JOURNAL OF COASTAL AND HYDRAULIC STRUCTURES

Review and rebuttal of the paper

A novel design method for wave-induced fatigue of flood gates

T.N. Joachim Kleiberg, Orson C. Tieleman, Marco Versluis, Wim Kortlever, Erik ten Oever, Bas Hofland

Editor handling the paper: Nils Goseberg

The reviewers remain anonymous.

Response to comments of Reviewer 1

1. *Line 4: "As sea levels rise the hydraulic loads …". Please add a reference here that supports this statement.*

   Author's response: The sentence has been rephrased and supported with two references.

2. *Figure 1: I would appreciate if you could add all forces or wave pressure distributions (basically the ones you described under section 3.2) acting on the gate in Figure 1. In my opinion, this would make it easier to understand which forces are relevant for the special case of the overhanging structure and which components are actually taken into account by your method.*

   Author's response: We agree that the addition of a schematic of the wave forces would help clarify which components are taken into account. It has been inserted in section 3.2 to make the link to the related equations clearer.

3. *Line 27: Could you indicate what lifetime in years is normally considered for flood gates.*

   Author's response: The design lifetime of flood gates in the Netherlands is normally around 100 years. We have added this indication in the paper.

4. *Introduction: There is some overlap between this manuscript and Tieleman et al. 2021. I would recommend specifically pointing out where the new manuscript comes in and how exactly the scope was extended over Tieleman et al. 2021, e.g., by also considering fatigue damage over the lifetime of the structure.*

   Author's response: The applied methods are indeed based on the previously developed model routine for the evaluation of the ultimate limit state by Tieleman et al. (2021).

   These methods are expanded in this study to evaluate fatigue damage by accounting for all expected loads over the lifetime of the structure instead of a single storm event. This explanation has been added to the introduction. Moreover, a gate with a realistic geometry that includes supporting beams, as implemented in Tieleman et al (2022), is applied in the present study. We believe that with the more realistic gate geometry and inclusion of a complete lifetime of loads in the model, are important steps to obtain a tool that can be used for realistic designs.

5. *Figure 2: The labelling of the y-axis seems to be reversed. Negative infinity symbol should be on the right side.*

   Author's response: This was indeed the case. This error has been fixed.

6. *Line 121-123: While this point is certainly outside the focus of the manuscript, I would still suggest briefly discussing the impact of a non-uniform wave attack and load distribution. What would the pressure field look like? What influences would be expected on the gate response and fatigue load?*

Author's response: We agree that this is a relevant point to discuss. Non-perpendicular waves result in lower overall impact loads. However, the resulting loads are non-uniformly distributed over the width of the gate and may therefore excite other, anti-symmetric, modes. This may result in local stress concentrations that differ from the case with perpendicular waves. The response model is fully capable of predicting the response to uniform wave loads. Given a suitable theory to predict non-uniform wave impact loads, the model routine can therefore be adapted relatively straightforwardly to include non- perpendicular waves. This discussion has been added in Chapter 6 (Discussion).

7. *Line 181: On which influencing variables does the impact duration depend? Are the specified values for the impact duration not dependent on the wave parameters such as wave length or steepness?*

   Author's response: De Almeida et al. (2019, 2020) have shown that different types of wave impacts can be expected for various wave parameters and overhang configurations based on experiments with regular wave conditions. The impact duration does vary over these type of wave impacts mainly as a function of the amount of entrapped air below the overhang (De Almeida et al., 2021) and the scale (Ramkema, 1978). The dependence between impact duration and irregular wave conditions is still a topic of ongoing research. In this study, we implicitly assumed the involved uncertainty can be captured in the distribution of the impact duration that is independent from the irregular wave conditions. Additional context has been added to section 3.2 and Chapter 6 (discussion) to reflect on this topic.

8. *Line 237-238: Not sure I understand this section. Why exactly did you decide to evaluate fatigue via principal stresses and not via von Mises stresses?*

   Author's response: This section discusses the way fatigue damage is evaluated in this study. We evaluate fatigue by means of the maximum principal stress in accordance with the Eurocode (CEN, 2012) in order to preserve direction. However, signed Von Mises stress is applied as an alternative in practice as well, which is also possible in the presented model routine. We have added this argumentation to paragraph 3.4.

9. *Line 261-265 and in general: Could you explain more clearly why the extra step of deriving / calculating waves from historic wind and sea level data is needed? Especially for the Dutch coast, high resolution historical wave data should be available for many locations from which spectral distribution functions can then be derived directly. Does the use of wind and sea level data make it easier to define specific load cases and their probability of occurrence? How long must the time window of historic data be to ensure accurate estimation of wave spectra?*

   Author's response: Indeed, this is a valid alternative approach and likely more accurate approach, given available high-resolution data and a valid method to extrapolate the historic data in terms of periods and wave heights to higher return periods. Since high-resolution wave data is not available everywhere, we opted for a more general method. We have edited section 3.1 to mention it as a valid alternative approach.

   The algorithm that generates the Dutch hydraulic boundary conditions (HYDRA-NL) generates extreme values for water levels, wind and waves along the entire coastline. However, it focusses at extremes, such that the required daily conditions are not available for all these locations. Therefore it was opted to use historical measurement data that were available near the sites of the hydraulic structures, which are wind and water level data. Additionally, this approach is more straightforward to explain and to reproduce by the readers. Because the loads that contribute most to the fatigue are generated at water levels that are not very extreme, the presently applied 50 years of data is certainly enough to describe the relevant loads, as the relevant loads do not have to be extrapolated.

The description of the waves could be further improved by using a well calibrated wave model like SWAN. However, the calibration of such a model requires measurement data that is not available, and would warrant a separate study.

10. *Line 272: I suspect that direct effects of climate change-induced sea level rise on fatigue damage will be small. Instead, the altered wave regime due to climate change is likely to be decisive for the fatigue damage. The future wave regime results, among other things, from the increased sea level but also from a presumably different wind forcing. In your case study you assume a sea level increase of 1m, which together with the pdf for the sea level data forms a convoluted pdf. A change of the future wind climate however is not considered, as far as I can tell. Future wind patterns are probably even more uncertain to estimate than sea level rise. Nevertheless, it should be considered and discussed whether and how a change in wind conditions could be taken into account in the model.*

    Author's response: It is an interesting suggestion to include the uncertainty involved in future wind patterns. We have added the remark on line 298 that this is possible within the proposed model routine.

    For the purpose of the case study in this paper, we deem it sufficient to only adjust the water level and not historical wind data for two reasons. First, the climate change scenarios for the Netherlands (Hurk et al., 2006) do not predict changes in wind climate within the lifetime of the structure considered here (up to the year 2100). We have adjusted the data accordingly. Second, the change in water level due to sea level rise is expected to be the more dominant factor for fatigue damage due to wave impacts, because the water level not only affects the expected wave conditions but also determines at what return periods waves will reach the overhang and with what impact velocity.

11. *Figure 9 and visualization in general: I would appreciate it if you would also put the parameter and the unit next to the colorbar in each figure, even if the parameter is normalized.*

    Author's response: We agree that this is clearer and have added the parameter with unit to each figure where relevant.

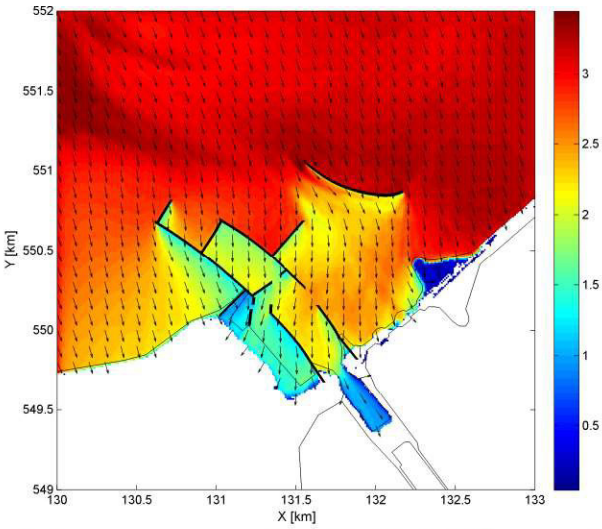
12. *Line 380: Has the modelled wave regime been compared with actual measured field data for validation?*

    Author's response: We agree this would be necessary for a real design. The purpose of the case study in this paper is however to demonstrate the proposed design method and is therefore hypothetical on several aspects. Section 5.1 has been edited to make this clearer.

    The bathymetry of the Waddenzee has for example been simplified strongly in the prediction of the wave conditions based on the wind and water level data. This will inevitably result in deviations from actual measured field data. More advanced modelling of the wave conditions is deemed outside the scope of this study. However, more advanced wave models are of course available and could be employed with the model routine presented in this paper. This remark has been added to Section 3.1.

So while we are of the opinion that it is not significant to the report, we agree it is always useful to check. In our model, the significant wave height with a 10.000 year return period (when all load cases are aggregated and weighted by probability of occurrence) is 3.4 m. The image below is from the SWAN model of the hydraulic boundary conditions report for the Afsluitdijk renovation.

At sea, the wave height is comparable (though this projection is for 2050 rather than 2100). After the wave breaker interferes the wave height decreases to roughly 2.5m. We did not take such effects into account in this paper, and therefore exposed the gate to the undiminished wave height.



Figuur 6.15 Golfhoogteverdeling rondom Den Oever bij een windrichting van 330°N en zichtjaar 2050 en herhalingstijd 10.000 jaar.

13. Line 393: As a next step, it might be interesting to consider a distribution of potential sea level rise scenarios instead of a fixed value as well. This would allow fatigue damage over the life of the structure to be directly attributed to different sea level rise scenarios.

    Author's response: We agree that this is an interesting next step. We have included this suggestion in the paper (in Section 4.1).

14. *Line 417: What exactly is the advantage of removing a particular mode instead of simulating the fatigue damage for just that mode? Could you elaborate on this?*

    Author's response: We agree that it would be more intuitive to simulate directly the fatigue damage caused by each mode. However, this is not possible due to the nonlinear relation between stress cycles and fatigue damage, which is logarithmic and includes a cut-off limit. The fatigue damage caused by most individual modes would fall below the cut-off limit on their own. This is mitigated by showing the incremental damage caused by including each individual mode relative to the total damage.

15. *Line 434: Here is says 500 Monte Carlo simulations whereas Figure 15 indicates 1000 simulations.*

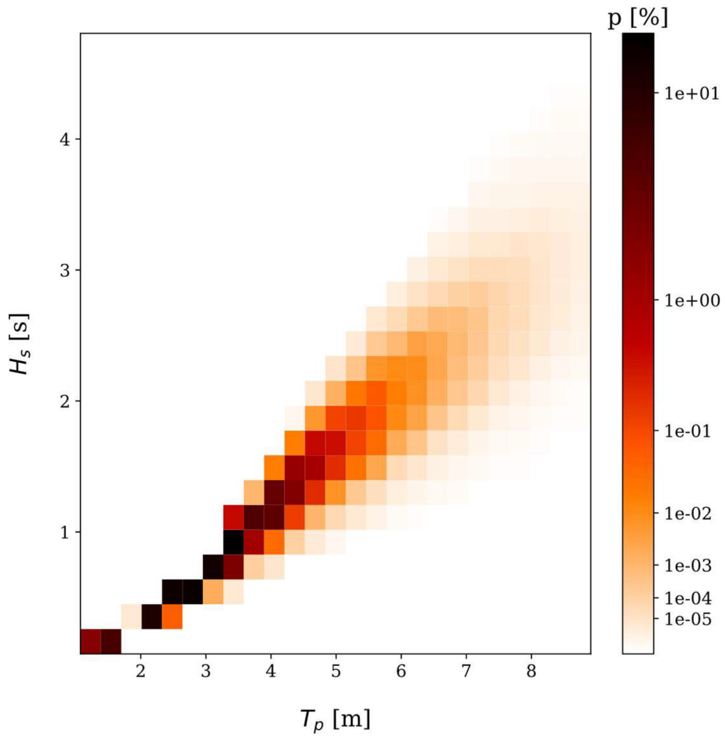
    Author's response: The correct number is 1000 simulations. This error has been fixed.

16. *Line 437: The area between the upper and lower bound looks surprisingly small. Is the reason for this that the commonly occurring intermediate wave heights in particular contribute to the fatigue damage, and these do not vary greatly over the years or per load case?*

    Author's response: There are several sources of uncertainty that contribute to the bandwidth. The uncertainty originating from the random phase-amplitude model and the wave impact duration does not lead to a large bandwidth over the high number of load cases and waves over the lifetime over the structure. Sampling uncertainty does lead to some bandwidth: by chance some lifetime simulations will have more or less high-impact events than on average. However, as stated by the reviewer, indeed mainly the more commonly occurring load cases with intermediate wave conditions and a water level at the overhang contribute to the fatigue damage. These high frequency of occurrence events lead to less sampling uncertainty than more rare extreme events. This explanation has been added to Section 5.3 of the paper.

17. *Case study in general: From an engineering perspective, it would be very interesting to get an indication of the actual wave spectra and wave parameters resulting from the input data sets. A figure similar to Figure 12 would be beneficial, but in which wave parameters, for example Hmo or Tp, are shown.*

    Author's response: We agree this is more intuitive and have generated the following image and added it to the report:



18. *Line 521: "Furthermore the error seems to have a minor dependence on the water level and wind velocity". What could be the reasons why the dependence on wind and water level is so low?*

    Author's response: The relative importance of interfering vibrations of the gate over multiple waves depends mainly on the amount of damping in the system and the time between impacts.

    The water depth has some effect on the amount of fluid damping due to surface waves and compressibility. However, the damping due to these effects is very minor compared

    to the material damping for the parameters applied in the case study. The dependence on the water level is therefore low.

    With increasing wind velocities the peak wave periods of the spectrum and therewith the time between impacts also increases. The relative error of neglecting interfering vibrations due to consecutive waves is therefore smaller for higher wind velocities. Here, there is thus indeed some dependence. Table 3 shows that the error for the higher wind velocity indeed is about 16-17% while the error for the lower wind velocity is around 20%. We have added this argumentation to Section 5.5.2 of the paper.

19. *Table 3: What does MDOF stand for?*

    Author's response: We have clarified in the text that MDOF here refers to the term Multiple Degree of Freedom that is used in the field of dynamics of structures.

Recommendation: Revisions Required

Reviewer B:

The manuscript provides a probabilistic approach for the estimation of the fatigue damage on flood gates sur to wave loads. The topic is of extreme importance and relevance to the journal. The state-of-the-art and the motivation for the research is well argued; the methodology is detailed and easy to follow. The language is also well rephased with very few mistakes. The results are well presented, and the conclusions are supported by the findings. In general, the manuscript is well written, and I suggest to accept as it is.

The only drawback is that the image quality is rather low in general, it's recommend to use vector images in the future, such as eps or tiff. However, the image quality in the manuscript does not impact the understanding of the context much.

Recommendation: Accept Submission

Author's response: We thank the reviewer for his positive feedback. We agree with the assessment of the image quality and have converted these to vector images where possible.