JOURNAL OF COASTAL AND HYDRAULIC STRUCTURES

Review and rebuttal of the paper

On the design of bank revetments at inland waterways subjected to ship-induced water level drawdown: A probabilistic infinite slope analysis

J.Sorgatz et al.

Editor handling the paper: Anton J. Schleiss

The reviewers remain anonymous.

1 Round 1 of review

1.1 Reviewer A

My remarks stand as presented in the attached file.

The manuscript needs some "strengthening" in terms of better explaining all authors' choices for this investigation, as well as their impact on this study's applicability to real-world cases of bank revetment design.

1.2 Autors responses to Reviewer A comments

First of all, we would like to thank the reviewers for the time and efforts taken to comment on our manuscript, which greatly assisted in improving the manuscript. We believe that we could clarify and include all issues raised by the second reviewer adequately.

Please find attached a marked version of the manuscript, indicating the amendments performed with regard to the paper submitted after the first review. Detailed answers to the reviewer’s comments are provided in this letter.

The convention for our answers is as follows

- *Reviewer comments are in Times New Roman.*
- Our replies in Times New Roman (black color).
- Quotation marks indicate excerpts from the manuscript.
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

The reviewer kindly provided detailed suggestions on grammar and expression, which we included in order to make a sentence more concise or easier to follow. These minor changes are not outlined in this reply to the reviewer's comments, but highlighted in the text. For the very few cases, where we did not follow the reviewer's suggestions, a reply to the reviewer's request is provided below.

Comments:

[R.01], p. 2, line 1: *I am not familiar with how keywords are selected, but I suggest adding: infinite slope analysis, hydraulic conductivity and effective friction angle.*

We agree that some of the proposed keywords may increase the findability of our paper. The original keywords "slope stability, ship-induced drawdown, revetment design, non-homogeneous ground properties, random fields" are replaced by "slope stability analysis, revetment design, ship-induced loads, non-homogeneous effective friction angle and hydraulic conductivity, random fields". Since the "infinite slope analysis" and "ship-induced drawdown" are already part of the title, we decided to omit these key phrases from the list of keywords.

[R.02], formerly p. 2, line 3 – 12 (see also [R.07]): *Rewrite the first two paragraphs.*

We agree that the proposed introduction is a bit lengthy and could benefit from streamlining. In the first paragraph, however, we felt it was important to point out that bank revetments are required to provide slope stability and protect the adjacent terrain against erosion. We revised the paragraphs as follows:

> "To ensure safety and ease of navigation, and to protect the adjacent terrain, sloped banks along inland waterways are commonly stabilized by bank protections. Revetments, which consist of loose or grouted armour stones on a filter layer, are the most common bank protection type used in German inland waterways. They provide slope stability and protect the bank against erosion (Rock Manual, 2007; GBB, 2010). Revetment design in an inland waterway must consider the loads imposed by moving ships. Particularly in artificial inland waterways, the ship-induced loads govern the design.
>
> ~~To protect the slope against erosion, the hydraulic design defines the minimum armour stone diameter necessary to withstand waves and currents. The geotechnical design evaluates the armour layer thickness required to ensure bank revetment stability under ship-induced drawdowns (Rock Manual, 2007; GBB, 2010). In the presented study, the required armour layer thickness is investigated. Furthermore, this study focuses on canals where ship-induced loads govern the design.~~"

[R.03], formerly p. 2, line 11: *Can this be replaced for inland waterways for consistency?*

Since both canals and rivers are referred to as inland waterways, we would like to emphasize that particularly in artificial inland waterways, the design is governed by ship-induced loads, whereas in rivers, natural currents and floods may govern the design. We therefore introduced the following sentence:

- p. 2, line 6 – 7: "To ensure safety and ease of navigation, and to protect the adjacent terrain, sloped banks along inland waterways are commonly stabilized by bank protections. […] Particularly in artificial inland waterways, the ship-induced loads govern the design."

Moreover, in text passages, where we initially used the term "canal", we checked whether the term "(inland) waterway" is a better choice of words. Resulting changes are indicated in the paper and listed below:

- p. 3, line 14 – 16: "The investigated drawdown combinations represent only a small proportion of all possible load scenarios observable in an inland waterway, as this study primarily aims at illustrating the effects of spatially variable ground properties on the revetment design."
- p. 4, line 15 – 16: "In the case of the investigated ship-induced drawdown, the difference between the pore pressure from hydrostatic conditions in the waterway and the current pore pressure in the soil's voids is termed excess pore pressure."
- p. 15, line 18 – 19: "Before the soil can react to the changes in water level, the water level in the waterway has already returned to normal."

[R.04], formerly p. 2, line 13: *Vessel vs ship. The paper uses these two terms interchangeably. Consider using one throughout the document for consistency.*

For reasons of consistency, we agreed on using only the term "ship" in the document. The corresponding changes are marked in the document.

[R.05], formerly p. 2, line 15: *Is this referring to displacement of water by the ship/vessel?*

We are referring to decreased cross-sectional area as a result of the waterway blockage caused by the ship. The text passage was modified for clarification.

> "A ship moving through a waterway with a limited cross-section produces a sequence of waves and currents (see Figure 1). First, water accumulates in front of the ship causing bow waves. The partial blockage of the waterway cross-section triggers a flow around the ship from the bow to the stern, the so-called return flow (GBB, 2010) or return current (Rock Manual, 2007)."

[R.06], formerly p. 2, line 19: *Adjust paragraph as follows: "At the stern of the ship, the flow conditions are re-balanced, resulting in a rise in the water level and the, so-called transversal stern wave."*

We have not adopted this change as it does not reflect our initial statement. The rise in water level is also referred to as transversal stern wave. We reformulated the sentence as follows:

> "At the stern of the ship, the flow conditions are re-balanced, resulting in a rise in the water level, which is also referred to as transversal stern wave."

[R.07], formerly p. 2, line 25 – p. 3, line 14: *Move and modify paragraph as suggested by the reviewer.*

We believe that the first sentence is required to clarify the scope of the paper. Yet, we can understand that the paragraphs benefit from streamlining. We thus moved the paragraph as by the reviewer suggested below the figure and agreed to the majority of modifications proposed by the reviewer.

> "This paper deals with the ~~ship-induced~~ drawdown of the primary wave system. The currents and waves generated by a moving ship can cause erosion of the foot and slope of the banks of a waterway, while the rapid drawdown can cause sliding or liquefaction of the banks (GBB, 2010). If the water level is lowered faster than the pore pressure in the soil can adapt to, in order to achieve a new hydrostatic equilibrium, excess pore pressure may develop (Köhler, 1989). The excess pore pressure leads to a reduced effective stress which lowers the shear strength of the soil. This may result in local slope sliding along a failure surface in the ground or soil liquefaction.
>
> The additional mass of the revetment increases the resistance of the bank against sliding failure and liquefaction. Therefore, while the hydraulic design defines the required armour stone diameter necessary to withstand waves and currents, the geotechnical design is critical to establish the armour layer thickness required to ensure local slope stability under ship-induced drawdowns (Rock Manual, 2007; GBB, 2010). In this study, the armour layer thickness required by geotechnical design is investigated, in the context of ship-induced drawdown in inland waterways."

[R.08], formerly p. 3, line 6: *I suppose it is possible but much less likely than erosion of the bank. Consider removing.*

Indeed, erosion of the bottom of a waterway is less likely to occur than of the slope. A fully dimensioned revetment at the bottom is rarely required. When we talk about protection of the "bottom", we are mainly referring to the toe of the bank, where armour stones serve as scour protection. We clarified the paragraph as follows:

> "The currents and waves generated by a moving ship can cause erosion of the foot and slope of the banks of a waterway, the rapid drawdown can cause sliding or liquefaction of the banks (GBB, 2010)."

[R.09], formerly p. 3, line 31:*Adjust paragraph as proposed.*

We slightly modified the proposed changes. The first proposed sentence was moved to a preceding section (see also [R.07]) as we believe it is important to emphasize the focus of this study at an early stage. The paragraph in question was adjusted as follows:

> "This study specifically investigates the effects of non-homogeneous vertical soil profiles on the required armour layer thickness."

[R.10], formerly p. 4, line 8: *Embankment vs bank. The paper uses these two terms interchangeably. In the context of an inland waterway, I believe bank is more appropriate, as embankments are usually built whereas banks are natural features.*

We agree that a clear terminology facilitates the comprehensibility of the paper. We thus agreed on using the term "bank" throughout the entire paper. The corresponding changes are marked in the document.

[R.11], formerly p. 4, line 28: *Should this be mentioned earlier in the Introduction?*

We agree that this information could be made available to the reader at an earlier stage. We thus moved the sentence to the Introduction.

> "Within the limitations of the infinite slope assumptions, the effects of a spatially variable friction angle and hydraulic conductivity are investigated by means of a 1D random field. Accounting for spatially variable soil parameters explicitly allows for an assessment of the level of safety obtained with current design approaches. In a parameter study that covers local and spatial variability, a deterministic benchmark solution and the results of the probabilistic random field analyses are compared. To ensure that the infinite slope assumptions are not violated, the investigations focus on the submerged part of the slope (GBB, 2010)."

[R.12], formerly p. 9, line 30: *I removed the word "rectangular" as I believe "trapezoidal" captures the geometry suggested.*

The term that is proposed by the reviewer is appropriate and increases the paper's comprehensibility. We therefore accepted the reviewer's revised wording.

> "The selected drawdowns are based on worst case assumptions regarding a ship passage in a waterway with a standard trapezoidal cross-section profile (MAR, 2008)."

[R.13], p. 14, line 4: *results?*

The sentence refers to the findings or results of the four case studies. For clarification we revised the wording as follows:

> "Since the findings of the four case studies (SU1, SU2, SW1 and SW2) do not differ significantly, in the following we only discuss the reliability as a function of the armour layer thickness for two case studies: the smallest (SW2) and largest required armour layer thickness (SU2)."

[R.14], formerly p. 15, line 11: *The previous section used the word "soil" and this section uses "ground". If they can be used interchangeably, I suggest we use one consistently throughout the document.*

We agree that a clear terminology facilitates the comprehensibility of the paper. The more generic terminology is “ground property”. But since we are only talking about soil, we modified the paper by using the term “soil property” throughout the entire paper. The corresponding changes are marked in the document.

2 Round 2 of review

2.1 Reviewer B comments

The manuscript of the article “On the design of bank revetments at inland waterways subjected to ship-induced water level drawdown: A probabilistic infinite slope analysis”, presents an interesting study on how friction angle and hydraulic conductivity affect the required armour layer thickness in bank revetments. The authors present their research rationale in Section 1, elaborate on the theoretical background of the methods used in Section 2, present their results in Sections 3-4, and follow with the discussion of said results and the conclusions drawn from this work in Sections 5-6.

This work deals with an issue of interest for hydraulic engineers, with clear focus to groundwater hydraulics and strong ties to geotechnical engineering. Some aspects of this work need to be presented in a more clear way, also considering that researchers not familiar with the BAW Code (GBB, 2010) would probably encounter difficulties understanding the methodological approach followed by the authors.

All in all: the content of this work falls within the scopes of the Journal; the manuscript’s structure is good and the use of English is at a high level; materials and methods are mostly well-presented; results are comprehensible; discussion and conclusions are coherent to the presented results. All the above with certain exceptions, as noted in remarks [R.01] to [R.07]. My recommendation for the specific manuscript is “Revisions Required” (according to JCHS classifications).

My remarks are to be found in the following; it is noted that page/line numbers are the ones of the available *.docx file.

Remarks

[R.01] General + Section 2.5 // As a hydraulic engineer, and since “ship-induced water level drawdown” is in this manuscript’s title, I would expect a somewhat more elaborate description of the effects ship-waves have on bank revetment stability and how these are eventually limited to the parametric analysis of Section 2.5. It is understandable that the authors follow the BAW Code approach; however, a clear description of the aspect mentioned above is missing and might lead to ambiguity. The authors should put some additional effort into this, highlighting the advantages and eventual limitations/shortcomings of their approach regarding ship-wave impacts. (Questions which might arise would include: Is there no distinction to be made between primary wave field, return flow and secondary wave field, and why? Do the worst-case assumptions about drawdown scenarios made in Section 2.5 cover a full investigation of the studied phenomenon and, if not entirely, what limitations/shortcomings does this create? Wouldn't a probabilistic approach about the drawdowns as well add to the attempted investigation?, etc.)

[R.02] P.5 • L.17-23 // What should readers perceive as "acceptable" approximation of the 2D problem by the 1D FED method? How does this affect this work's applicability to real-world cases of bank revetment design? Elaboration needed.

2.2 Authors responses to Reviewer B comments

First of all, we would like to thank the reviewer for the time and efforts taken to comment on our manuscript, which greatly assisted in improving the manuscript. We believe that we could clarify and include all issues raised by the reviewers adequately.

Please find attached a marked version of the manuscript, indicating the amendments performed. Detailed answers to the reviewer's comments are provided in this letter.

All changes made to the text are highlighted in the manuscript. The convention for our answers is as follows:

- *Reviewer comments are in italic Times New Roman.*
- Our replies in standard Times New Roman (black color).
- Quotation marks indicate excerpts from the manuscript.
- Refers to new text added to the manuscript
- ~~Refers to text deleted from the manuscript~~

In few cases, we made minor adjustments to the wording in order to make a sentence more concise or easier to follow, e. g., "Admittedly, the flow caused by a rapid drawdown" (p. 5, L19) was replaced by "Admittedly, the fluid flow in response to a rapid drawdown" (p. 5, L30). These minor changes are not outlined in this reply to the reviewers' comments, but highlighted in the text.

Moreover, although implemented correctly in our code, we discovered a minor mistake in the equations outlined in ***Section 2.2***. We thus revised eq. (10) and eq. (11).

"The governing balance equations for coupled flow deformation can be written as:

$$\nabla \cdot \boldsymbol{\sigma}' + \nabla p + \rho_m \boldsymbol{g} = 0 \tag{9}$$

$$\frac{n_s}{K'}\frac{\partial p}{\partial t} \; \cancel{\rho_m} + \nabla \cdot \frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot \boldsymbol{q} = 0 \tag{10}$$

where $\boldsymbol{\sigma}'$ is the effective stress, ρ_m is the density of mixture, ~~the~~ porous medium and fluid, $\boldsymbol{g}$ is the gravity vector, ~~and~~ $\boldsymbol{q}$ is the seepage velocity vector determined by Darcy's law, K' is the effective bulk modulus of the pore fluid and n_s is the porosity of the solid material ~~with $\boldsymbol{k}$ as the tensor of the hydraulic conductivity~~. ~~The change of ρ_m over time is a function of the effective bulk modulus of the pore fluid K', the porosity of the solid material n_s and the pore pressure.~~

$$\cancel{\frac{\partial \rho_m}{\partial t} = \frac{n_s}{K'}\frac{\partial p}{\partial t}} \tag{11}$$

The density of ~~the porous medium and fluid~~ ρ_m, see eq. (11), is the mixture density of the solid ρ_s, the water ρ_w and the gas ρ_g and the degree of saturation S which is the percentage of the void space filled with water

(Montenegro, 2016). The lower *S*, the more gas the water-gas mixture contains and, thus, the more compressible the mixture."

Comments:

***[R.01] General + Section 2.5** // As a hydraulic engineer, and since "ship-induced water level drawdown" is in this manuscript's title, I would expect a somewhat more elaborate description of the effects ship-waves have on bank revetment stability and how these are eventually limited to the parametric analysis of Section 2.5. It is understandable that the authors follow the BAW Code approach; however, a clear description of the aspect mentioned above is missing and might lead to ambiguity. The authors should put some additional effort into this, highlighting the advantages and eventual limitations/shortcomings of their approach regarding ship-wave impacts. (Questions which might arise would include: Is there no distinction to be made between primary wave field, return flow and secondary wave field, and why? Do the worst-case assumptions about drawdown scenarios made in Section 2.5 cover a full investigation of the studied phenomenon and, if not entirely, what limitations/shortcomings does this create? Wouldn't a probabilistic approach about the drawdowns as well add to the attempted investigation?, etc.)*

We agree with the reviewer that the effects ship-waves have on bank revetment stability could be elaborated in more detail. We therefore made the following amendments to the manuscript:

Section 1:

"When a vessel passes through the water in a waterway with a limited cross-section, a sequence of waves and currents is induced (see Figure 1). First, water accumulates in front of the vessel causing bow waves. The discharge conditions trigger a flow around the vessel from the bow to the stern, the so-called return flow (GBB, 2010) or return current (Rock Manual, 2007). The acceleration of the water flow velocity causes a lowering of the water level next to the vessel which is subsequently referred to as drawdown (e. g., Taylor et al., 2007; GBB, 2010). At the stern of the vessel, the flow conditions are re-balanced, which is associated with a rise in the water level, the so-called transversal stern wave. If the transversal stern wave breaks, transient pressure fluctuations and a current in the opposite direction to that of the vessel called the slope supply flow occur. The described sequence of bow wave, drawdown and stern wave is called the primary wave system. The secondary wave system consists of short period oblique and transverse waves. In contrast to the primary waves, the height of secondary waves remains approximately constant as the distance from the vessel increases (Gesing, 2010).

This paper deals with the ship-induced drawdown of the primary wave system. ~~The drawdown results from the cross section reduction by the vessel which causes an increase in flow velocity and, thereby, a lowering of the water level next to the vessel (Gesing, 2010). For the design of the armour layer thickness, the ship-induced drawdown is crucial (GBB, 2010).~~ While the currents and waves can cause erosion of the bottoms and banks of a canal or river, the rapid drawdown may result in sliding or liquefaction of the banks (GBB, 2010). If the water level is lowered faster than the pore pressure in the embankment soil can adapt to in order to achieve a new hydrostatic equilibrium, excess pore pressure may develop (Köhler, 1989). The excess pore pressure leads to a reduced effective stress which lowers the shear strength of the soil. This may result in a local slope sliding along a failure surface in the ground or soil liquefaction. The additional mass of the revetment increases the resistance of the embankment against sliding failure and liquefaction."

Section 2.5:

Moreover, we included a reference that explains why a probabilistic approach about the drawdowns is not appropriate at present and we provided additional information on the underlying assumptions used to approximate the ship-induced drawdown in our calculations. We added the following explanations:

"In the presented investigations $S = 85$ %, $E_S = 30$ MPa and $n_s = 0.45$ are specified as conservative estimates.

The duration t_a and height z_a of the drawdown, as well as the drawdown velocity ($v_a = z_a / t_a$) in combination with the hydraulic conductivity k, are the main factors that determine the development of the excess pore pressures (Köhler, 1989, 1997). At present, available field data do not allow approximating z_a and t_a by means of random variables. As shown in Sorgatz and Kayser (2021), who investigated the slope stability of a bank revetment with random t_a and z_a, drawdowns must always be considered as a combination of t_a and z_a as there is no significant correlation between these two parameters; otherwise the calculations will lead to disproportionately large armour layer thicknesses. In this paper, we therefore use selected drawdown combinations that follow the definitions in the German design standards (MAR, 2008; GBB, 2010). GBB (2010) provides analytical equations to determine ship-induced loads for different vessel types, sizes and geometries. MAR (2008) provides construction details and load scenarios for standard bank and bottom protections on inland waterways in Germany based on the GBB (2010) equations.

The selected drawdowns are based on worst case assumptions regarding a vessel passage in a standardised rectangular trapezoidal profile of a waterway cross-section (MAR, 2008). In MAR (2008) the design speed is set at 97 % of the critical vessel speed. This value takes account of the economic efficiency both in terms of the vessel's performance and the design of the revetment (MAR, 2008). Furthermore, it is assumed that the vessel passes the shore approximately 1 m over the toe of the embankment. ~~No distinction is made between bow and stern drawdown caused by the primary wave system.~~ From all load combinations available in MAR (2008), the most unfavourable are chosen based on a small parametric study."

Section 5:

The limitations of the GBB (2010) approach are now discussed in Section 5 (see also Comment R05).

"Since the definition of ship-induced loads follows that of GBB (2010), the herein presented investigations are mainly valid for the conditions covered in GBB (2010): waterways with predominantly parallel banks, with fairways confined both laterally and in depth, with depths that are virtually constant except in the vicinity of the banks (i.e. no berms) and with a maximum ratio of the water surface width to ship's length of around 2:1. The analytical equations comprise several simplification, e. g., for the calculation of hydraulic actions caused by recreational craft and craft with short stocky hulls, and for the decrease in wave height as the waves move away from a vessel. Furthermore, GBB (2010) is limited to single wave events. It does not account for a pressure accumulation due to successive wave attacks.

The length of the drawdown wave corresponds to the length of the ship (Gharbi et al., 2010) and the wave heights are a function of the ship speed and the ship's cross-section in relation to the waterway cross-section (GBB, 2010). Therefore, the investigated drawdown combinations represent only a small proportion of all possible load scenarios observable at a waterway. This simplification is justifiable, as this study primarily aims at illustrating the effects of spatially variable ground properties on the revetment design. In combination with the selected soil types, the selected drawdown combinations are worst-case scenarios for German inland waterways characterised by a standard geometry (see MAR, 2008), e g., the majority of the Dortmund-Ems Canal and the Wesel-Datteln Canal. The selected soil types with their properties cover a broad range of soils typical for Germany. However, for different waterway geometries as well as for different characteristic ground properties and variabilities the observed effects may be more or less pronounced. Thus, when considering a particular location for revetment design, additional investigations with local information are beneficial.

For the slope stability analyses, it is assumed that the secondary wave system does not contribute to slope sliding failure. In the case of inland waterways, this is a valid assumption as the inertia of the system means that the excess pore pressures caused by the short-period water level fluctuations of the secondary waves do not exceed the excess pore pressures caused by the primary waves due to the inertia of the system. Before the soil can react to the changes in water level, the water level in the canal has already returned to normal. However, as secondary waves can cause liquefaction on slopes with low inclination (GBB, 2010), additional stability calculations may be required for variations in slope geometry.

In addition, the current investigations do not take a toe support into account, which significantly reduces the required armour layer thickness due to the activation of additional supporting shear stresses."

***[R.02] P.5 • L.17-23** // What should readers perceive as "acceptable" approximation of the 2D problem by the 1D FED method? How does this affect this work's applicability to real-world cases of bank revetment design? Elaboration needed.*

We agree that the formulation "acceptable" approximation of the 2D problem may confuse the readers. We clarified the wording and added some lines in the discussion and conclusions section regarding the applicability to real-world cases.

Section 2.2:

"However, as demonstrated by Ewers et al. (2017), who compared the development of excess pore pressures in soils of different compressibility properties in a 1D finite element column model to that of a 2D finite element slope model, 1D and 2D computations of the spatial distribution of the excess pore pressure response to drawdown agree well when the resulting strains are small."

Section 5:

"The presented investigations illustrate the effects of a spatially variable friction angle and hydraulic conductivity on the revetment design for selected drawdown and ground property combinations. It allows a generic, non-site-specific analysis on how the spatial variability of ground properties affects revetment design. According to GBB (2010), the infinite slope model is the preferred choice for slope stability analyses in the context of revetment design. The representation of excess pore pressures over depth by means of a one-dimensional calculation also corresponds to the common design practice. Therefore, these approximations seem acceptable. Nevertheless, the applied methodology is not suitable for direct comparison with the existing German standard, since the excess pore pressures determined by an FE model based on Biot's approach (Biot, 1956) are different to the excess pore pressures calculated using the analytical approximation defined in the GBB (2010). However, the parameter study indicates a strong model sensitivity to the excess pore pressure profiles, which once more emphasises the significance of an accurate method to describe the development of the pore water pressures."

Section 6:

"Further investigations regarding the comparability of the target reliabilities available in current probabilistic design codes and the level of safety of the current design are required. Moreover, the investigations should consider the correlation between the soil parameters and the spatial variability of the elastic soil properties. To achieve an improved representation of the slope failure mechanisms, an extension towards two-dimensional pore pressure and slope stability analyses should be pursued. Finally, it is emphasised that further investigations of the probabilistic distribution of the loads are necessary in order to con-duct a fully probabilistic revetment design."

***[R.03] Use of the term "field"** // Since the term "field" - within the general context of bank revetment design - can be used to refer to either the flow field, wave field, or the banks' soil, it might be beneficial for the readers if some distinction was made.*

We reviewed the terminology and added if missing the specific field names as suggested by the reviewer.

p. 4 / L25:

"The unknowns ~~fields~~ are then the displacements $\boldsymbol{u}$ of the solid and the pore-fluid pressure p over the time t."

p. 5 / L17:

"As initial conditions we assume a vector field of zero displacements and a scalar field of hydrostatic pore pressures."

p. 6 / L5:

"The standard normal random field is next transformed to the appropriate distribution based on the mean μ and coefficient of variation (cov) of the variable being modelled."

***[R.04] Section 2.3 + Section 3.4/Fig.10** // Some elaboration and/or literature review is needed on why the* *"random field method" was selected to be used in this work. What added value does it bring to the investigation, and how does this value compare to the combined effect other assumptions have (e.g. infinite slope approach along with parametric worst-case drawdowns). Summarizing the influence of the studied parameters on randomly generated fields (Section 3.4 -Fig.10) is not intuitive and would merit some further elaboration.*

To address the reviewer's comment, we added information on our previous probabilistic investigations without random fields. Furthermore, we provided literature that shows that random fields are a common method to investigate the effects of spatially variable ground properties.

Section 2.3:

"In Sorgatz and Kayser (2021) the effects of the statistical uncertainty of ground properties on the geotechnical revetment design were investigated by means of uncertainty analyses with random, but spatially homogeneous variables. However, it is well known that soils are spatially variable. To investigate how spatial variability affects geotechnical behaviour, soils should be modelled as multidimensional multivariate randomly varying processes (ideally 3-dimensonal). This allows the investigation of questions such as "does the soil strength depend on the weakest link or on an average?" and "how does spatial variability affect the probability of failure?". Random fields are a common approach to model spatial variability (e. g., Baecher and Christian, 2003). In the case of the herein presented study, the spatial variability of ϕ' and k is modelled by means of two independent random fields."

Section 2.4:

Additional explanations were added to describe the effects of the random field on the revetment design more clearly. The figures were revised to depict the described processes more clearly. Furthermore, we included a generic figure (Figure 4) that corresponds to Figure 10 (formerly Figure 9) and that illustrates the effects of the revetment.

"Reviewing eq. (2) and eq. (4), it becomes clear that the application of the armour stones will increase the vertical overburden load and, thereby, stress and strength. However, whereas the shear stress τ rises proportionally with increasing overburden load, the shear strength $\bar{\tau}$ rises non-proportionally due to the multiplication of σ_n' by $\tan\phi'$, see eq. (5). The resulting difference between stress and strength requires more armour stones after initial equilibrium. Thus, the required armour stone layer thickness has to be found by means of iterative analyses.

Figure 4 demonstrates the function of the armour stone layer. The limit state function and the shear strength are shifted from the negative, unsafe region to the positive, safe region while the excess pore pressure does not change. For a "safe" structure the limit state function is not allowed to cross the vertical dashed line towards the left. The smaller g_{min} and the closer d_{crit} towards the surface, the more revetment is required to "push" g_{min} towards the safe region. Moreover, as observed in Figure 4, the formulation of the model allows for negative values of the shear strength. It is emphasised that the model itself is a theoretical construct and that a slope without any armour stone layer subjected to the design drawdown will certainly fail.

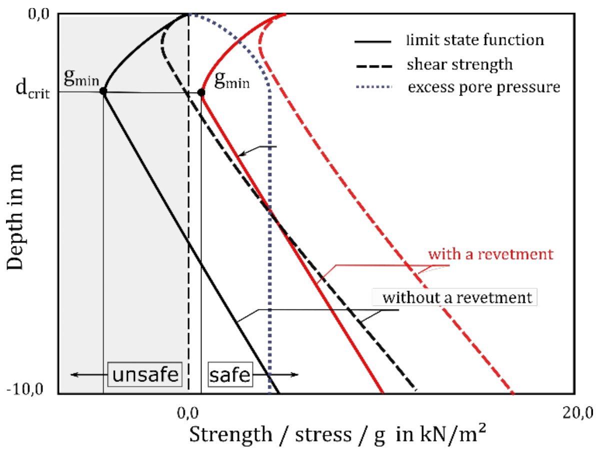

Figure 4: Limit state function and stress and strength profiles with and without revetment"

Section 3.4:

"The consideration of vertically heterogeneous ϕ' and *k* leads to two competing mechanisms. While areas of larger ϕ' increase the stability of the embankment and thus require less armour stones, the presence of smaller *k* leads to larger excess pore pressures and thereby to a thicker required armour stone layer. These observations can be best explained by Figure 4 and Figure 10. Figure 10 displays the stress, strength, excess pore pressure and limit state profiles over depth with the corresponding random fields for a best-case and a worst-case simulation of the sand and the silty sand. Naturally, larger excess pore pressures occur in the presence of low values of *k*. A worst case scenario is characterised by a low *k* (and a low ϕ') close to the surface; conversely, a higher *k* close to the surface leads to smaller excess pore pressures in the area close to the surface.

Considering once more Figure 4 and eq. (14), the required armour layer thickness is determined by g_{min}. In particular, when geotechnical units of low *k* and a thickness greater 0.25 m are located close to the surface, large excess pore pressures can occur as indicated by the dotted lines in Figure 10. As a result of the excess pore pressures the effective shear strength depicted by the dashed lines in Figure 10 decreases. The solid plotted limit state function, the difference between effective shear strength and shear stress, then moves towards the left unsafe region (cf. Figure 4). In the case of a low overburden weight of the soil close to the surface, this can only be compensated by a larger ϕ', which will increase the effective shear strength (cf. eq. (5)). In areas of larger ϕ', it is thus more likely that the maximum excess pore pressure can be compensated by the material strength. As a consequence, for revetment design, subsoil investigations and subsequent stability analyses should pay special attention to the variability of *k* and ϕ', in particular close to the surface."

Section 5:

We agree that the paper can benefit from a discussion on how the value of the newly introduced random fields compares to the combined effect introduced by other assumptions. The discussion section was thus supplemented to emphasize the more generic aim of our study.

"The presented investigations illustrate the effects of a spatially variable friction angle and hydraulic conductivity on the revetment design for selected drawdown and ground property combinations. It allows a generic, non-site-specific analysis on how spatial variability of ground properties affects revetment design."

[R.05] P.8 • L.10-14 (see also [R.01] + Sections 5-6 // *Following the rationale of* ***[R.01]****, elaboration is needed about the drawdown scenarios' selection (typical single case, no distinction between bow/stern drawdown, etc.), and the effect this investigation choice has on the validity of the conclusions drawn from this work in the wider context of bank revetment design.*

Firstly, we tried to clarify the scope of the investigations in the introductory section:

Section 1:

"This paper investigates the effects of non-homogeneous vertical soil profiles on the required armour layer thickness. For this purpose, an infinite slope model was modified to account for ship-induced drawdowns, resulting excess pore pressures and the armour layer. The investigated drawdown combinations represent only a small proportion of all possible load scenarios observable at a waterway as this study primarily aims at illustrating the effects of spatially variable ground properties on the revetment design. Within the limitations of the infinite slope assumptions, the effects of a spatially variable friction angle and hydraulic conductivity are investigated by means of a 1D random field."

Admittedly, we differentiated between bow and stern drawdown as we considered a small, but fast drawdown (bow, case studies denoted by "1") and a large, slower drawdown (stern, case studies denoted by "2"). Secondly, we thus outlined the selection criteria for the chosen worst-case load scenarios and explained the two drawdown scenarios by adding the following lines:

Section 2.5:

"In the presented investigations S = 85 %, E_S = 30 MPa and n_s = 0.45 are specified as conservative estimates.

The duration t_a and height z_a of the drawdown, as well as the drawdown velocity ($v_a = z_a / t_a$) in combination with the hydraulic conductivity k, are the main factors that determine the development of the excess pore pressures (Köhler, 1989, 1997). At present, available field data do not allow approximating z_a and t_a by means of random variables. As shown in Sorgatz and Kayser (2021), who investigated the slope stability of a bank revetment with random t_a and z_a, drawdowns must always be considered as a combination of t_a and z_a as there is no significant correlation between these two parameters; otherwise the calculations will lead to disproportionately large armour layer thicknesses. In this paper, we therefore use selected drawdown combinations that follow the definitions in the German design standards (MAR, 2008; GBB, 2010). GBB (2010) provides analytical equations to determine ship-induced loads for different vessel types, sizes and geometries. MAR (2008) provides construction details and load scenarios for standard bank and bottom protections on inland waterways in Germany based on the GBB (2010) equations.

The selected drawdowns are based on worst case assumptions regarding a vessel passage in a standardised rectangular trapezoidal profile of a waterway cross-section (MAR, 2008). In MAR (2008) the design speed is set at 97 % of the critical vessel speed. This value takes account of the economic efficiency both in terms of the vessel's performance and the design of the revetment (MAR, 2008). Furthermore, it is assumed that the vessel passes the shore approximately 1 m over the toe of the embankment. ~~No distinction is made between bow and stern drawdown caused by the primary wave system.~~ From all load combinations available in MAR (2008), the most unfavourable are chosen based on a small parametric study. For this purpose, the design drawdown pairs (z_a, t_a) summarised in MAR (2008) are used to compute the excess pore pressures in a homogeneous soil (SW, SU) with random ϕ' and c'. Subsequently, the two drawdowns that yielded the largest excess pore pressures were chosen for the parametric study: a small, but fast drawdown (bow drawdown, case studies denoted by "1") and a large, but slower drawdown (stern drawdown, case studies denoted by "2"). Combining the load combinations and soil types, the four representative case studies summarised in Table 1 are investigated."

Section 5:

The validity of the conclusions drawn from this drawdown selection in the wider context of bank revetment design is now discussed in the following paragraph in Section 5:

"Since the definition of ship-induced loads follows that of GBB (2010), the herein presented investigations are mainly valid for the conditions covered in GBB (2010): waterways with predominantly parallel banks, with fairways confined both laterally and in depth, with depths that are virtually constant except in the vicinity of the banks (i.e. no berms) and with a maximum ratio of the water surface width to ship's length of around 2:1. The analytical equations comprise several simplification, e.g., for the calculation of hydraulic actions caused by recreational craft and craft with short stocky hulls, and for the decrease in wave height as the waves move away from a vessel. Furthermore, GBB (2010) is limited to single wave events. It does not account for a pressure accumulation due to successive wave attacks.

The length of the drawdown wave corresponds to the length of the ship (Gharbi et al., 2010) and the wave heights are a function of the ship speed and the ship's cross-section in relation to the waterway cross-section (GBB, 2010). Therefore, the investigated drawdown combinations represent only a small proportion of all possible load scenarios observable at a waterway. This simplification is justifiable, as this study primarily aims at illustrating the effects of spatially variable ground properties on the revetment design. In combination with the selected soil types, the selected drawdown combinations are worst-case scenarios for German inland waterways characterised by a standard geometry (see MAR, 2008), e g., the majority of the Dortmund-Ems Canal and the Wesel-Datteln Canal. The selected soil types with their properties cover a broad range of soils typical for Germany. However, for different waterway geometries as well as for different characteristic ground properties and variabilities the observed effects may be more or less pronounced. Thus, when considering a particular location for revetment design, additional investigations with local information are beneficial.

For the slope stability analyses, it is assumed that the secondary wave system does not contribute to slope sliding failure. In the case of inland waterways, this is a valid assumption as the inertia of the system means that the excess pore pressures caused by the short-period water level fluctuations of the secondary waves do not exceed the excess pore pressures caused by the primary waves due to the inertia of the system. Before the soil can react to the changes in water level, the water level in the canal has already returned to normal. However, as secondary waves can cause liquefaction on slopes with low inclination (GBB, 2010), additional stability calculations may be required for variations in slope geometry.

In addition, the current investigations do not take a toe support into account, which significantly reduces the required armour layer thickness due to the activation of additional supporting shear stresses."

[R.06] P.12 • L.9-13 *// Elaboration is needed on the selection of solely SW2 and SU2 case studies.*

In our investigations we covered all four case studies. However, since the effects do not differ significantly between the two in the paper presented case studies and the omitted case studies, we decided to omit the SU1 / SW1 case studies in the paper. To clarify this issue for the readers, we revised the paper as follows:

Section 4:

"The design or assessment of a revetment may target a specific reliability. The reliability of the revetment is a function of the drawdown, the slope inclination, the soil parameters and the armour layer thickness. Since the effects between the four case studies (SU1, SU2, SW1 and SW2) do not differ significantly, in the following we only discuss the reliability as a function of the armour layer thickness of two case studies, the smallest (SW2) and largest required armour layer thickness (SU2). ~~Since drawdown, geometry and soil parameters are commonly defined on the basis of available field information, the representative parameter sets of case studies SW2 and SU2 are selected to investigate the reliability as a function of the armour layer thickness.~~ Each of the two case studies is investigated the following combinations:"

[R.07] Figs.6-7-8-10 *// The authors should consider changing the markers for SW case studies in Figs.6-7-8. The distinction between circles and squares is hard to make, especially when markers are close to one another (doable only >120% zoom on a screen - would probably be really hard to make in print). The same applies to the markers in Fig.10.*

As suggested by the reviewer we revised the figures and changed the marker symbols and their size to increase readability.