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Guidelines for harmonization of source scenarios for use in tsunami hazard and risk assessment

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EXECUTIVE SUMMARY

The present document gives a brief overview and a set of guidelines concerning tsunami source modelling. Three types of tsunami sources are included; earthquakes, landslides, and volcanoes.

These guidelines are primarily developed to assist tsunami modellers in choosing appropriate source models and properly documenting their use, with a focus on tsunami modelling for tsunami hazard assessment and tsunami forecasting (e.g. for early warning).

The source guidelines do not include technical details on how to set up the models, and the readers are here referred to the many references within the document. While the guidelines are mostly focussed on describing mechanical source processes and typical techniques for source simplifications, we also briefly discuss input data for establishing source probabilities. However, the guidelines do not attempt to describe the probabilistic treatment of the sources in a hazard or risk assessment context, which is instead the focus of other ASTARTE deliverables in WP8.

To date, approaches for tsunami hazard analysis are not well standardized. The present ASTARTE deliverable is just a first and preliminary attempt to provide a more standardized and transparent way of designing sources and reporting their input. On a longer term, it is expected that the source guidelines will be updated, for instance by the Global Tsunami Model (GTM, www.globaltsunamimodel.org), a network of coordinated action for tsunami hazard and risk assessment worldwide. This GTM has already been endorsed by GFDRR and by UN-ISDR, with the auspice of contributing to the implementation of the 2015-2030 Sendai framework for disaster risk reduction (http://www.unisdr.org/we/coordinate/sendai-framework).

Nevertheless, this attempt for source modelling standardization has already been employed in the production of previous deliverables in ASTARTE WP3, namely D3.12 and D3.16, along with the characterisation of the NEAM source region. These efforts constituted, as said, the basis for hazard assessments in WP8 (e.g. D8.8), for a critical review of uncertainty in tsunami and tsunami hazard modelling in D4.13 and D8.39, and for the construction of warning-oriented earthquake source databases in D6.24. To this end, another application of the standardization is related to the source modelling presently being carried out the in the TSUMAPS project (http://www.tsumaps-neam.eu/), where the first common probabilistic set of tsunami hazard maps are developed for the NEAM region.

The report is organized as follows: Section 0 gives a general introduction of tsunami sources and their modelling. Section 1 attempts to discuss the general modelling aspects for the various kinds of sources. Sections 2, 3, and 4 describe modelling of earthquakes, landslides, and volcanoes, respectively. Finally, Section 5 discusses possible development of source standardization for the future.

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Introduction

Submarine earthquakes have generated about 80% of all tsunami events recorded globally. The majority of tsunamigenic earthquakes occur at subduction zones along the Ring of Fire in the Pacific Ocean, while other important source regions include the Sunda Arc and the Makran subduction zone in Indian Ocean, the north-eastern Atlantic, the Mediterranean and connected seas, eastern Indonesia and the Philippines, and the Caribbean Sea. Subduction zone earthquakes with magnitudes above M9 cause the largest tsunamis and these can propagate across oceans, however, smaller earthquakes can also generate locally damaging tsunamis. Finally, a class of earthquakes termed "tsunami earthquakes" generate more intense tsunamis than expected from their seismic moment magnitude.

Frequency-wise, the second most important tsunami sources are volcanoes and landslides, the latter often triggered by earthquake ground shaking. Tsunami hazard and risk assessment methods for these sources are less well established than those for earthquakes, because they happen more seldom, and because their tsunami generation mechanisms are more complex and diverse. Some of the most powerful tsunamis in history, however, have been caused by these sources, such as the 1883 Krakatau (Indonesia) volcanic tsunami, and the 1958 Lituya Bay earthquake-triggered landslide in Alaska. Compared with earthquakes, landslides and volcanoes tend to produce tsunamis that are more spatially localized, although they can result in much higher run-ups; so, they are often an important local risk driver.

The tsunami risk worldwide is dominated by rare, but often destructive low frequency/high impact events. Our historical tsunami records are too short to reveal run-up heights at the level of hazard we need to prepare for. Traditionally, the threat due to tsunamis was analysed by modelling the inundation for just a few scenarios, sometimes termed credible worst-case scenarios. In this way, neither the relative likelihood of events of different sizes is generally assessed (the natural or aleatory uncertainty), nor is generally addressed the subjective degree of belief that one has regarding different plausible and yet alternative models of the same phenomenon (the epistemic uncertainty). Presently, however, probabilistic tsunami hazard assessment (PTHA) is progressively replacing the traditional and deterministic worst-case scenarios methods, which remain an important initial screening tool, or for analysing particular cases in detail. Nevertheless, the present guidelines represent means to construct sources for both the scenario based and the probabilistic methods.

Tsunami source modelling often needs to balance between feasibility and lack of data, on one hand, and, on the other hand, realistic and complex enough source modelling. By feasibility we mean the need for limiting the computational cost of source simulation; for example when a very high number of tsunami simulations is needed for hazard assessment. By lack of data we mean the very common situation in which several aspects of the source process are not well enough constrained by observations, or even not completely understood. In general, an overly complex source treatment cannot necessarily be justified in situations where the physics of the source process is not known, or the necessary background data is not available. In a probabilistic source treatment, the uncertainty is explored by modelling the source and the tsunami under a number of different possible combinations of the values of the source parameters. Hence, in the majority of all applied tsunami source and generation models reasonable and fairly extensive simplifications are needed. Such simplifications comprise for instance depth-averaging of dynamic properties, as done for conventional tsunami inundation modelling of Nonlinear Shallow Water (NLSW) type, or in geometry, structural, and mechanical simplifications, as for instance done in uniform slip Okada type models for earthquake initial conditions by considering the faulting process as occurring on a flat surface immersed in a homogeneous and elastic half-space. However, when needed and when possible, in several circumstances and for certain sources, more complete models are used.

1. General source descriptions and definitions

In this section, we briefly describe general terminology for source models, including general categories of modelling assumptions for the three classes of sources handled herein (earthquakes, landslides, and volcanoes).

We refer to two types of source descriptions, that is those based on mechanical models for the sources (solving the governing equations of motion for the sources, sometimes coupled to the fluid phase in the vicinity of the source, Subsection 1.1) or those based on a pure kinematic description of the source interface to the fluid (Subsection 1.2). We also review some standard hydrodynamic coupling parameters in Subsection 1.3. We do not attempt to provide an exhaustive set of requirements to formulate general source inputs in this section. Rather, this description is meant as a brief guideline for documenting the three types of sources in a transparent way, and for introducing the source specific guidelines in Sections 2-4.

1.1 Mechanical description of source models (general)

By a mechanical (or dynamic) tsunami source, we here mean *sources derived by solving the source equations of motion for a given level of complexity for the source motion, possibly including its coupling to the wave generation*. In this case, we can ideally link the tsunami generation directly to the mechanical properties and source geometry. The mechanical model may or may not include simulation and coupling of the fluid phase with the solid phase (the source). Different aspects of the source process and of the tsunami generation process may be more or less emphasised depending on the application and type of source. For example, while an approach involving dynamic seismic rupture modelling together with full coupling between the solid phase and fluid phase is seldom used, a full coupling may often be of key to modeling tsunamis due to subaerial landslides (e.g. Liu et al., 2005; Abadie et al., 2012). The latter example is the most general one of the two, involving simulation of multiphase flow (e.g. Navier Stokes equations with fully coupled phases for the source and fluid motion).

Most practical applications use numerical models that simplify the source equations of motion to an extent (e.g. a linearized finite element model for a subduction zone fault, or a depth-averaged landslide model), or a fully dynamic model of the source, yet uncoupled from the tsunami generation (e.g a dynamic seismic rupture with a rate and state friction law). In the first example (using a depth averaged landslide model), dynamic equations of motion for the landslides are solved assuming a certain velocity distribution, because fully resolving the detailed flow field is computationally too expensive. In the latter example, the sea floor displacement caused by the rupture is often considered instantaneous (infinite rupture velocity and negligible rise-time of the slip), since the tsunami propagation is slow in comparison with the fault slipping process (e.g. Geist and Oglesby, 2014). For relatively slow or long ruptures the slip history may have an effect on the tsunami wavefield; in such cases the displacement time history is dissected into a series of discrete pulses transferred to the water column, which may happen at different instants and with different rise-times.

A transparent description of a mechanical source model must specify all relevant input parameters that enter the analysis. This comprises for instance complete descriptions of the material properties of the source (e.g. yield strength, density, etc.) as well as fully specifying the numerical input (e.g. numerical scheme, resolution in time and space, etc.). Mechanical source models may also be used to produce (time-dependent) kinematic boundary conditions (explained in Subsection 1.2) as input to the tsunami model. The specification of the fluid coupling must also be given (examples of one-way hydrodynamic coupling formulations are given in Subsection 1.3).

1.2 Kinematic source descriptions (general)

By a kinematic source type, we mean an imposed, pre-defined, volumetric source displacement history of the source boundary acting on the fluid in time and space. *The kinematic source does not reveal any details of the origin of the source mechanics by itself, it merely describes the source motion relevant for the tsunamigenesis*. The kinematic source is here assumed to describe a moving impermeable boundary that acts on the water body, displacing its water mass. Kinematic boundary conditions may typically be used to describe one-way coupled sources, where we assume that the source-tsunami coupling can be neglected. They can be applied either to depth-averaged tsunami models (e.g. shallow water or Boussinesq) or three-dimensional tsunami models (e.g. full potential models or Navier-Stokes). Examples of such sources can be time dependent or instantaneous displacement patterns from earthquake rupture, or the time dependent surface of a submarine landslide.

As far as earthquakes are concerned, the term kinematic source refers also to imposing the earthquake faulting parameters (e.g. strike, dip, rake, fault size and average slip) without modelling the seismic rupture dynamic process; in case a heterogeneous slip distribution is used this is often modelled as a linear superposition of individual sub-faults or fault nodes depending on the chosen numerical modelling strategy. Depending on the cases, and similarly to dynamic models, this initial condition may be instantaneous or time-dependent. A similar analogy for submarine landslides is the boxed shaped source with prescribed kinematics use impose time dependent volumetric surface displacements of the water (see e.g. Løvholt et al., 2005).

A transparent description of a kinematic tsunami source must specify the complete set of the source surface fields adjacent to the water body in time and space. If sufficiently simple, the kinematic description can be specified as an analytical function of the source shape as a function of time and space. However, a general description is most often required, for each source time-step providing fields of the source surface file input to the numerical tsunami model. For depth-averaged tsunami models, it simplifies to fully specifying the fields of the temporary bathymetric height changes $\Delta h(x,y,t)$. Alternatively, one may specify the source flux density that enters as the temporal derivative of the depth in the continuity equation ($\Delta h(x,y,t)/\Delta t$, see for instance Pedersen and Løvholt, 2008).

1.3 Hydrodynamic coupling

Interaction between the tsunami sources and the ambient water may be of importance for the tsunami generation, and the degree of coupling therefore needs to be specified. Generally, very few or no tsunami models includes a complete coupling of the solid and fluid phase, because it is not presently feasible to resolve the detailed boundary layers between the solid and the fluid phase in practical situation. Still, fairly general two-way coupled simulations allow for sophisticated source model description, which is used to model landslide tsunami generation involving large non-linearities (e.g. Liu et al., 2005, Abadie et al., 2012). However, unless this two-way coupling of the source and the ambient fluid is taken into account, the hydrodynamic coupling will involve major simplifications.

Simplifications that are commonly encountered in tsunami literature are often related to treating the source model as one-way coupled (assuming that the ambient fluid does not influence on the source behaviour, see e.g. the analysis of Jiang and Leblond, 1992) or assuming that seabed deformation is copied straight to the sea surface.

Hydrodynamic resistance forces can retard the source motion (for landslides). By including factors such as viscous drag and added mass, the source speed and acceleration can be corrected for (see e.g. Watts, 2000; Grilli and Watts, 2005; Løvholt et al., 2015).

Copying the seabed deformation to the sea surface can provide good source representation when the length scales of the seafloor motion are much longer than the water depth. When sources involve shorter length scales, a hydrodynamic transfer function for the wave generation (conveying the seabed response to the sea surface) is needed. A standard approach for this purpose is the full potential filter of Kajiura (1963), derived for uncompressible flow. We note that other, and more general solutions that take into account the compressibility of the ocean and the water surface response (see e.g. Levin and Nosov, 2015) these are less frequently used as the tsunami response from p-waves often separates from the surface wave component of the tsunami. Finally, we note that for earthquakes, the horizontal displacement of the water due to local bathymetric changes sometimes needs to be taken into account (Tanioka and Satake, 1996).

2. Guidelines for modelling and describing earthquake sources

2.1 Background information and models for quantifying temporal earthquake slip and probability

Methods for estimating and/or modelling earthquake tsunami sources and their induced tsunami probabilities are far more developed than the corresponding landslide sources (Geist and Oglesby, 2014, Davies et al., 2015; LeVeque et al., 2016; Murphy et al., 2016; Selva et al., 2016). The reason for this is partly that earthquakes are more frequent than landslides and volcanoes, their source statistics is better constrained, and their mechanisms are less diverse. Because of their supreme importance for tsunami hazard, a large number of approaches have been applied for modelling earthquake tsunami sources. Without being exhaustive, we list a few of the standard methods and data sources for establishing tsunami earthquake source parameters and likelihood below. To this end, we note that standard ways of representing the earthquake geometry is described separately in Subsection 2.2.

In tsunami forecasting, and if using a kinematic approach, it is necessary to describe the earthquake fault slip. The simplest generally used approach for representing earthquake tsunami sources usually assumes a plane fault geometry with constant dip angle a focal depth ζ and slip angle (rake) θ that determine the strike and dip components of the slip for a given scenario. We can represent an earthquake by its mean slip D, average fault lengths and widths L and W, and rigidity μ (or shear modulus). Then, the associated seismic moment is $m_0 = \mu DLW$ and the moment magnitude $M_w = 2/3 \log_{10}(m_0) - 10.7$. In traditional source treatments, these average components are treated as constants, and derived from earthquake scaling laws that determine relationships between earthquake magnitudes (e.g. Blaser et al., 2010, Strasser et al., 2010). A more sophisticated technique is to treat the slip as heterogeneous across the fault. As shown first by Geist (2002), heterogeneous slip has a large influence on local tsunami run-up. Recently, Davies et al. (2015) developed a set of scaling laws that link heterogeneous slip correlation lengths to the moment magnitude by power laws for the corner wavenumber. Their work, and similar scaling relations for non-uniform slip, can be viewed as an extension of the classical types of scaling laws on mean earthquake quantities (e.g. Blaser et al., 2010, Strasser et al., 2010) to variable slip.

Earthquake scaling laws relate the fault slip, width, and length to the moment magnitude, but not the rigidity μ. The parameter μ may be derived from independent scaling relations (Dziewonski and Anderson, 1981, Bilek and Lay, 1999) and its mean value varies with the focal depth, and typically being smallest at shallow depth. Small values of μ may be related to tsunami earthquakes (Kanamori, 1972), and a possible reason for their atypical earthquake slip. We note that the product $LWD = m_0/\mu$, and not m_0 or M_w itself is of primary importance for the earthquake tsunamigenic strength (along with the focal depth and local ocean depth). As the seismic moment is often used as an input parameter, ensuring a correct value of μ is important, particularly in the case of shallow depth earthquakes that imply a higher occurrence probability for tsunami earthquakes. As a consequence, a possible strategy is to determine μ prior to employing any scaling relation for the other earthquake quantities L, W, and D, when determining earthquake parameters.

While earthquake tsunami source models traditionally have assumed instantaneous rupture, model hindcasts of recent events, for instance of the 2011 Tohoku tsunami (Satake et al., 2013; Romano et al., 2014), reveal that the rupture propagation had a significant influence on the tsunami generation. The abovementioned studies made use of joint inversion techniques to establish the time-dependent rupture. Time-dependent slip can be unravelled in more advanced dynamic rupture models (e.g. Murphy et al., 2016). These models also demonstrate processes for slip amplification towards the trench (see also Geist, 1998), and the necessity of including enhanced shallow slip also in instantaneous stochastic models of the slip distribution. This can be important for assessing the slip distribution spatial probability in the context of hazard assessment or for our understanding of future earthquake tsunami hazard, including those originating from tsunami earthquakes.

Temporal probability of earthquake sources is most often determined from the magnitude frequency distribution linking the moment magnitude (MFD) to an exceedance probability. A variety of different MFD's have been proposed, e.g. tapered Gutenberg-Richter (GR), Pareto, gamma distribution, etc. For a review of models determining earthquake source probability, we refer to Geist (2009). It is important to note that moment magnitudes of many earthquakes that cause large tsunamis are in the tail of the MFD, often in the range when the MFD taper off. Hence, simple logarithmic (non-tapered) GR relations based purely on seismicity may not be appropriate for tsunamis, as tsunami magnitude depends on slip magnitude, and hence it doesn't tend to saturate for increasing earthquake magnitude. Tectonic slip rates and coupling factors should be used as alternative and/or additional input where available. It is clear that long and complete enough catalogues are generally not available for robustly constraining the frequency of biggest and rarest events in the tail of MFDs, and consequently, the temporal probability of large earthquake and tsunamis is almost inherently subjected to large epistemic uncertainty.

2.2 Earthquake geometry representation in linear slip models (Faults, Grids, and zonation)

Models for earthquake sources often make use of linear elastic models, assuming constant or linearly varying slip over a given fault or fault patch. Because of linearity, the fault patches can be treated as unit sources, and their induced seabed deformations can be superimposed in linear combinations. Popular models for computing the seabed elevations due to constant slip assume a homogeneous elastic material (Mansinha and Smylie, 1971; Okada, 1985), whereas corrections for the layered response (Wang et al., 2003) and a 3D heterogeneous crust (Romano et al., 2014) have also been put to use. In linear models where the slip is prescribed, the different ways of setting up the source model will depend on the assumed causative fault geometry. For this purpose, three types of source geometries/approaches (fault, grid, zonation, see Figure 1) are defined. These source types, their required input and required documentation, are given below.

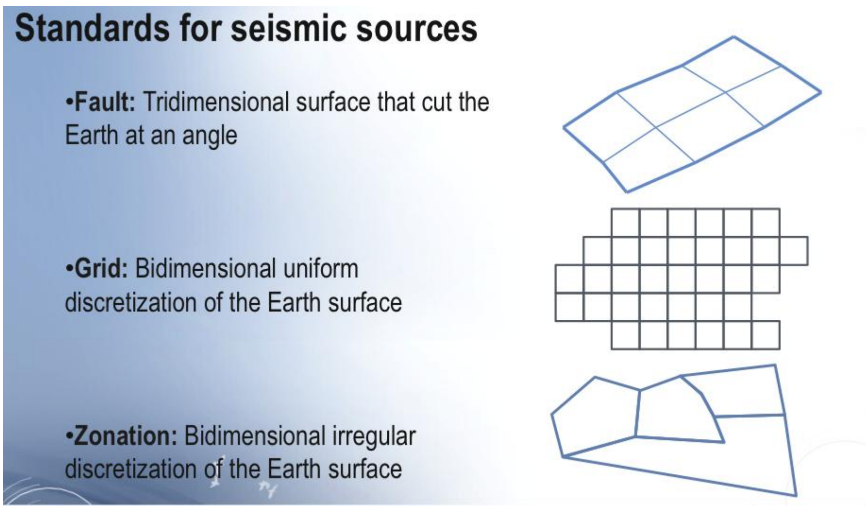

Figure 1: Schematic representation of Earthquake Source Parameterization Types

2.2.1 Earthquake fault sources

When the geometry of a fault is considered enough well-constrained for tsunami modelling purposes, fault sources models can be used. In their simplest and most commonly adopted representation, they are three dimensional planes that cut the Earth at an angle, thus defining the aspect ratio of the earthquake rupture (fault length L, fault width W, and dip angle θ). The surface is discretized by irregular quadrangles or triangles (subfaults).

Each fault can be represented with one or more subfaults. For an individual earthquake scenario, a different slip value can be assigned to each subfault for specifying an earthquake slip distribution. The elastic parameters (crustal rigidity, Poisson's ratio), and type of surface displacement model (Okada, Wang, FEM, etc.) used to generate tsunami initial condition must be specified together with the geometric source information (including the slip distribution with dip and strike components).

In view of a collaborative and transparent process, for example with tsunami modellers and hazard practitioners (as it happened with for example WP8 partners in ASTARTE), it is emphasized that additional information leading to the specification of the source properties, such as earthquake scaling laws (e.g. Wells and Coppersmith, 1994; Blaser et al., 2010, Strasser et al., 2010) or slip distribution scaling relations (e.g. Davies et al., 2015) should be specified. Similarly, information leading to the temporal source probability, if defined, such as the local moment frequency distribution, should preferably be provided along with the source information.

Earthquake subfaults are often used for representing precomputed uniform slip unit sources also in the tsunami warning context, subdividing large fault zones such as subduction zones, which are represented by collections of non-overlapping connecting faults. Examples comprise for instance the NOAA/SIFT global database of sources that are linked to the Commit Model (e.g. Titov et al., 2011).

2.2.2 Earthquake grids

Earthquake grids are bidimensional uniform or non-uniform geographic grids used for the discretization of the Earth surface. Once a cell center has been defined, which will be the surface projection of the geometrical fault centers, the volume below is discretised to model the allowed focal depths within the range of a minimum and a maximum depth in the Earth's crust seismogenic layer. All the other source parameters are defined analogously to the faults sources described in the previous section, within each cell, i.e. with the within the volume below the grid cell.

This approach can be used in tsunami studies and in tsunami hazard assessments when the offshore faults are not completely well known (see e.g. discussion in Basili et al., 2013), or to allow background seismicity parameters (including position) to vary around the known faults (e.g. Selva et al., 2016), or for example when modeling intra-slab seismicity above a subduction interface.

Diverse methods and datasets are generally used as for example an input seismicity catalogue, fault catalogues, methods for deriving dominant focal mechanism/s, plus assumptions already described for faults: elastic parameters (rigidity, Poisson's ratio), earthquake scaling law, moment frequency distribution, by means of which the earthquake parameters have been derived; finally, different types of models (Okada, Wang, FEM, etc.) can be used to generate tsunami initial condition. All of these choices and assumptions, and the data used, should be documented.

A similar approach, which defines unit sources distributed in the Earth Crust at regular intervals, is used in the context of tsunami warning operations by the Japan Meterological Agency (Kamigaichi, 2009).

2.2.3 Earthquake zonation

At a lower level in an ideal hierarchy of modelling tools for tsunamigenic earthquake modelling lie the zonation, which can be seen as an input to the two previous approaches, in the sense that zonation is usually the method used for defining the spatial distribution of earthquake parameters probability generally basing on tectonic considerations and on seismicity analysis.

Zonations are classically used in seismic hazard analysis as a first step to build catalogues of potential earthquakes occurring within a volume. Sometimes this approach has been used for PTHA (Sørensen et al., 2012), or as first step and in combination with faults, or with grids (e.g. Selva et al, 2016; http://www.tsumaps-neam.eu/).

The zonation divides a region in zones with different source probabilities and assumptions for faulting mechanisms (Figure 2). The zonation (or a tectonic regionalization) is used as background information for the definition of the probability and mechanics of background sources for the faulting mechanisms in each zone.

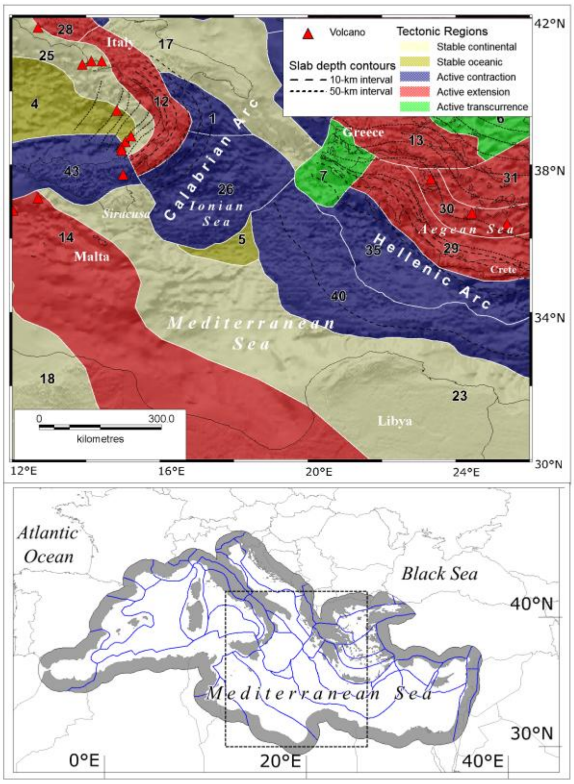

Figure 2: Example of a zonation (tectonic regionalization) employed for the Mediterranean Sea, to be used as input to a source zonation.

3. Guidelines for modelling and describing landslide sources

Landslide differs from most earthquake sources by the fact that their motion and duration is in many cases important for the generation of the wave. Therefore, we find that the landslide dynamics (speed and acceleration) to a larger extent controls the tsunami generation than just the slide geometry and volume. The simple example is that the 4500 BP Trænadjupet landslide with a volume exceeding 500 km^3 did not produce a major tsunami (Laberg and Vorren, 2000), whereas the 1998 PNG tsunami (Synolakis et al., 2002, Tappin et al., 2008) involving a volume 100 times smaller produced run-ups exceeding 10 m. The landslide source types are therefore typically characterised by their underlying dynamic assumptions rather than their pure geometrical properties. In addition, the two way fluid-structure interaction may be of important for some landslide tsunamis.

3.1 Background information and models for quantifying temporal landslide source probability

Submarine landslide probability is generally more difficult to quantify than for submarine earthquakes, and involves larger uncertainties (Geist and Lynett, 2014). Therefore, there exist few probabilistic studies. Of the few studies that exist, there are two dominant directions. The first makes use of the statistics of landslide MFD's to quantify the probability of a landslide volume (e.g. ten Brink et al., 2006). Such methods may be successful when a significant number of landslide volumes is available, and the dating is relatively well constrained (see for instance Lane et al., 2016). Alternatively, the source probability can be derived from geotechnical analysis (e.g. Grilli et al., 2009), often by assuming infinite slope stability analysis. To this end, ten Brink et al. (2009) used seismicity information as a proxy for relative release probability, combined with infinite slope analysis.

In many cases, sparse amount of data are available, which renders tsunami probability estimate uncertain. In any case, the following information may be used to construct landslide source probabilities for volumes and material parameters:

- Volumes, extents, and failure mechanisms (classification) of existing landslides. This can be used to build landslide MFD's (landslide-volume-frequency relations).
- Conditions and locations for slope instability: possible trigger mechanisms in the source region (e.g. seismicity, evidence of gas in sediment, weak layers).
- Background material: bathymetry, seismic reflection, material properties from sediment coring and drilling, literature, identification of scars of possible previous events, pre- and post-failure topographic data etc. of possible previous events, eyewitness accounts.

3.2 Parametrised initial conditions for subaqueous landslides

The simplest possible source landslide tsunami source is the instantaneous generation, where only the tsunami surface elevation is specified as the input condition. This form of representation become celebrated in the aftermath of the 1998 PNG tsunami, where analytical dipole functions were used to specify the initial wave (Synolakis et al., 2002; Watts et al., 1999; Tappin et al., 2008). This simple representation was possible due to the impulsive nature of the 1998 PNG event, as the dipole roughly represents the hydrodynamic response of a rotational slump. A key to this source representation is exact specification of the function specifying the geometric input parameter. To this end, in some previous applications, the authors' have not reported the actual applied shapes, meaning that many such slide sources cannot be easily reproduced by others. Moreover, the source behaviour is not easily traced using this type of source. The initial condition landslide source type commonly involves only specification of the initial tsunami elevation. A more general source treatment would also include a matching set of initial water velocities.

3.3 Landslide block models for subaqueous landslides

A simple and popular model for representing subaqueous landslides is the moving block, also referred to as a flexible blanket. To represent the block landslide in a tsunami model, the shape function and shape parameters of the block (for instance, length, width, and thickness), the landslide trajectory, and the landslide speed as a function of time must be specified. Because the initial acceleration and stages of landslide motion often govern the tsunami generation (see e.g. Løvholt et al., 2015), the landslide velocity has often been prescribed (e.g. Harbitz 1992, Løvholt et al., 2005). Alternatively, the equations of motion for the block may be solved (see e.g. Harbitz 1992; Pelinovsky and Poplavsky, 1996; Watts, 2000):

$$\rho_s V(1+C_m)\frac{dU}{dt} = (\rho_s - \rho_w)gV(\sin(\theta) - \mu\cos(\theta)) - \frac{1}{2}C_D\rho_w A U^2$$

Here, ρ_s denotes the landslide density, ρ_w denotes the water density, V the landslide volume, U the block velocity as a function of time t, θ the slope angle, g the gravitational acceleration, C_D the skin friction coefficient, C_m the added mass coefficient, and A the landslide surface area. Because this model assumes that the landslide moves coherently as a block, this source representation may be conservative when landslide deformation matters for the tsunami generation.

A special case of block type landslides are the retrogressive block slides (Løvholt et al., 2016). These can be modelled as a sequence of blocks failing subsequently on a glide plane. However, it remain doubtful that a simple block representation is sufficient for such landslides, as they involve complex cascading failure mechanisms.

3.4 Depth-averaged mechanical subaqueous landslide models

Compared to the simpler model types reviewed in Subsections 3.2-3.3, mechanical landslide models allow for increased sophistication as they allow for taking into account the mechanical properties of the landslide material as a function of time. As the volumes and run-out submarine landslides often cover large areas, most landslide source models employed simulating tsunami generation are depth averaged. Different depth averaged models are typically distinguished by their rheological (material) properties. Among the most common type of depth averaged flow models include (for more details, see the comprehensive review of Yavari-Ramshe and Ataie-Ashtiani, 2016):

- Viscous shallow-water type models (e.g. Fine et al., 2005). This comprises the simplest type of the depth averaged landslide models, assuming hydrostatic pressure and a depth averaged viscosity and drag. Apart from that, viscous models do not incorporate material models such as granular or viscoplastic models (see below).
- Coulomb-type friction or granular landslide models (e.g. Kelfoun et al., 2011; Pudaisini, 2012; George and Iverson, 2014). These models take into account the granular interaction forces. The models involve different complexity, some include also a simplified representation of a Bingham plastic (see below), two-way interaction between the fluid and granular phase. It should first be

noted that most of the granular type models have originally been developed for subaerial applications, such as rockslides. Generally, they are therefore most appropriate for modelling subaerial landslides, or coarse grained submarine landslides. Secondly, granular models designed do not necessarily contain drag and added mass terms, as some of them are designed for terrestrial applications.

- Viscoplastic Hershel-Bulkley rheologies, including Bingham plastic formulations (e.g. Imran et al., 2001; Lastras et al., 2005; De Blasio et al., 2006). Viscoplastic models are appropriate for modelling submarine landslide, and silty and clay rich landslides in particular. Hershel-Bulkley rheologies and Bingham type models are less developed for use in tsunami models than their Coulomb type counterparts, and are mostly in one horizontal dimension. By including remoulding factors, effects such a time dependent slope failure development (retrogression), can be incorporated too (Gauer et al., 2005). We note that some of the most popular models (e.g. BING, Imran et al., 2001), do not contain drag and added mass terms, which renders them conservative for use in tsunami applications. For applications of Bingham type models for tsunami generation, see e.g. Løvholt et al., (2014) or Glimsdal et al. (2016).

3.5 Source representation for subaerial landslides

Subaerial landslides often hit the water body at high speeds, thus giving rise to a different and a hydrodynamically more complex generation mechanism than what is observed for subaqueous landslides. Often, an impact crater, which cannot easily be incorporated by depth averaged models, is formed (Fritz et al., 2004). While the landslide block models (Section 3.3) or depth-averaged landslide models (Section 3.4) can be used in combination with long-wave models to model subaerial landslide tsunamis to some extent (see e.g. Gylfadottir et al., in press), essential parts of the physics may be lost using such approaches. More general procedures take into account the fully coupled multiphase flow described in Section 1.1 (e.g. Løvholt at al., 2008; Abadie et al., 2012; Crosta et al., 2016). However, because such models are highly resource intensive, the landslide material representation is often simplified in such models.

4. Guidelines for modelling and describing volcano sources

4.1 Source background information

Below follows what needs to be reported for volcano sources to make them transparent. Here we consider only eruptive source mechanisms: underwater volcanic explosions, caldera collapse and pyroclastic flows. Other sources such as "cold" volcanic mass flows (flank collapses, debris flows, collapses of lava bench, etc.) are covered by Section 3. Note that there is overlap for eruptions associated with both explosions and flank instability.

- Background material: literature, eyewitness accounts, volcano monitoring, bathymetry and topography (before and after the eruption if available).
- Location and style of volcanic eruption, possible trigger mechanisms.
- Source geometry: initial location, runout, area affected, volume.
- Kinematics: flow path (pyroclastic flows), duration, velocity, flux.
- Dynamics: flow rheology (for debris and pyroclastic flows).

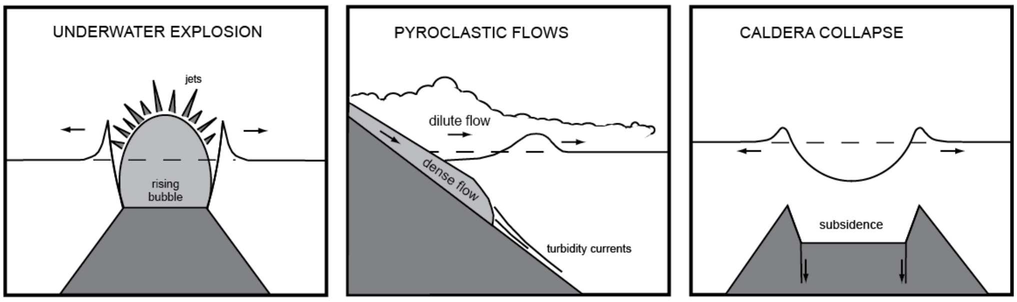

Figure 3: Eruptive source mechanisms of tsunamis

Table 5-1: Different types of volcanic eruptions and their associated source mechanisms of tsunami (Paris et al., 2013). Dark and light grey cells represent the main and the secondary tsunamigenic mechanisms, respectively.

Type of eruption	Type event	Earth-quake	Underwater explosion	Caldera subsidence	Pyroclastic flow	Flank failure
Phreatomagmatic explosions in shallow waters	Myojin-Sho 1952 Karymsky Lake 1996					
Plinian eruption forming a submarine caldera	Krakatau 1883 Santorini LBA 3.6 ka					
Plinian eruption forming a subaerial caldera	Tambora 1815 Aniakchak 3.5 ka					
Explosive eruption with dome growth and collapse	Montserrat 2003 Paluweh 1928					
Explosive paroxysm of strombolian cone	Stromboli 2002 Tinakula 1971					
Massive flank failure	Ritter 1888 Oshima-Oshima 1741	?				

4.2 Underwater explosions

After an underwater explosion and while different jet flows are ejected, a development of water crater is initiated. Subsequent expansion, rise and collapse of the spherical vapor cavity are at the origin of water disturbances generating radially propagating water waves (dissipative leading wave).

Gravitational collapse of the crater makes the water rush inward and forms the secondary bore accompanied by a number of smaller undulations. These water surges expand radially while decreasing in amplitude.

Complex interactions between dispersed pyroclasts of different sizes, gaseous bubbles and water make it hard to simulate this process dynamically. We thus recommend using a semi-analytical approach. Underwater eruption is approximated by and imposing a specific initial water disturbance whose propagation is modelled numerically (e.g. Torsvik et al., 2010; Ulvrova et al., 2014). This strategy reproduces satisfactorily characteristics of the wave field over a uniform depth at a far distance using nonlinear and linear wave theory in comparison with artificially generated underwater explosions (Le Méhauté, 1971; Mirchina & Pelinovsky, 1988).

The initial surface displacement mostly depends on the depth and energy released during the explosion. There exist only purely empirical relations that estimate the initial wave shape as a function of explosion energy, which can be estimated after observations and size of the submerged vent (e.g. Sato & Taniguchi, 1997). We thus recommend testing different vent sizes corresponding to different energy releases, and at different locations. In order to have a homogenous circular source deformation (explosion), it is recommended to use fine mesh (grid). Coarse mesh would result in a poor-resolution of the source (few pixels) and artificial directivity of propagation. While not largely explored at present, possible modeling improvements may be inherited from related phenomena, such as modeling of asteroid impacts (e.g. Shuvalov et al., 2002).

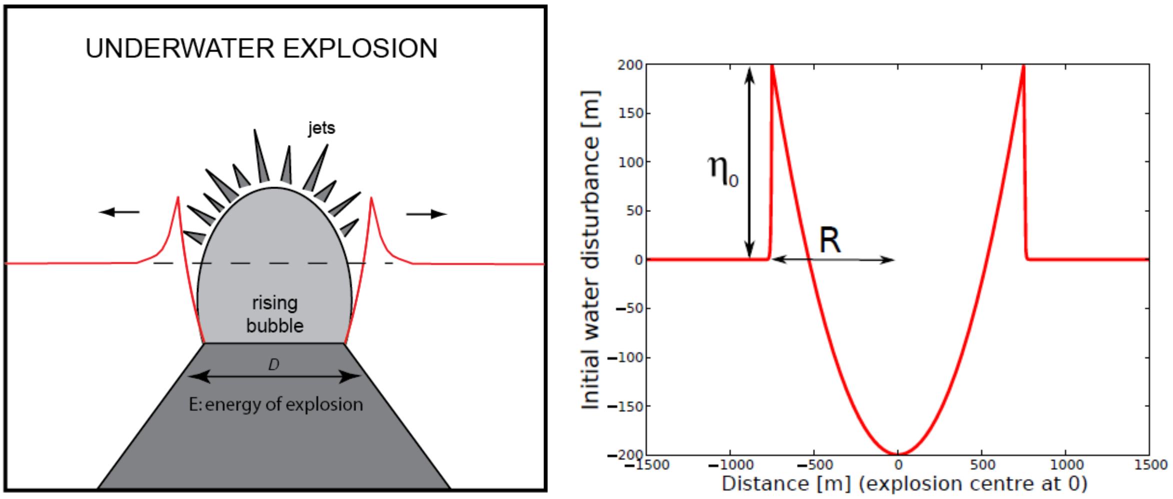

Figure 4: Initial water displacement generated by an underwater explosion. R corresponds to the radius of the water crater (D being the diameter), and η0 to the height of the rim.

4.3 Caldera collapse

Large explosive eruptions often results in the collapse of the central part of the edifice, thus forming a caldera. The duration of a caldera collapse is poorly constrained (from minutes to hours) and the geometry varies from a single block to multistage subsidence of sub-blocks. In case of a subaqueous eruption, the collapse generates a subsidence of the water surface that initiates the propagation of a leading trough (e.g. Nomanbhoy & Satake, 1995).

A complication in the field of volcanic tsunami comes from the fact that several tsunamigenic processes can be associated, thus complicating the interpretation of observational data (such as tide gauge records) and the determination of input parameters for numerical simulations. For instance, caldera-forming eruptions may involve five tsunamigenic processes: pyroclastic flows, underwater explosions, earthquakes, the caldera collapse itself, and failures of the caldera walls (Paris et al., 2014). Here we consider only the collapse of the central part of the volcano as a source of tsunami.

The initial subsidence of the water surface depends on the geometry and duration of the collapse. The formation of the caldera can occur as a single block or as a multistage collapse of sub-blocks. Maeno and Imamura (2011) found that the water elevation above the caldera was the largest for a dimensionless collapse speed of 0.01 (scaled by the hydrostatic wave celerity). The duration of a caldera collapse is poorly constrained (from minutes to hours) and field and experimental studies suggest various geometries and collapse mechanisms.

Note that high discharge rate eruption of silicic magmas (e.g. rhyolite) during subaqueous caldera-forming eruptions might also generate pyroclastic ponds resulting in a dome of water, thus having an opposite effect of caldera subsidence (Cas & Wright, 1991).

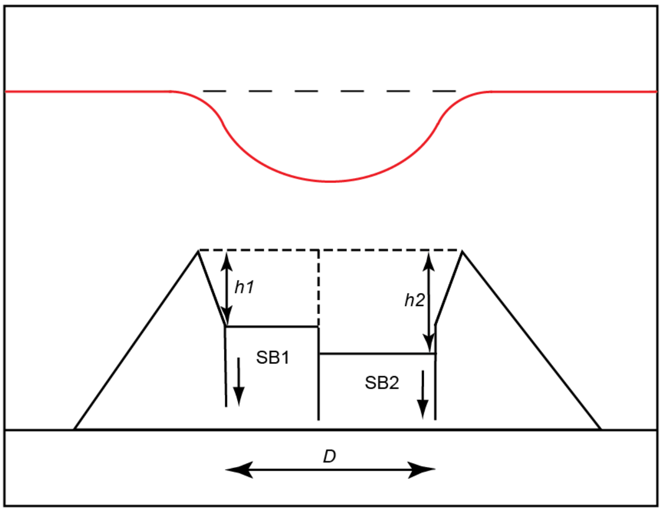

Figure 5: Subsidence of the water surface generated by a caldera collapse. D is the diameter of the collapse. SB1 and SB2 are sub-blocks (in case of multistage collapse) of height h1 and h2 respectively (h being the difference between the top of the volcano before the collapse and the floor of the resulting caldera).

4.4 Pyroclastic flows

Pyroclastic flows are hot mixtures of gas and particles generated by volcanic eruptions, particularly in case of dome collapse and plume collapse. There is growing evidence of tsunami generated by pyroclastic flows, but the phenomenon is quite complex, especially at the boundary flow / water. Mechanisms of interaction between pyroclastic flow and water as well as the conditions required to generate a tsunami remain partly elusive because the scientific community lacks observations of this complex phenomenon, and because experimental as well as theoretical studies are rare. Boundary conditions between hot gas-supported flows and ambient water are not well understood and may differ depending on the characteristics of the flow at the shoreline. Watts and Waythomas (2003) demonstrated that the most energetic and coherent water waves are produced by the dense, basal debris flow component of the pyroclastic flow. Other phenomena such as steam explosion, flow pressure and shear, and pressure impulse would theoretically generate smaller waves.

The important parameters controlling the interactions between pyroclastic flows and water bodies are the bulk density of the flow and its preservation or disaggregation underwater, the discharge rate, the angle of incidence, and the transport distance from the vent (Cas and Wright 1991; Carey et al., 2000; Maeno & Imamura, 2011). Freundt (2003) demonstrates that flows with a bulk density near that of water generate waves, whatever their temperature.

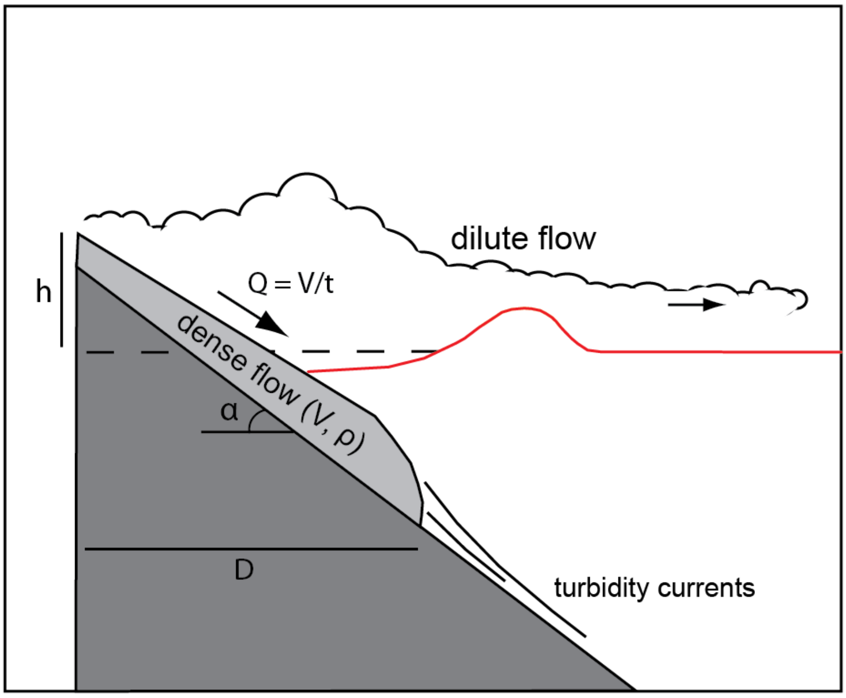

Figure 6: Physical parameters of a pyroclastic flow entering a water surface. The dense part of the flow is characterized by a volume V (m³) at a density ρ (kg/m³), entering the water during a duration t (s), thus determining a volume flux Q (m³/s). Note that pyroclastic flows are often described in term of discharge rate (kg/s). D represents the runout distance (m), α the angle of incidence (°), and h the altitude (or depth) of the vent of emission. Interactions at the boundary flow / water are not represented here (mixing, turbulence etc.), except density flow segregation.

5. Conclusions – way forward

The present ASTARTE source modelling guidelines are developed to assist tsunami modellers in choosing appropriate source models and properly documenting their use. They review briefly modelling techniques of both general and source specific nature. The present guidelines are focussed on describing mechanical source processes and typical techniques for source simplifications, but also briefly discuss input data for establishing source probabilities.

It is stressed that this modelling standardization has been employed in the production of previous deliverables in ASTARTE WP3, namely D3.12 and D3.16, along with the characterisation of the NEAM source region. These efforts constituted the basis for hazard assessments in WP8 (e.g. in D8.8), for a critical review of uncertainty in tsunami modelling in D4.13 and D8.39, and for the construction of warning-oriented earthquake source databases in D6.24. To this end, another application of the standardization is related to the source modelling presently being carried out the in the TSUMAPS project (http://www.tsumaps-neam.eu/), where the first common probabilistic set of tsunami hazard maps are developed for the NEAM region.

To date, approaches for tsunami hazard analysis are not well standardized. The present ASTARTE deliverable is just a first and preliminary attempt to provide a more standardized and transparent way of designing sources and reporting their input. On a longer term, it is expected that the source guidelines will be updated, for instance by the Global Tsunami Model (GTM, www.globaltsunamimodel.org), a network of coordinated action for tsunami hazard and risk assessment worldwide.

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