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BENDING VIBRATIONS OF THE AFSLUITDIJK GATES SUBJECTED TO WAVE IMPACTS: A COMPARISON OF TWO DESIGN METHODS

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ABSTRACT

This paper describes a first case study of the application of a newly developed fluid-structure interaction model to the design of flood gates. The gates in the Afsluitdijk, that will be replaced in the coming years, are considered. Due to the presence of a concrete beam in front of the gates breaking wave can occur, leading to high impact pressures acting on the gate. For this case both a quasi-static approach and a more detailed semi-analytical model representing the dynamic behaviour including fluid-structure interaction are applied to determine the maximum deflection of the gate. Results show the capability of the model to efficiently quantify flood gate vibrations while considering the involved fluid-structure interaction. For the Afsluitdijk case this leads to a slightly lower maximum deflection of the gate, and therefore potentially allows a more economical design.

INTRODUCTION

A vast amount of flood defence structures contribute to the safety and water regulation in coastal areas. Gates form essential parts of these systems as they regulate the discharge between bodies of water. During storm conditions these structures are often subjected to high water levels and waves. When breaking waves impact on a gate, this generally involves high peak pressures of short duration in the order of a few milliseconds (Bagnold, 1939; Hofland et al., 2011; Ramkema, 1978). Such impulsive loads lead to vibrations of the structure, potentially amplifying internal stresses compared to the static situation.

From 2018 to 2022 the Afsluitdijk in the Netherlands is being renovated, including the replacement of 25 steel flood gates in two discharge sluice complexes. Due to the presence of the overhanging monumental concrete defence beam as shown in Figure 1, inpacting waves were expected to result in high impact pressures. This was confirmed in physical scale experiments performed in the Deltares Scheldegoot (Hofland, 2015), where peak pressures were measured corresponding to 32 times the significant wave height related pressure, $\rho g H_{m0}$. The gate strength required to withstand these pressures lead to a gate design with high weight, having consequences for the lifting mechanism and towers as well. The decision was therefore made to remove the monumental defence beam.

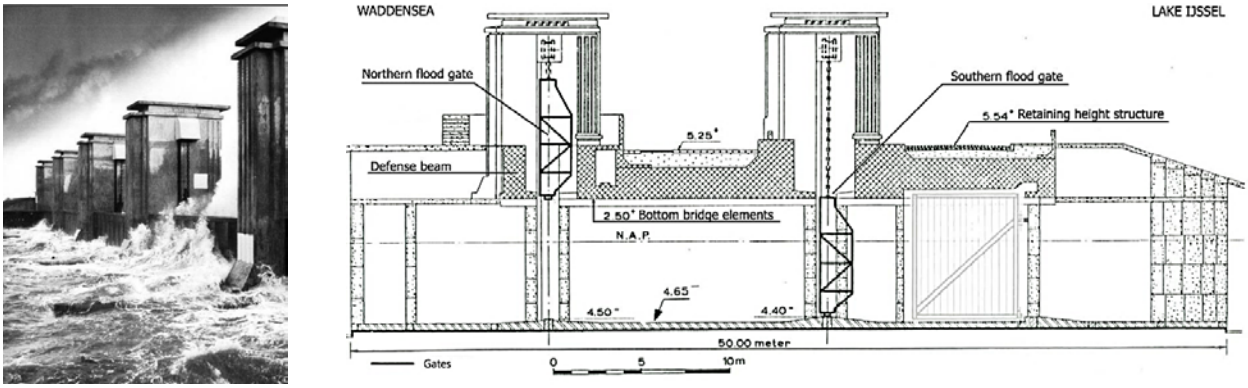

Figure 1: Wave impacts on the defence beam (left) (Thijsse, 1972) *and a cross-section of one discharge sluice at Den Oever (right)* (Tieleman, 2016)

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Due to the two-way interaction between the structure and fluid, detailed prediction of these dynamic interactions can become very complex. Advanced numerical methods exist, but are still computationally expensive for three-dimensional problems (Erdbrink, 2014). For this reason in common engineering practice a quasi-static approach is often used in which an amplification factor is applied to the time-varying load to account for dynamic behaviour of the gate (Kolkman & Jongeling, 2007a, 2007b, 2007c). Such an approach however lacks behind in accuracy and resolution compared to design standards in other fields, and gives little insight in the actual behaviour of the structure. For this reason, a semi-analytical model using fundamental theory of dynamics of continuous systems was developed (Tieleman, 2016)In the present study, a comparison is made between outcome of the common design method and the semi-analytical model for the case of the Afsluitdijk flood gates. It is shown that explicitly predicting the dynamic behaviour of gates including the fluid-structure interaction may lead to different outcomes and more economic designs.

CASE DESCRIPTION

After the renovation of the Afsluitdijk the seaside gates in the discharge sluices will retain the water during storm conditions; the other gates are for water regulations during daily conditions. The gates are required to withstand the net hydrostatic force due to the water level difference and the wave impact force corresponding to 1/10,000 year return frequency hydraulic boundary conditions. In the present study the latter is considered.

A gate design was made by an engineering firm as shown in Figure 2. The design wave impact pressures have been determined in scale experiments and are considered to be acting simultaneously over the full width of the gate. The spacing between the horizontal girders is reduced towards the top of the gate to increase its resistance at the location where the wave impact leads to the highest pressures.

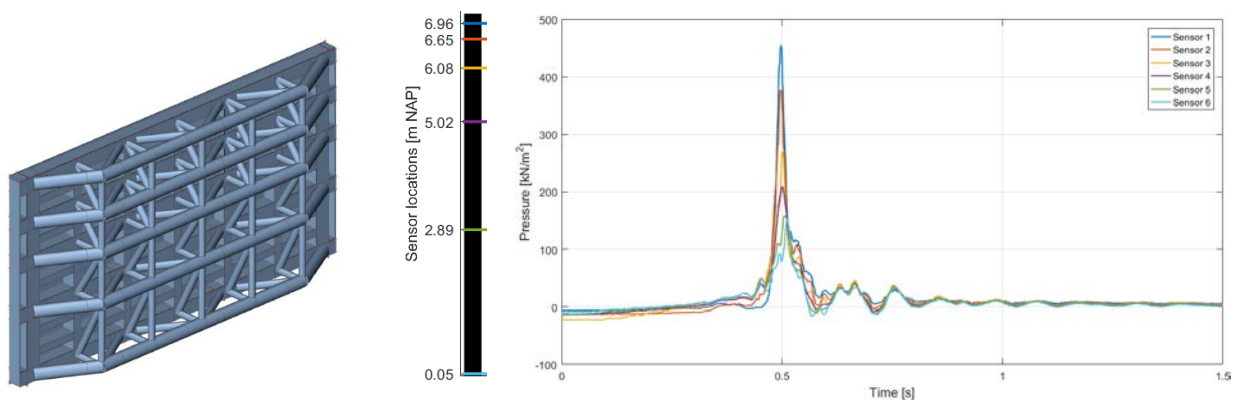

Figure 2: Conceptual flood gate design for the Afsluitdijk (Witteveen+Bos, 2016) *(left), and the governing wave impact pressure as measured in scale experiments at 6 locations with z = 0 at the bottom of the gate (right). Data:* (Hofland, 2015). *In this study the gate is represented by a thin plate.*

In the present study, the gate is represented by a thin plate with equal total mass. The stiffness is chosen such that the fundamental dry frequency of the thin plate is equal to that of the realistic gate design. The thin plate is expected to be a reasonable approximation when considering the deflection of the gate. However, it does not give correct insight in the occurring stresses in the realistic gate design. In contrast to the real gate design, the mass and stiffness are equally distributed over the uniform plate. The gate is simply supported at both vertical sides and is stress-free at its top and bottom. The sluice is assumed infinitely long, which simplifies the derivation of the hydrodynamic response to gate vibrations. The gate is slightly wider than the sluice due to sockets at this location. An overview of the model geometry is shown in Figure 3. All case parameters and their values are summarised in Table 1.

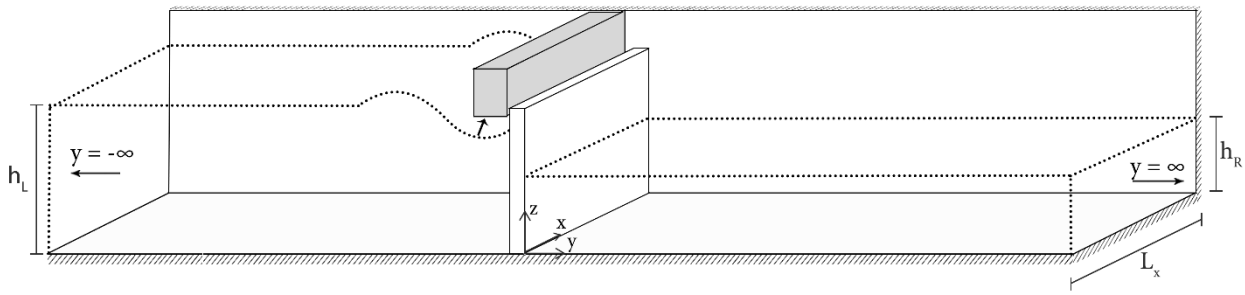

Figure 3: Three dimensional overview of the model geometry

Table 1: Case parameters

Structural parameters	Symbol	Value	Unit	Fluid parameters	Symbol	Value	Unit
Gate width	L_x	12.5	m	Sluice width	L_x	12	m
Gate height	L_z	7.25	m	Water level sea	h_L	7.25	m
Plate thickness	t	0.64	m				
Bending stiffness	D	$4.36 \cdot 10^9$	Nm^2	Water level lake	h_R	3.35	m
Distributed mass	ρ_s	929	kg/m^2	Fluid density	ρ_f	1025	kg/m^3
Modulus of elasticity	E	$2 \cdot 10^{11}$	Nm^2	Fluid sound velocity	c	1500	m/s
Moment of inertia	I	$2.17 \cdot 10^{-2}$	m^4	Gravitational constant	g	9.81	m/s^2
Poisson's ratio	v	0.3	-				
Yield strength (steel)	f_y	$355 \cdot 10^6$	N/m^2				

MODEL APPROACH

The motion of the plate is solved analytically in the frequency domain by a so called modal analysis, including the effect of the surrounding fluid. The motion of the homogeneous and isotropic thin plate is described by the following equation:

$$\rho_s w_{tt} + D[w_{xxxx} + 2w_{xxzz} + w_{zzzz}] = -f_L + f_R + f_e \tag{1}$$

in which w denotes the displacement of the mid-surface of the plate, f_e the time signal of the external force on the plate, and f_L and f_R define the fluid pressures at either sides acting on the surface of the gate. The external force is in this case the measured wave impact pressure signal. As the plate is considered thin, shear deformation is neglected in equation (1). The boundary conditions of the plate are as follows:

$$w(0,z) = M_x(0,z) = w(L_x,z) = M_x(L_x,z) = 0 \tag{2}$$

$$V_z(x,0) = M_z(x,0) = V_z(x,L_z) = M_z(x,L_z) = 0 \tag{3}$$

in which M_x and M_z are the bending moments in x- and z-direction respectively, and V_z is the net shear force in z-direction.

The fluid is described as a compressible potential flow with a boundary condition that accounts for the generation of surface waves. At the moment, the effect of the defence beam on the responsive fluid pressures is excluded, i.e. the free boundary condition of the fluid is not altered at this location. The equation of motion and boundary conditions for the fluid domain at the right side of the gate are:

$$\nabla^2\phi - \frac{1}{c_p^2}\phi_{tt} = 0 \tag{4}$$

$$\phi_{tt}(x,y,h_R,t) + g\phi_z(x,y,h_R,t) = 0 \tag{5}$$

$$\phi_x(0,y,z,t) = \phi_x(L_x,y,z,t) = \phi_z(x,y,0,t) = 0 \tag{6}$$

$$\phi_y(x,0,z,t) = w_t(x,y,t) \tag{7}$$

in which ∇ is the Nabla operator, ϕ is the fluid potential, and c_p is the sound velocity in water. Further, the radiation condition at $y = \infty$ should be satisfied at all times. The boundary conditions for the left side of the gate are similar with $y = -y$.

An analytical solution to this system can be derived by describing both the structure and fluid as a summation of their modal shapes (W_{km}, Φ_{pr}) multiplied by yet unknown modal constants (A_{km}, B_{pr}):

$$w = \sum_{k=1}^{\infty}\sum_{m=1}^{\infty} A_{km} W_{km} \tag{8}$$

$$\phi = \sum_{p=1}^{\infty}\sum_{r=1}^{\infty} B_{pr} \Phi_{pr} \tag{9}$$

in which k and m denote the modal shapes of the structure in x- and z-direction, and p and r those of the fluid. The modal shapes and corresponding natural frequencies can be found either analytically or numerically. Subsequently, the following semi-analytical solution can be obtained by describing the motion of the entire fluid-structure system fully in terms of the modal coefficients of the structure:

$$\sum_{k=1}^{\infty}\sum_{m=1}^{\infty} \left[\rho_s(\omega_{km}^2 - \omega^2)\delta_{kl}\delta_{mn}\Gamma_{ln} + L_{km,ln} + R_{km,ln}\right] A_{ln} = F_{ln} \tag{10}$$

in which ω_{km} are the natural frequencies of the plate modes, δ_{kl} and δ_{mn} are Kronecker deltas, Γ_{ln} is the result of the surface integration $\iint_S W_{km}\, W_{ln}\, dx\, dz$, $L_{km,\mathrm{ln}}$ and $R_{km,\mathrm{ln}}$ are the the fluid impedances at both sides of the gate, S is the surface area of the plate or fluid in the x,z-plane, the modal force $F_{ln} = \iint_S \hat{f}_e\, W_{ln}\, dx\, dz$, and $\hat{f}_e$ is the representation of the wave impact force in the frequency domain. For an extensive derivation and description of the fluid impedances is referred to (Tieleman et al., 2018; Tsouvalas & Metrikine, 2013).

To solve the system of equations, the summation should be truncated to a finite number of structural and fluid modal shapes. The obtained frequency domain solution can be transferred to the time-domain by an inverse Fourier transform.

QUASI-STATIC ANALYSIS

The existing design analysis for the flood gates is based on a quasi-static approach by means of a finite element model. This analysis includes several assumptions that cannot be translated when regarding the dynamic response of the gate to the measured full time signal of the occurring wave pressures. Secondly, the uniform thin plate will change the static behaviour compared to the actual gate design. In this section, a similar quasi-static design approach is therefore applied by means of the analytical plate model to allow for a good comparison with the results of the dynamic analysis in the following section. Regular load and safety factors are excluded for clarity. Only the deflection of the gate is considered for the comparison, internal stresses are not quantified, but can be obtained from the model.

Amplification of the deflection due the dynamic response of the gate was considered based on the theory of (Kolkman & Jongeling, 2007b) for impulsive loads and single degree of freedom systems. The duration of the impulsive part of the vertically integrated pressure signal was estimated to be τ = 30 ms. This value is based on a scale model, so could be prone to scale effects. The fundamental period of the gate in dry condition is approximately T = 45 ms. The ratio τ/T is in this case close to the point where according to Figure 4 maximum amplification of $1{,}85 * \pi/4 = 1{,}45$ occurs. This factor was therefore applied to the maximum wave force to obtain the design load, and will be included in the present analysis as well.

It must be noted however that the theory of (Kolkman & Jongeling, 2007b) allows one to consider the hydrodynamic mass when estimating the resonance frequency of the gate. The hydrodynamic mass increases the resonance period of the gate, leading to a different amplification factor.

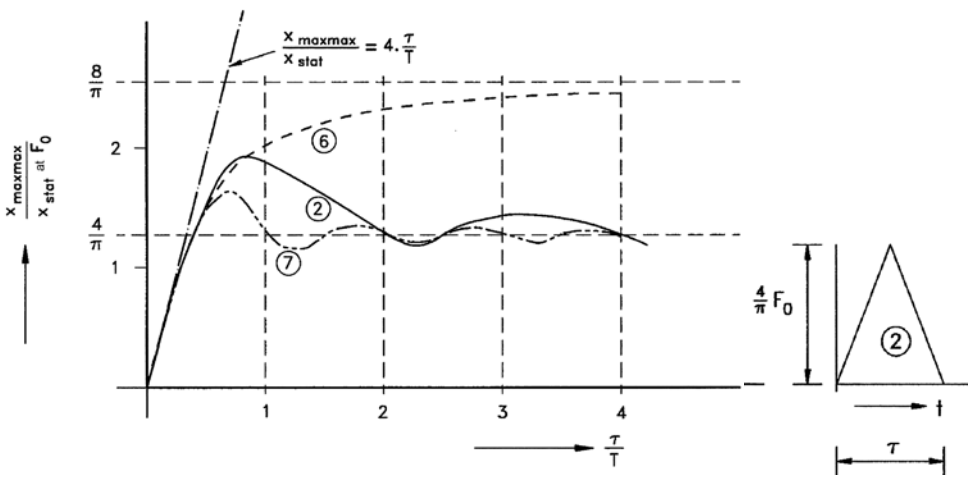

Figure 4: Amplification of a single degree of freedom structure to a triangular-shaped impact force signal (Kolkman & Jongeling, 2007b)

The applied wave pressure force including amplification factor and the determined static response of the gate to this force are shown in Figure 5. The deflection is found with equation (10), excluding the fluid impedance which is zero in the static situation. The maximum static deflection of 21.8 mm is found at the top middle of the gate. The maximum stress in the plate occurs at the same location and equals 84.8 N/mm^2. The static response of the gate to the hydrostatic force (difference) is an order of magnitude smaller, and not considered further. The modal decomposition and the static response predicted by the analytical model have been validated by FE software.

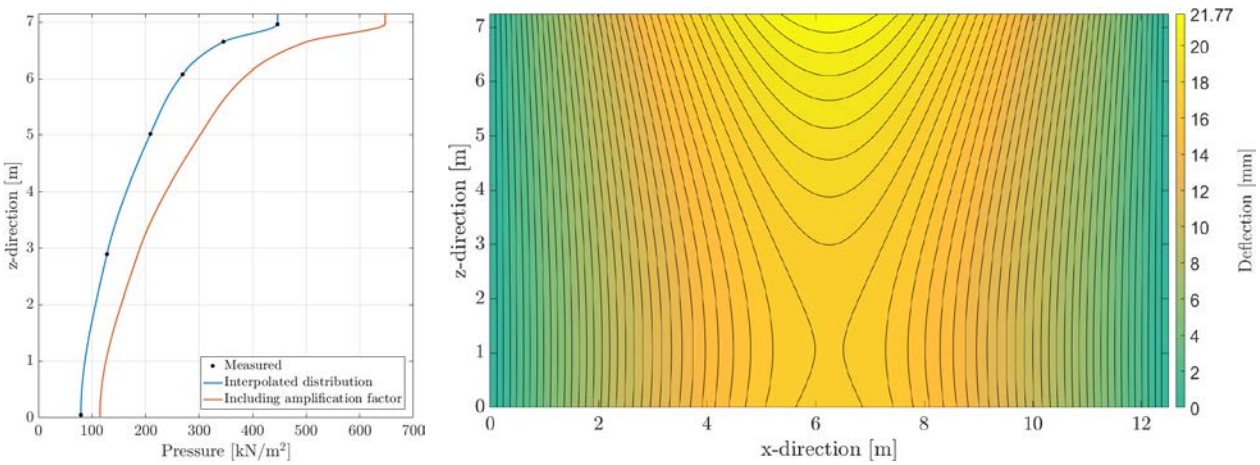

Figure 5: Maximum measured wave pressures with and without amplification factor (left) and the static response of the gate to the wave force including amplification factor (right)

DYNAMIC ANALYSIS INCLUDING FLUID-STRUCTURE INTERACTION

In the following analysis the dynamic behaviour of the plate is solved by means of the analytical solution in eq. (10), which implicitly takes into account the effect of the hydrodynamic pressures resulting from the motion of the gate. The full time-domain wave pressure signal is applied, which varies over the vertical of the gate, and is assumed constant over the width. For the present analysis the summation of 25 structural modal shapes is considered. The first four modal shapes are shown in Figure 6.

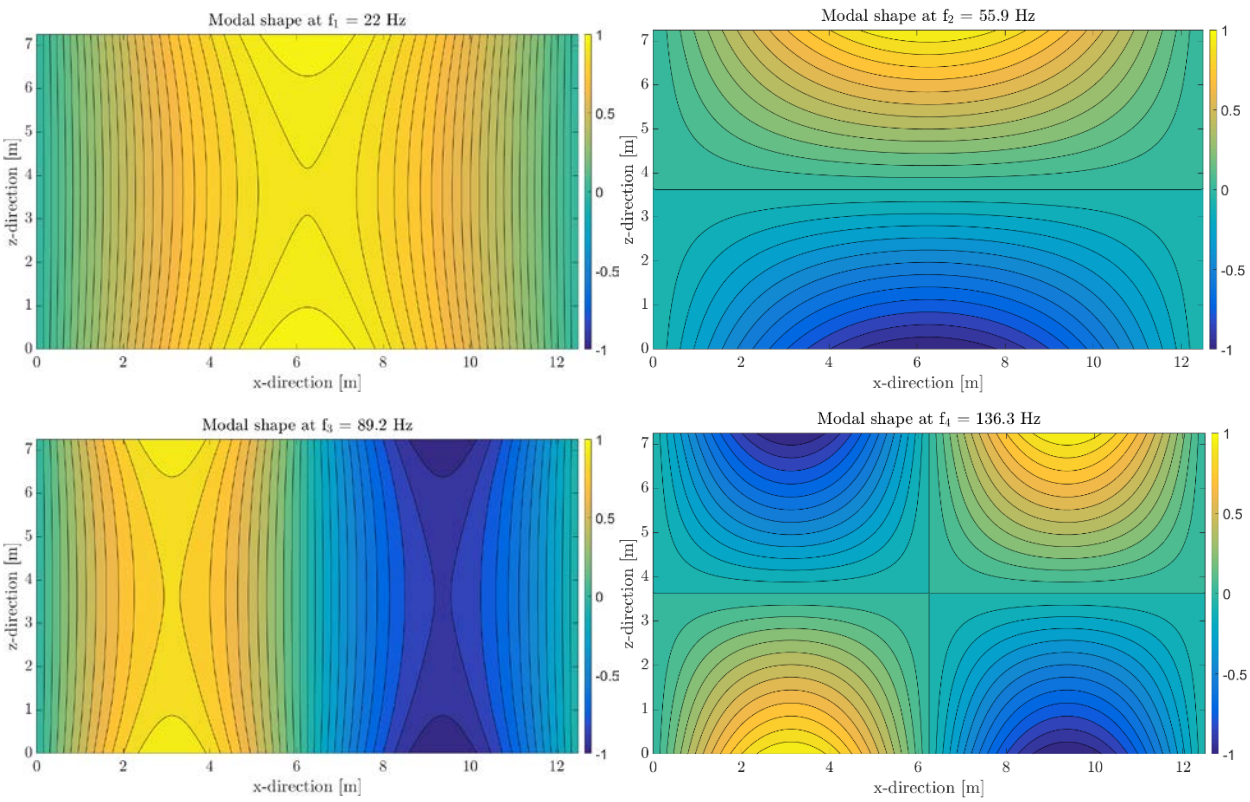

Figure 6: First four natural frequencies of the plate in dry condition

Due to the hydrodynamic pressures the resonance shapes and frequencies of the gate-fluid system are different from those of the gate in dry condition. The hydrodynamic mass significantly reduces the resonance frequencies, as shown in Table 2. Since the wave pressure acts simultaneously over the entire width of the gate in this case, the antisymmetric modes in this direction are not excited.

Table 2: Resonance frequencies of the gate in vacuo and in submerged condition

Condition	f_1	f_2	f_3	f_4	f_5	f_6
In vacuo [Hz]	22	55.9	89.2	136.3	189.8	201.9
Submerged [Hz]	10	32	44.2	83.1	108.2	116.2

To obtain a stable time signal after application of the inverse Fourier transform, a small amount of material damping is introduced in the model by applying a complex bending stiffness $E = (1 + \eta i)\, E$ with damping coefficient $\eta = 0.01$. In Figure 7 the deflection of the mid bottom and mid top of the gate are shown in time. The maximum deflection now occurs at the bottom of the gate, contrary to what was found with the quasi-static approach. Decreasing the strength of the gate towards the bottom as was done in the gate design of Figure 2 might therefore not be beneficial. The maximum deflection equals 19.9 mm and the maximum stress at this location is 79.4 N/mm^2. The relatively difference between stress found in the quasi-static and dynamic analysis is slightly less than for the deflection, as higher modal shapes result in larger stresses for the same deflection.

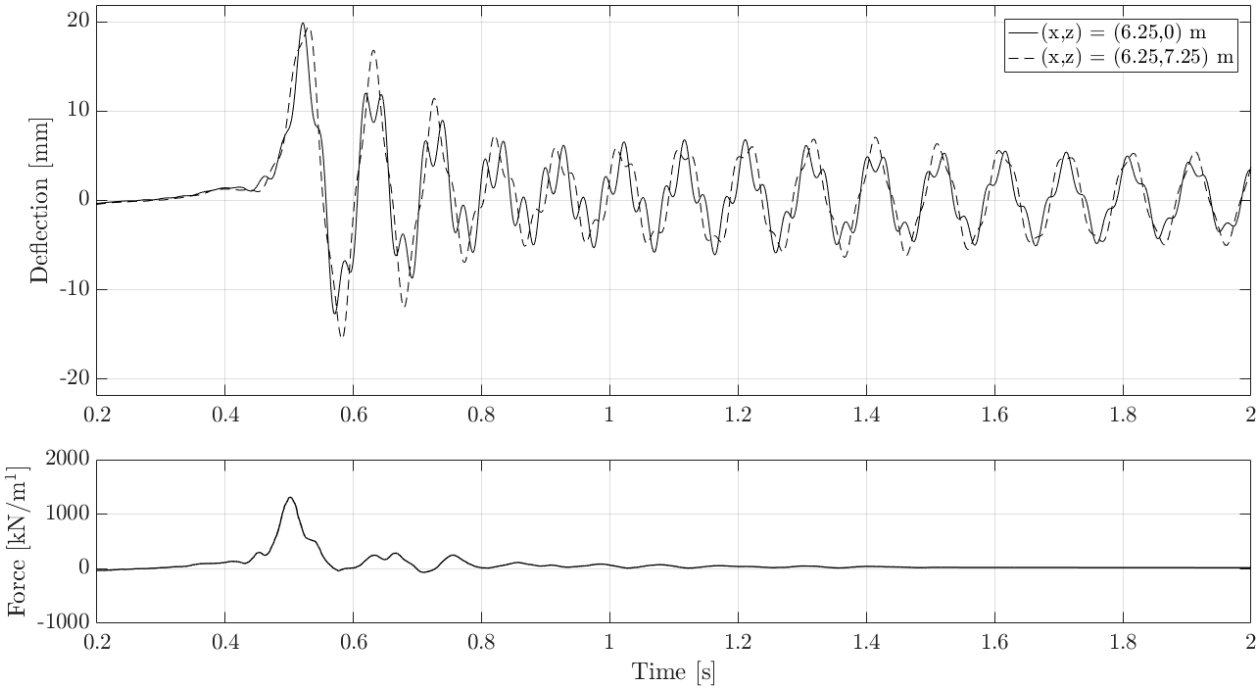

Figure 7: Deflection of the middle top and bottom of the gate as a result of the wave impact

The maximum deflection obtained at the top of the gate is 19.47 mm, which is about 11% lower than what was found in the quasi-static analysis. The second modal shape of the plate is amplified the most, while the first modal shape does not amplify as much as the quasi-static approach assumes. Due to the domination of the first mode in this case, the net effect is relatively small compared to the quasi-static approach. This is however not given for other designs or wave signals.

Table 3: Deflection at the top of the gate in mm as found by both methods compared to the static deflection without amplification

Structural mode	Deflection (static)	Amplification (quasi-static)	Deflection (quasi-static)	Amplification (dynamic)	Deflection (dynamic)
1	13.45	1.45	19.50	1.29	17.30
2	1.60	1.45	2.32	1.39	2.22
3 to 25	-0.04	1.45	-0.06	1.25	-0.05
Total	15.01	1.45	21.76	1.30	19.47

DISCUSSION

The semi-analytic model describes the dynamic behaviour of the gate-fluid system including the involved fluid-structure interaction. Further validation of the model is still required. Small scale model tests are planned to obtain this validation.

The effect of the defence beam on the hydrodynamic response to the motion of the gate was neglected in the analysis. This simplification is expected to significantly change the fluid pressure distribution. For a more accurate analysis the boundary conditions imposed by the defence beam should therefore be included when determining the modal shapes of the fluid. This can be accomplished by including a separate fluid domain with closed boundary condition at the top of which the modal decomposition is matched to the domain seaward of it. Additionally, when determining the fluid modal shapes the water level is considered to be constant. In reality, over a certain distance the free surface is altered due to the incoming breaking wave.

The comparison between the two design approaches was based on the representation of the gate by a thin plate. Although this may give a good indication of the relative difference between the two design methods, this does not accurately represent the deflection and internal stresses of a more realistic gate design. With the presented semi-analytical model it is possible to apply modal shapes of the gate found by FE software.

In this way, it is possible to utilise the precision of the FE model to determine the gate deflection and internal stresses while including the fluid-structure interaction in a computationally efficient manner.

In reality a storm consists of thousands of waves, and the impact with the highest impact does not necessarily give the largest response. Hence, in a real case, more or all impacts need to be considered. As the duration of impacts is prone to scale effects (the total impulse is expected to be scaled well), some variation in the duration of the impacts is to be taken into account as well.

CONCLUSIONS

The semi-analytic model represents the dynamic behaviour of the gate more precisely than the common quasi-static approach on several aspects. First of all, the interaction with the surrounding fluid is taken into account. As expected, the hydrodynamic mass is shown to have a substantial effect on the natural frequency of the designed gate, leading to a different response and in case of the Afsluitdijk a lower amplification of the first modal shape of the gate. The method allows to determine the effect of the temporal and spatial distribution of the measured wave impact signal on the gate's response. Finally, multiple gate vibration modes were included in the analysis. For the Afsluitdijk case, the second modal shape of the gate was significantly excited as well. The net result was a slightly lower deflection and internal stress.

Compared to application of the maximum dynamic amplification factor to the entire measured wave force signal, it is expected that more detailed inquiry into the dynamic behaviour of the gate will generally result in better gate designs.

ACKNOWLEDGMENT

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