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Interactive comment on "Combined numerical and experimental study of microstructure and permeability in porous granular media" *by* Philipp Eichheimer et al.

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Response to comments of Kirill Gerke on the manuscript "Combined numerical and experimental study of microstructure and permeability in porous granular media" by Philipp Eichheimer et al., se-2019-199.

We thank Kirill Gerke for his great review. His constructive and useful comments that helped us to improve our manuscript.

Please find below a point by point response to the comments (comments of the reviewer in black and our response in blue).

Sincerely,
Philipp Eichheimer on behalf of the authors

The paper is interesting and follows logically from the previous paper of the same main Author. If I understood correctly, the paper was not accepted for review by 3 potential reviewers and for this reason finally ended up with me (again). I found the idea of lab experiment and pore-scale simulations to be very relevant, we do lack such studies. But while reading this manuscript more deeply i was somewhat taken aback by Kozeny-Carman relationships the Authors use. While I find lab vs. modelling work to be very important and do support this paper to be published with SE (after some re- branding), i regret to say that I have a major point of criticism here as well. It really puzzles me why would modern researchers utilize Kozeny-Carman relationship and why everybody at some point want to establish some kind of K-C relationship? How useful is that? We know very well already that what works for spheres does not work for real porous media samples. Moreover, the concept of hydraulic tortuosity, while still popular, provides very low information bulk measure of flow velocity field (as Authors show depending on the methodology to compute tau, the results are quite different). It may be so that computed tau values are interesting to show that they are different from previously computed, this again provides close to zero scientific value. So, while Authors proposed a "novel" Kozeny-Carman model, my question – how is it even useful, practical or simply scientifically valuable? This puts the conclusion for this work into a state of not really going anywhere. If compared against lab measurements or simulations K-C produces orders of magnitude errors, as is evident from your figures. To relate to previous results for spheres or another K-C relationship you could refer to: Martys, N. S., Torquato, S., & Bentz, D. P. (1994). Universal scaling of fluid permeability for sphere packings. Physical Review E, 50(1), 403. Garcia, X., Akanji, L. T., Blunt, M. J., Matthai, S. K., & Latham, J. P. (2009). Numerical study of the effects of particle shape and polydispersity on permeability. Physical Review E, 80(2), 021304. Now, around lines 270-275 you discuss why the results of permeability for simulations are different from these of lab measured values. While you mention that size and boundary effects could influence your results (for such small volumes i would warily estimate an error due to boundary condition to be up to 20-50%, and in this regard you could refer to Gerke, K. M., Karsanina, M. V., & Katsman, R. (2019). Calculation of tensorial flow properties on pore level: Exploring the influence of boundary conditions on the per- meability of three-dimensional stochastic reconstructions. Physical Review E, 100(5), 053312), i think the main reason is different. As you can see from figure 2 you have very high porosity contrast along z-axis. Now, if you have 0.05 porosity down there – this part will dominate the porosity for the whole sample. This makes sense, as you lab values are always lower. What i would do with your (really good!) data? I would leave all this K-C and tortuosity thing, but rewrite it as not useful and your data clearly shows that (which is, again, good). Now, you could assemble all these small pieces of 3D images you modelled with FDM solver into a 3d matrix of permeability values and upscale it (as simply as harmonic means should do the trick i suppose) to compare again the lab. This could lead to something interesting – at least you would be able to show how different model and lab values are. You could use these simple upscaling schemes as inspiration: Jang, J., Narsilio, G. A., & Santamarina, J.

C. (2011). Hydraulic conductivity in spatially varying media - a pore-scale investigation. Geophysical journal international, 184(3), 1167-1179. With this little addition you paper could be completely rebranded from meaningless K-C to something really relevant to our field (kind of full core comparison between lab and modelling). Hope this helps and does not introduce too much addition work. Otherwise it is very hard for me to accept the paper as is - i think we have to automatically reject all papers dealing with K-C (just because it is wasting of time, money, pages, you name it).

Thank you for your detailed comment regarding the usage of the Kozeny-Carman relation. We rebranded and restructured our manu-script as suggested in your comment to not only focus on the Kozeny-Carman relation. We refrained from completely removing the Kozeny-Carman equation from the paper, as it is still frequently used in different scientific areas.

Instead, we now evaluate different published permeability parameterizations. We find that the modified Kozeny-Carman equation and the parameterization by Martys et al., 1994 provide a similarly good fit to the numerical and experimental permeability values, but also that they fail to capture second-order microstructural effects.

We also incorporated your comment on permeability upscaling and now report permeabilities not per subsample, but as the geometric mean of all subsamples.

In the methods section we now also discuss your comment regarding the minimum effective porosity controlling the permeability entire sample and modified figure 5 to account for the minimum effective porosity. We decided to keep the results on hydraulic tortuosity in the manuscript as the parameter of hydraulic tortuosity is quite important not only for the Kozeny-Carman relation but is highly interesting for several engineering disciplines.

1. Table 1 – is porosity measured (as computed from mass and volume?) or computed from images? How A is computed? Do all samples have the same trends in porosity as in Fig.2, if so, does porosity represent an average for the whole cylinder?

   1) The porosity in our study is computed from the obtained CT-images only. An experimental technique using a pycnometer, as suggested by reviewer #2, is not possible as we do not have access to such a device.
   2) The cross-sectional area A we used to determine permeability is obtained using ImageJ.
   3) Nearly all samples show a densification trend in porosity. Only samples with very low porosity do not show densification. Reported porosities are averages for the whole cylinder. We now also report the minimum effective porosity for each sample.

2. 2.6 – do you state that you use phi_eff for all later computations as porosity? If so, please, make it easier to guess.

   Thank you for this remark. We now state this issue more clearly (Page 8, line 160 ff.).

3. 2.7 – how do you compute the area? By voxel counting and summarizing the interface as voxel faces?

   We computed the area of an isosurface from the CT images using MatLab. In detail we compute an isosurface of the binary images and then the area of the resulting isosurface.

4. Eq.10-11 and Eq.12 utilize different V_b and V_B values but i guess refer to the same volume.

   We corrected the equations.

5. Not clear why you report Eq.14-17 if you use Eq.13 (which seems to me to be superior as it calculates hydraulic tortuosity using streamlines instead of lausy porosity-based relationships).

   As the computation and interpretation of the hydraulic tortuosity is still under debate we wanted to give a brief overview for the reader, which relations have been proposed by other authors to which we compare our results later in figure 4. We specifically wanted to show that the porosity-based relationships do not perform well compared to our data.

6. 3.2 – your model is basically the same as of Koponen. The scatter is huge, is there any point in using such relationships? (Later I see you also substitute the points instead of this relationship, but I do not see the difference between them, is there any?)

   This is a good point. We now only use the arithmetic average of the tortuosity as an input for the Kozeny-Carman equation. We also noted that using either a fit to the porosity-tortuosity relationship by Koponen or an arithmetic average only have a minor effect on predicted permeabilities. However, as hydraulic tortuosity itself (besides its potential effect on permeability) is of interest in different scientific fields, we think it is important to report our results here.

7. Eq.23 have simply tau, not tau_H (as i guess it should be?).

   We corrected this mistake.

8. around line 230: sorry, but i could not follow your explanation of critical exponent through, including this paragraph and also appendix D. How did you evaluated phi_c?

   We based the critical porosity threshold on porosity measurements of the samples used in our study. By systematically analyzing each sample we observed that for samples below 1% porosity we did not find any connected cluster, while samples with porosities slightly higher than 1% contained a percolating cluster. For this reason, we employed a critical porosity threshold of 0.01 instead of the published value of 0.03. As the additional description provided in Appendix D was not specifically concerned with this issue, but rather with a general explanation on why a critical porosity threshold exists, we chose to remove the appendix and the corresponding figure, as this caused too much confusion.

9. Could you, please, also describe the sample preparation procedure a bit more, in particular how do you wrap it into resin? I could not get it completely from the current description.

   Thank you for your comment. In a first step we wrap the sintered glass bead sample into a high viscous resin. This can be done as this resin has a very high viscosity and can be deformed by hand. For this reason the sintered glass bead sample is literally wrapped or rolled into the resin. Just the top and bottom surface, which are needed for the experimental permeability measurements are left open. After drying, the glass bead sample with the attached highly viscous resin is embedded into a low viscous resin to create a surface, which can be sealed during the experiments. To avoid any leaks between the sample and the attached O-rings of the permeameter, both surfaces, top and bottom, are polished.