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Inundation Risk due to a Landslide-Generated Tsunami in the North Sea

Rohit Kulkarni, Nicolas Zimmermann,
Thijs Lanckriet, Alexander Breugem.
International Marine and Dredging Consultants
(IMDC nv)
Antwerp, Belgium
rku@imdc.be, nzi@imdc.be, thl@imdc.be, abr@imdc.be.

Abstract — A tsunami is a wave generated by the displacement of large volume of water. The water displacement can have different sources, such as earthquakes, asteroid impacts or underwater landslides. A series of massive landslides, known as the Storegga slides, occurred in the Norwegian Sea around 8000 years ago, leading to massive tsunamis in the North Sea basin. A study was performed, in which the inundation risk due to such a landslide-generated tsunami was determined for a sensitive industrial site situated behind the coastal dunes on the Dutch Coast. Thereto, two TELEMAC-2D models were setup. In a large-scale model, which includes the North-eastern Atlantic Ocean, the propagation of a tsunami up to the Dutch coast was simulated. A high-resolution small-scale model was nested in the large-scale model, to perform a detailed inundation study. Finite Element discretization was used for both the large-scale propagation and the small-scale inundation model.

The tsunami that was modelled is the so called Maximum Credible Event (MCE). The MCE is a concept introduced after the Fukushima disaster, to assure that no important changes in the plant status occur beyond the Design Basis Event-level (called margin assessment). It may correspond to a return period of 1 million years or more. It encompasses both the Design Basis Event (DBE) and the Beyond Design Basis Event (BDBE), which were already in use before Fukushima and corresponds to return periods of typically 10,000 years to 100,000 years. The MCE was selected from different potential landslide scenarios, and its magnitude was determined based on previous investigations. This leads to a Storegga-like slide at the entrance of the Norwegian trench.

The model is initially validated against propagated tsunami field of Hill et al. (2014) in the North Sea and to a time series of Harbitz (1992) offshore station in Aberdeen. The model results were found to be in good accordance with the peer reviewed results of Hill et al. [1] and Harbitz [2]. The results of the tsunami calculation are discussed which shows that in a MCE of a tsunami in the North Sea inundation is calculated on the coast of Netherlands through the dune openings.

Keywords: Tsunami model, TELEMAC 2D, inundation

I. INTRODUCTION

The two most studied types of tsunamis and most relevant for engineering purposes are earthquake- and (sub-aerial or submarine) landslide-induced tsunamis. These two types of tsunamis have clearly distinct characteristics and need to be treated differently. [6]

It is important to note that landslides are often co-seismic. Often a combination of an earthquake and an earthquake-triggered landslide is needed to explain the high tsunami run-up values observed, such as in Papua New-Guinea in 1998 and in Tohoku (Japan) in 2011.

Landslide-induced tsunamis can be particularly dangerous because the warning time is often too short for evacuation (unless in the case of a cataclysmic event generated farther). Initial free surface elevations of landslide-induced tsunamis can be up to an order of magnitude larger than most earthquake-induced tsunamis.

The current study focuses on a landslide-generated tsunami in the North Sea initiated off the coast of Norway. The model generated for the study is initially calibrated with the tsunami generated from the landslide at Storegga, 8000 years ago which was calculated to be a design event with a return period of 100,000 years. Currently, the Storegga slide is considered as stable, although there are certain locations around the northern Norwegian shelf, which can be considered as potential events which may affect the European coast.

For the propagation of the tsunami, dispersion becomes important when the wavelength is not much larger than the depth. This is the case for landslides with rapid acceleration or deceleration producing a large content of short wave length components [2]. For waves generated by large and subcritical submarine landslides with moderate acceleration or deceleration (0.005 m/s^2 – 0.033 m/s^2), such as the Storegga landslide, dispersion is of secondary importance.

For the purpose of this study, the calibrated hydrodynamic model is then used to calculate a Storegga-like slide further south of the coast of Norway which would generate a tsunami front incident directly through the North Sea. The inundation on the coast of Netherlands is further

[1]The Storegga submarine slide qualifies as cataclysmic event.

calculated with a smaller nested model which derives its boundaries from the larger domain.

The dune system on the coast of the Netherlands is seen to act as a barrier in case of any inundation. Although, there are certain gaps in the dune system to allow access to the beach area. The inundation study considers one of these ‘openings’ to demonstrate the risk of possible inland flooding.

II. Model Details

This section outlines the software used for the study, the model prepared and the various settings used for the simulations. The unstructured model TELEMAC-2D based on the shallow water equations is used. Dispersion is neglected, as justified previously.

The simulations are carried out in two steps. Initially a large domain (CSM - Continental Shelf Model) covering the North Sea and parts of Atlantic Ocean is simulated with the initial condition by applying the water levels depicting the start of the tsunami and subsequently the results from the large-scale model are used as a boundary condition for a smaller and detailed (local) model near the project area, to study the resulting coastal inundation.

The simulation results and model details presented in the report are in WGS84 geographic system (latitude/longitude). The bathymetry and water levels applied are relative to NAP (Normaal Amsterdams Peil).

A. Grid and bathymetry

In the initial step, the large-domain model was simulated with the design scenario of the tsunami. The CSM model is based upon an existing, calibrated hydrodynamic model of the North Sea continental shelf. The CSM model has been tested previously and has been shown to reproduce the tidal propagation quite accurately with a RMSE of 0.16 m near the coast of Netherlands. [3]

The model grid covers a part of North Atlantic Sea and extends to Iceland in the west and extends towards the north of Norway. The model also extends to the Bay of Biscay and covers the western coast of France. Fig. 1 shows the extents of the model which is 3300 km wide and 5500 km long along with the model grid and bathymetry. The model resolution decreases gradually from 75 km near the North Atlantic boundary to 5 km in the Norwegian Sea and the North Sea. The model resolution is increased to 1 km near the Norwegian coast, and around the tsunami source term to better capture the pattern of the initial waves. The maximum element size is restricted to 200 m near the Netherlands to facilitate nesting of the smaller local model with sufficient boundary points from the CSM model. The CSM model consists of close to 1.45 million elements. The independence of model results in the area of interest on resolution has been confirmed by a sensitivity test.

In a second step, nearshore results from the CSM model are imposed on a local nested model. This nesting allows to decrease the computation time of the CSM model, which is restricted by the size of the smallest element.

At each point along the offshore boundary of the local model, water levels and horizontal velocities derived from the large-scale model are prescribed (spatially varying boundary conditions), by linear interpolation from the large-scale model grid results. At the offshore boundary of the local model, the local and large-scale models have the same grid resolution.

The local model covers the northern part of the Dutch coast and contains around 360,000 elements. Fig. 2 shows the extent of the model grid which covers 5 km on land around the considered project site and also spreads out to 10 km offshore. The mesh of the local model domain varies gradually from 200 m offshore to 20 m on land. Fig. 2 also shows the mesh details near the study area and the opening in the dunes (inset) which are included in the model with a high resolution of 5 m to better calculate the propagation of the tsunami inundation front. The dune openings have a width of around 30 m.

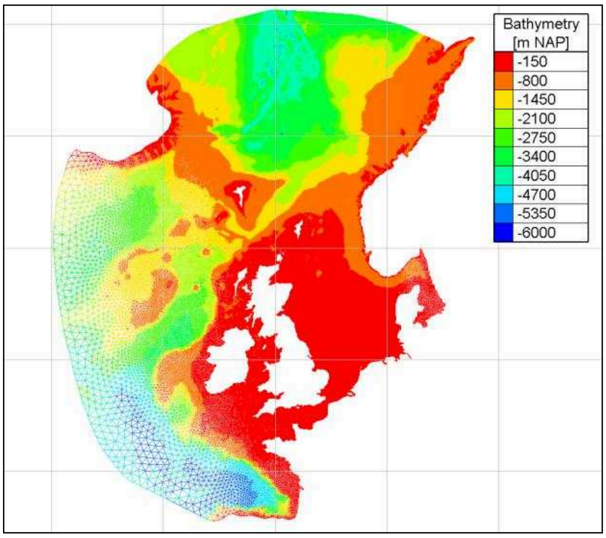

Figure 1. *CSM domain extent and mesh with bathymetry*

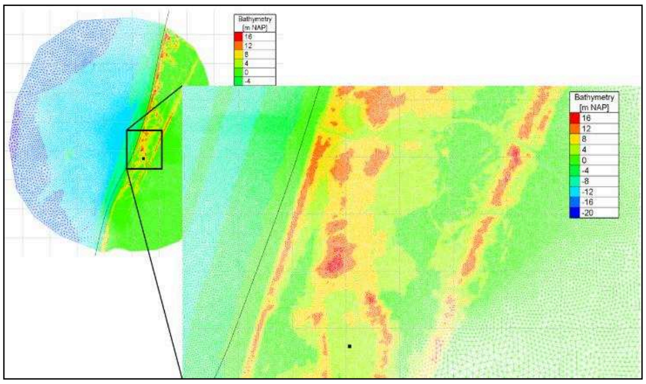

Figure 2. *Local mesh details*

B. Model Settings

For the CSM model, the time step was set to one second to resolve the initial tsunami propagation. A Manning’s roughness coefficient of 0.02 was used for bottom friction. The model was simulated for a period of 24 hours to allow both the initial and secondary waves to reach the study site.

The initial water level is set to the design water level in the entire model domain. Non-reflecting boundaries are considered over the North Atlantic Ocean (Iceland to Spain) and Norwegian Sea (Iceland to Norway). The location of boundaries was based on the source term location and was kept far enough to minimize boundary effects on the tsunami propagation.

The local model is also run with a time step of one second, which is restricted by the smallest element size in the domain (5 m). The time steps between the models were kept same because for the larger model, the restricting criterion was to capture the reflected wave off the coast of Norway correctly whereas, for the local model, the time step was a requirement due to the small grid size. The maximum Courant number was always calculated to be below one, guaranteeing the numerical accuracy of the results. Similar to the CSM model, the initial water level is set to the design water level in the entire model domain, excluding land. After several tests, the advection schemes used for velocities was chosen as Characteristics and water levels were calculated using conservative PSI-scheme. A Manning's roughness coefficient of 0.02 was used for bottom friction, similar to the CSM model. No distinction has been made between the roughnesses at sea and on land. The land surface in the path of the tsunami is mostly covered by sand (which has approximately the same roughness as the sea bed), a narrow concrete / asphalt road (which has a similar roughness as sand) and dune grass. The dune grass has a higher roughness, creating additional dissipation of the tsunami run-up, and omitting the higher roughness of the dune grass is therefore conservative. However, it is expected that some of the dune grass will be removed by the tsunami flow, converting the bottom type at these locations to sand.

C. Tsunami Initialisation Source

The tsunami source term is derived from the analytical model of Grilli and Watts [4] and Watts et al. [5]. This semi-empirical formula has been derived from a large set of simulations with a near-field numerical model, itself validated on physical modelling results. The numerical implementation by IMDC of the analytical model of Grilli and Watts [4] and Watts et al. [5] has been validated based on test cases provided in the papers.

Due to its extreme nature, the selected scenario falls outside the applicability range of the analytical model for the slide kinematics. The depth-to-length ratio of less than 0.01 falls outside of the applicability domain (>0.06) resulting in an unrealistically high terminal slide velocity.

However, equation (1) of the model of Watts et al. [5] can be used with carefully selected parameters to manually define the shape of the initial surface elevation:

$$\eta(x,y) = -\frac{\eta_{0,3D}}{\eta_{min}} \operatorname{sech}^2\left(\kappa \frac{y-y_0}{w+\lambda_0}\right)\left(\exp\left\{-\left(\frac{x-x_0}{\lambda_0}\right)^2\right\} - \kappa' \exp\left\{-\left(\frac{x-\Delta x-x_0}{\lambda_0}\right)^2\right\}\right) \quad (1)$$

Where:

- $\eta(x,y)$ is the initial surface elevation [m]
- $\eta_{0,3D}$ is the maximum surface elevation [m]
- η_{min} is the minimum of the function on the right hand side of the equation, excluding the amplitude [m]
- κ is set to 3 according to Watts et al. [5]
- x_0 and y_0 are the coordinates of the slope bottom (end of slide movement)
- w is the landslide width [m]
- λ_0 is the characteristic near-field tsunami wave length [m]

κ' and $\Delta x = x_0 - x_g$ are parameters controlling the shape for given x_0 and λ_0 values.

Parameter values in TABLE 1 have been chosen such that the resulting initial surface elevation is comparable to that computed by Hill et al. [1] with a model including the dynamics of the slide (Fig. 3).

The initial maximum tsunami elevation has been selected to match that of Harbitz et al. [6], the slide width and characteristic tsunami length have then been chosen to match the displaced water volume of [1].

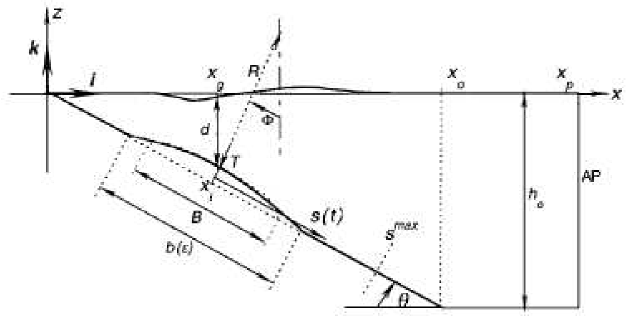

Figure 3. *Schematisation of slide in the analytical model of Grilli and Watts [4]*

In dynamic simulations such as in Harbitz et al. [6], Hill et al. [1], because the slide takes place over a long duration, the initial wave trough reflects against the coast of Norway and creates an asymmetric tsunami wave. Equation (1) however assumes a symmetric tsunami wave, i.e. equal minimum and maximum initial surface displacements.

This effect cannot be well corrected by varying parameter κ' which partly controls the asymmetry. It has hence been chosen to focus on the maximum surface displacement and to accept an error on the minimum surface displacement.

This approach is a pragmatic intermediate step between research models which generally include this dynamic coupling [2][7][1], and models more suitable for consultancy which generally impose a time series of water level along a straight line between Scotland and Norway [8][9]. The model is validated in the next section.

TABLE 1. PARAMETER VALUES OF THE DESIGN TSUNAMI

Parameter	Value
$\eta_{0,3D}$	-8.19 m
w	750 km
λ_0	700 km
x_0 , y_0	150 km, 0 km
κ'	1
Δx	75 km

The tsunami initialization source, based on the tsunami sources of Hill et al. [1] and Harbitz et al [6] is deemed conservative, since these models from literature have inferred the initial tsunami characteristics by comparing the calculated *nearshore tsunami height* to observed geological tsunami deposits. The *tsunami run-up* on the other hand can easily be twice larger, as evidenced by the present study. Calibrating the initial tsunami characteristics on the tsunami run-up instead of the nearshore tsunami height, would have resulted in a smaller initial tsunami height.

III. MODEL VALIDATION

The model has been validated with the well-studied Storegga landslide event which occurred around 8000 years ago. Model results are compared to the propagated tsunami field of Hill et al. [1] in the North Sea and to a time series of Harbitz [2] offshore station in Aberdeen, two other model studies published in peer-reviewed scientific journals and using present-day bathymetry for the computation.

Fig. 4 shows the model results over the first hour as the imposed tsunami propagates from the source term. After around an hour, a part of the wave enters the North Sea, with a leading wave trough.

Fig. 5 shows that the tsunami propagation in the North Sea is fairly similar to that described in Hill et al. [1] in their simulation with the present day bathymetry. The model is able to capture the subsequent wave crest and trough propagation in the North Sea fairly accurately, which is important for the calculation of inundation at the Dutch coast.

Model results are also compared to the time series at Station 8 from Harbitz [2], located offshore Aberdeen, Scotland (Fig. 6). Results of Hill et al., [1] at that location are not available. This station is used as validation point in the study of Chacon-Barrantes [9]. Note that the time axis origin (t = 0 s) in the time series of Harbitz is at the moment of landslide initiation, whereas the time axis origin in the present model is at the moment when the initial water level begins to propagate outward. The model reproduces reasonably well the maximum water elevation and the wave period. The model calculates a water elevation of 3.44 m reaching the station while the Harbitz [2] model calculated a water elevation of 3.41 m at station 8. Results of Harbitz [2] at other stations show the same qualitative agreement. The model is hence suitable for inundation modelling.

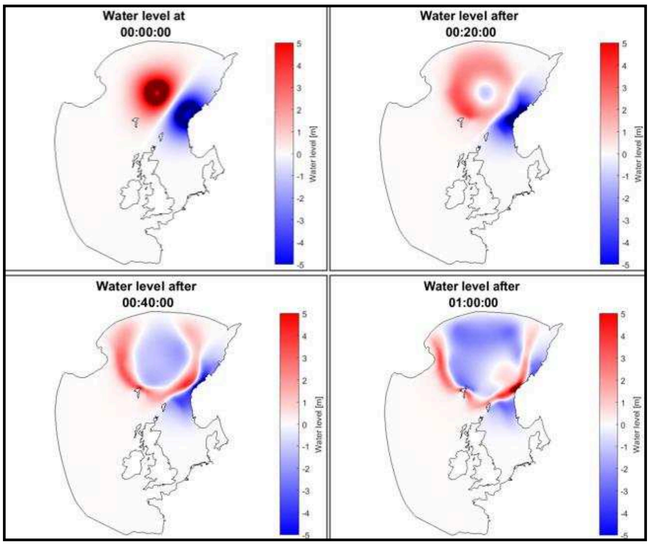

Figure 4. *Tsunami propagation over a period of 60 minutes for Storegga tsunami.*

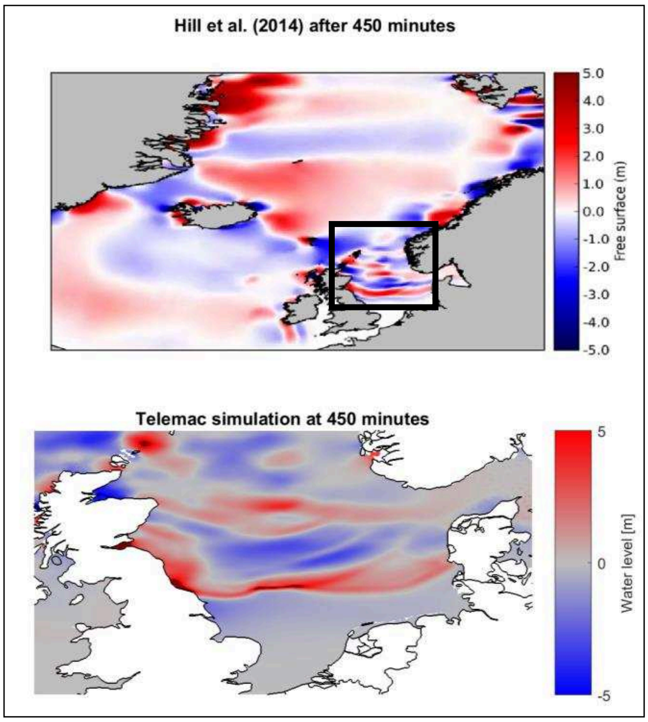

Figure 5. *Tsunami propagation after 7 h 30 min in Hill et al., [1] (top) and in the present study (bottom)*

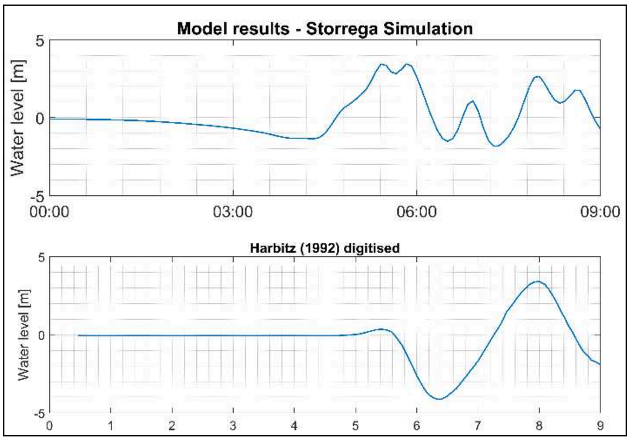

Figure 6. *Tsunami time series offshore Aberdeen in the present study (top) and at station 8 in Harbitz [2] (bottom).*

IV. Model Results

This section presents and discusses the simulation results for the Maximum Credible Event. It consists of a Storegga-like slide at the entrance of the Norwegian trench.

A. CSM Model

Fig. 7 shows the initial propagation of the tsunami until it enters the North Sea basin. The design scenario results in a larger wave front entering the North Sea compared to the Storegga tsunami. This is due to the fact that for the Storegga tsunami, a major part of the wave is blocked by the coast of Norway, whereas if the landslide occurs at the entrance of the Norwegian trench, the tsunami wave front propagates unobstructed.

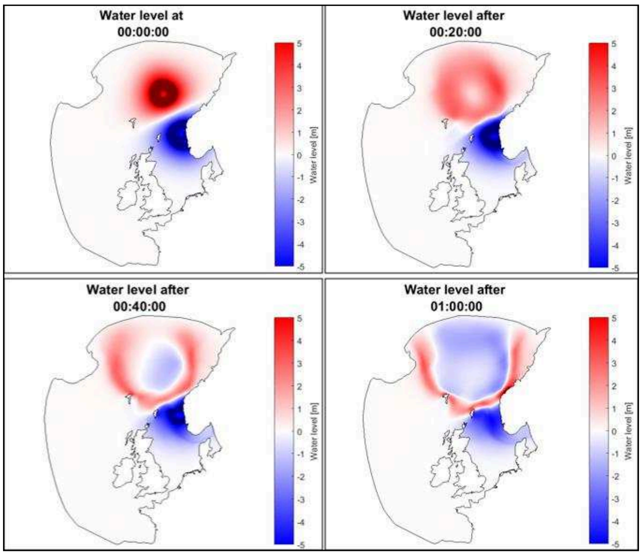

Figure 7. *Tsunami propagation over the first 60 minutes for the Maximum Credible Event (design scenario).*

Details of the tsunami propagating through the North Sea are shown in Fig. 8. The tsunami displays a similar pattern to the Storegga tsunami, although the wave length and wave amplitude are calculated to be larger. As the tsunami approaches the Dogger Bank area, its wave amplitude increases due to the shallow depth. The wave initially impacts the Wadden islands, the high waters then propagate along the Dutch coast.

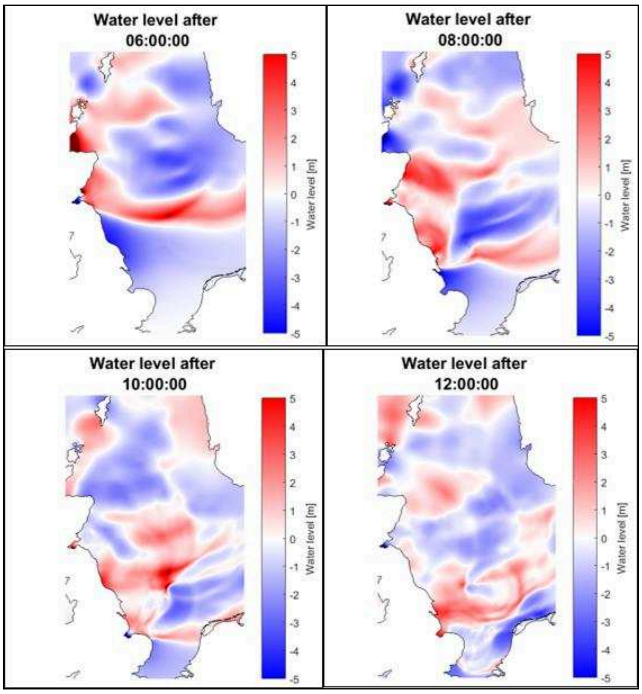

Figure 8. *Tsunami propagation in the North Sea for the Maximum Credible Event (design scenario) over a period of 6 hours. Initial water level subtracted from the results.*

B. Local Model

The Maximum Credible Event results in inundation at the coast, without significant impact on the infrastructure behind the first dune defence. Fig. 9 shows the time series of the water level near a gap in the dune system, including the run-up (initial water level subtracted from the results). The first effects of the tsunami become tangible about 6 hours after initiation. The second tsunami wave has the strongest impact and reaches the coast of Netherlands about 12 hours after initiation, with a maximum drawdown of 3.5 m over 2 hours and a maximum run-up of about 7.5 m over the next one hour (total water level close to 11 m). The run-up peak itself lasts about 20 min (Fig. 10). Secondary waves still reach the site during the next 12 hours due to the numerous reflections of the tsunami wave in the North Sea basin.

As seen in Fig. 11, the Maximum Credible Event results in a maximum flow depth of 3.5 m in a low lying area behind the dunes. Near the second row of dunes the maximum water depth is around 1 m. No overtopping of the dunes occurs and the inland areas are still safe from the inundation. The water inundates the hinterland via the opening in the dune field. It stops before it reaches the second row of dunes because entering water volumes are limited by the size of the opening. Note that the model does not take into account a possible enlargement of this opening by erosional processes due to the high velocities involved, which may potentially increase the hazard at the project area.

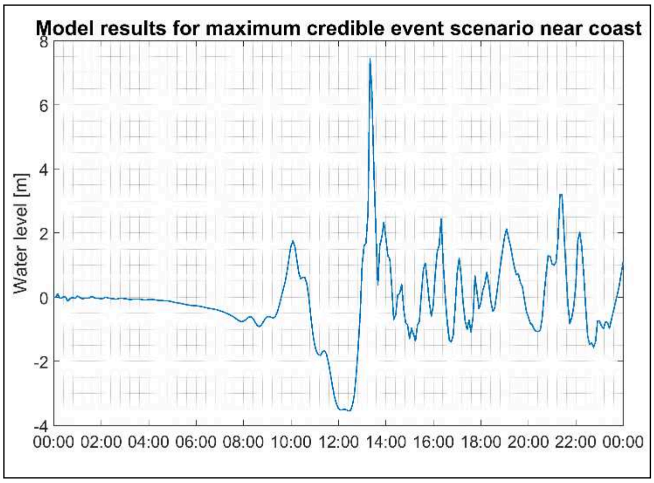

Figure 9. *Time series of water level near the project site (run-up included).*

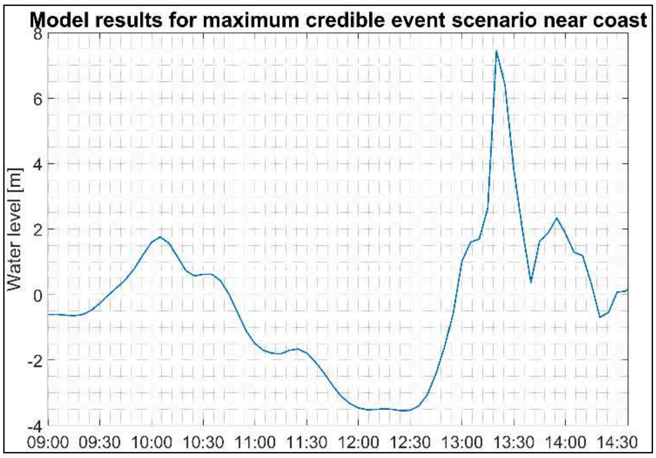

Figure 10. *Time series of water level near the project site (run-up included): zoom on the primary tsunami wave.*

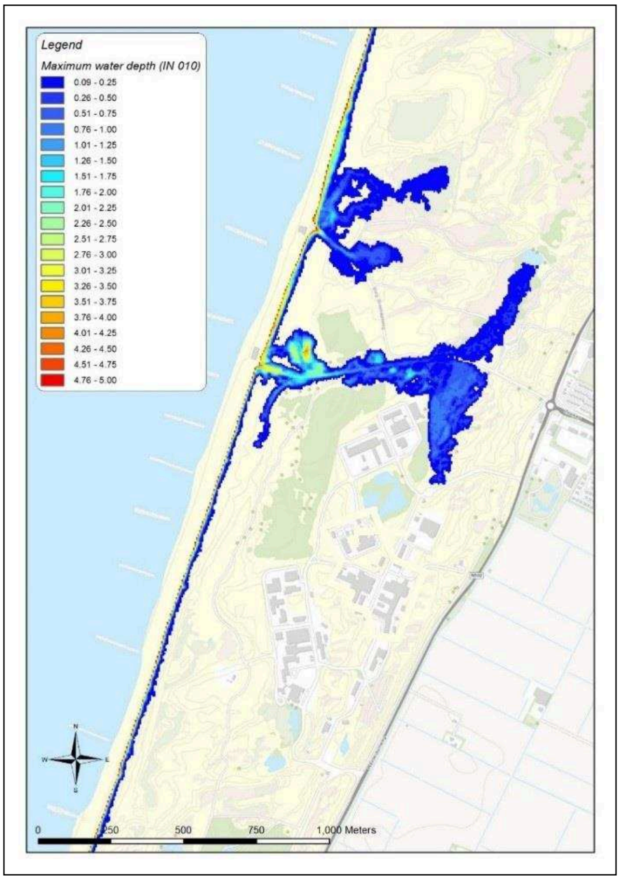

Figure 11. *Maximum water level in m NAP reached at each point for the Maximum Credible Event.*

V. Conclusion

The study outlines the efforts taken towards calculating propagation of tsunami generated in the North Sea and resulting inundation on the Netherlands coast. A previously validated model (CSM) is modified to better capture tsunami propagation through the North Sea. The model is validated against peer reviewed studies by calibrating the tsunami initialization source term and grid optimisations against the Storegga slide. A two model approach is taken to calculate the propagation of tsunami and inundation of the generated wave on the Dutch coast.

The results show a good correlation with the model studies published and also at measurement station in Aberdeen, Scotland. For the Storegga tsunami, the calculated tsunami wave front shows that a majority portion of the wave travelling towards the Netherlands is the wave reflected off the coast of Norway.

The maximum credible event (MCE) tsunami shows inundation on the coast of Netherlands through the opening in the coastal dune system. Although, the inundation is calculated to be restricted to the first line of coastal dune system. The total run-up during the MCE is calculated to be about 7.5 m. A maximum water depth of 3.5 m is calculated as a result of inundation behind the first dune system.

A coupled model simulating the landslide dynamics and its impact on the initial water motion, is expected to better reproduce the initial tsunami propagation reported in literature for the Storegga landslide, which was used for the model validation. However, considering the large uncertainty surrounding the initial landslide and tsunami characteristics, this approach is only expected to significantly improve the modelled tsunami drawdown.

Further improvements can be carried out by modelling the actual landslide separately which would generate the initial water level displacement to be modelled for further propagation.

Acknowledgement

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References

[1] J. Hill, G. S. Collins, A. Avdis, S. C. Kramer, and M. D. Piggott, ‘How does multiscale modelling and inclusion of realistic palaeobathymetry affect numerical simulation of the Storegga Slide tsunami?’, *Ocean Modelling*, vol. 83, pp. 11–25, Nov. 2014.

[2] C. B. Harbitz, ‘Model simulations of tsunamis generated by the Storegga Slides’, *Marine Geology*, vol. 105, no. 1, pp. 1–21, Mar. 1992.

[3] W. A. Breugem, T. Verbrugghe, and B. Decrop, ‘A continental shelf model in TELEMAC 2D’, in *TELEMAC User Conference, Proceedings*, 2014.

[4] S. T. Grilli and P. Watts, ‘Tsunami Generation by Submarine Mass Failure. I: Modeling, Experimental Validation, and Sensitivity Analyses’, *Journal of Waterway, Port, Coastal and Ocean Engineering*, 2005.

[5] P. Watts, S. T. Grilli, D. R. Tappin, and G. J. Fryer, ‘Tsunami Generation by Submarine Mass Failure. II: Predictive Equations and Case Studies’, *Journal of Waterway, Port, Coastal and Ocean Engineering*, 2005.

[6] C. B. Harbitz, F. Løvholt, G. Pedersen, and D. G. Masson, ‘Mechanisms of tsunami generation by submarine landslides: a short review’, *Norwegian Journal of Geology*, vol. 86, 2006.

[7] S. Bondevik, F. Løvholt, C. Harbitz, J. Mangerud, A. Dawson, and J. I. Svendsen, ‘The Storegga Slide tsunami—comparing field observations with numerical simulations’, *Ormen Lange–an Integrated Study for Safe Field Development in the Storegga Submarine Area*, pp. 195–208, 2005.

[8] A. Dababneh, B. Ferguson, and D. Barton, ‘Probable Maximum Tsunami Along the Dutch Coastline’, *Proceedings of ISOPE, Rhodes, Greece, June 17-22, 2012*, 2012.

[9] S. Chacon-Barrantes, R. Narayanan, and Mayerle, ‘Several tsunami scenarios at the North Sea and their consequences at the German Bight.’, *Journal of Tsunami Society International*, vol. 32, no. 1, 2013.