SPECTRAL ANALYSIS OF WAVE FORCES FOR THE DESIGN OF ROLLING GATES OF THE LOCK OF AMSTERDAM

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1. INTRODUCTION

In the Dutch city of IJmuiden, a new ship lock is currently under construction. With a lock chamber of 500 m long and 70 m wide, it will be the largest lock in the world. The latest generation of seagoing vessels will be able to access the harbour of Amsterdam using this lock. The lock closes with rolling gates constructed in steel. The attenuator mechanism (equipment to close or open the gate) of the lock gates needs to generate a driving force to overcome external and internal hydraulic forces. Wave forces acting on the gate have a major contribution to the total forces on the gate. The lock of IJmuiden will be available for navigation up to the hydraulic conditions corresponding a 10-year return period storm. When the wave field exceeds the 10-year return period (H_{m0}=1,5m, T_{m-10}=4s), the lock will be closed for navigation. For the 10-year period storm, a maximum period of the gate mission (opening or closing the gate) has been set.

Figure 1: Artist impression of the lock (ZUS, 2016)

Waves push the gate onto its supports. To open or close the gate, the attenuator mechanism should overcome the friction forces in the supports generated by waves, the longitudinal wave forces generated by the waves, and ‘other loads’ like density differences, translatory waves, etc. (Voortman, et al., 2017). The attenuators must have sufficient driving force to reduce the probability and the period of delay of the gate mission. Choosing an attenuator with too little driving force would result in unacceptable delay for navigation. Choosing an attenuator with a very large driving force would be unnecessary expensive.

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Normally the wave force is calculated using either the formula of Goda (Goda, 2010), or the linear wave theory for a single wave height and wave period. However, the wave spectrum loading the gate consists of two peaks:

- Long waves (swell; <0,14 Hz
- Wind waves (>0,14 Hz)

Due to the large depth of the lock of 20 meters, long waves penetrate down to the toe of the gate, generating a large force at the gate. This force cannot accurately be calculated using general wave theories:

- When using a formula based on only one wave height and one wave period, the force during gate mission is constant. To calculate the duration of delay of a gate mission a wave force time series must be generated.
- The wave spectrum is required for deriving the force spectrum and elaborating the probability density function of the wave force and to express the probability of delay.
- The method of Goda appears to overestimate the total wave force due to the linear schematization of the wave pressure between still water level and the toe of the gate. The calculated force will result in a very large required attenuator capacity, resulting in high costs.
- Linear wave theory only using the significant wave height and wave period gives an underestimation of the wave force. This results in insufficient driving force of the attenuators and too much delay.

To include the effect of long waves, and to be able to calculate the wave force time series and gate mission delay, a spectral design approach based on the linear wave theory is applied (Holthuijsen, 2007). A response function is derived for the full gate mission (opening or closing of the gate) and for the full range of occurring wave frequencies (0Hz up to 1Hz) to calculate the wave force in each gate support. During gate mission the gate acts as a cantilever beam, this results in a combined absolute reaction force in the supports larger than the total incoming wave force. To calculate the total friction force during gate mission, the reaction force is multiplied with a friction coefficient. The cantilever effect is included in the final response function as the total friction force. The total friction force, delay and probability of exceedance of the delay duration is derived by the following steps:

1. Application of the linear wave theory for the lock gate
2. The conversion of the wave spectrum to wave force spectrum describing the transverse wave loads. (Figure 2; force number 1).
3. The conversion of the wave spectrum to a wave force spectrum describing the longitudinal wave loads. (Figure 2; force number 2)
4. The conversion of the transverse wave force spectrum in a longitudinal friction force spectrum. (Figure 2; force number 3)
5. The transformation of the total wave force spectrum to required driving forces and delays.

Remark: The results of the analysis are visualised in graphs. Because of the confidential status of the design of the lock gate, the axis representing variance densities, wave forces, and delays are not numbered.

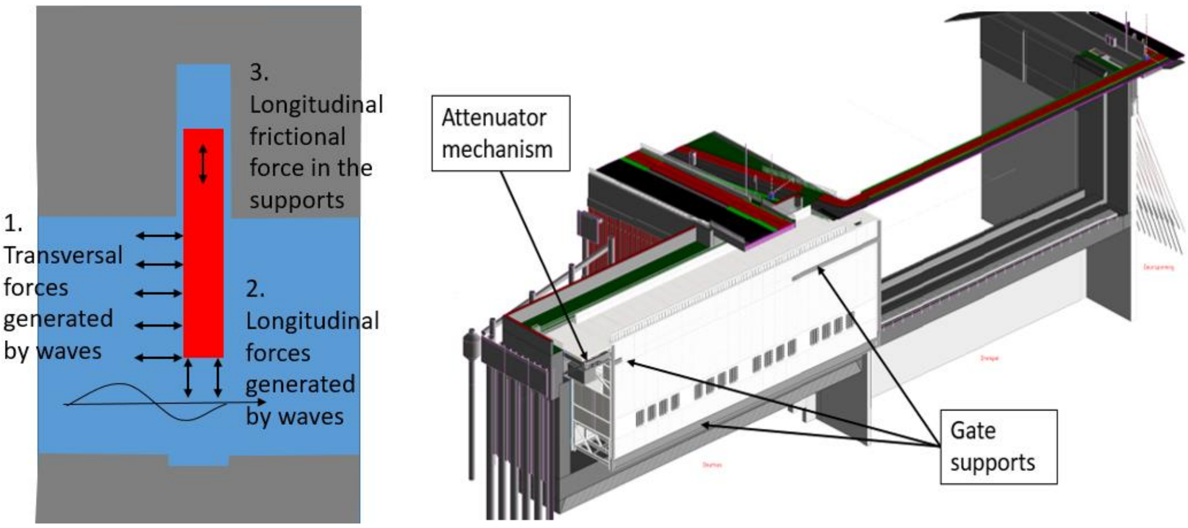

Figure 2: Overview of wave forces on the gate

2. METHODOLOGY – LINEAR WAVE THEORY

A wave spectrum of the incoming wave field which covers the wave energy directing towards the gate is the starting point of the analysis. The wave spectrum is shown in Figure 3 by the dashed line. The wave spectrum has two peak frequencies:

- A minor peak at 0.1 Hz corresponding to long waves penetrating the harbor from sea
- A major peak at 0.2 Hz corresponding to wind waves mainly generated in the harbor basin.

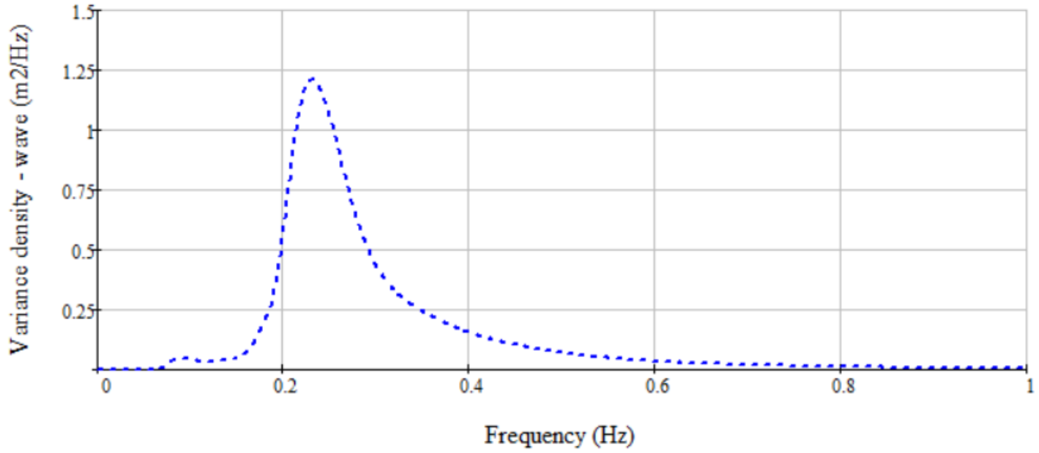

Figure 3: Wave spectrum

The wave spectrum is transferred into a wave force spectrum by using a transfer-function (Holthuijsen, 2007). The wave force spectrum is derived by multiplying the wave spectrum $S_{\eta\eta}(f)$ by the square of the response function $R_{F\eta}(f)$ *(1)*. We assume/know beforehand that the eigen-period of the gate itself is much shorter than the period of the waves. Therefore, dynamic amplification of the loads can be safely ignored.

$$S_{FF}(f) = R_{F\eta}^{2}(f) S_{\eta\eta}(f) \qquad (1)$$

In which:

$S_{FF}(f)$	=	Variance density of the wave force field (kN^2/Hz)
$S_{\eta\eta}(f)$	=	Variance density of the wave field (m^2/Hz)
$R_{F\eta}(f)$	=	Response function (kN/m)

3. SPECTRUM OF TRANSVERSE WAVE FORCES

The methodology given in chapter 2 is applied to find the spectrum of the transverse wave force. The transverse wave load is shown as force 'number 1' in Figure 2.

Response function below still water level

The wave pressure is the largest at still water level (SWL) and decreases with depth as presented in the left pressure figure of Figure 4. The rate of decline is related to the depth and frequency. The total transverse wave force is calculated by integrating the wave pressure over the height and multiplying the pressure by the width of the gate. The response function below SWL is derived by dividing *(2)* with the amplitude. Reflection is included in the equation by means of variable *r* (Ministerie van Verkeer en Waterstaat, 2000).

$$F_{sub}(f) = (1+r)\,\rho_w\, g\, a\, B_{eff} \int_{h_{gate\_low}}^{h_w} \frac{\cosh(k(f)\,(\eta - h_{gate\_low}))}{\cosh(k(f)\,(h_w - h_{gate\_low}))}\, d\eta \qquad (2)$$

In which:

f	=	frequency	B_{eff}	=	Width of gate subjected to waves
r	=	reflection	k	=	wave number
ρ_w	=	density water	h_w	=	still water level
g	=	gravitation constant	h_{gate_low}	=	bottom of gate
a	=	wave amplitude			

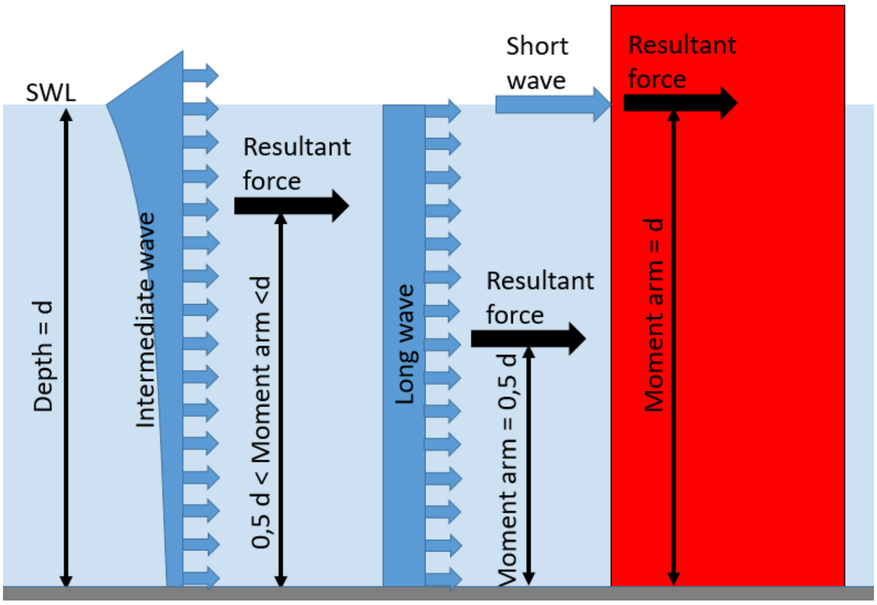

Figure 4: Wave forces acting on lock gate

Response function above still water level

The response above SWL is assumed to be of triangular shape which is illustrated in the left pressure figure in Figure 4. The wave pressure above SWL is a quadratic function of the wave amplitude. This expression cannot directly be used for the derivation of the response function, since a spectral approach requires response to be linear in the wave amplitude. We linearize the function by replacing the variable height of the pressure figure by a constant reference amplitude (a_{ref}) which is given in *(3)*. The response function is given in equation *(4)*.

$$F_{top} = (1+r)\frac{1}{2}\,\rho_w\,g\,a^2 \rightarrow linearization \rightarrow F_{f\eta_{top}} = (1+r)\frac{1}{2}\,\rho_w\,g\,a_{ref}\,a \qquad (3)$$

$$R_{f\eta_{top}} = \frac{F_{f\eta_{top}}}{a(f)} = (1+r)\frac{1}{2}\,\rho_w\,g\,a_{ref} \qquad (4)$$

In which:

a_{ref} = $\frac{1.5H_{m0}}{2}$

Response function of combined wave forces.

The total response is derived by combining the response of a wave below and above SWL. The response functions of each load signal must be added first before calculating the wave force variance density as given in equation *(5)*.

$$S_{FF}(f) = (R_{f\eta_{sub}}(f) + R_{f\eta_{top}})^2\,S_{\eta\eta}(f) \qquad (5)$$

Response functions below and above SWL are given in Figure 5. The relative contribution of low frequency waves is considerably larger than for high frequency waves. This can be explained by the longer waves penetrating deeper into the water column and thus loading the gate over a larger height as visualized in Figure 4. For an increasing frequency, the response is declining due to the larger decline of wave pressure. This results in a factor of 3,5 between the response of a 0.1 Hz wave compared to a 0.2 Hz wave. The contribution of the wave force below SWL dominates the response. A small error made by linearization for the wave above SWL can be accepted.

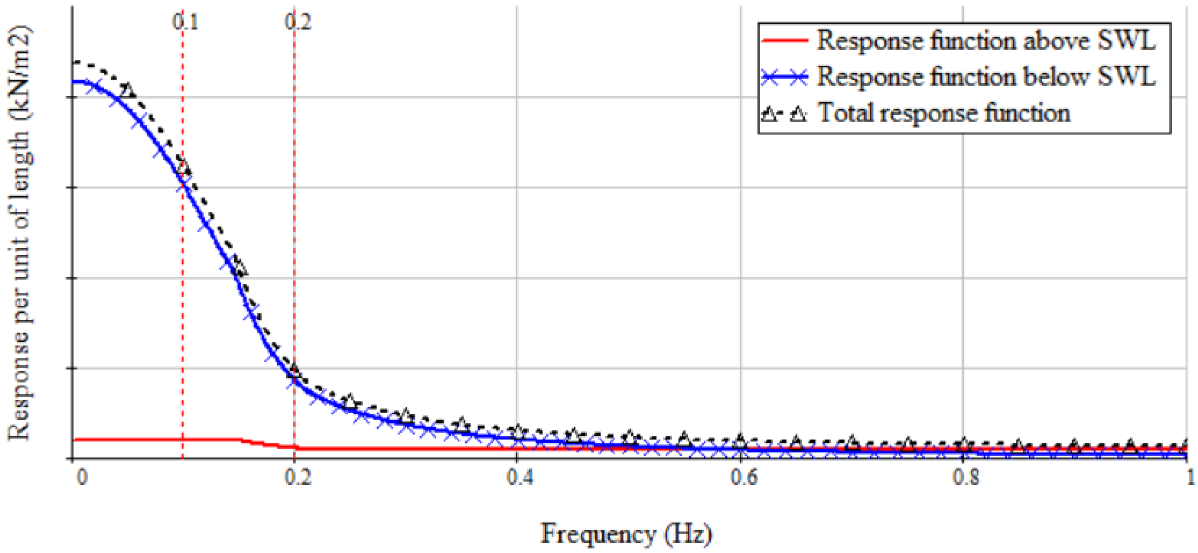

Figure 5: Response functions above and below still water (SWL)

Crest length effect

Low frequency waves are generally long crested; as the frequency increases and the waves becomes shorter the waves become short crested. This principle is illustrated in Figure 6.

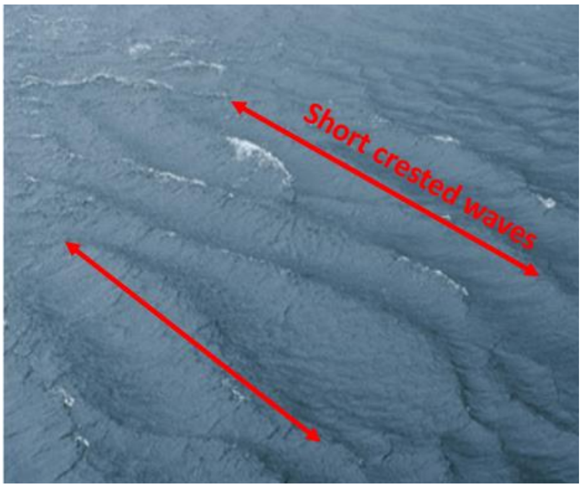

Figure 6: Low frequency waves (left) high frequency waves (right)

Waves with a crest length equal or larger than the available length of the gate in the lock chamber will exert an equal load over the whole length of the gate. Higher frequency waves have a shorter crest length than the available length of the gate in the lock chamber. Therefore, only a fraction of the gate is loaded by shorter waves. This crest length effect imposes a reduction of the total load.

To include this effect a crest length factor is applied (Ministerie van Verkeer en Waterstaat, 2000). When the gate starts to move from the recess into the lock chamber, a fraction of the gate is subjected to wave loads. In this case, the crest length of short waves is equal or larger than the available length of the gate and the reduction factor is equal to 1 (no reduction). When the gates move further into the lock chamber, the crest width of the short waves is smaller than the available gate length and the reduction factor is smaller than 1 with a minimum of 0.7 as presented in Figure 7.

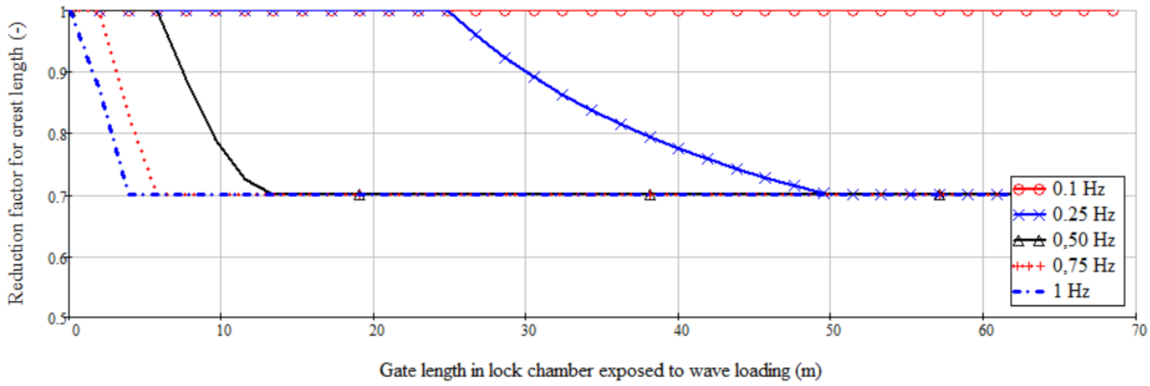

Figure 7: Crest width reduction factor

Due to this effect, the wave force variance density *per running meter* is larger for a gate exposed to waves over a small length than for a gate loaded by waves over the full length. This can be seen in the variance densities given in Figure 8. So, the total wave force is dependent upon the projected length of the gate in the lock chamber and therefore of the timing of the wave load within the gate mission.

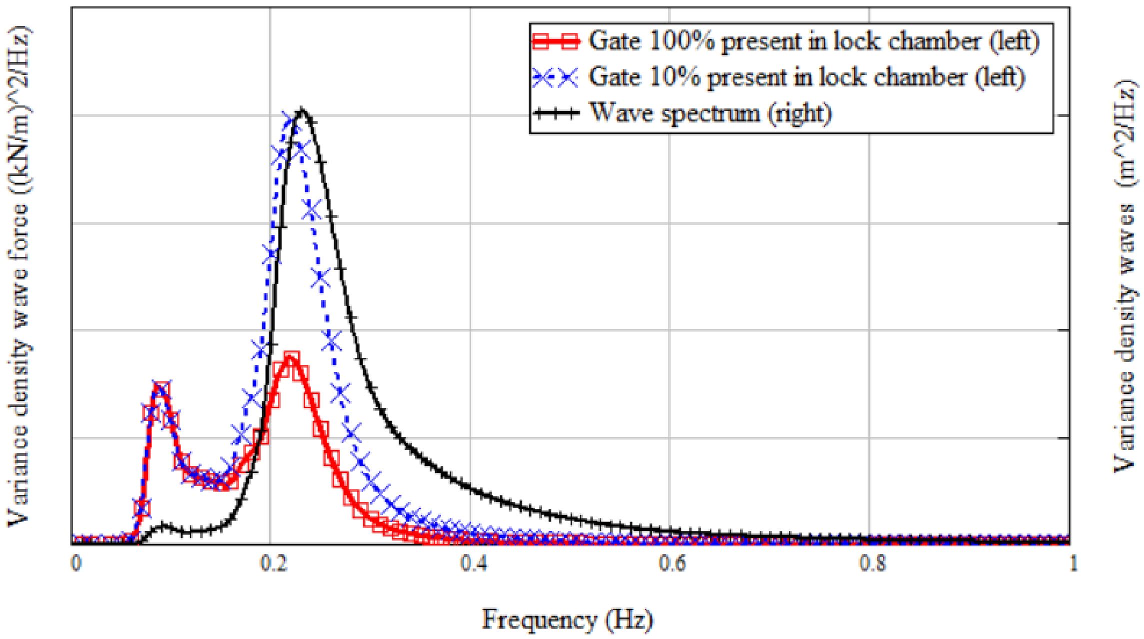

Figure 8: Spectrum of transversal wave force per meter running length

For a gate fully exposed to waves (red line Figure 8). The relative contribution per running meter of the wave force variance density for low frequencies is considerably larger than for the higher frequencies. This can be explained by the longer waves penetrating/reaching deeper into the water column and thus loading the gate over a larger height. A minor contribution of low frequency waves (2% of the wave energy) causes a major contribution to the total wave force (approximately 20% of the total wave force).

4. SPECTRUM OF LONGITUDINAL WAVE FORCES

When the gate is (partially) open, a wave can propagate into the lock chamber. The wave propagates in between the end of the gate and the concrete structure of the lock as indicated in Figure 2. Due to the large cross-sectional area of the gate, a force is generated by the waves traveling by. A wave peak will push the gate into its recess, a trough pulls the gate into the lock chamber. The magnitude of the force strongly depends on the wave length. Waves with a wave length equal or longer than to 2 times the thickness of the gate will push the gate over the full width into the recess. In this case, the peak of the wave is present from side to side of the gate. This is shown in the left figure of Figure 9. As waves become shorter, the gate is simultaneously loaded by multiple peaks and troughs. The net force pushing the gate into its recess will become zero if the wave length fits exactly a discrete number of times in the gate thickness. For short wave lengths not exactly fitting, the wave force will be small because the peaks counteract the troughs.

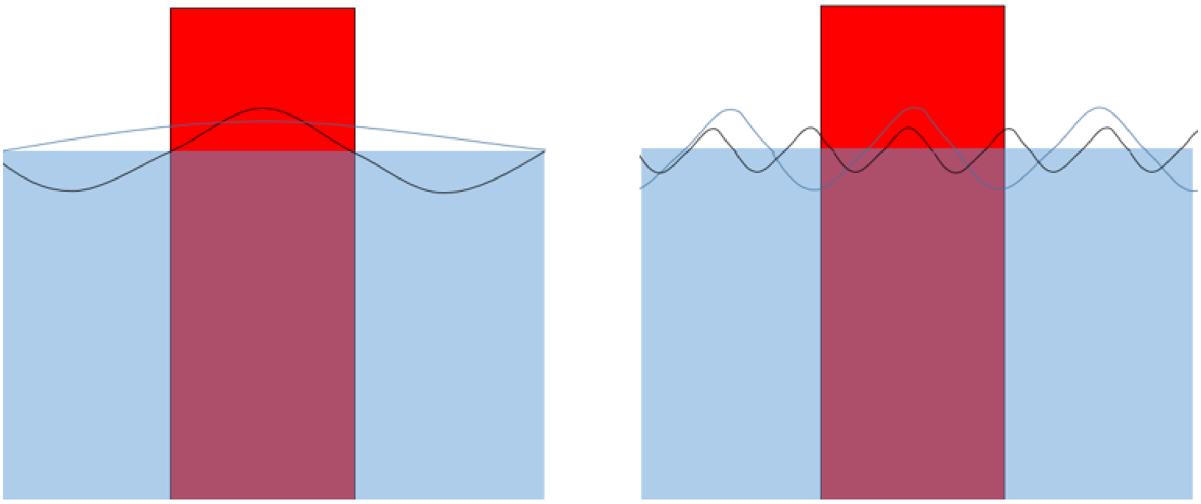

Figure 9: Waves at the end of the gate. Left: gate loaded by long waves, right: gate loaded by short waves.

To find the wave force, the wave pressure is integrated over the width and the height of the gate. The force below SWL is given in *(6)*. The largest forces are generated for waves which have a wave peak in the middle of the gate as illustrated in Figure 9. Therefore, the angular velocity is multiplied by a period shift Δt in *(6)* and *(7)*.

$$F_{sub} = \rho_w \, g \, a \int_{-\frac{B_{gate}}{2}}^{\frac{B_{gate}}{2}} \int_{h_{gate\_low}}^{h_w} \frac{\cosh(k\,(\eta - h_{gate\_low}))}{\cosh(k\,(h_w - h_{gate\_low}))} \sin(\omega\,\Delta t - k\,x)\ \mathrm{d}\eta\,\mathrm{d}x \qquad (6)$$

The force above still water level is based on ***(7)***. Only the wave force above still water level is relevant for obtaining a conservative force, the negative wave force of the wave throughs is filtered out by setting the pressure to 0. The force above SWL is calculated using *(7)*. The response and the spectra of wave forces are given in Figure 10 and Figure 11. Due to the presence of multiple peaks and troughs, the force is negligible after 0.4 Hz. Long waves, which penetrate deep into the water column show the largest response for reasons explained earlier.

$$F_{top} = \frac{1}{2}\,\rho_w \, g \, a \, a_{ref} \int_{-\frac{B_{gate}}{2}}^{\frac{B_{gate}}{2}} \begin{matrix} \sin(\omega\,\Delta t - k\,x)\ if\ \sin(\omega\,\Delta t - k\,x) > 0\,m \\ 0m\ otherwise \end{matrix}\ \mathrm{d}x \qquad (7)$$

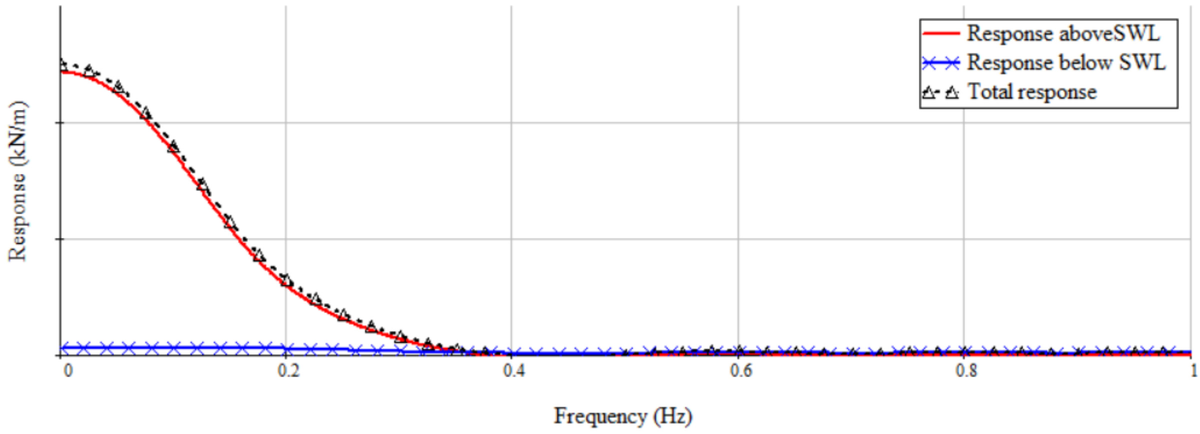

Figure 10: Response functions above and below still water (SWL)

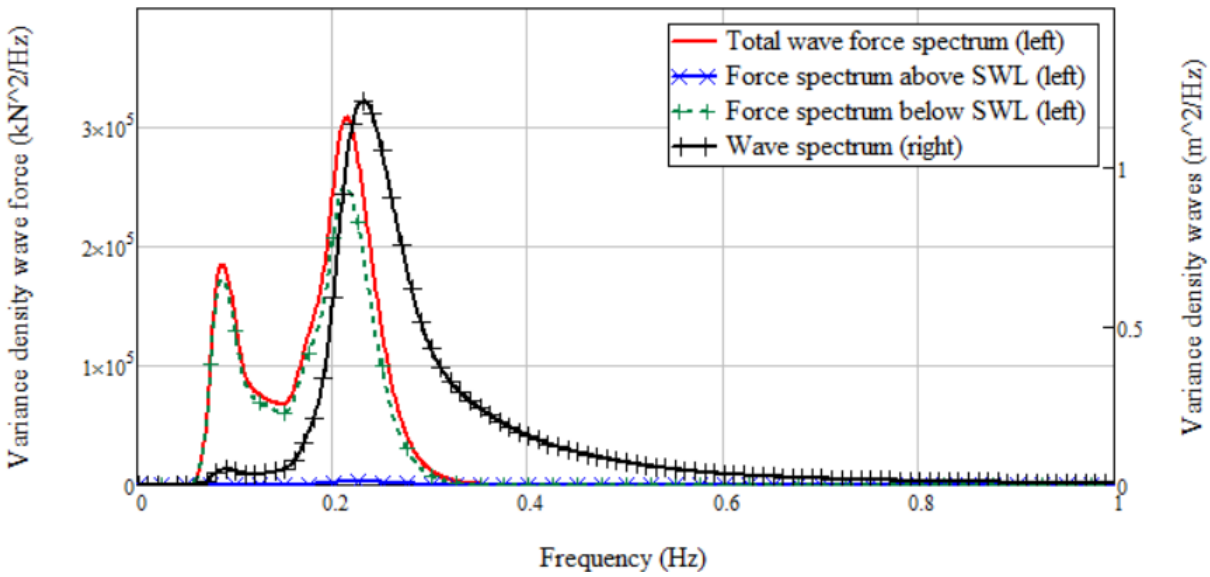

Figure 11: Longitudinal wave force variance density on gate

5. CONVERSION FROM TRANSVERSAL WAVE FORCE SPECTRUM TO LONGITUDINAL WAVE FORCE SPECTRUM

During gate mission, the gate is pushed or pulled by waves onto its supports. The attenuator mechanism needs to pull the gate along the supports. Between gates and supports, friction forces are generated which are always directed opposite to the gate motion. To calculate the total longitudinal force, the transversal wave force addressed in chapter 3 needs to be transformed into a longitudinal frictional wave force. The friction force is calculated by the multiplication of the transverse force by a friction factor as shown in the left section of Figure 12 for a simply supported beam. However, the gate is supported in three points (Figure 13, support A, B and C) resulting in a less simple mechanical scheme. When the gate is loaded by a wave with a resultant force located above the rotational axis shown in Figure 12, the gate acts as a cantilever beam. For a cantilever beam, the forces in one support counteracts the forces in another support as shown in the right section of Figure 12. The summed absolute values of the forces in the supports is larger than the total wave force, because the friction force depends on the absolute value of the support forces and not on their direction. With the equilibrium of the wave force ensured, the fiction force is equal to the absolute wave force (*F*) multiplied by an amplification-factor (*Fac*) for the structural behaviour of the system, multiplied by the friction factor (ϑ).

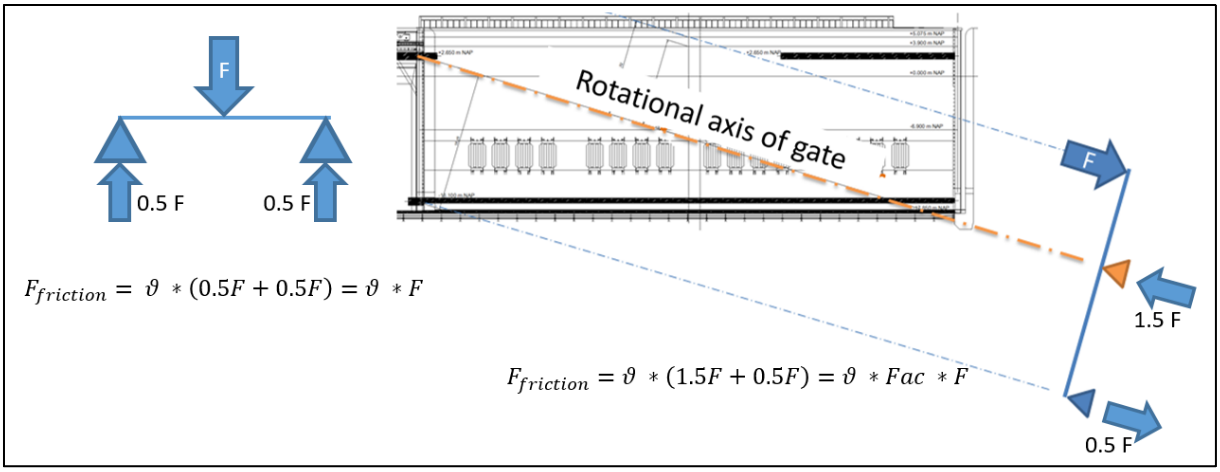

Figure 12: Mechanical behavior of a simple supported beam and the lock gate

The transversal wave forces are divided over three supports which are named A, B and C, Figure 13. Two supports (A and C) will cope with the direct wave force. Waves loading the gate above the rotational axis (dashed line in Figure 12 and Figure 13) will turn the gate over. A force will be generated in support B (B) to prevent the gate from turning over. The friction force is present in each support, irrespectively the sign of the force (positive for A and C negative for B).

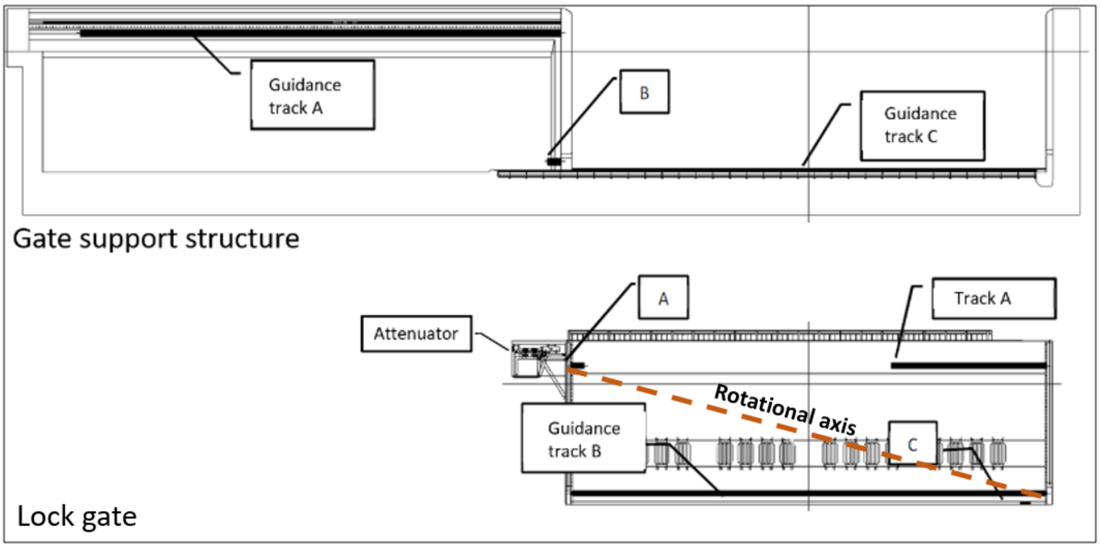

Figure 13: Gate schematization and location of supports

Derivation of response functions for each support

The transverse wave load is distributed over the supports. The magnitude of the force in each support depends on:

- Wave frequency
- The position of the gate.
    - During opening/closing of the gate the orientation of the rotational axis will change resulting in a different division of forces over the supports.

To calculate the force distribution over the supports, the distance relative to the bottom of the resultant wave force for a variable frequency is derived by dividing the wave tilting moment response function by the wave force response function. The tilting moment is calculated for every frequency, because the shape of the pressure distribution varies as a function of frequency as indicated in Figure 4. The moment response function is derived by multiplying the force response function by the moment arm. This results in the moment arm function given in *(8)* and Figure 14.

$$A_{moment}(f) = \frac{R_{M\eta}(f)}{R_{f\eta}(f)} \qquad (8)$$

In which:

A_{moment} = Moment arm; distance between resultant force and bottom of gate (m)
$R_{M\eta}$ = Tilting moment response function
$R_{F\eta}$ = Wave force response function

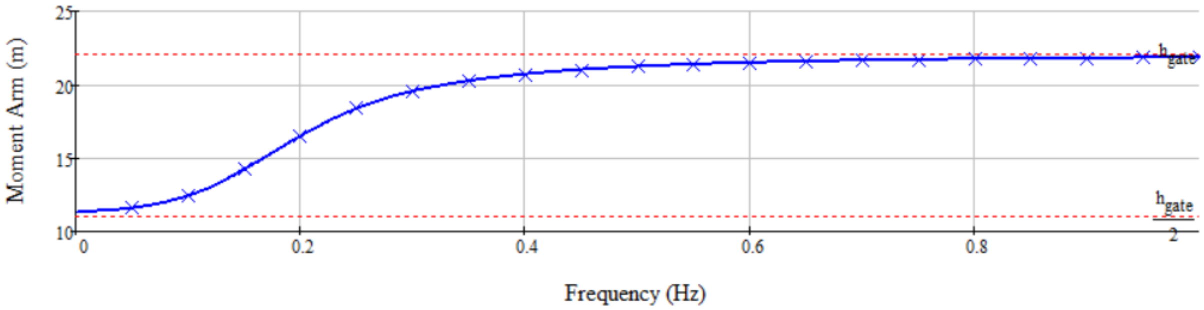

Figure 14: Moment arm as function of wave frequency

By knowing the moment arm and the wave force for each frequency and the orientation of the rotational axis for each position of the gate, the distribution of the wave force over the supports is derived by solving:

- the horizontal equilibrium of forces,
- the moment equilibrium over the x-axis
- and the moment equilibrium over the y-axis.

The result is given in Figure 15. The distribution of wave force over the supports is quantified as a factor between the total incoming wave and the reactional force in each support. The relative sum of the factors must always be equal to -1 to make equilibrium with the total incoming wave (set equal to +1). The absolute sum of the factors is always equal or higher than 1 due to the cantilever effect of a wave loading the gate above the rotational axis.

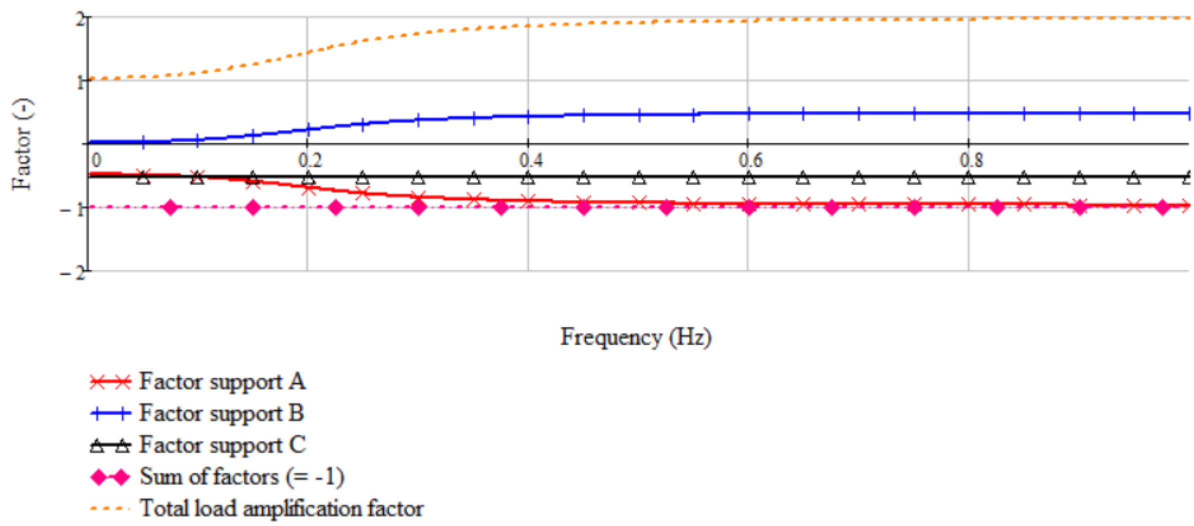

Figure 15: Relative factors for the division of the incoming wave force over the supports A, B and C

For infinitely long waves, the gate is loaded directly on the rotational axis. The reaction forces are equally distributed over support A and C and the extra compensating force in B is zero as shown in Figure 15. When the waves become shorter for an increasing frequency, the resultant force will be located above the rotational axis generating an extra compensating force in support B up to a maximum of 0.5 times the incoming wave force. To compensate this extra force in B, support A will experience an extra force with a maximum of 0.5 times the incoming wave force. In short: the amplification of the load which corresponds to the absolute sum of the factors in each support is 1 for infinitely long waves and increases to a maximum of 2 for shorter waves.

The response function of each support is calculated by multiplying the response function of the incoming transversal wave by a friction factor (ϑ) and the function of the unitless amplification factor (*Fac*) given in Figure 15 for each support. The spectra of the friction force for each support is given in Figure 16.

$$R_{support} = \vartheta\, Fac\, (R_{f\eta_{sub}} + R_{f\eta_{top}}) \qquad (9)$$

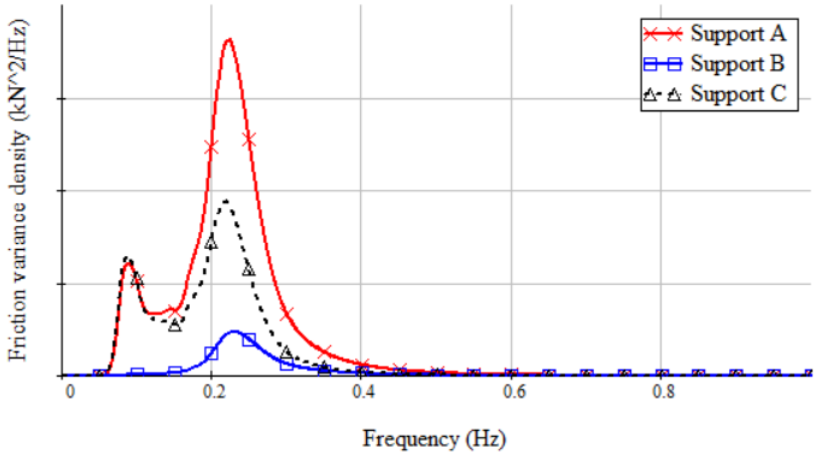

Figure 16: Variance densities of friction forces in supports, gate exposed over full width to waves.

Total longitudinal wave force spectrum

To derive the spectrum for the total longitudinal force, the spectrum of friction forces is combined with spectrum of longitudinal wave forces derived in chapter 4. The total longitudinal wave force spectrum is found by the square of the summation of the response functions as given in *(10)*.

$$S_{FF\ attenuator}(f) = (R_{suppprt\ A} + R_{support\ B} + R_{support\ C} + R_{longitudinal})^2\, S_{\eta\eta}(f) \qquad (10)$$

In which:

$S_{FF\ attenuator}(f)$	=	Variance density required for attenuator (kN²/Hz)
$R_{support\ A}$	=	Response function support A
$R_{support\ B}$	=	Response function support B
$R_{support\ C}$	=	Response function support C
$R_{longitudinal}$	=	Longitudinal response function
$S_{\eta\eta}(f)$	=	Wave spectrum

The attenuator mechanism should have sufficient driving force to guarantee a sufficient low probability of delay of a gate mission for the spectrum of total wave forces given in Figure 17

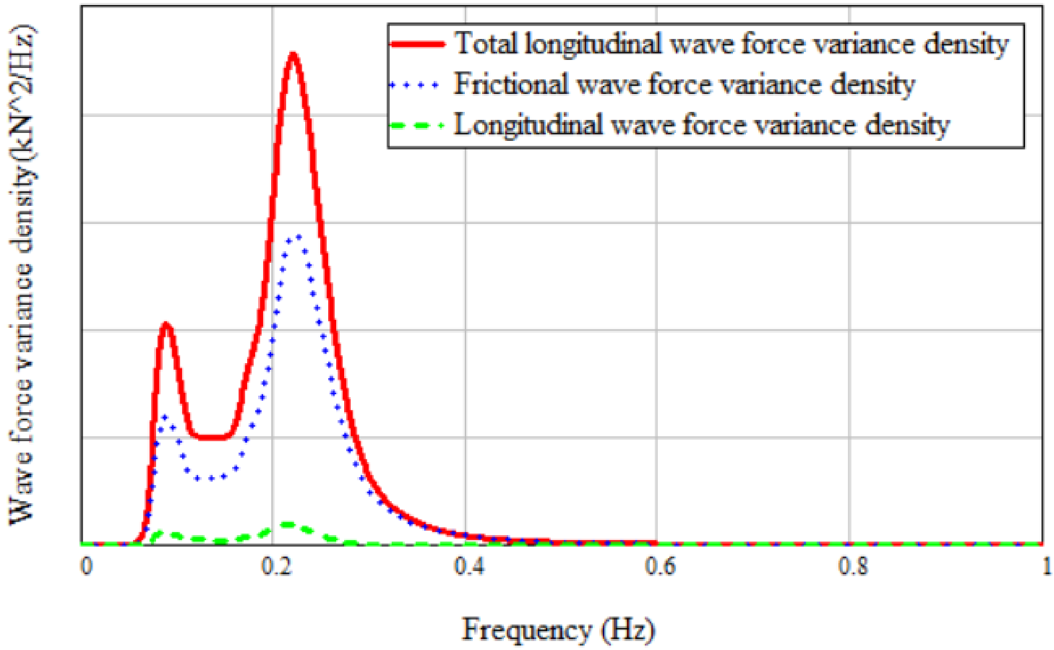

Figure 17: Total longitudinal wave force variance density, gate exposed over full width to waves.

6. CONVERSION FROM FORCE SPECTRUM TO DESIGN LOADS

The gate moves through a random wave field corresponding to the wave spectrum. A maximum force during the motion of the gate cannot be defined due to the randomness of the waves. Therefore, a probability distribution of the total longitudinal wave force is made based on the wave force spectrum (Figure 17). Using the probability distribution and the period between up-crossings a design choice is made for the required driving force of the attenuator mechanism.

Exceedance of the driving force by a wave does not immediately result in significant delay. The gate will not come to a standstill, but will only loose speed for a brief period since the mass of the gate prevents it from stopping immediately. To quantify the delay of a gate mission, a wave force time series is derived. The probability of delay and the period of delay is calculated by modelling numerous gate missions using the wave force time series.

In this chapter, the derivation of the wave force statistics, the wave force time series and the calculation of delay are described in three sections.

Wave force statistics

A first estimate of the required force of the attenuator mechanism is obtained by calculating the probability distribution. For the design of a general hydraulic structure, a significant wave height multiplied with a factor would have been applied. For example, quay walls or (smaller) hydraulic structures are designed using the significant wave height (probability of exceedance of 13%) multiplied by a factor 1.8 or 2.25. An exceedance of the installed capacity will only result in delay which is of minor importance for smaller hydraulic structures However, large delays are not allowed for the lock of Amsterdam. Therefore, more insight in the probability of exceedance and the number of exceedances during gate missions is required.

Following (Holthuijsen, 2007) a Rayleigh distribution is assumed for the wave forces. However, that choice is based on theoretical arguments and the validity is not fully ensured. Therefore, statistics have also been derived based on a peaks-over-threshold method using the wave force time series (see next section) and compared to the Rayleigh distribution using m_0 of the wave force spectrum. The found distribution closely resembles the Rayleigh distribution, so the latter was used in the remainder of the study. The result is given in Figure 18. Using this graph, a first estimation of the required force can be evaluated based on a 'risk classification' corresponding to the significant wave force times a factor.

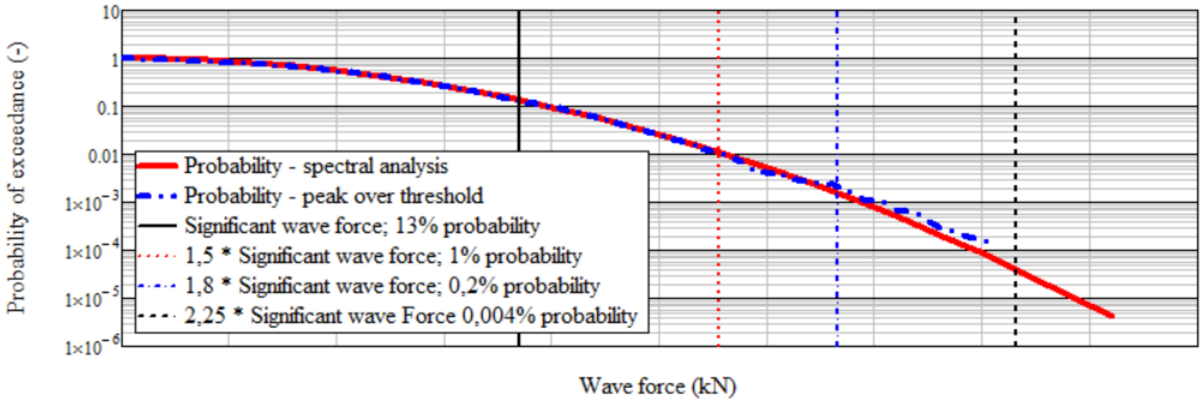

Figure 18: Probability of exceedance of wave forces

The duration of a gate mission is in the order of four minutes. The expected duration between exceedances of critical load levels for a single gate mission is therefore important, as it is related to the number of exceedances we can expect within a single mission.

To evaluate the number of exceedances of a certain wave force during gate mission the average time interval between successive up-crossings of a force is evaluated. The total number of up-crossings during a gate mission is found by dividing the time interval required for a gate mission by the average time between successive up-crossings. The average time interval between successive up-crossings is illustrated in Figure 19. The time interval is calculated using *(11)* (Holthuijsen, 2007). The periods between wave force up-crossings for a given wave force (η_{force}) are found by deriving the zeroth order and second order moments of the wave force variance density. The number of up-crossings during a gate mission is derived by dividing the period of the gate mission by the average time interval between up-crossings as given in *(12)*.

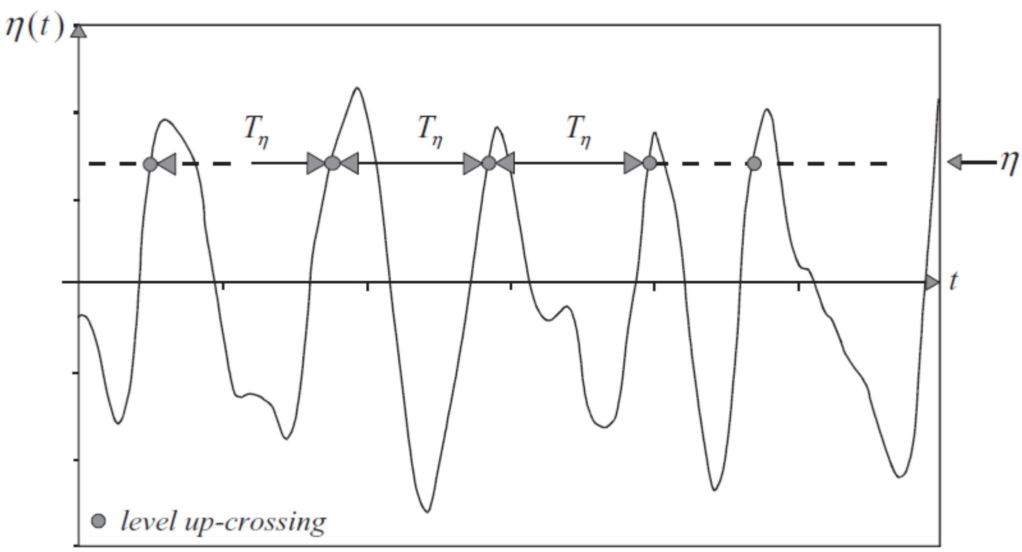

Figure 19: The up-crossings of the sea-surface elevation through level η and the corresponding time intervals T_η in a (statistically) stationary wave record (Holthuijsen, 2007)

$$\bar{T}_\eta(\eta_{force}) = \frac{\sqrt{{m_0}/{m_2}}}{e^{\left(-{\eta_{force}}^2/{2m_0}\right)}} \tag{11}$$

$$nr_{up-crossings}(\eta_{force}) = \frac{T_{motion}}{\bar{T}_\eta(\eta_{force})} \tag{12}$$

In which:

$\bar{T}_\eta(\eta)$ = Average time interval between successive up-crossings through level η

η_{force} = Level of up-crossing; wave force

m_0 = Zeroth order moment of the total force variance density

m_2 = Second-order moment of the total force variance density

T_{motion} = Required period to open or close the gate

$nr_{up-crossings}(\eta)$ = Number of up-crossings through level η during gate motion

The number of up-crossings during a gate mission for a variable force η_{force} is given in Figure 20. The significant wave force will on average be exceeded for 10 times during one mission. Therefore, the required installed driving force must be larger than the significant wave force. A force equal to 1.5 times the significant wave force will on average be exceeded once during a mission. To avoid frequent delay, the installed force of the attenuator should be larger than this force. Wave forces higher than 1.8 times the significant wave force will on average be exceeded one time per ten gate missions. So, expected delays during gate mission will be sufficient low by installing a higher driving force than 1.8 times the significant wave force. The expected quantity of delay cannot be evaluated using Figure 20. Therefore, the time series of the total longitudinal wave force derived and are further evaluated below.

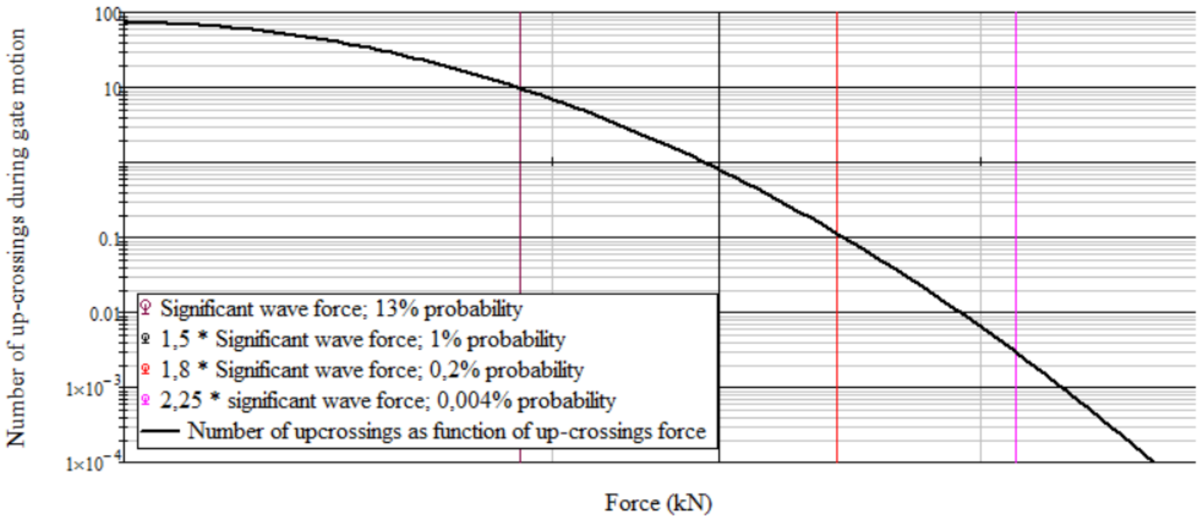

Figure 20: Number of up-crossings through level η during gate motion

Wave force time series and expected delays

The total delay of a gate mission depends on the statistics of the wave forces acting on the gate (the severity of storms) and the delay occurring within a single storm. To estimate the expected delay, we switch to an analysis in the time-domain. Using the variance density, a wave force time series is derived (Holthuijsen, 2007). The time series is derived by:

- Drawing a random phase from a uniform distributed probability distribution.
- Calculating the amplitudes from 0Hz till 1Hz with a step size of Δf using the wave force variance density given in Figure 17.
- Combining the calculated wave force amplitudes with the random phases.

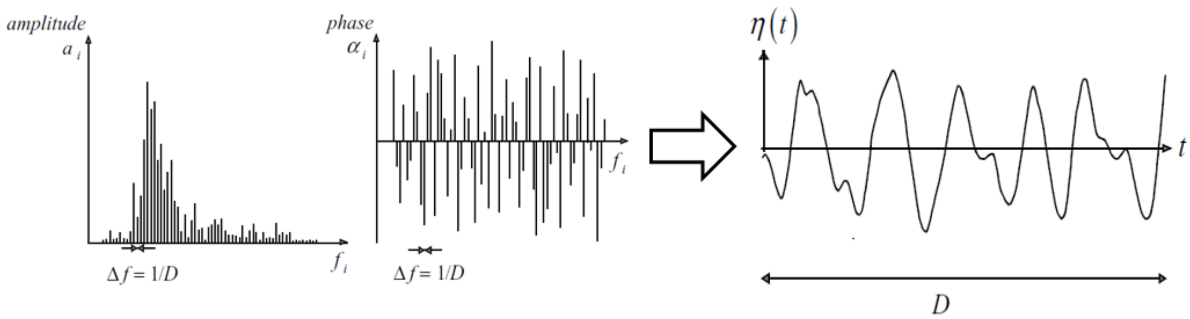

Figure 21: Generation of a time series (Based on (Holthuijsen, 2007))

As stated in Figure 2, the gate is loaded by a transversal and longitudinal force generating friction. The transversal force is pushing the gate onto the supports for a wave peak and pulling the gate onto the supports for a wave trough. Hence, for a wave peak or trough a positive transversal load is generated. To calculate the total longitudinal load on the attenuators, the absolute value of the frictional forces generated by the transversal force is used.

For longitudinal forces, a wave peak pushes the gate into the southern recess of the lock. This generates a positive force when the gate is opening and has a velocity towards the recess by itself. When the gate is closing and moving into the lock chamber a wave peak generates a negative force because the gate motion is opposite to the direction of the wave force. The opposite holds for a wave trough.

For the calculation of the wave force time series the absolute value of the frictional forces is combined with the relative value of the longitudinal load. The resulting wave force time series is given in Figure 22. Most of the times, the wave force is positive. For a fraction of the time the wave force is negative which means that the negative longitudinal load due to a wave through at the edge of the gate is larger than the friction force load. This time series is used for the calculation of delay.

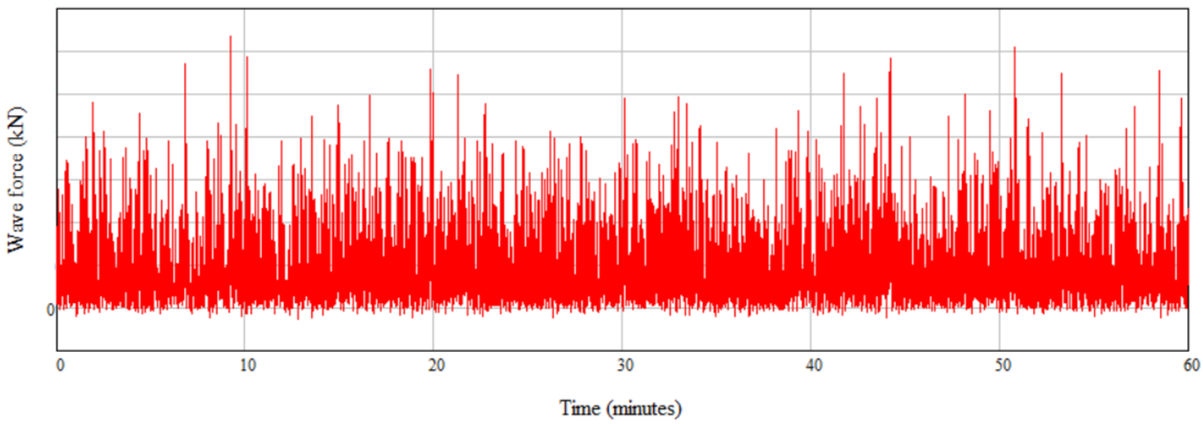

Figure 22: Wave force time series (10-year return period)

Calculation of delay

The total force to be overcome by the attenuator mechanism consists of the wave forces and “other loads” like density differences, translatory waves, etc (Voortman, et al., 2017). When the total load exceeds the installed driving force, the net available force for the gate mission becomes negative. According to the second law of Newton (F=m*a) the gate will slow down.

To evaluate the probability of delay, a wave force time series has been made corresponding to a storm of 10 hours. The wave force has been added up by the ‘other loads’ (Voortman, et al., 2017). In this time series, the gate is continuously being opened and closed to calculate the delay. In total 131 gate missions have been simulated of which a couple of gate missions have been shown in Figure 23. The total delay for each gate mission is calculated and transformed into a cumulative probability function which is shown in Figure 24.

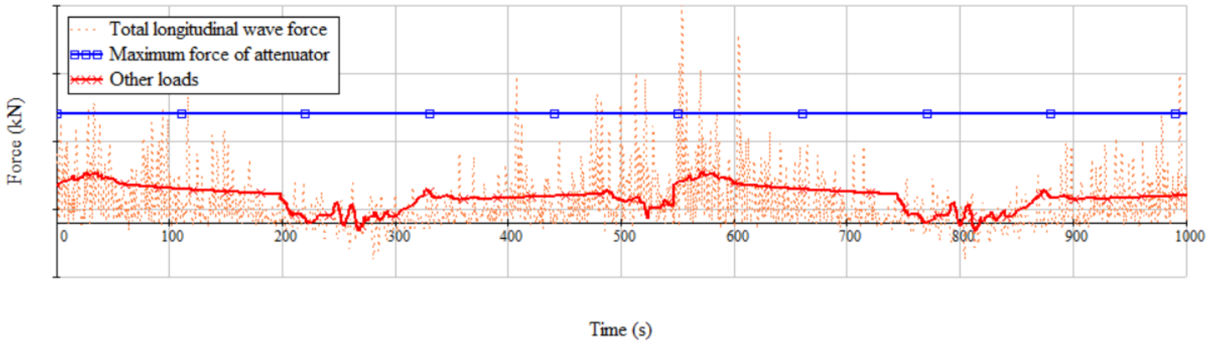

Figure 23: Total forces (red) and installed driving force (blue)

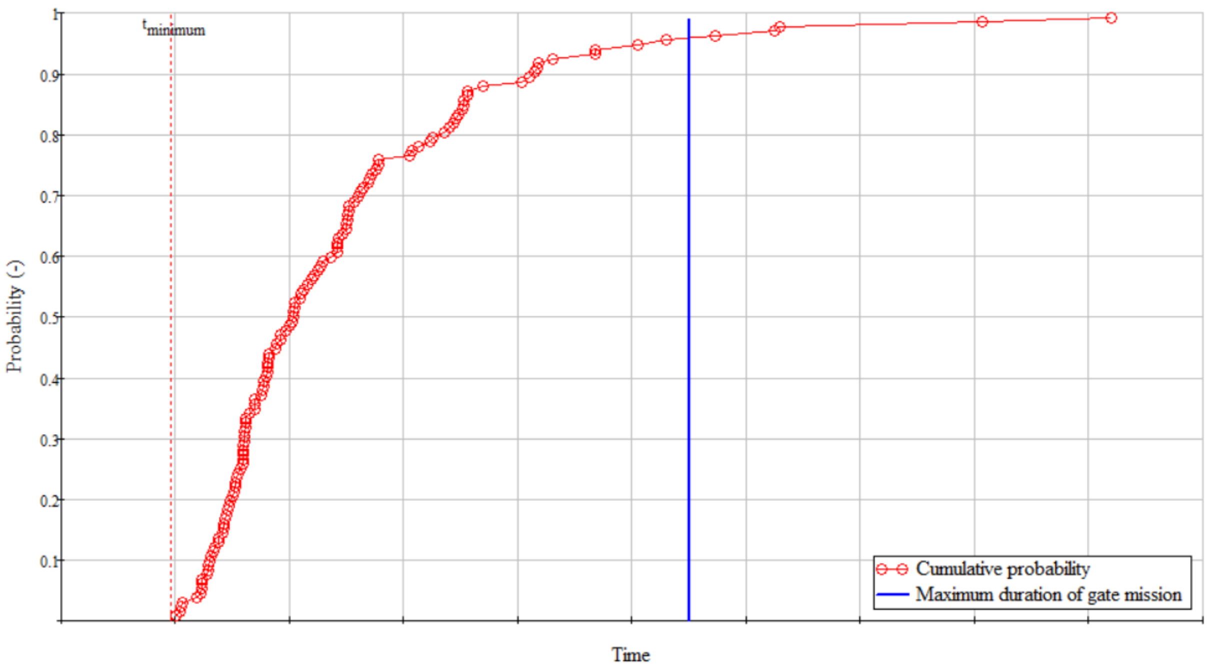

Figure 24: Probability of delay during a 1/10 per year storm

The required maximum duration for the gate mission is indicated by the blue line in Figure 24. The probability of exceedance of the set duration is 5% which is sufficient low. So, based on the estimated required driving force using the wave force up-crossings (Figure 20) a sufficiently low probability of exceedance is obtained for the duration of a gate mission.

CONCLUSION

The use of the linear wave theory gives more insight compared to other theories for a robust design and analysis of the attenuator mechanism of a lock gate.

Using the linear wave theory, representative forces are derived which are indirectly loading the attenuator mechanism. The spectral model showed that a double peaked wave spectrum with a minor contribution of low frequency waves resulted in a double peaked spectrum of longitudinal forces with a significant peak at low frequencies. Based on this model, the representative forces on the attenuator mechanism are well-derived. 1,5% of wave energy below 0,14Hz results in 17% of the total wave force. A small amount of wave energy gives a major contribution to the total wave force which would not be calculated when using only one wave height and wave period using either Goda's method or the linear wave theory. The proposed methodology gives an optimal evaluation of the loads on the attenuator mechanism for normal wave conditions up to a wave field with a return period of 10 years (H_{m0}=1,5m, T_{m-10}=4s).

The longitudinal wave force spectrum gives detailed information for the evaluation of the driving force of the attenuator mechanism. By evaluating the number of up-crossings during a gate mission a good first estimate for the driving force is derived. The driving force is verified using time series of the wave force. A model is developed in which the delay of a gate mission for a random wave force field could be derived. The probability of exceedance of the required period of a gate mission for a 10-year return period storm given the driving force evaluated using the up-crossings would only be 5% which is acceptable low. This analysis cannot be done when using a theory based on only one wave height and wave period, like is practice for the theory of Goda.

The results have been incorporated in the design of the gates and the attenuator mechanism. The gates and attenuators are currently being constructed. The lock is expected to be fully operational by the end of 2019.

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