HYDRODYNAMIC EFFICIENCY AND LOADING OF A TSUNAMI-FLOODING BARRIER (TFB)

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The Tsunami-Flooding Barrier (TFB) is an impermeable vertical structure proposed at relatively large water depths, at which it is theorised that a tsunami will reach the structure before turning into a bore. The proposed hypothesis is tested in this study by means of a validated Computational Fluid Dynamics (CFD) model. The hydrodynamic efficiency of the impermeable TFB structure is confirmed and the effect of different aspects on the hydrodynamic efficiency of the structure are studied. These aspects include water depth, free board, surface roughness and the consideration of a deflecting parapet (named here as a surge stopper). Further, a new method is developed for calculating the tsunami-like solitary wave run-up and loads on the structure. The method is then compared to the Goda method for calculating storm wave loads on vertical impermeable structures. It is concluded that using the Goda method will severely underestimate the tsunami-like solitary wave load on the TFB structure.

Keywords: Tsunami; barrier; solitary waves; wave loading; deflecting parapet; surge stopper

INTRODUCTION

The Tsunami-Flooding Barrier (TFB), as proposed by Scheel (2014), is a novel defense structure to eliminate the risk of tsunamis attack on coastal zones. Two main proposed cross sections are given by Scheel (2014); a single-fence TFB (Figure 1a) and a double-fence TFB (Figure 1b). The proposed study aims at providing a description and an understanding of the hydrodynamic processes involved in tsunami-TFB interaction (e.g. wave run-up) as well as the TFB hydrodynamic efficiency including effects of parameters such as wall roughness, water depth, free board, wave characteristics and the effect of the surge stopper.
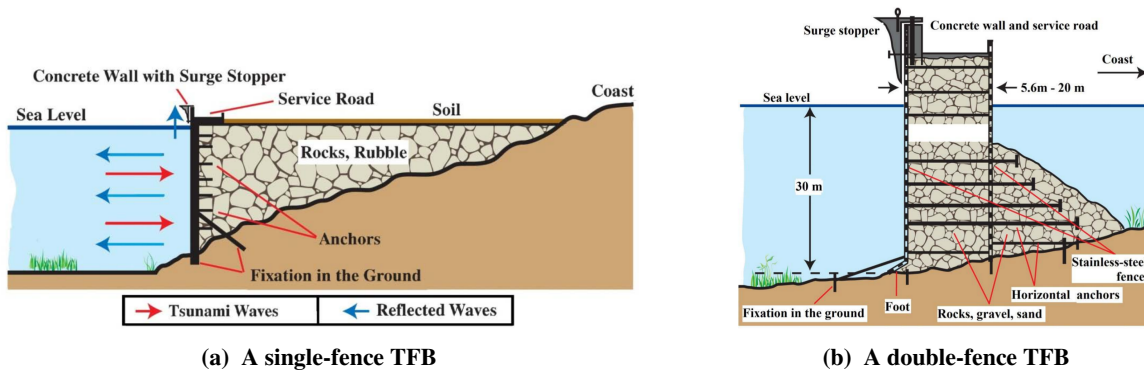

(a) A single-fence TFB　　　　**(b) A double-fence TFB**

Figure 1: Schematic cross section of the TFB with a service road and a surge-deflecting parapet (Scheel, 2014)

In the following sections, the hydrodynamic model system is described and the CFD model is validated against physical model tests of solitary waves. The model is then used for a systematic hydrodynamic parameter study of the structure. Additionally, new formulae are developed to estimate wave run-up and loading on the TFB structure. Finally, a summary of the study and outlook for future work are presented.

HYDRO-DYNAMIC MODELLING OF TSUNAMI-FLOOD BARRIER (TFB)

The *hybrid2D3D* toolbox (adapted from El Safti et al. (2014) as an extension to *waves2Foam*; Jacobsen et al. (2012)) is modified in this study to couple a far-field depth-averaged Boussinesq-type model, *pCOULWAVE* (Lynett et al., 2008), with a near field Navier-Stokes CFD model (Elsafti, 2015). The far-field model is used to simulate the propagation and transformation of realistic tsunami waves over long distances (i.e. thousands of kilometers), then the coupling utilities is used to transfer the output of the far-field into input to the near-field, in which the fluid-structure interaction can be simulated more accurately with much less computational time. This procedure provides more accurate properties of the tsunami as well as more accurate simulation of the fluid-structure interaction in the near-field.

The coupling procedure developed in this study is adapted from the coupling procedure presented in El Safti et al. (2014). In El Safti et al. (2014), the *hybrid2D3D* toolbox was developed to couple 2D and 3D CFD models into one

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hybrid CFD model system. The model system was applied to large-scale physical tests of (freak/focused) water wave interaction with slender pile-groups. The numerical model system (concept and implementation) was validated for inline moment on selected pile group configurations in El Safti et al. (2014).

The concept of the hybrid numerical model system is given in Fig. 2. As illustrated in this figure, advantages of using this model system include:

- Removing redundancies in far-field simulations

- Reducing the size of the computationally expensive near-field model significantly

- Independent time and space democratization of both the far- and near-field models

Unfortunately, no physical experiments were found in the literature of a solitary wave attacking a vertical impermeable barrier. One set of scaled physical experiments for a tsunami solitary wave attacking a vertical column was found (Han et al., 2015). Results from these experiments were digitized and used for comparison with the numerical model for

Figure 2: Coupling depth-averaged and depth-resolved models: concept and outline (modified from El Safti et al. (2014))

a vertical wall and a vertical column of a square cross section, Fig. 3. The results of the scaled model was in the same range as the numerical model (about 10% difference) for the vertical column (see Fig. 3b). Additionally, a comparison between the run-up and wave pressure on the wall and the square column can be seen in Fig. 3b. The results from this comparison show that the results from the numerical model can be reliably used for the prediction of forces on the TFB. As seen in Fig. 3b, the hydrodynamic pressure and run-up on a continuous impermeable wall are nearly double the pressure and run-up on a vertical square column. The difference is due to the 3D effect on the column allowing flow around it, which is prohibited in the case of the continuous impermeable wall. However, more comparison cases with similar configurations to the TFB structure will be needed in the future.
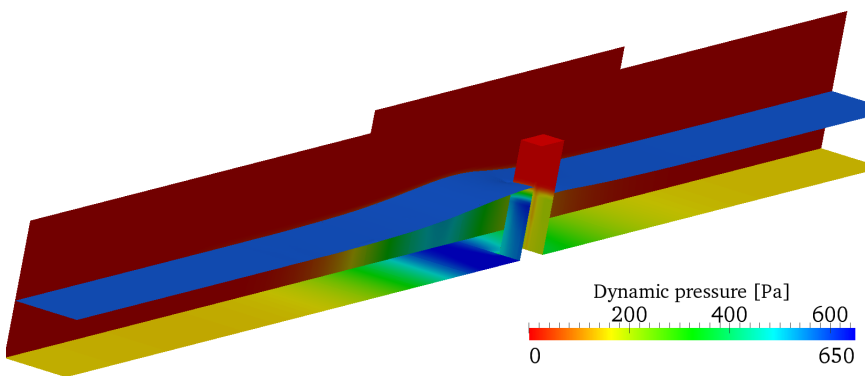
(a)
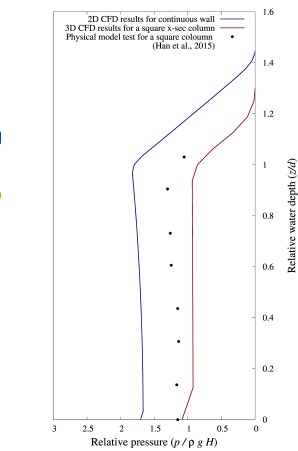
(b)

Figure 3: Hydrodynamic model validation: (a) Visualisation of the output from the 3D CFD simulation of the Han et al. (2015) experiments and (b) Vertical wave pressure distribution: comparison between physical scaled model results from Han et al. (2015) and numerical CFD model for the extended vertical wall and the vertical column of a square cross section
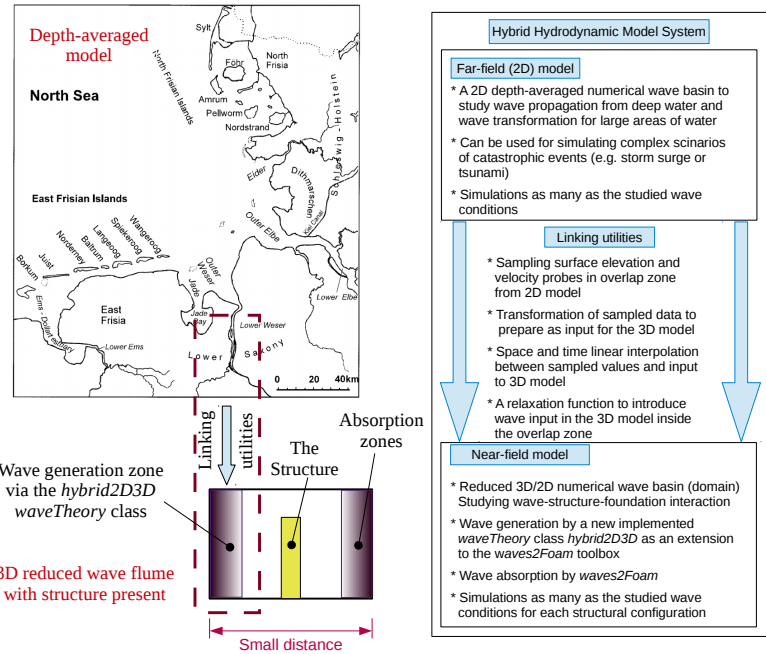
ANALYSIS OF THE RESULTS FROM THE NUMERICAL MODEL STUDY

In this section, the results of the numerical simulations of TFB subject to tsunami-like solitary wave loading are presented. Figs. 4 and 5 show visualisations of the tsunami approaching a TFB without and with a surge stopper. It is evident that the surge stopper can increase the efficiency of a TFB in hindering tsunamis.
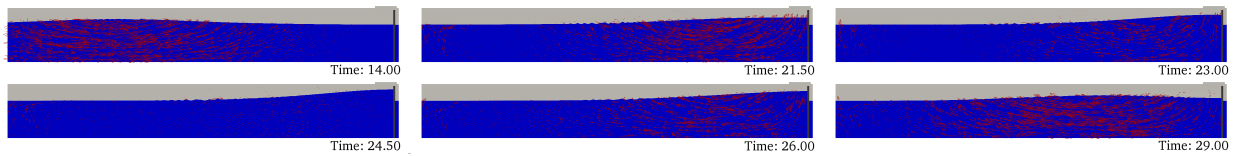

Figure 4: Tsunami approaching an impermeable TFB structure, results from CFD simulations for the VOF function (phase fraction) and vectors representing particle velocities, without overtopping ($d = 20m$, $H = 4m$ & $f = 8m$).
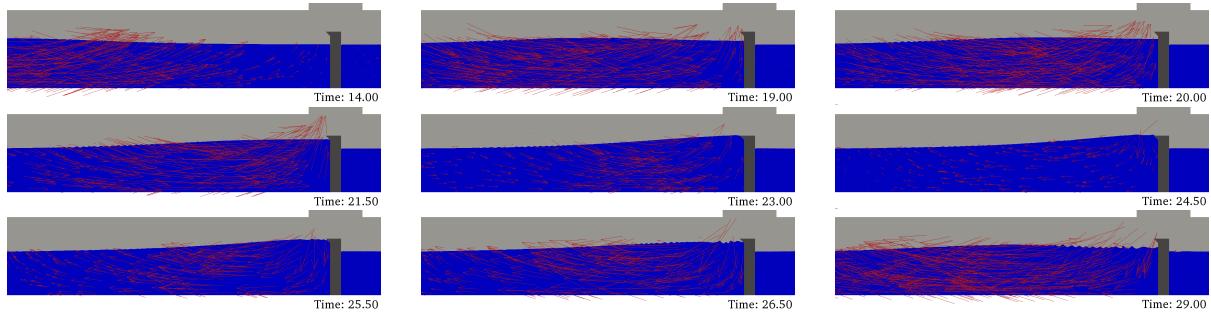

Figure 5: Tsunami approaching an impermeable TFB structure with a surge stopper, results from CFD simulations for the VOF function (phase fraction) and vectors representing particle velocities, the surge stopper results in no overtopping in this case ($d = 20m$, $H = 4m$ & $f = 4m$).

Outline of the Parameter Study

A parameter study is carried out using the numerical model presented in Section   in order to determine the coefficients which are required to apply the simplified wave load and run-up formulae proposed in Section   for different tsunami categories described by Scheel (2014). Additionally, the effect of different relevant parameters is studied. the cases considered include: Calculating no-overtopping forces on TFB (without surge stopper), effect of surface roughness of the TFB structure on wave loads and wave run-up (no overtopping and no surge stopper), effect of TFB freeboard on wave loads and wave run-up (with and without a surge stopper), effect of water depth on wave loads and wave run-up (without a surge stopper and no overtopping allowed), effect of tsunami height on wave loads and wave run-up (with and without a surge stopper), and effect of the surge stopper dimensions on wave loads and wave run-up (angle, $\alpha_{parapet}$,

Figure 6: Definition sketch for the main parameters of the deflecting parapet (surge stopper)

and width $B_{parapet}$). The outline of the parameter study conducted (in this section) is given in Table 1. Fig. 6 shows the definition of the most relevant parameters of the deflecting parapet (surge stopper) in terms of its hydraulic efficiency. a tsunami height at the shoreline can be estimated and the tsunami category can be considered according to the Horikawa classification $A_1 = A_d \sqrt{\sqrt{d}}$, considering a water depth of 1m as the depth for calculating wave amplitude at the shore in order to estimate the tsunami category.
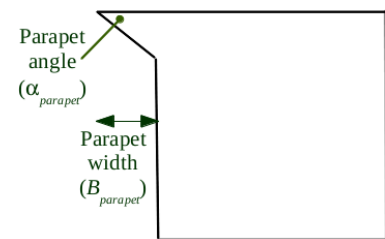
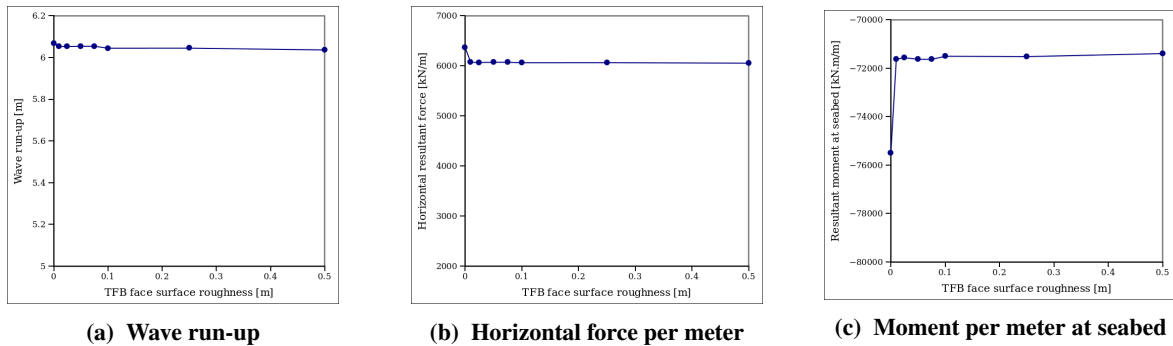**Effect of TFB Front Face Roughness (No Overtopping and No Surge Stopper)**

The effect of the front face roughness of the TFB structure was studied for the case of no surge stopper and no overtopping (Fig. 4). The increase in the front face roughness reduces the wave run-up and wave reflection (increasing energy dissipation); however, the effect of the front face roughness is not significant and can be neglected (TFB as a smooth front face) for preliminary analysis and design of the structure. Increasing the front face roughness can reduce the run-up and forces by a maximum of 0.5%, which is negligibly small (Fig. 7).

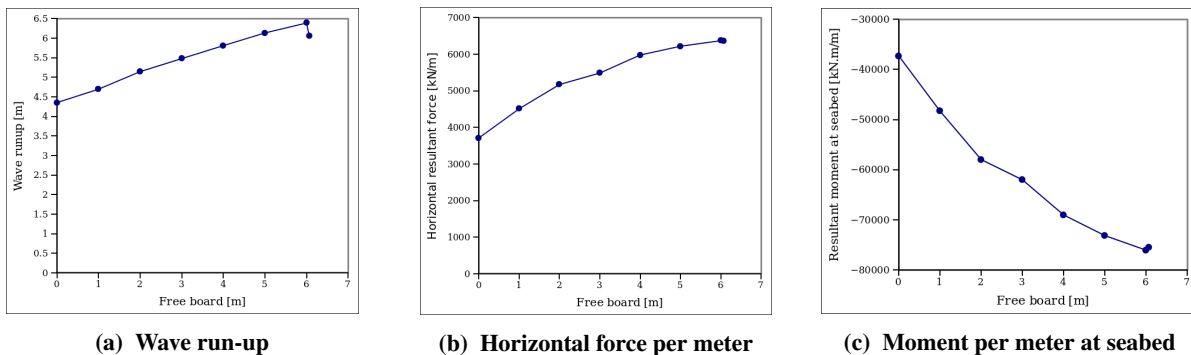**Effect of TFB Freeboard (with and without a Surge Stopper)**

Increasing the freeboard reduces (and eventually eliminates) the transmitted wave energy by wave overtopping. Therefore, as long as wave overtopping takes place, the force on the TFB structure increases with increasing the

Table 1: Range of tested parameters

Parameter	Range
Water depth (d) [m]	5, 10, 20, 25, 30 and 40
freeboard (f) [m]	0, 1, 2, 3, 4, 5 and 6
Front face roughness [cm]	0, 1, 5, 7.5, 10, 25 and 50
Tsunami height [m]	1, 2, 3, 4 and 5
Tsunami category	0, 1, 2 and 3
Deflecting parapet (surge stopper) width [m]	0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0
Deflecting parapet (surge stopper) angle [θ]	15, 30, 45, 60, 75 and 90

(a) **Wave run-up**   (b) **Horizontal force per meter**   (c) **Moment per meter at seabed**

Figure 7: Effect of TFB wall surface roughness (without a surge stopper): $H = 3m, d = 20m$

freeboard due to the reduced wave overtopping associated with larger freeboard. The surge stopper can be very effective in reducing the run-up as long as it can affect the hydrodynamics of the wave at the wall. This means that if the freeboard is "too" large, the efficiency of the surge stopper is reduced and may even vanish. This means a study of the optimum freeboard to allow maximum efficiency of the surge stopper for any TFB is needed.

(a) **Wave run-up**   (b) **Horizontal force per meter**   (c) **Moment per meter at seabed**

Figure 8: Effect of TFB freeboard (without a surge stopper): $H = 3m, d = 20m$

Considering the TFB without a surge stopper (Fig. 8), the wave run-up increases linearly with the freeboard. However, the wave loads (horizontal force and moment) on the structure increase non-linearly with the freebooard (at a decreasing rate) with the freeboard. This suggests that the increase in the freeboard results in a more appreciable increase in wave run-up as compared to wave loads, until no overtopping takes place.

On the other hand, considering a surge stopper (Fig. 9) reduces the wave run-up (compared to the case without a surge stopper). The increase in wave run-up with the freeboard can also be considered linear, with a smaller gradient than that without a surge stopper. The increase in wave loads is, again, similar to the case without a surge stopper, nonlinear at a decceasing rate as the freeboard increases. The data point at $f = 4m$ suggest a possible anomolie to the trend. This could point to a hidden peak point for higher wave run-up and reduced wave loads on the TFB structure. However, more data points near $f = 4m$ are needed to arrive at a more solid conclusion.
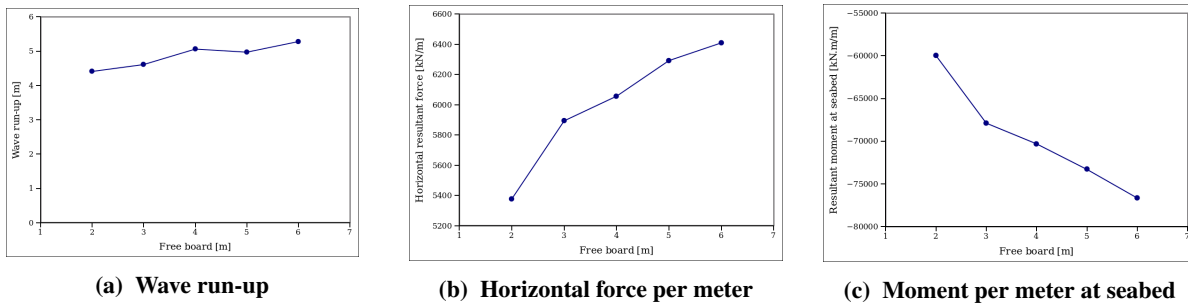
| (a) Wave run-up | (b) Horizontal force per meter | (c) Moment per meter at seabed |

Figure 9: Effect of TFB freeboard (TFB with a surge stopper: $\alpha = 45° \& B_{parapet} = 2m$): $H = 3m, d = 20m$

From the results in this section, it is clear that the freeboard plays a major role in deciding the efficiency of the surge stopper. It is therefore important to test several scenarios of freeboard surge stopper combinations to reach an optimum design for a TFB structure.

Effect of Water Depth (without a Surge Stopper and No Overtopping Allowed)

The depth at which the TFB structure is placed affects both wave run-up and pressure on the TFB for the same wave height. Therefore in this section, the water depth at the structure location is varied from 5 to 40m for an incident wave height of $H = 3m$, to study the effect of the water depth at which the structure is constructed for the case without a surge stopper.

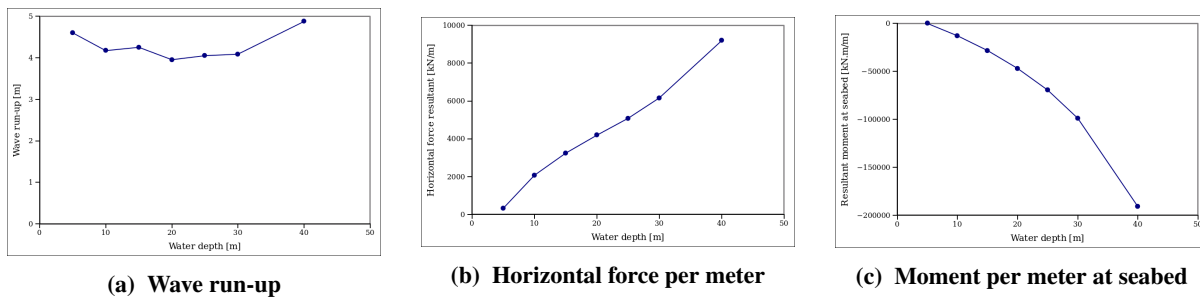| (a) Wave run-up | (b) Horizontal force per meter | (c) Moment per meter at seabed |

Figure 10: Effect of water depth (TFB without a surge stopper): $H = 3m$ and no overtopping

As shown in Fig. 10, for the same wave height, the wave loads increase nonlinearly with the increase in the water depth. This is because the kinetic energy of tsunami-like solitary waves increases with increasing water depth. Additionally, for the presented study, the wave run-up has the smallest value at 20m depth. This result implies that for the optimum design of a TFB structure, many water depths should be considered to provide the optimum design (smaller freeboard and wave loads).

Effect of Tsunami Height (with and without a Surge Stopper)

In this section the effect of the wave height is studied for the case with and without a surge stopper. For this part of the study, the water depth, wave height, freeboard and TFB width were kept constant ($d = 20m$, $f = 3m$, $H = 3m$ and $B = 5m$) for comparison. The freeboard to wave height ratio of $\frac{f}{H} = 1$ was selected to ensure that the surge stopper strongly interacts with the waves, instead of considering a too large freeboard that may prevent the surge stopper interaction with the wave.

From Figs. 11 and 12, it is evident that the relationship between both the wave run-up and wave loads to the wave height is linear. For the results herein, the effect of the surge stopper in reducing the run-up and reducing/preventing wave overtopping is evident. The surge stopper provides a reduction of about 10% in wave run-up and wave loads for the case of a 4m wave height and a free board of 3m.

Effect of the Surge Stopper Dimensions (Angle, $\alpha_{parapet}$, and Width $B_{parapet}$)

In this subsection, the effect of the surge stopper relevant parameters ($\alpha_{parapet}$ and $B_{parapet}$, Fig. 6) is studied. Fig. 13 illustrates the interaction between the wave and the surge stopper. As illustrated in Fig. 13, the surge stopper can deflect the wave energy as it interacts with the wave at the wall. Nevertheless, to ensure maximum efficiency of the
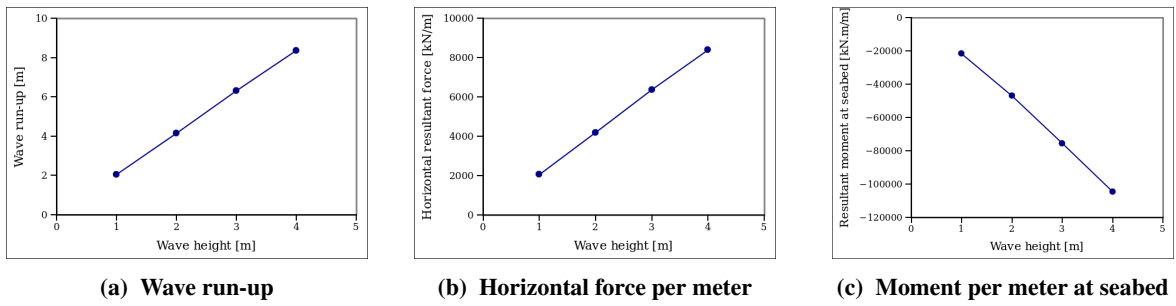
(a) **Wave run-up**   (b) **Horizontal force per meter**   (c) **Moment per meter at seabed**

Figure 11: Effect of tsunami height (TFB without a surge stopper): $d = 20m, f = 3.0m$ **and** $\mu = 0$

(a) **Wave run-up**   (b) **Horizontal force per meter**   (c) **Moment per meter at seabed**
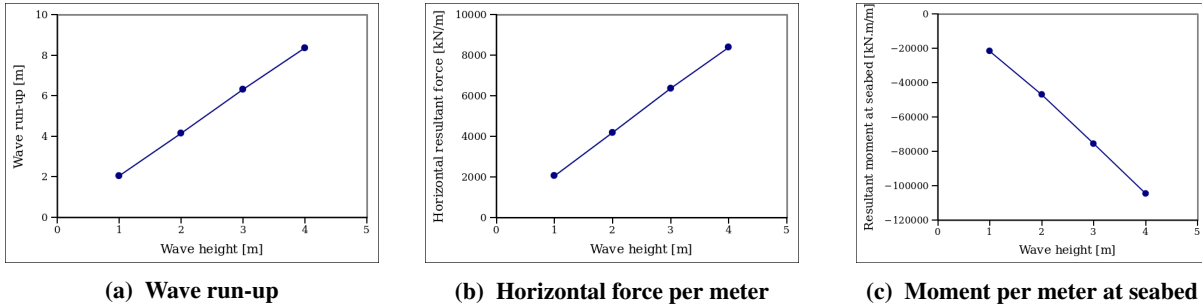
Figure 12: Effect of tsunami height (TFB with a surge stopper $B_{parapet} = 2m$ **&** $\alpha_{parapet} = 45°$**):** $d = 20m, f = 3.0m$ **and** $\mu = 0$

parapet, several freeboard options should be considered in the design process.

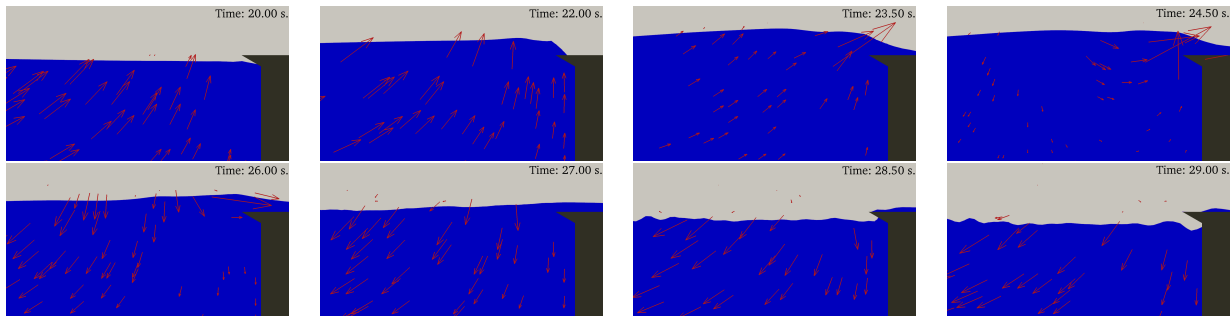**Figure 13: Effect of the surge stopper on the flow in front of the TFB structure:** $\alpha = 30°, B_{parapet} = 2m, d = 20m, H = 3m, f = 3m$

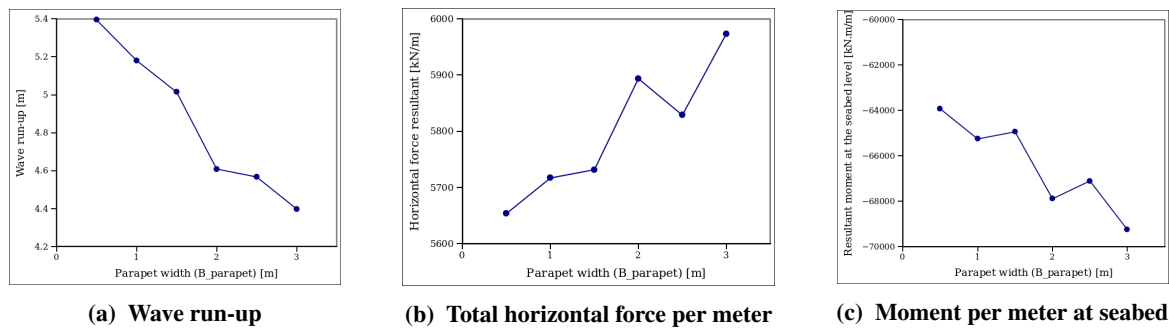(a) **Wave run-up**   (b) **Total horizontal force per meter**   (c) **Moment per meter at seabed**

Figure 14: Effect of the surge stopper width $B_{parapet}$ **(TFB with a surge stopper:** $\alpha = 45°$**):** $H = 3m, d = 20m$ **and** $f = 3m$

(a) Wave run-up

(b) Horizontal force per meter
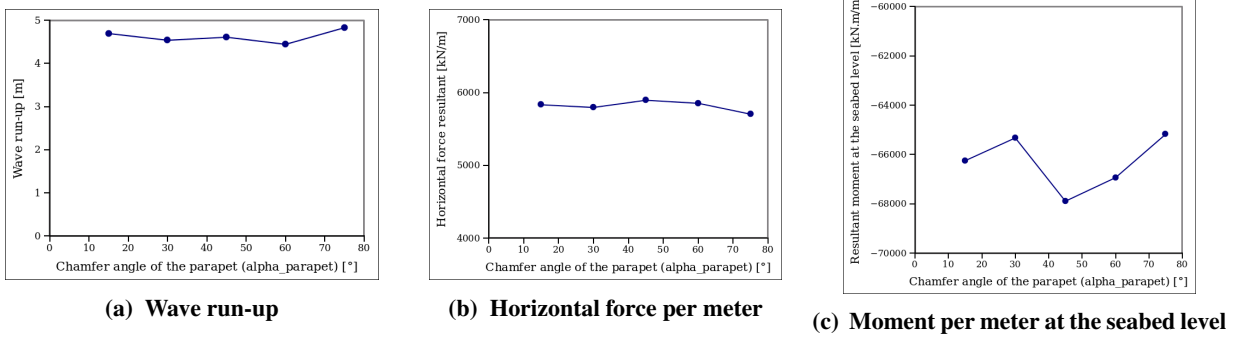
(c) Moment per meter at the seabed level

Figure 15: Effect of the surge stopper angle $\alpha_{parapet}$ **(TFB with a surge stopper:** $B_{parapet} = 2$**):** $H = 3m, d = 20m$ **and** $f = 3m$

From the results presented here (Figs. 14 and 15), it is obvious that increasing the parapet width ($B_{parapet}$) reduces the run-up while increasing the wave loads on the TFB structure. Changing the parapet angle ($\alpha_{parapet}$) has a less clear trend, but in the conducted study, an angle ($\alpha_{parapet}$) of 30° seems to provide reduced wave run-up (28.72%) and reduced wave loads of about 8.25% (horizontal and moment) on the TFB structure. These reductions in the total loads should not overshadow the fact that the surge stopper must be designed to withstand the loads on it as a structural element.

TSUNAMI-LIKE SOLITARY WAVE LOADS ON A TFB STRUCTURE

Total forces on the impermeable TFB for an example simulation are given in Fig. 16 for the X-direction resultant force and the corresponding moment about the Z-axis at the mid-point of the TFB structure base.
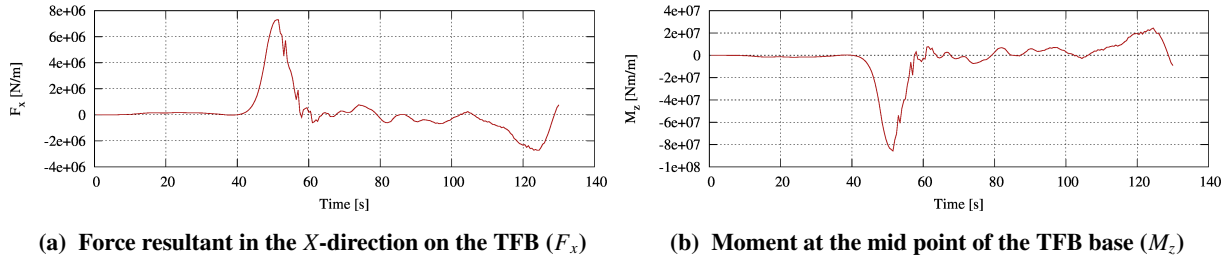

(a) Force resultant in the X-direction on the TFB (F_x)

(b) Moment at the mid point of the TFB base (M_z)

Figure 16: Forces on the impermeable TFB structure ($d = 20$m, $H = 4$m $f = 4$m).

The colour map of the pressure distribution on a TFB structure accompanied with the water free surface of a tsunami wave attacking the structure is illustrated for selected different time steps in Fig. 17. Further, Fig. 18 shows the pressure distribution profile on the TFB structure face for different time step for the exemplary case presented here.

From the results of the numerical simulations, the pressure distribution can be simplified in a relatively similar manner to that proposed in the study by Han et al. (2015). However, the value of parameters proposed by Han et al. (2015) seriously under estimates the pressure disribution because they deal with a vertical column rather than a wall. Fig. 19 illustrates a sketch of the proposed pressure distribution in the current study as opposed to the typically calculated profile from CFD simulations. From this figure, it can be seen that this study provides an approximation on the safe side for the pressure profile.

As shown in Fig. 19, the pressure distribution in this study is simplified as a uniform part under the water surface (for the whole water depth) with pressure intensity p and the pressure is reduced linearly until zero at the highest point attained by the water (maximum wave run-up η^*). The pressure distribution has a resemblance to the widely used Goda pressure distribution. However, the Goda distribution is developed for periodic waves rather than solitary waves. Therefore, different parametersâ™ values are expected. The simplified pressure distribution on a TFB structure can be calculated as described herein (consider Fig. 19). The maximum wave run-up (η^*) can be calculated as:
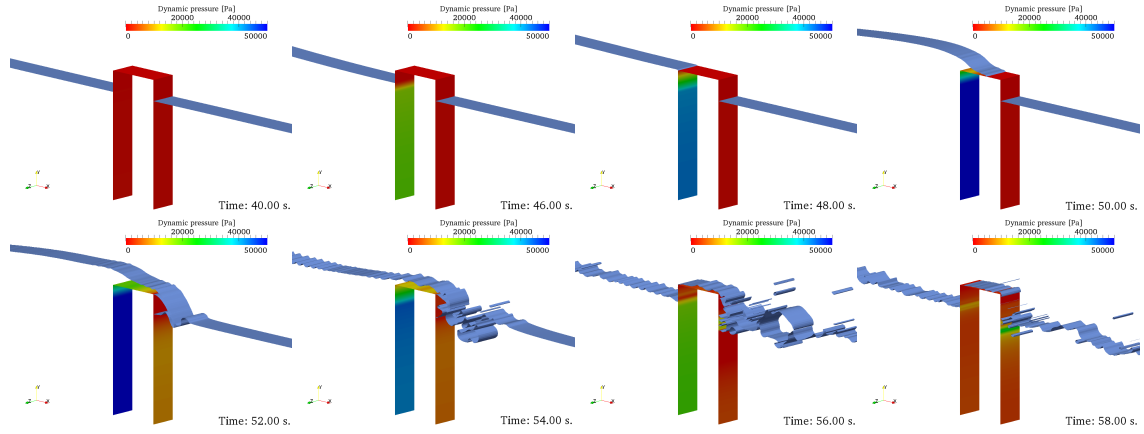
$$\eta^* = \beta H \tag{1}$$

Figure 17: Colour map of pressure distribution on the TFB structure caused by tsunami attack (from CFD simulation; $d = 20m$, $H = 4m$ and $f = 4m$)
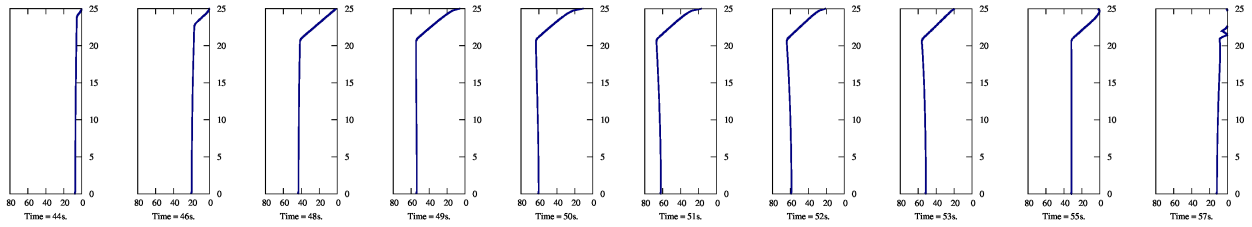

Figure 18: Plot of pressure distribution on impermeable TFB structure in a depth 20m and wave height 4m calculated by CFD (X-axis is pressure in kPa and Y-axis is water depth in m; for $d = 20m$, $H = 4m$ and $f = 4m$)
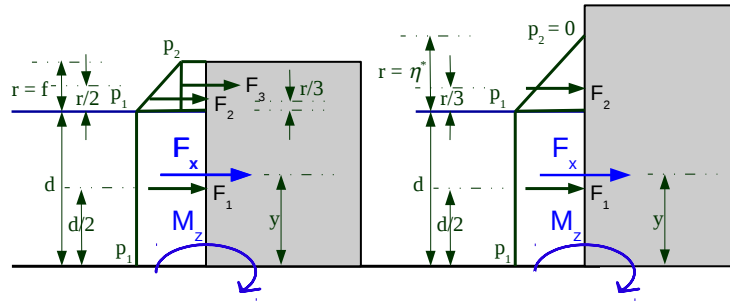

Figure 19: Definition of wave loads on the TFB structure (uniform until the still water level)

According to Goda, $\beta = 1.5$ for periodic waves advancing perpendicular to the structure, whereas from the results of this study the value of β can be calculated as a function of wave length L (from regression analysis):

$$\beta = 2.19 - 0.000682L \tag{2}$$

The dynamic pressure at the SWL (still water level), p_1, is calculated by the Goda method as:

$$p_1 = c_{Goda}\rho g H \tag{3}$$

where $\rho = 1025$ kg/m^3 is water density, $g = 9.81$m/s^2 is the gravitational acceleration, H is the wave height and c_{Goda} is a coefficient that is calculated from a given expression for the Goda formula and given as $c_{Goda} = 1.1$ by Han et al. (2015) for a vertical column with a square cross section. A new proposed expression for the dynamic pressure p_1 value is based on the wave celerity, which can be considered equal over the hole water depth according to the shallow water wave assumption as:

$$p_1 = \frac{1}{2}\alpha\rho C^2 \tag{4}$$

where α is a coefficient that corrects the pressure value according to the results from CFD simulations (e.g. to account for pressure reductions caused by wave run-up). According to the solitary wave theory, the wave celerity C can be calculated as (Dean and Dalrymple, 1991):

$$C = \sqrt{gd}\left(1 + 0.5\frac{H}{d}\right) \tag{5}$$

A simplified version for long waves (shallow water) according to the linear wave theory is $C = \sqrt{gd}$. For solitary waves, the theoritical wave length is infinity. Nevertheless an approximation can be considered to calculate the effective wave length (containing 95% of the wave volume, Dean and Dalrymple (1991)):

$$L = \frac{2.12d}{\sqrt{\frac{H}{d}}} \tag{6}$$

which implies that the wave length is also a function of the water depth and the wave height. From the regression analysis of the results from the parameter study carried out, the following expression for α can be used (from regression analysis):

$$\alpha = 3.516\left(\frac{H}{d}\right)^3 - 7.213\left(\frac{H}{d}\right)^2 + 4.4455\left(\frac{H}{d}\right) - 0.0209 \tag{7}$$

The pressure at the crest of TFB structure p_2 is calculated as:

$$p_2 = \begin{cases} 0 & \eta^* \le f \\ \frac{p_1(\eta^*-f)}{\eta^*} & \eta^* > f \end{cases} \tag{8}$$

where f is the freeboard. The horizontal global force resultant on the TFB structure (F_x) can be calculated as (Fig. 19):

$$F_x = F_1 + F_2 + F_3 = p_1 d + p_2 r + \frac{p_1 r}{2} \tag{9}$$

where $r = \min(f, \eta^*)$. The resultant moment at the seabed level around the Z axis (M_z) can be calculated as (Fig. 19):

$$M_z = F_1\frac{d}{2} + F_2(d + r/3) + F_3(d + r/2) = \frac{p_1 d^2}{2} + \frac{p_1 - p_2}{2}r(d + r/3) + p_2 r(d + r/2) \tag{10}$$

SWLStill Water Level

To enable the structural design of the elements of the TFB, forces on local elements can be calculated based on the height of the structure supported by this structural element ($h_{element}$) and the position of the element (e.g. above or below the SWL). For instance, considering a structural element below the SWL, the line forces on that element can be calculated as:

$$F_{element} = p_1 h_{element} \tag{11}$$

For a structural element positioned $y_{element}$ above the SWL (Fig. 20) and below the maximum wave run-up ($y_{element} < \eta^*$), the line forces on the the element can be approximated as:

$$F_{element} = p_{element} h_{element} \tag{12}$$

where:

$$p_{element} = p_1\frac{\eta^* - y_{element}}{\eta^*} \tag{13}$$

Because the wave forces act on the front face of the structure, only its height significantly affects the loads. This effect is accounted for by considering overtopping. The surface roughness of the wall face plays a minor role in
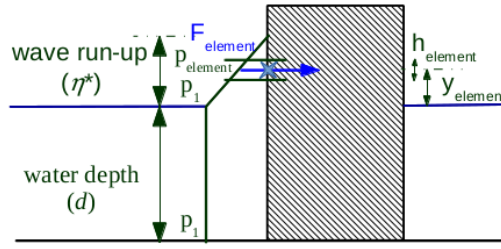
Figure 20: Pressure and line force per meter on a structural element positioned above the SWL

reducing the wave run-up and the reflected wave energy. Therefore, it is not significant enough to be considered in the simplified forces model.

A tutorial is given herein to calculate forces on a TFB structure using the developed simplified method Consider the following case:

Design tsunami height	6m
Water depth	30m

First, calculate the wave length (L) and celerity (C) at the construction water depth (d) as follows:

$$L = \frac{2.12d}{\sqrt{\frac{H}{d}}} = \frac{2.12 \times 30}{\sqrt{\frac{6.0}{30}}} = 142.214m \tag{14}$$

$$C = \sqrt{gd}\left(1 + 0.5\frac{H}{d}\right) = \sqrt{9.81 \times 30}\left(1 + 0.5\frac{6.0}{30}\right) = 18.871m/s \tag{15}$$

To caculate the maximum wave run-up on the wall η^*, the parameter β needs to be calculated as:

$$\beta = 2.19 - 0.000682L = 2.19 - 0.000682 \times 142.214 = 2.088 \tag{16}$$

The maximum wave run-up on the wall η^* is then:

$$\eta^* = \beta H = 2.088 \times 6.0 = 12.532m \tag{17}$$

This means the TFB minimum freeboard should be considered as 5.4m to prevent any overtopping. To calculate the pressure p_1 on the TFB wall, calculate the parameter α first, as follows:

$$\alpha = 3.516\left(\frac{H}{d}\right)^3 - 7.213\left(\frac{H}{d}\right)^2 + 4.4455\left(\frac{H}{d}\right) - 0.0209$$
$$= 3.516\left(\frac{6}{30}\right)^3 - 7.213\left(\frac{6}{30}\right)^2 + 4.4455\left(\frac{6}{30}\right) - 0.0209 = 0.608 \tag{18}$$

Then p_1 is calculated as:

$$p_1 = \frac{1}{2}\alpha\rho C^2$$
$$= \frac{1}{2} \times 0.608 \times 1025 \times 18.871^2 = 110925.965Pa = 110.926kN/m^2 = 11.093t/m^2 \tag{19}$$

The pressure distribution on the TFB structure, horizontal force and moment per meter are shown in Fig. 21. The horizontal force per meter on the TFB structure (F_x) can be calculated as (where $r = \eta^*$ and $p_2 = 0$, no overtopping):

$$F_x = F_1 + F_2 = p_1d + \frac{p_1 r}{2}$$
$$= 110925.965 \times 30 + \frac{110925.965 \times 12.532}{2} = 4022831.291N/m = 4022.831kN/m = 402.283t/m \tag{20}$$

And the moment per meter at the seabed level:

$$M_z = F_1\frac{d}{2} + F_2(d + r/3) = \frac{p_1 d^2}{2} + \frac{p_1 - p_2}{2}r(d + r/3) = \frac{110925.965 \times 30^2}{2} + \frac{110925.965}{2} \times 12.532 \times (30 + 12.532/3)$$

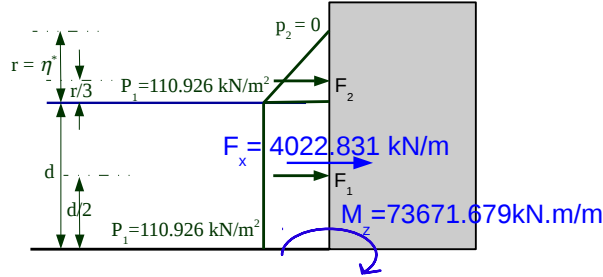$$= 73671679.3N.m/m = 73671.679kN.m/m = 7367.168t.m/m$$

$$(21)$$

Figure 21: Pressure distribution and forces on the TFB structrue subject to a tsunami-like solitary wave of $H = 6.0m$ **at water depth** $d = 30m$

To calculate the local force on a structural element located at 8m height from the seabed and loaded by a 1.5m height:

$$F_{element} = p_1 h_{element} = 110925.96 \times 1.5 = 166388.95N/m = 166.389kN/m = 16.639t/m \qquad (22)$$

The Goda method, was developed for periodic waves induced by storms and is the most widely used method for calculating non-impact wave loads on vertical impermeable breakwaters with a rubble foundation. Here the developed formulae is compared with the Goda method to illustrate why the latter cannot be applied for tsunami-like solitary waves.

According to Goda method, the maximum wave run-up $\eta^* = 1.5H = 1.5 \times 6.0 = 9m$ as compared to $\eta^* = 12.532m$ calculated in the example application earlier. The force on the TFB using the Goda method can be calculated for $h/L = 0.21$ and $H/L = 0.0422$ as $F_h = 1122.166$ kN/m.
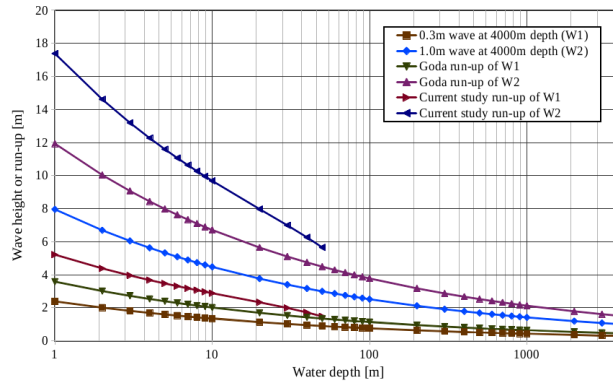

Figure 22: Incident wave height (no TFB) and run-up (in front of a TFB) calculated by the Goda method and the method proposed in this study, against water depth, for two tsunami examples of wave height 0.3m and 1m, respectively, at water depth of 4000m

The comparison between the proposed method and the widely used Goda method (for vertical breakwaters on a rubble foundation), indicates that the use of the conventional Goda method will result in a severe underestimation of forces and wave run-up on the TFB structure (for this example 30% for run-up and 358% for force), see Table 2.

Similar to Figure 2 from Scheel (2014), Fig. 22 illustrates the propagation of a tsunami wave against the water depth for the case without a TFB structure, compared to the run-up calculated in front of the structure in case a TFB structure is to be placed at any given depth using the Goda method and the method developed in this study. In Fig. 22 two tsunamis are considered: 0.3m and 1m wave height at a 4000m water depth, respectively.

Table 2: Comparison between the developed simplified method for tsunami loads on TFB structures and Goda's method

method	Goda	TsuBar
Wave run-up [m]	9.00	12.532
Horizontal force [kN/m]	1122.166	4022.831

SUMMARY AND OUTLOOK

From this study, the following can be concluded:

- The impermeable TFB structure is very effective in preventing all or most of the tsunami energy from reaching the shore

- The wave run-up on the wall may reach more than twice the incident wave height (a formula was developed for approximate prediction). This means that for a tsunami wave height H expected at depth d, the water surface at the wall reaches an elevation η^* above the still water level (SWL), which can be calculated according to the proposed formulae Eqs. 1 and 2.

- The pressure distribution on the wall can be considered as uniform under still water level and for non-overtopping condition as triangular above the still water level to the highest point of the water surface (η^*), see given example application and the developed simplified method

- The pressure intensity can be calculated as $p = \frac{1}{2}\alpha\rho g C^2$. α can be calculated according to the developed expression through this study

- The front face roughness of the TFB wall reduces the wave run-up and reflection but not significantly. The wall front roughness can be ignored in preliminary analysis and design

- Overtopping the structure results in a transmitted wave that can loose energy as it propagate towards the shore

- Considering a deflecting parapet (surge stopper) can increase the efficiency of the TFB structure and reduce/eliminate wave overtopping. However, for design of TFB structures, a study should be carried out to determine the free-board that results in maximum efficiency of the parapet

Future work should include a CFD-CSD study of the TFB structure to study its structural stability.

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