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Interactive comment on "X-ray CT analysis of pore structure in sand" *by* Toshifumi Mukunoki et al.

Anonymous Referee #1

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Thank you very much for this paper. It match's perfect into the scope of the special issue in Solid Earth. General comments: The paper reports a XCT analysis of pore structure in a natural sand, compare proposed image analysis results with experimental water retention curve and discuss this in respect to REV of pore space. Mostly all details of developed and used methods are described (later follows some remarks and questions) and the application for this case study are demonstrated and discussed. Although the content and nice work presented in this paper, but it needs a major revision. But now looking more into details, first some remarks to the general structure of the presented paper and general questions: The paper overall is a bit "over-structured", some chapters contains short and large sub-chapters with sometimes similar content. Also several different kind of numerations lists (called step 1,2 . . . and other enumerations) hampers fluent reading and capturing the content. In the Introduction and also in the Discussion chapter, often a lot of literature is only numerate and it is not clear, who is doing what, except the reader knows the cited papers and authors. Better is

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Discussion paper

to rearrange citations and relate directly as reference for the field of research for example (specially p2,l4-6 and p2,l28-p3,l1). Same thing, but here it is better written in p13, l16-33). In general: many groups recently working in the field of pore scale imaging, pore morphology approaches and experiments, discussing REVs and a lot of work are published. I missing some recent citations (e.g. Hilfer et al., 2015 for multiphase REVs and length scales or very similar to you a work from Yang et al., Extraction of pore-morphology and capillary pressure curves from porous media from synchrotron-based tomography data, Scientific Reports, 5:10635, DOI: 10.1038/srep10635, 2015, and others ... The pore-morphology methods are meanwhile highly developed and include drainage and imbibition with different contact angels in complex geometries and realized in software packages (like GeoDict, see geodict.com). It would be nice to demonstrate more your approach of your combined image processing and pore-morphology methods, specially your combination of GIA and VPM looks interesting As we see in many publications, the development of interfacial area between different phases in multiphase flow (experiments and simulations) plays a fundamental rule in this topic. Multiphase flow processes deliver other REVs (and length scales) as “only” single phase or static systems (see Hilfer et al.). I missing here a discussion.

The material: you use Toyoura sand: on p4,l22-23 you give the number of dry density and porosity. What is the mineralogy of the sand? In Fig. 7a you can clearly see, there are different mineral phases. It would be also useful to have a grain size distribution curve (from sieving experiment) and if available some more sedimentological data about this sand (like grain shape analysis which have a lot of impact to pore space geometry) and compare this with your image analysis tools. In general: your image analysis implies that the pore structure (grain packing) is not changed over time (e.g. during compaction). You are sure, that in the water retention experiment compaction was not happened? You did only one experiment? Figures: The paper contains 24 figures! I think this is too much and should be reduced. E.g. figure 1 and figure 5 (illustration of sphere packings) is trivial and not necessary to show, also the figure 3 showing the CT scanner is not necessary. Also better would be a combination of fig. 4

and 14, as the experimental setup. The ordering of the figures should have rearranged. Better is to start with an CT reconstructed raw image (like fig. 7) and demonstrate, how the Toyoura sand is composed and represented as a XCT scan. Next figures can be fig. 15 as a segmented 3D image and 7b to demonstrate different boxel-sizes for determining the REVs. By the way: mark boxel sizes with 100**3 voxels, 200**3, voxels and so on ... Fig. 2 is a good starting point (from image segmentation into your pore-morphology approach), but should arrange into a new order Fig. 6 is relative unclear to me. What are the colors? There is no description. Later more remarks for the appropriate chapter ... (maybe delete) Fig. 8: it would be better to combine the real porosity/surface each boxel with absolute numbers and RSD in a different axis or as error bars. Fig. 9: shows grain distribution curve in respect to boxel sizes. Do you have only 2 points measured data for the grain size distribution curve of this sand or is this an accident in the figure? Fig. 10: better remove or combine with fig. 9 Fig. 11: nice to show how the VPM analysis works (very similar to other pore-morphology methods). 11 b): what are the gray levels (or colors) in the GIA treated image? Is that more or less the same as in fig. 17? If so, then please combine. Fig. 11 again: I think this is VPM in the segmented pore space not in grains! Fig. 12: same content like fig. 11, but in 3D. Maybe combine or remove. Fig. 13: is that a profile? I think this is a diagram, showing occupied pore space with VPM balls. It would be better to combine and demonstrate the outcome of VPM with Fig. 19. Fig. 14&15: see above Fig. 16: As I understood, this is a combination between GMI and GIA (shown in fig. 11). To reduce amount of figures, please only how fig. 17 as a final result of GMI, description how it works is the text and demonstrated principally in fig. 11 Fig. 18: Question: is that segmented air phase? How do you segment the air? This is not described and demonstrated in the paper. Maybe combine with description of image segmentation in general. As I understood, you use Otsu's method ... Fig. 19: Do you have "only" 5 data points for the experiment, showed in fig. 18? I think you need more measurements between Sr=99% and Sr=28.9%. hp not corresponding to the hp in fig. 18 Fig. 20 shows a strong discrepancy between different boxel sizes and measure points (see remarks to the related

chapter) Fig. 21: is unclear to me. What is y-axis? Fig. 22: please remove. It can contribute in the text; content to REV and discussions Fig. 23: shows a discrepancy between AIM and VPM. This, I think needs more clear discussion in respect to a measured pore size distribution Fig. 24 also shows a clear a strong discrepancy between GMI and VPM (needs discussion) Text (please also see general remarks for structuring the paper and rearrangement of figures): P1, L27: I think you mean Young-Laplace law . . .. P2, L20: what means “pore dimensions”? P2, L23: MIT: I know it as MIP (mercury intrusion porosimetry) P3, L6-9: this is a bit unclear in the text. Please give an information why it is still under discussion. I think I know what you mean, but it needs to address more or delete this passage. P3, L11-12: often the language and formulations are not perfect, here repeating’s like “this paper . . .” P3, L23: “this material has a uniform grain shape.” That’s NOT true! If you looking your images, there are different grain shapes! P4, L1-L13: can be shorter, because it is standard . . . P4, L23: please put some informations about mineral composition of the used sand P4, L26-27: do you use special ROI (region of interest) reconstruction method? P5, L3: “The pores has a . . .”, not one pore alone . . . P5-P6: please summarize and compact the text, often (e.g. P6, L21-22) repeats something . . . P6, L2: why only use 13 sphere elements? Is this the largest sphere radius? P7, L25: what are the real effect of rotation? If this used directly in the further image processing? As I understood, you use later only spheres (see L31) P8, formula 5: how do you calculate the surface? A kind of surface rendering or voxel surface count? Please give an information or cite something P8: there are often repeated text from pages before. (e.g. P8, L23ff). Please rewrite and compact P8, L21: as an idea: you can use cylindrical coordinates, so you are not limited to 700**3 voxels to determine REV. With cyl. oordinates you can use the full field of view of the scanned cylinder. For REV analyses, see my general remarks before. Table 2: what is the exposure/integration time for each projection? What hardware filter do you use to minimize beam hardening effect? Resulting voxels: you binned the projection image or use a ROI CT scheme? For all next pages, please follow my general remarks about the text and figures After rearrangement figures and text, it would be much easier to

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follow the text content and discussion chapter

I would be happy, reviewing this paper after major revision.

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