Reply to Review Comments

Dear Editors:

Thank you for seeing our effort and helping us further improve the manuscript, "Soil infiltration characteristics and pore distribution under freezing-thawing conditions", which was invited for revision in The Cryosphere. We really appreciate your thoughtful comments. We have taken these comments to heart and substantially improved our manuscript in response to the review comments we received.

In summary:

1) We acknowledged the limitations of the relevant fundamental theory and materials.
2) We added the data of soil porosity and pre-freezing moisture content of samples.
3) We showed the unfrozen water content and ice content of the frozen samples.
4) We revised formatting and detail mistakes based on comments of reviewers.
5) We conducted a detailed self-review, and the revised manuscript was re-polished by a professional institution.

Below, please find a detailed set of responses to specific comments. We referred to the most related lines in the unmarked version of the manuscript. If there is anything else you feel needs to be revised, please feel free to contact us.

Comments from Referee #1: Mohammed, Aaron

Comments: An assumption underpinning the authors' tension infiltration analysis is the assumption that larger pores only flow fully saturated (no air-water interface inside the pore) and excludes the formation of an air-water interface with flowing water in larger pores. Recent work has shown this flow mode does indeed occur (see the multitude of works by Drs. John Nimmo and Peter Germann). It would be nice for the authors to acknowledge these limitations in their work.

Response: We added the assumptions and limitations of large pore flow in Discussion, which can be seen in L355-359.

Comments: What was the pre-freezing soil moisture content of the samples? You should show this data.

Response: These data are now presented in Table 2, in L141.

Comments: What was the porosity of the samples? If the pre-freezing volumetric moisture content was 0.3 as the authors suggest (should state more explicitly), then when frozen that will result in relatively high content if the soil porosity is say…0.4 to 0.45. The authors need to clarify and discuss this.

Response: The data of soil porosity were also placed in Table 2.

Comments: How was the pre-freezing moisture content held consistent between samples, and after BF tests?

Response: For each of the four temperature treatments, at least three soil columns were made for each soil type. We made over 40 soil columns in total, and the columns that were subjected to the BF tests were not subjected to other treatments. We explained this in L131.

Comments: In unfrozen tension infiltrometer experiments, the soil moisture is assumed to be that imposed by the applied tension. If samples were frozen before infiltrometer experiments, then is it assumed that the applied tension then only affects the pores that are active during infiltration?

Response: As shown in Table 2, the water content of the soil had been unified to about 0.30 before the infiltration experiments. We believe that after the freezing of the soil, the infiltration process is mainly influenced by the pores that have not been blocked by ice crystals.

Comments: How was the pre-freeing water content controlled?

Response: Each soil column was treated with only one type of temperature treatment test, so the pre-freeze water content of each soil column is approximately the same, controlled at about 0.3.

Comments: L51: Inappropriate reference, the review paper of Jarvis (2016) hardly mentions frozen soil dynamics, other than we do not understand it enough.

Response: Another review paper of Hayashi (2013) was cited here as a reference.

Comments: L56: 'characterization of freezing-thawing soil infiltration' sounds awkward. Do you mean infiltration into freezing/thawing soils?

Response: It has been changed to 'quantitative studies of the infiltration process in freezing-thawing soils.'

Comments: L60: Daniel et al (1997) should be Stadler et al. (1997). Could also cite some other field studies on frozen soil infiltration and deeper soil percolation and refreezing effects, such as Hayashi et al (2003) and Mohammed et al. (2019).

Response: We corrected the author's name of the reference and cited the recommended papers, it can be seen in L59-62.

Comments: L71-73: Zhao et al. (2013) did not introduce the 'impedance concept', it was proposed far earlier, at least as early as Jame and Norum (1980).

Response: Sorry to have confused you again. We only mean that the method used by Zhao in his article is related to the impedance coefficient; we do not consider the 'impedance concept' to have been proposed by Zhao.

Comments: L75: 'results in hydraulic conductivity estimation'… confusing, can the authors clarify?

Response: It has been changed to 'results in an overestimation of hydraulic conductivity.'

<u>Comments</u>: L89: What does the authors mean by 'freezing profiles'? Do you mean the soil freezing characteristic?

<u>Response</u>: Yes, the 'freezing profiles' has been changed to the 'soil freezing characteristic curves.'

<u>Comments</u>: L152: Authors should state clearly that pure water was used as the infiltration solution for the unfrozen experiments. Also were the samples gravity drained after the unfrozen test? Were the samples adjusted to ensure consistent pre-freezing soil moisture among samples?

<u>Response</u>: The infiltration solution for the unfrozen experiments we used is still deionized water; this was stated clearly, as can be seen in L157. As we have mentioned before, all soil columns were subjected to only one temperature treatment test, so there is no need to adjust the pre-freezing soil moisture.

<u>Comments</u>: L279: What do the authors mean by saturated water content of the frozen soil? Weren't all the samples unsaturated, so how then can there be a saturated water content?

<u>Response</u>: Here has been revised to 'because the unfrozen water content and saturated hydraulic conductivity were low after the soil freezing', now it can be seen in L289.

<u>Comments</u>: L282-289: Was there any correlation between the amount of decrease in hydraulic conductivity from -5°C to -10°C and clay content or organic matter content among the soil samples?

<u>Response</u>: As we stated in L327-328, we also believe that some specific experimental phenomena may be related to the higher organic matter content or clay content of black soils. However, we did not do any further research on these and nor did we find any suitable references to support this point, so we did not discuss it.

<u>Comments</u>: L322-341: This is fascinating, and in my opinion, is the most novel part of this study. But this is conjecture, and there are quantitative ways to examine soil structure before and after freezing, see for example Holten et al. (2018) and Ding et al. (2019), who actually apply geophysical imaging techniques to quantity pore structure in relation to frozen soil infiltration.

Response: I also think this is the most valuable part of our study. Geophysical imaging techniques are indeed an effective method, and our department is in the process of purchasing an NMR analyzer for soil research. However, these instruments are often expensive and difficult to carry around. The tension infiltrometer used in this article is affordable and widely used, and we believe that this article can provide an important reference for its use in winter field tests.

Comments: L353: I agree, but you need to show those water and ice contents of the soil samples.

Response: Unfrozen water contents and ice contents of the soil samples were listed in Table 5, L245.

Comments: L368-372: Not sure I agree with this statement, as your data contradicts it, and at atmospheric pressure, air-filled macropores will conduct most water, regardless of antecedent moisture.

Response: Despite the fact that air-filled macropores will conduct most of the water, the freezing of the soil moisture could considerably change the arrangement and bonding of the soil particles and thus change the soil structure (Bullock et al. 2001). Freezing and thawing could also lead to the mechanical fragmentation of coarse soil particles and the aggregation of fine soil particles (Zhang et al. 2016). Therefore, the pore connectivity and hydraulic conductivity of freezing and thawing soils will also be affected.

Relevant references

Bullock M S , Larney F J , R.César Izaurralde, et al. Overwinter Changes in Wind Erodibility of Clay Loam Soils in Southern Alberta[J]. Soil ence Society of America Journal, 2001, 65(2):423-430. Ze Z , Wei M A , Wenjie F , et al. Reconstruction of Soil

Particle Composition During Freeze-Thaw Cycling: A Review[J]. Pedosphere 26:167–179.

<u>Comments</u>: L376-403: I have a few issues with the discussion in this section, mostly because of a point that the authors themselves bring up…that these experiments were performed on repacked, air-dried samples. So, although they cite other studies that show that macropores may still play a role in re-packed soil samples, they did not show so in their own data. Also, the notion that macroporosity is decreased after freezing goes against other experimental studies that explicitly investigate the effect of multiple freeze-thaw cycles on soil structure (Ding et al., 2019). This may be an artifact of the fact that this was the first freeze-thaw cycle after the sample was repacked.

<u>Response</u>: We believe that the data in Figures 6 and 7 about the number of pores, the effective porosity, and the percentage of the pore flow in the saturated flow have been able to show that macropores may still play a role in re-packed soil samples. The macroporosity did decrease after freezing, but the thawed soil had a higher porosity and a greater number of pores of different sizes compared to unfrozen soil, which does not conflict with the study (Ding et al., 2019) whose conclusion is 'FTCs resulted in larger pores and more small pores maintaining high infiltration'. In addition, the research methods used in this article are significantly different from ours, for example, prior to the start of each FTC, the injection solution was added from the top into the soil column to the point of saturation. Indeed, just as you suggest, it is possible that our conclusions may be an artifact of the fact that this was the first freeze-thaw cycle after the sample was repacked, so this speculation was added to the discussion, can be seen in L411-412.

Comments from Anonymous Referee #2

<u>Comments</u>: My main concern about the manuscript regards how the results can be related to infiltration of water in soil, as the solution used here has different properties from water (e.g. viscosity). Are the presented values of estimated hydraulic conductivity for the glycol solution or for water? It would be most helpful to present values for water, or perhaps permeability values rather than hydraulic conductivity values.

<u>Response</u>: The estimated hydraulic conductivity of frozen soil is considered for the glycol solution, and the hydraulic conductivity of unfrozen soil is considered for the water. The saturated hydraulic conductivity can reflect the permeability of the soil to some extent, and the values of saturated hydraulic conductivity are given in Table 4. Values for water of frozen samples as shown in Table 5. In addition, the use of ethylene glycol aqueous solution in frozen soil infiltration can minimize the effect of ice crystal erosion, except for comparison with the hydraulic conductivity of unfrozen soils, the main use of these unsaturated hydraulic conductivities is to calculate the soil pore distribution. The use of ethylene glycol aqueous solution is feasible in the experimental method, but if applied to real soil water model requires subsequent in-depth study, in the discussion section we added about the limitations, can be seen in L418-421. This suggestion will be the direction of our future efforts, we believe that a field experiment or an in-situ soils for indoor freezing tests would be more useful to research the relevant issues.

<u>Comments</u>: Clarification of the water content of samples is needed to understand how these freezing processes can be related to freezing of soil in field conditions. Is there water in the samples before the solution is added, and if so how much? Is it the water (which was already in the soil before addition of solution) that freezes in the soil pores or is it the added solution that partly freezes?

<u>Response</u>: The water content of the soil sample is given in the main text, as seen in L136. The pre-freezing water content of the soil column was preset to 0.3, and after the column was filled, the sensor showed a moisture content in the range of 0.30 ± 0.02. These data are now presented in Table 2

<u>Comments</u>: L20-24: The sentence seems incomplete.

<u>Response</u>: As you suggest, the statement here is indeed incomplete. The expression was changed to 'black soils, meadow soils and chernozem were selected as test subjects.'

<u>Comments</u>: L26: Replace first comma with "and". Throughout, insert space after semicolon when several references are listed within a parenthesis.

<u>Response</u>: Punctuation issues has been corrected.

<u>Comments</u>: Table 1. What are the soil textures for meadow and chernozem soils?

<u>Response</u>: We have identified the cause of the format conversion problem during submission. The soil textures of the meadow and chernozem soils are both silt loam. Now, they have been correctly presented.

<u>Comments</u>: L188-189: Remove subscript format from reference.

<u>Response</u>: Formatting issues has been corrected.

<u>Comments</u>: Methods: What was the initial water content of samples? Was water or the aqueous solution used for the experiments, or both? How much of the liquid was frozen?

<u>Response</u>: The initial water content of the samples was 0.3, and water and aqueous solutions were both used for the experiments. In a supplemental experiment, we used an electric drill to collect soil samples and then dried them. Unfrozen water contents and ice contents of the soil samples were listed in Table 5, L245.

<u>Comments</u>: Big difference in viscosity for water and the aqueous solution. So conductivity is for this solution and not for water – should be converted to water?

<u>Response</u>: The hydraulic conductivity in frozen soil is for glycol solution, and that in unfrozen soil is determined for water.

<u>Comments</u>: Figures 3 and 4 – are both needed? Don't they more or less show the same thing?

<u>Response</u>: Figures 3 and 4 do have similarities, but cumulative infiltration and infiltration rate are different concepts, and we believe they provide a more complete reflection of the changes in soil infiltration capacity.

<u>Comments</u>: L45: Do you mean figures 3 and 4?

<u>Response</u>: Figure 4 represents the infiltration rate over time under the different treatments. The unsaturated hydraulic conductivity is shown in Figure 5, and the saturated hydraulic conductivity is given in Table 6.

<u>Comments</u>: Figure 5 would benefit from a more detailed description and discussion in text. There is a lot of information in this figure and I cannot distinguish 12 separate lines in each plot. What is really unsaturated hydraulic conductivity and why is this included? Hydraulic conductivity should vary with saturation, but is there a fixed level of saturation and if so, what saturation level is this?

<u>Response</u>: Figure 5 has been modified, the previous legend had an error, there are only 8 separate lines in each plot. The saturation of the soil changed significantly after freezing, and the saturated hydraulic conductivity better reflected the relevant issues.

<u>Comments</u>: L273: What is meant by "stable frozen"? Is all water/liquid turned to ice at this temperature?

<u>Response</u>: The stable frozen state usually indicates that no drastic changes in temperature and water content occur.

<u>Comments</u>: Check Y axis title Fig 6: is there any uncertainty related to these estimates?

<u>Response</u>: The Y-axis of the internal expansion chart was standardized to scientific notation.