmark is useful to see the capabilities of Telemac-2D to deal with generation and propagation of waves due to bed motion.

The expressions of the initial bed motion are given by:

- Exponential motion :
  $\xi(x,t) = \xi_0(1-e^{-\alpha t})H(b^2-x^2)$
- Sinusoidal motion:
  $\xi(x,t) = \xi_0\left[\frac{1}{2}\left(1-cos\left(\frac{\pi t}{t_r}\right)H(t_r-t) + H(t-t_r)\right)\right]H(b^2-x^2)$

Where H is the Heavyside step function and ξ is the amplitude of the bed motion. Dimensionless varibles are defined as :

$$x^* = \frac{x}{h}, b^* = \frac{b}{h}, \xi_0^* = \frac{\xi_0}{h}; t^* = t\sqrt{\frac{g}{h}}; t_r^* = t_r\sqrt{\frac{gh}{b^2}}$$

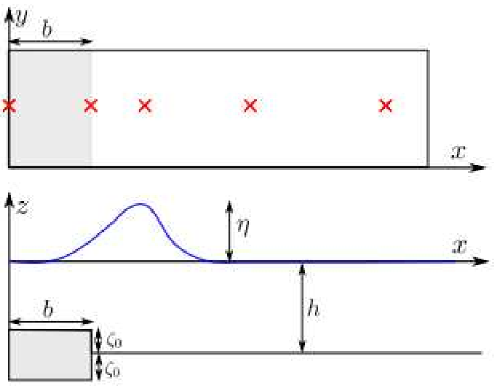


Figure 11. *geometry and initial setting of case GS01*

Three ranges of velocities has been identified:

- Impulsive motion: $t^* \ll 1$
- Creeping motion: $t^* \gg 1$
- Transitional motion where t* is in between.

This benchmark is clearly outside the range of assumption of shallow water equations. The Boussinesq version of Telemac-2D, as well as, Telemac-3D were used together with the code Mysthic (Euler equations with irrotational assumptions, Benoit et al. [14]). The obtained results are shown in Fig. 12.

As it can be observed, during the generation event, all models give good results which fit well reference solution. However, the propagation step, given by time profiles at x*=b* shows that Telemac-3D is still giving satisfactory results for the three types of flows. However, when transient effects are large, Boussinesq model fails to remain stable and shows spurious numerical wiggles. These observations are even worse for the case of sinusoidal generation motion.

This case shows clearly that the Boussinesq model needs to be improved.

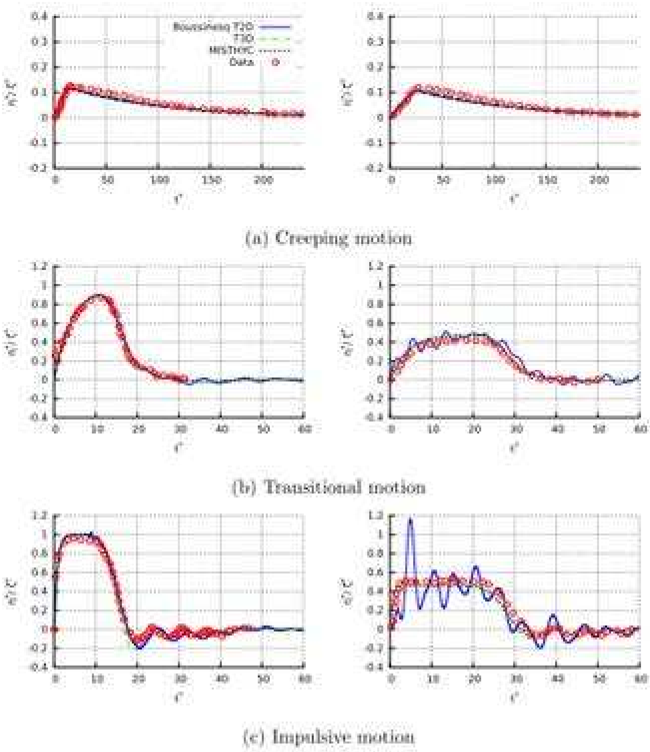


Figure 12. *Results of the exponential bed generation*

4. Case RS07: run up on a uniform beach [15]

This case aims at reproducing the run up of a solitary wave on an oblique beach is given in [15]. This benchmark allows to assess the numerical abilities of Telemac-2D to handle propagation, shoaling, run up and finally flooding of dry beach.

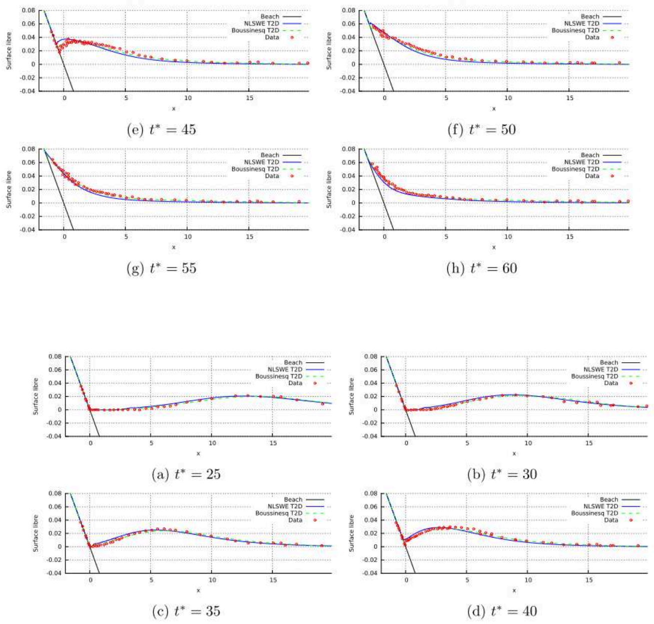


Figure 13. *Results for the case RS07:-part 1 (up), part 2 (down)*

The obtained results are partially shown in Fig. 13. It can be seen that overall behaviour of the code with its Boussinesq and shallow water versions, is really satisfactory. Shallow water equations overestimates arrival times and thus the draw-down phenomenon. Boussinesq model gives really good results for this case.

5. The Tohoku tsunami

The last case we present here, is the well-known tsunami of Tohoku (March 11th, 2011). This case is a very interesting one for plenty of reasons, among which the huge quantity of available data (bathymetry, hydraulics, gauges, seismic data, satellite data, flood marks, etc.). Moreover, all tsunami steps are represented in this events which makes it as one of most important validation cases for the Telemac-Mascaret suite.

In this paragraph we will present briefly the model and focus on the propagation aspects. The flooding part will be discussed in the next section.

The outline of the mesh represents the north-western quarter of the Pacific Ocean. It was originally proposed by the study of Sasaki et al. [16]. The finest mesh includes 680 000 nodes with an element edge length between 10 m in the bay of Iwate and 15 km at the eastern boundary. The density of the mesh is varying with the bathymetry gradient.

As for the Gisborne case, the generation of the Tohoku tsunami, several source techniques were tested (Shoa et al, Satake et al, classic Okada). The propagation step is computed using the nonlinear shallow water equations of Telemac-2D. Obtained results are compared to DART gauges located along of the eastern Japanese coast (Fig. 14) with gauge readings shown in Fig. 15.

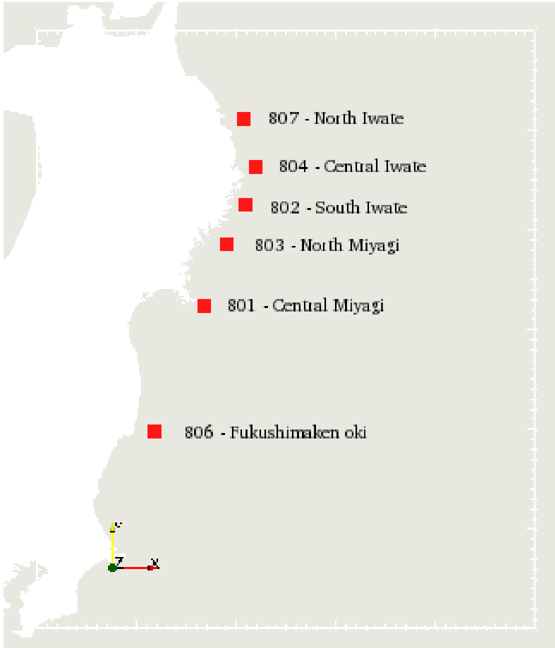


Figure 14. *DART gauge locations*

We can see that depending on the used source model, results fit more or less with data. Shao et al. generation gives nice fits in the far-field domain while it predicts the wave in the near-field. The Satake solution tends to under-estimate the wave amplitude in far-field but fits much better to data in the near-field. The CPU time for the propagation of this event is of 13 min on 48 processors which is really encouraging.

C. *Flooding*

To assess the coastal impact and flooding, several benchmarks were proposed. We will discuss only 2 of them to demonstrate the capabilities of the Telemac-Mascaret to deal with this important feature.

1. The Tohoku 2011 case:

To deal with flooding aspects at the end of a tsunami event, modeller often chooses to use separate model in order to alleviate computation costs. However, with the Telemac-Mascaret system, this reason is no more valid. In dead, in the framework of the thesis of le Gal, the built models includes both propagation and flooding aspects. This choice was applied both for the Tohoku and the Gisborne events.

Fig. 16, 17 and 18 show the used meshes which go behind the shoreline in order to take into account for the flooding aspects.

The computational time for the Gisborne model was of 21 min on 24 processors.

The final feedbacks show that advection schemes of the Telemac-Mascaret suite can handle both propagation and coastal flooding. However, it is important to indicate that the method of characteristics can have some unstable behaviour when boundaries of the model have complex geometry, which was the case of the Japanese model. Addition optimization steps of the mesh were necessary to overcome these issues.

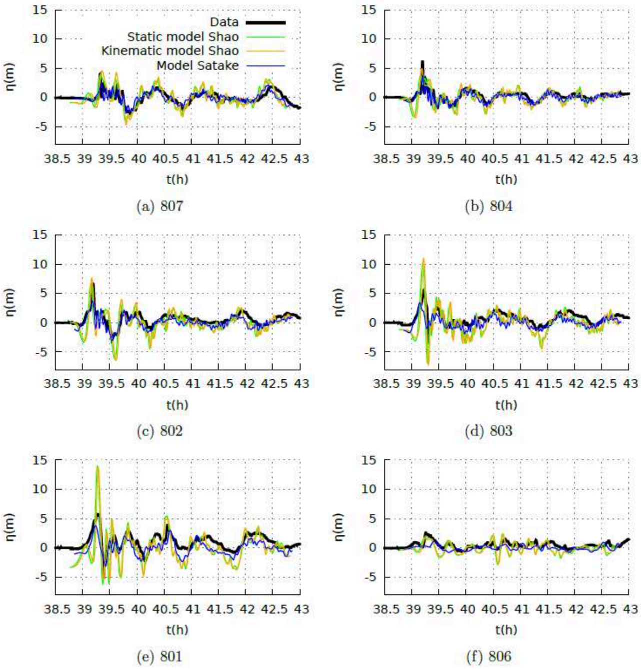


Figure 15. *Propagation results of the Tohoku tsunami- comparison with DART gauges*

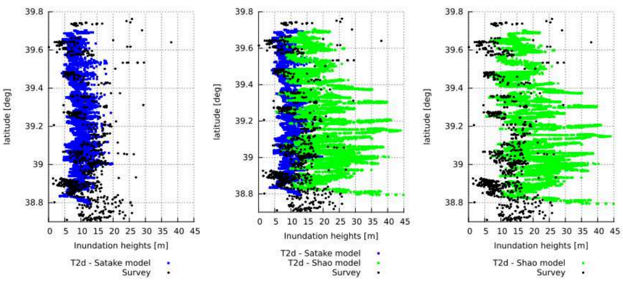


Figure 16. *The Tohoku tsunami: effect if the generation source.*

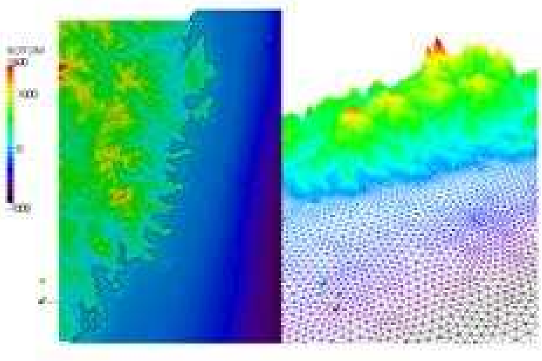


Figure 17. *used mesh for Tohoku tsunami- zoom on the coastal flooded area of the Iwate bay*

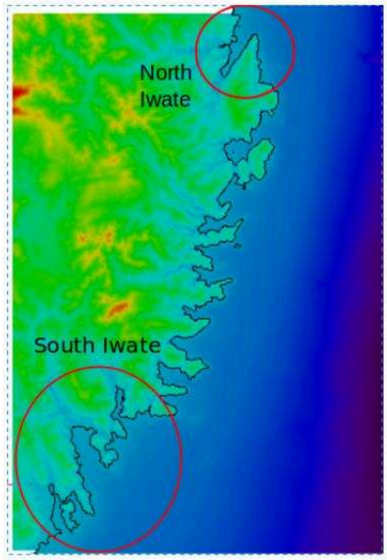


Figure 18. *coastal flooding of the Iwate bay.*

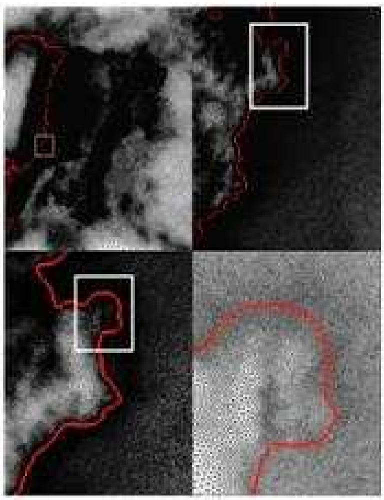


Figure 19. *mesh used for the Gisborne event of 1947. Zoom on the shore region.*

Lots of efforts have been done to improve capabilities of the Telemac-Mascaret system to tackle tsunami phenomenon. This have led to a wide use of this code throughout the numerical community. Several issues remains open and needs further investigations. Mainly:

- The Boussinesq version of Telemac-2D needs further improvements. In several cases, it shows unstable behaving.
- Advection schemes needs to be improved (in order, numerical diffusion, accuracy and stability). Schemes able to handle wetting and drying remains more expensive. In the other hand, the characteristic scheme, which is the most optimal in machine cost, reveals some weakness when mesh boundaries are complex.

- Telemac-3D needs to be improved to handle in a more accurate way the propagation of nonlinear solitary waves. Even though dispersive properties are well retrieved, the dependence of the results to the numerical parameters needs real investigation.
- To handle dispersive Boussinesq-type source terms with shallow water equations, schemes with high order in space are required. Besides, a refined time discretization is also needed.
- Coastal flooding which needs very often to include urban areas and dense vegetation, can benefit from porosity option in order to alleviate mesh refinement. This option is still not well assessed and thus needs further investigations.

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