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Prof. Dr. Jan Vanderborght
Executive Editor Soil

Cover letter revision "Characterization of stony soils' hydraulic conductivity using laboratory and numerical experiments".

Dear Dr Vanderborght,

Please find attached the revised version of our paper "Characterization of stony soils' hydraulic conductivity using laboratory and numerical experiments".

First, we would like to thank all the reviewers for their helpful comments on the paper. Their questions helped us to correct ambiguities and to improve our paper.

You will see that abstract, introduction, material and methods, discussion and conclusion were rewritten following the comments of the reviewers. Complementary measurements are introduced in the current version. Consequently to these new analyses and major revision, we are asking to change authors' order as well as to add a new co-author. We would like to adapt the author list as follows : E. Beckers, M. Pichault, W. Pansak, A. Degré, S. Garré.

We also attach a file that includes all the changes we made in the article to answer reviewers comments.

We hope that this revision will suit you and the reviewers and we thank you again for your help in handling this manuscript.

With our best regards,

Sarah Garré and co-authors.

Reviewers' comments are in italic, our answers are in bold, and manuscript modifications are underlined.

Referee comments #1

General comments

The manuscript presents a study in which lab and numerical experiments were conducted to study the influence of rock fragments on soil hydraulic conductivity. It is interesting to use 2D numerical simulations to study the influence of rock size and shape on soil hydraulic conductivity. However, some conclusions in this research were not convincing or at least drawn rashly for the reasons below:

(1) Lab experiments have no sufficient replications: **4 more replications with rock fragments for Rv 0-20-40-60% were conducted. Results are slightly modified but the global trend of a linear increasing of Kse with Rv is confirmed (Kse-Rv60% significantly greater than Kse-Rv20% and Kse-Rv0%). This has been added in the paper, <u>see 2.4 p.10 lines 19-27 and 3.1. p.11 lines 20-28</u>**

(2) The authors knew that the influence of new created voids were not considered in numerical experiments but neglected this point when evaluating the effects of rock size and shape. **The numerical simulations aim at showing the shape and size influence only. In fact, shape and size could have a different impact on soil structure modification and so on hydraulic conductivity but since we – the research community – do not have information about the link between these two factors, it cannot be modelled. Besides, voids creation is a suggested phenomenon to explain Kse increase but it has not been observed directly here and can thus not be included in prospecting simulation. The text has been modified to express more clearly that shape and size are studied as individual factors even though they can have a different impact on soil porosity while comparing numerical simulations. <u>See 3.2 p.13 l.2-3+p.14 l.10-16.</u>**

(3) There are not enough comparisons between the results herein and those in literature, especially the contents about the soils with glass beads and the results on unsaturated hydraulic conductivity. **This has been addressed with text modifications, <u>see 2.1 p.5 lines 12-17 and 3.1 p.11 lines 29 and following.</u>**

The manuscript is not written concisely and logically. There are also some grammar errors. Therefore, I am not convinced that the manuscript can be published in its current form.

Specific comments

(1) Why not conducted evaporation experiments with more rock fragment contents? I think experimental results can be more convincing than the simulated data for the great influence of possibly new created voids by stones shown in Figure 1. **As mentioned in the text, with a Rv greater than 20% it is quite impossible to insert tensiometers in the samples. Indeed, given that small variations of the hydraulic gradient can lead to substantial changes in the hydraulic conductivity estimates, the tensiometers should be ideally positioned out of the direct influence of one particular stone in order to obtain generalizable results. This implies the need for relatively low stone contents (< 30% according to Zimmerman and Bodvarsson (1995)). <u>See text paragraph 2.4 p.10 l. 13-18.</u>**

Because only the effects of reducing cross sectional area for water flows and increasing the tortuosity of water flow paths were considered in the numerical simulations, I don't think the conclusion "Indeed, under unsaturated conditions, the models seem to represent the hydraulic behaviour of stones reasonably well" in abstract can be drawn from the results in this research. **We performed 2 replications of evaporation experiments at 0 and 20%, which can help observe a trend and draw some conclusions about unsaturated mechanisms. The fact is that for unsaturated experiments, the presence of inclusions tends to conduct to similar results than those predicted by models for both our replications. But as the reviewer points, we do not have enough measurements to conclude so drastically. The abstract has been modified to address this comment, <u>see p.1 l.27 and following</u>.**

(2) In the manuscript, there are no replications of the experiments to measure K_{se} with different R_v. I don't think the explanation ("We did not perform any replications since the setup was totally artificially controlled") in the manuscript is sufficient. Normally, the variation of the saturated hydraulic conductivity of stony soils is greater than other soils, and thus at least three replications are required to obtain the representative values of K_{se}. **Four more replications with rock fragments for Rv 0-20-40-60% were realized. Results are slightly modified but the global trend of a linear increasing of Kse with Rv is confirmed. <u>See 2.4 p.10 lines 19-27 and 3.1. p.11 lines 20-28</u>**

(3) What is the size of glass bead used in experiments? Without replications, the reliability of the experimental data of soils with Glass Balls in Figure 1 is questionable. **Glass beads are 1cm in diameter (<u>see 2.2.1 p.5 lines 22-23</u>). Glass beads were used to check rock shape and perviousness influence on our conclusions about Kse. Since results with glass beads show similar trend than the 5 replications with rock fragments, we can say that it is not the rock fragment itself that produces bigger Kse, but the presence of a certain volume of inclusions (and probably the sampling procedure and soil texture). The difference between these types of inclusions could indicate that shape has an influence. These elements are further investigate through numerical simulations. <u>See 3.1 p.12 lines 16-25</u>.**
I am surprised the almost linear increase of K_{se} with R_v, even at the range of low R_v, for soils with glass beads, which is so different from the results of Peck and Watson (1979) and Ravina and Magier (1984) and the numerical results with circular inclusions in this research. Please explain it.
First, Peck and Watson (1979) used an analogy (based on heat flow theory) to express the variation of bulk hydraulic conductivity with stone fraction, but their results do not lie on hydraulic conductivity measurements. We can also explain the differences with other research results by the procedure of sampling, the soil texture and inclusions nature. Concerning Ravina and Magier (1984) results, it has to be noted that they got similar results for compacted soils with rock fragments. Their sampling procedure is not described in details, but we could suppose that our sampling procedure and the bulk density we reach induce a compaction of the soil and similar results than Ravina and Magier (1984). For the differences with numerical simulations, it seems quite logical to say that they come from the fact that inclusions have an impact on soil structure, which is not directly modelled. It can be seen as a supplementary clue for voids creation in rock vicinity.

(4) Which data were used in Figure 1 to represent numerical experiments? If the data from all the numerical experiments of soils with different sizes and types inclusions were used, why not show error bar in the Figure 1. **Results from numerical experiments in figure 1-old (now fig 2) are coming from numerical simulations with 12 circular inclusions. We've added this information in the legend of the figure, <u>see fig. 2.</u>**

Maybe we can confirm from Figure 2-4 that the shape and the size of inclusions have influence on K_{se}, but compared to Figure 1, I cannot draw the conclusion "the shape and the size of inclusions have a significant effect on K_{se}" on line 12 in page 1119. **The reviewer is right, we have no mean to say it has a significant effect. We can observe that these factors (could/fig 1.) have an impact (fig 2-4 old). Still, error bars have been added to Rv replication for rock fragments. See fig 2 + 3.2 p.13 l.21.**

(5) Generally, there is a problem when inserting a tensiometer into a stony soil with influence on soil structure as little as possible. I am interested of the size of the tensiometers used in evaporation experiments, when and how did the authors placed them in stony soils. It should be explained in more details in the main text. **As now mentioned in the text, tensiometers are 6 mm in diameter and 24.9 mm long. Tensiometers are inserted when the soil is saturated. A pin with similar dimensions has been used to make a hole in the soil and facilitate tensiometer insertion. See 2.2.2 p.6 l.18-22.**

(6) Most of the stony soils in literature are coarse texture. However, the soils used in this research have high clay content (55%). Soil texture may considerably affect the relationship between soil hydraulic properties and Rv. The possible effect of soil texture on the surprising result in Figure 1 (if it is true) should be discussed. **We developed the discussion about soil texture in the text, see 3.1 p.12 l.13-14+25-32, 3.2 p.14 l.17-21, 4 p.16 l.9-14.**

(7) As for the influence of new created voids by stones, no new insights or explanations were given in this research. Whether in virtual evaporation experiments or in permeability test, the influence of new created voids was not considered. The authors mentioned to use X-ray CT to study the influence of new created voids. It is a good idea but unfortunately they did not conduct in this research. I suggest removing this part of contents and concentrating this research on the influence of rock size and shape, which may change soil tortuosity or influence zone area overlapped. It is better to add figures to show the rock arrangement in soils for each treatment of virtual experiments. **In fact, voids have not been observed directly in our experiments. But it has been observed by other researchers (Ravina and Magier, 1984). We think that it is a high plausible explanation considering our observations, but it is not presented as a truth. The text has been modified to better express author's opinion regarding voids creation.**

(8) Some sentences are difficult to understand and there are also some grammar errors such as:
Line 19 in page 1112, "permeameter tests" should be "permeability tests".
Line 23 in page 1115, "permeameter experiment" should be "permeability experiment".
The sentences on lines 5-12 in page 1114 are not clear.
Line 2 in page 1117, "Beibei et al. (2009)" should be "Zhou et al. (2009)".
Line 29 in Page 1118, "E.g." should be "For example" .
All these expressions have been modified following the reviewer comment.

(9) The size of soil columns used in lab experiments should be added. **See 2.2.1 p.5 lines 20-21 + 2.2.2. p.6 l.16-17: The experiments were performed over cylindrical Plexiglas samples of 1 L (height: 65 mm, diameter: 142 mm)**

(10) The names in the references are wrong. The correct formats are
Zhou, B.B., Shao, M.A. and Shao, H.B.: Effects of rock fragments on water movement and solute transport in a Loess Plateau soil, Comptes Rendus Geosci., 341, 462–472, 2009.

Ma, D.H. and Shao, M.A.: Simulating infiltration into stony soils with a dual-porosity model, Eur. J. Soil Sci., 59, 950–959, 2008.
Ma, D.H., Zhang, J.H., Shao, M.A. and Wang, Q.J.: Validation of an analytical method for determining soil hydraulic properties of stony soils using experimental data, Geoderma,159, 262–269, 2010. **All these expressions have been modified following the reviewer comment. We'd like to precise however than in the paper "Effects of rock fragments…" it is indicated to cite it as Beibei et al. (2009). We are a little bit confused about the way to cite it eventually.**

(11) Normally, tortuosity factor l = 0.5 in van Genuchten model. In Table 1, the authors used l = -0.135. Why? **The parameter has been fitted on measurements. It is not rare for l to be negative when fitted to data (see Hunt A.G., Ewing R.P., Horton R., 2013. What's wrong with soil physics? *Soil Sci Am J* 77, 1877-1887).**

(12) The contents in Table A1 are repeated in Figure 2-4. I suggest removing it. **It has been modified following the reviewers comment: <u>table 1 was kept and introduced as part of the main text and not as extra material.</u>**

(13) The evaporation method is well known for measuring unsaturated hydraulic conductivity. I do not think it is needed to describe it with so many words in page 1111. **The text has been simplified, <u>see 2.2.2 p.7 l.6 and following</u>.**

Referee comment #2

This paper presents an interesting experimental and numerical study on the effect of soil stoniness on the soil hydraulic properties. Stony soils cover a substantial area of the terrestrial land surface. A proper characterization of their hydraulic properties is therefore important. But, experimental data of hydraulic properties of stony soils are scarce, also because it is a challenge to take undisturbed samples from such soils. The main results of these studies are that the relation between stone content and saturated hydraulic conductivity can be non-monotonous with an increase of saturated conductivity with increasing stone content when a threshold stone content is reached. Theoretical models and numerical simulations were not able to reproduce the increase of conductivity with increasing stone content. This because they do not consider that at the interface between stones and bulk soil, the structure of the porous medium can be disturbed and different from its structure in the bulk fine soil material. On the other hand, for unsaturated conditions, the hydraulic conductivities decrease with increasing stone content. For unsaturated flow conditions, the interface between the soil and bulk soil is not playing an important role since the larger pores or voids at this interface are drained. Besides the effect of different properties at the interface, also the shape and size of the stone fragments on the hydraulic properties was investigated and was found to play a role in addition to the total volume fraction of the stones, especially when the stone content is high.
The authors found that for unsaturated conditions, the hydraulic properties could be fairly well reproduced by simply scaling the unsaturated conductivity function with the relative saturated hydraulic conductivity of the stony sample. This indicates that the same shape parameters could be used for the stony and non-stony soils. However, I think that this conclusion only holds for the considered case. When the saturated conductivity of a soil with a higher stone content is higher than expected based on the fraction of fine soil whereas the hydraulic conductivity at lower pressure heads corresponds with the fraction of fine soil, then the shape parameters of the unsaturated conductivity curve of the stony soil should differ those of the fine soil fraction. **The reviewer is right, the text is not written correctly. We do think –as the reviewer- that the shape parameters are different for stony soil than for fine earth only. In fact the sentence "According to these experiments, hydraulic conductivity in the unsaturated zone is well defined using a correct K_{se} and shape parameters do not depend on the stoniness" relates models and simulations assumption. Besides these elements**

and the ones pointed by the reviewer, we can add that comparing measured and modelled (so based on these assumptions) retention curves with a Rv 20%, we can see that shape parameters are different. We didn't include it in the paper but we've modified the text to precise this part, <u>see 2.1 p.5 l.9-17 and 3.3. p.14 l.27-31.</u>

The text is in general well written but the authors should try to be more precise in their formulation at some locations.

Detailed comments
Abstract p 1104 ln 16: I would reformulate this sentence. It is not presence of rock fragments by itself that counteracts the effect of a reduced volume available for flow. It is the presence of voids at the interface between rocks and bulk soil that is responsible for this effect. Therefore, I propose to merge this sentence with the next sentence.
Abstract p1104 ln 18: Why 'Nevertheless' Skip that maybe.
P1105: ln 9: Their usage tendS to increase
P1105: ln 28: '… tends to increase to higher Rw.' This suggest that Kse will increase to a value that is equal to Rw. I think you mean: '… and then at higher Rw, Kse tends to increase with Rw.
P 1105 ln 29: change 'greater Kse' to 'larger Kse'
All these comments have been addressed in the text.
P1106: ln 4: This sentence is confusing. Increasing negative pressure heads means that the pressure head becomes less negative and comes closer to zero. I suppose that you mean the opposite. I would propose to write: 'with decreasing pressure heads.. (more negative pressure heads). **This sentence does not exist anymore following the modifications asked by another reviewer.**

General comment on the introduction part: the stoniness of the soil can be quantified using either a volumetric or gravimetric stone content. In the literature, both numbers have been used. In order to bring data from different studies together and compare them, it would be better to use the same parameter. Therefore, I would propose to include calculated volumetric stone contents if gravimetric stone contents are given. These calculations will have to use estimates of the stone density and bulk soil density but I suppose that these can be derived from the literature sources or that an estimate can be made. **The text has been modified, <u>see 3.1 p.11 l.29 and following</u>.**

P1107 ln 7: The equations that were derived by Peck and Watson based on the heat transfer theory, did they assume that the heat conductance of the cylindrical and spherical inclusions was equal to zero? To make the analogy to water flow, this is important. **Yes, indeed.**
P1107: In the equation of Novak et al. (eq. 5), an additional empirical parameter a is introduced to account for the hydraulic resistance of the stony fraction. I suppose that the model of Ravina and Magier assumes that the resistance of the stony fraction is infinite (this means that there is no water flow through the stony fraction). So, if you account also for flow through the stony fraction, assuming that its resistance is not infinite, then I would expect that the conductivity of the stony soil is larger than when you assume that there is no flow through the stony fraction. Therefore, I would expect that Eq. 5 should give a higher conductivity than Eq. 3. This can be achieved by choosing a to be smaller than 1. But, the authors write that a is larger than one for clayey soils. I do not understand this in combination with the explanation that was given for a parameter. **The parameter a accounts for the hydraulic resistance of flow but considering size and number of inclusions. It is not related to the imperviousness of inclusions as Novak et al. (2011) performed numerical simulations with impermeable circular inclusions. <u>See 2.1 p.4 l. 24-26</u>.**
P 1108: ln 3-4: '…hydraulic properties of water'. I suppose you mean hydraulic properties of unsaturated soil. **Indeed. The text has been modified, <u>see 2.1. p.5 l.1-2.</u>**
P 1108 ln 13-14: Explain why it could be a plausible assumption that the shape parameters of the hydraulic functions of stony soils are the same as the shape factors of the functions that describe the hydraulic functions of the fine soil fraction. **The text has been modified to better express this part. In**

fact we just presented the model from Hlaváčiková and Novák (2014), and we don't think that shape parameters are independent on stoniness. Our results will be discussed regarding the assumptions on which the model relies. <u>**See 2.1 p.5 l.9-17 and 3.3. p.14 l.27-31.**</u>

P 1108: Sample preparation. I think it is necessary to include the number of replicate samples that were prepared. I propose to include also a bit of information about the rock fragments that were used. **This has been done as asked by the reviewer. Concerning rock fragments and glass beads, we propose to include a picture of inclusions as it is clearer than text,** <u>**see fig 1.**</u>
P1109: 'experiments were performed USING cylindrical Plexiglas samples …'
Data processing: This part is not consistent I am afraid. The flux is generally defined as:
Where z is defined positive in the upward direction. This is not consistent with equation 9. That should read:
I suppose the authors took instead of the pressure heads, the absolute values of the pressure heads.
P1111: ln 10 and 11: should be 'difference in tensiometer k and j.'
These parts do not exist anymore following the modifications asked by another reviewer but your comments are right.
P1112: ln 6: the hydraulic gradient is dh/dz + 1 and is different from the pressure head gradient dh/dz. The authors should indicate which of both they used. Furthermore, the hydraulic gradient for upward flow should be negative. Therefore, change to a criterion for the absolute value of the hydraulic gradient. **It has been modified in the text. Since we used this definition of the hydraulic gradient :** $\nabla K = \frac{\Delta|h|}{\Delta z} - 1$**, the value of the limit used is 1 cm/cm.** <u>**See 2.2.2 p.7 l.16-17**</u>
P1112 ln 18: Skip 'infiltration'
P1115: ln 19-20. I do not agree that the artificial control of the experiment implies that no replications are needed. Also the evaporation experiments can be considered to be artificially controlled. Besides the compaction of the fine soil, also the location of the stones in the sample has an impact on the hydraulic properties and may vary between different setups. For the same Rv, it is possible to have different configurations of the stony fractions which leads to a variability in hydraulic properties between different replicates. **This has been address in the text,** <u>**see 2.4 p.10 lines 19-27 and 3.1. p.11 lines 20-28**</u>
P1116: 95% confidence intervals of what? I find the word confidence interval not appropriate here. I would rather speak of the range of the model predictions. Instead of a 95% confidence interval, I would just show the largest and the smallest model prediction. **The interval is the 95% around the median of the predicted values. So it is not a confidence interval, but an interval of the variation between models results. This has been modified in the text,** <u>**see 3.1 p.11 l.18 and fig 2**</u>**.**
P1117: ln 5: 'Our experiments show a similar behavior for dry soils' This is confusing since the experiments were done under saturated conditions. I propose to chance to 'dry packed soils'
P1119 ln 9: 'The Kr predicted by the models is always higher than the Kr determined by the simulations, except for soils containing one inclusion on its shortest side. One can conclude that the shape and the size of inclusions have a significant effect on Kse, which is usually neglected by the models.' Isn't the smaller Kse that is obtained from numerical simulations than from the theoretical model also caused by the fact that theoretical models consider a three-dimensional flow field whereas the simulations are for a two-dimensional flow field? **It is now explained in the text,** <u>**see 2.3 p.8 l.27 and following + 3.2 p. 14 l.10**</u>
Figure 5: I am wondering whether the plot wouldn't be more clear if K is also plotted on a logarithmic scale. Then Figure 5 would be consistent with figure 6. **It has been modified,** <u>**see fig 4 and fig 5.**</u>
P1119: 'Shape parameters do not depend…'
P 1120: I would propose not to use pF but use pressure heads instead. If you want to use pF, then you would have to define it.
P1121: ln 11: 'many -> may be ill-founded.'
These comments have been addressed.

Referee comment #3

CONTENT
The authors performed laboratory experiments on soil cores of 1 liter volume, packed with a clay soil and with stone or glass beads inclusions, to determine saturated hydraulic conductivity by constant-head method and unsaturated conductivities by evaporation experiments. A series of numerical 2D simulations were additionally performed to study the effects of volume fraction, shapes, and sizes of stone inclusions on effective hydraulic conductivity. For saturated conductivity, some existing simple predictive models exist which are used for comparison.
The main message of the paper is that for saturated conductivity, increasing fractions of inclusions into a fine textured matrix can lead in practice to an increase of conductivity, which is contrary to predicted effects, and is hypothesized to be due to the formation of a macropore system that drains water on preferential flow paths along the stone-fine earth interfaces. For unsaturated conductivity, inclusions caused a general decrease of conductivity as compared to the reference case, and experimental observation and numerical simulations agreed qualitatively. The decrease in the simulations depended on volume fractions of inclusions, number of inclusions, and shape of inclusions.

ASSESSMENT
Altogether, this study is well done and well written. The results are interesting and suitable for readers of SOIL. However, I do have some annotations, which will be listed below. Some more technical remarks are listed later in this review.

As major remarks, I address the following points:

1) The authors compare (i) results from predictive models for effective saturated conductivity (K_{Se}), (ii) results from numerical simulations, and (ii) results from physical experiments. In their paper they use sometimes a slightly confusing nomenclature, such as "virtual experiments", "numerical experiments", "numerical model", "virtual permeameter tests", "virtual constant-head permeameter experiments", "virtual permeameter and evaporation experiments" and so on. I suggest to STRICTLY address the results from the different sources as "predictive K_{Se} models", "[numerical] simulations", and "experiments". If this nomenclature is strictly kept throughout the paper (and also in the captions), it will be easier to understand the discussion. **It has been done as asked by the reviewer.**

2) Interestingly, the authors do not mention in any single word the problem of 2D vs. 3D flow fields. Whereas I understand that simulations in 3D are so demanding at this moment that one cannot request to repeat the simulations in 3D, I would expect at least a qualitative statement and a hint that this problem has been recognized an should be further addressed in the future. As a side note – I assume that the authors used an areal fraction in their 2D simulations that is equal to the volumetric fraction in the true 3D system (which is ok for a perfectly isotropic distribution), right? This information might be added in a side sentence. **The reviewer is right, we considered an areal fraction equal to the 3D volumetric fraction. These elements have been addressed in the text, <u>see 2.3 p.8 l.23+ l.27 and following.</u>**

3) In evaluating the simulations with respect to unsaturated conductivity, the authors used tensiometric values at the top and at the bottom of their soil columns I must say that this is quite a "dangerous" strategy, because the validity of the simplified evaporation method has not been shown to be valid for such an extreme setup (see Peters et al., 2015: Journal of Hydrology 527, 531-542, for more information on that issue). Note that once stage-2 evaporation is reached, the top of the sample dries so much out that the pressure head drops extremely and it is doubtful to apply the SEM. Furthermore, it is quite unnecessary to take that risk, because from the numerical simulations any *position of the tensiometers could be used (maybe, even averaging tensions along a line to circumvent the problem of differences due to the distorted flow field is applicable). On the other hand, the authors restrict the depicted K data to values < pF 2.5; for the clayey matrix, this might be still wet enough to allow their method to yield valid results (which can be checked easily for the sample without stones).* **To answer this comment, we've included some text, <u>see 2.3.1 p.9 l.11-19</u>. The point is to present the limits of the method we used, but also the reason we did it. In fact, as the reviewer notes it, the setup is extreme, but in the range of the ones considered by Peters et al. Besides, because of the presence of inclusions, it was difficult to consider observation nodes deeper in the sample. Results of our numerical simulations show numerical instability near inclusions. Besides, as pointed by the reviewer, the texture of the soil studied allows taking into account values in the pF range considered here. Finally, we've checked that pressure head was linear in the sample, which was the case.**

4) Chapter 2.4: I am not happy with the overview over the experiments and believe it can be improved. In particular, I find the formulation misleading that says "the accuracy of the conductivity curve from the evaporation experiments in the near-saturated zone was improved by using real and virtual permeameter tests". In fact – you cannot improve the conductivity estimation in the near-saturated zone. You can just add a single saturated conductivity point as end point of the function. Considering the interesting finding that saturated conductivity might increase in reality with increasing stone fraction, whereas it will always decrease under unsaturated condition, it is not only unjustified to speak of an "improvement of the near-saturated conductivity estimation" by your methodology – it is even misleading, because rather the contrary is true: you just interpolate smoothly the suction range where you have no direct results. So just stick to the simple facts. You have unsaturated conductivity up to pF 1.6, and then the saturated value. **The text has been modified, <u>see 2.4. p.10</u>**

5) I found the description of the packing procedure a bit meagre. Giving slightly more detail is to be considered, since the authors speculate that the compaction by the packing procedure causes voids along the stones and glass spheres. It is not easy to understand for me how this should happen. **As described in the text, we build the stony samples layer layer-by- layer: soil-stones-soil etc. Each layer of soil was compacted in order to obtain a specific bulk density (each layer had to have a specific depth). Even though the filling and compaction procedure was conducted with precision, it is probably impossible to avoid local bulk density heterogeneity as stones can move and/or soil between stones can be less compacted due to difficult access of the area close to the stone during compaction. . <u>See 2.2.2 p.6 l.2-6 + fig 1</u> for a better representation of the setup.**

6) As a personal view, I am not sure whether Figures 2 to 4 are required at all, since it is all contained in nice and concise form in Table A1 (which should be part of the main text anyway). But if the authors have enough money to pay the charges … the figures don't hurt. **It has been modified following the reviewers comment: <u>table 1 was kept and introduced as part of the main text and not as extra material.</u>**

SPECIFIC ANNOTATIONS
P 1105, line 16: please define your term "effective saturated hydraulic conductivity". To my understanding, it is the saturated conductivity of the sample, so "effective" is not really necessary and opens a realm of theoretical difficulties.
P 1106, line 5: There is no such thing as "decreasing hydraulic properties".
P 1106, line 25: "numerical experiments", "numerical permeability experiments" and so on: please refer to my remark (1). Furthermore, you "performed" (rather than "completed") simulations.
P 1108, line 6: "… based on the pore size distribution of Mualem" – Wrong. You refer to the pore-bundle model of Mualem.

Page 1108, line 10: In soil physics, we refer to S_e as "effective saturation" (not "saturation state").
Page 1108, line 21: "… rock fragments with a mean diameter between 1 and 2 cm" – a reader asks himself what is meant with "mean" diameter, and how the distribution might look like. I suggest to delete "mean" or else to define it.
All these comments were addressed as the reviewer asked.
Page 1109, line 4: "… equal to the mean bulk density …" – from where do you know the mean bulk density if that material? Measured at the site where the samples are from? **Indeed, the bulk density was measured in situ. It is now indicated in the text, <u>see 2.2.1 p.5 l.27-28.</u>**
Page 1109, line 21: "… In order to avoid preferential flow due to the introduction of the tensiometers […] vis-à-vis the center of the tube" – This is hard to understand to me. I am sure you can express this more clearly, so that somebody who has not seen the experimental setup will understand it.
Page 1109, line 26: "Tensions beyond the consolidation point were not taken into account". I work my life long with tensiometers, but I never heard of a "consolidation point"! Even if you explain it afterwards, the terminology appears strange. Maybe, you can avoid the terminology or cite a proper source? **It is the term that is not adequate. It is the air-entry point, the text has been modified, <u>see 2.2.2 p.6 l.26-27.</u>**

Page 1113, line 21f: "The parameters …" – Please be more specific here –just a half sentence is not sufficient to explains what you did. Did you fit the hydraulic function to the SEM data, or did you do an inversion of the Richards-based numerical simulation of an evaporation experiment? If the latter applies: What was used in the object function, and how did you determine/set the weights of the different data types? **We fit the hydraulic function to the SEM data. The text has been modified to better express it, <u>see 2.3 p.9 l.24-26.</u>**

Page 1114, line 9ff: "As numerical errors occur…" – this passage is written in a very diffuse and non-specific manner. I see from Figure 5 that K-data are only determined above pF 1.6 – which is clearly not the threshold that can be reached by the numerical accuracy of simulations. It appears that the authors sacrificed some accuracy by deriving tensiometric gradients in a non-optimal manner? To me, this does not hurt the value of the paper, but they should specify more precisely how they numerically derived the conductivities. Either, the accuracy of the tensiometric values were limited by the number of digits in the output, or else they had problems with the numerical stability of the simulation that could be possible improved with some altered numerical parameters? **The text has been modified to better express it, <u>see 2.3.1 p.9 l.20-24.</u>**

Page 1114, Chapter 2.4: As indicated in the major comments, this section can be improved. Also re-consider the organization of Table 2 and consider using symbols for the used soil shapes that are more suggestive: ⍰⍰⍰⍰⍰⍰⍰⍰⍰⍰filled circle, filled triangles, and vertical and horizontal slabs (available certainly in special fonts – but I had to look myself…). **It has been adapted, see table 2 and table 3.**
Page 1116, line 15: "95 % confidence intervals" – I do understand how you calculate the median, but I do not understand how you calculate a 95% confidence interval for the median. Please specific in the methods section. **The interval is the 95% around the median of the predicted values. So it is not a confidence interval, but an interval of the variation between models results. This has been modified in the text, <u>see 3.1 p.11 l.18 and fig 2.</u>**
Page 1119, line 23: "… inclusion vicinity…" – consider re-phrasing. **The entire paragraph has been modified.**
Page 1120, line 26: You cite "Gras, 1994", but I did not find it in the references. **The sentence with this reference has been removed from the text.**
Page 1121, line 22: "We also hypothesize …" – this comes out of the blue and was not mentioned nor discussed in the paper. So, you cannot bring it in the conclusion. I suggest to delete the sentence, or to specify what brings you to the conclusion. **The conclusions have been modified to address this comment as well as the other modifications in the paper.**

Page 1126 and 1127: As indicated above, I suggest to use more suggestive symbols for the five shape variants.
Page 1128, Figure 1: Where are the error bars for the lab experiments? I understand all of them were performed in two replicates? Hence, the difference is equal to the estimate of the standard deviation (it makes no sense to show 95 % confidence intervals, since the t-value is huge). Furthermore: how did you calculate the 95% confidence intervals of the median? **At first we had only one replication for Ks measurements. Now we have 5 replications and error bars have been added. Concerning the IC, the interval is the 95% around the median of the predicted values. So it is not a confidence interval, but an interval of the variation between models results. This has been modified in the text, <u>see 3.1 p.11 l.18 and fig 2.</u>**
Page 1132, Figure 5: Please scale the y-axis on a log scale, as is usually done for K plots (and as you do in Figure 6). Furthermore, consider to start the plot at pF 1 and indicate by symbols on the left Y-Axis the values for saturated conductivities (please note that saturated values are NOT related to pF 0, as is presently suggested). The same applies to Figure 6. **<u>Figures have been modified (now fig 4 and 5).</u>**

Characterization of stony soils' hydraulic conductivity using laboratory and numerical experiments

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Abstract

Determining soil hydraulic properties is of major concern in various fields of study. ~~Though~~Although stony soils are widespread across the globe, most studies deal with gravel-free soils so that the literature describing the impact of stones on ~~soil's~~the hydraulic conductivity of a soil is still rather scarce. Most frequently, models characterizing the saturated hydraulic conductivity of stony soils assume that the only effect of rock fragments is to reduce the volume available for water flow and therefore they predict a decrease in hydraulic conductivity with an increasing stoniness. The objective of this study is to assess the effect of rock fragments on the saturated and unsaturated hydraulic conductivity. This was done by means of laboratory experiments and numerical ~~experiments~~simulations involving different amounts and types of coarse fragments. We compared our results with values predicted by the aforementioned predictive models. Our study suggests that considering that stones only reduce the volume available for water flow might be ill-founded. We pointed out several drivers of the saturated hydraulic conductivity of stony soils, not considered by these models. On the one hand, the shape and the size of inclusions may substantially affect the hydraulic conductivity. On the other hand, ~~the presence of rock fragments~~laboratory experiments show that an increasing stone content can counteract and even overcome the effect of a reduced volume in some cases~~. We attribute this to the creation of voids at the fine earth-stone interface. Nevertheless, these~~: we observed an increase in saturated hydraulic conductivity with volume of inclusions. These differences are mainly important near to saturation. However, ~~we come up~~

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~~with a more nuanced view regarding the validity of the~~comparison of results from predictive models ~~under~~and our experiments in unsaturated conditions~~. Indeed, under unsaturated~~ shows that models and data agree on a decrease in hydraulic conductivity with stone content, event though the experimental conditions~~, the models seem to represent the hydraulic behaviour of stones reasonably well.~~ did not allow testing for stone contents higher than 20%.

Keywords: stony soils, hydraulic conductivity, evaporation method, hydrodynamic behaviour, permeameter, soil water content.

1. Introduction

Determining soil hydraulic properties is of primary importance in various fields of study such as soil physics, hydrology, ecology and agronomy. Information on hydraulic properties is essential to model infiltration and runoff, to quantify groundwater recharge, to simulate the movement of water and pollutants in the vadose zone, etc. (Bouwer and Rice, 1984). Most unsaturated flow studies~~ only~~ characterize the hydraulic properties of the fine fraction (particles smaller than 2 mm of diameter) of supposedly uniform soils only (Bouwer and Rice, 1984; Buchter et al., 1994; Gusev and Novák, 2007). Nevertheless, in reality, soils are heterogeneous media and may contain coarse inclusions (stones) of various sizes and shapes.

Stony soils are widespread across the globe (Ma and Shao, 2008) and represent a significant part of the agricultural land (Miller and Guthrie, 1984). Furthermore, their usage ~~tend~~tends to increase because of erosion and cultivation of marginal lands (García-Ruiz, 2010). Yet little attention has been paid to the effects of the coarser fraction~~, so that the literature describing the impact of stones~~ on soil hydraulic characteristics, so that the relevant literature is still rather scarce (Ma and Shao, 2008; Novák and Šurda, 2010; Poesen and Lavee, 1994).

Many authors consider that the reduction of volume available for water flow is the only effect of stones on hydraulic conductivity. This hypothesis has led to ~~formulas~~models linking the hydraulic conductivity of the fine earth to those of the stony soils. They predict a decrease in ~~effective~~ saturated hydraulic conductivity of stony soil (K_{se}) with an increasing volumetric stoniness (R_v) (Bouwer and Rice, 1984; Brakensiek et al., 1986; Corring and Churchill, 1961; Hlaváčiková and Novák, 2014; Novák and Kňava, 2011; Peck and Watson, 1979; Ravina and Magier, 1984).

~~However, a number of studies do not observe this simple indirect relationship between the hydraulic conductivity and the stoniness (Beibei et al., 2009; Ma et al., 2010; Russo, 1983; Sauer and Logsdon, 2002). Russo (1983) conducted some in situ measurements of the K_{se} in soils containing a large amount of stones (R_v > 35%) and, even if the K_{se} decreases with the stone content, he measured higher values of conductivity than expected based on the aforementioned models. In another study by Beibei et al. (2009), permeameter tests over samples of different gravimetric rock content (R_w) reveal that the K_{se} initially decreases at low R_w to a minimum value at R_w = 40% and then tends to increase to higher R_w. Laboratory tests conducted by Ma et al. (2010) showed the same overall behaviour, and found in addition a greater K_{se} at R_v = 8% than the one of the fine earth alone. Sauer and Logsdon (2002) also~~

came up with surprising results while carrying out in situ infiltration tests. In saturated conditions, they measured higher hydraulic conductivity with increasing rock fragment content. However, with increasing negative pressure head (and particularly at h = -12 cm), they measured decreasing hydraulic properties with increasing rock fragment content. These controversial results suggest that other factors may play a substantial role in specific situations (Ma et al., 2010).

Indeed, ambivalent phenomena can intervene simultaneously, which makes the understanding of the effective hydraulic properties of stony soils very difficult. The reduced volume available for flow might be partially compensated by others factors. One contradictory effect might be, as pointed out by Ravina and Magier (1984), the creation of large pores in the rock fragments' vicinity. These authors directly observed large voids by cutting across a soil sample after its compaction, presumably due to translational displacement of densely packed fragments. This is in agreement with the observed increasing conductivity with increasing R_v. Indeed, the creation of new voids at the stone-fine earth interface can generate preferential flows and hence increase the effective hydraulic conductivity (Beibei et al., 2009; Cousin et al., 2003; Ravina and Magier, 1984; Sauer and Logsdon, 2002).

These statements define the general context in which our study takes place. The main objectives are (i) to assess the effect of rock fragments on the hydraulic conductivity of soil and (ii) to test the validity of the aforementioned models.

2. Material and Methods

We performed evaporation experiments and constant-head permeameter tests to studyHowever, a number of studies do not observe this simple relationship between the hydraulic conductivity and the stoniness (Zhou et al., 2009; Ma et al., 2010; Russo, 1983; Sauer and Logsdon, 2002) and suggest that other factors may play a substantial role in specific situations. Indeed, ambivalent phenomena can intervene simultaneously, which makes the understanding of the effective hydraulic properties of stony soils difficult. The reduced volume available for flow might be partially compensated by others factors. One contradictory effect might be, as pointed out by Ravina and Magier (1984), the creation of large pores in the rock fragments' vicinity. Indeed, the creation of new voids at the stone-fine earth interface could generate preferential flows and hence increase the saturated hydraulic conductivity (Zhou et al., 2009; Cousin et al., 2003; Ravina and Magier, 1984; Sauer and Logsdon, 2002).

These statements define the general context in which our study takes place. The main objectives are (i) to assess the effect of rock fragments on the hydraulic conductivity of soil and (ii) to test the validity of the aforementioned models.

2. Material and Methods

We studied the effect of R_v on saturated and unsaturated hydraulic conductivity by means of laboratory experiments (evaporation and permeability measurements) and numerical ~~experiments~~simulations involving different amounts and types of coarse fragments. ~~We also completed numerical permeability experiments in order~~The latter serve also to further investigate the effect of the ~~stones'~~stone size and shape on the K_{se}.

2.1. Models predicting soil hydraulic properties of stony soils

Multiple equations have been proposed to estimate the ~~effective~~ saturated hydraulic conductivity of stony soil (K_{se}) from the one of the fine earth (K_s) assuming that rock fragments only decrease the volume available for water flow. The relative saturated hydraulic conductivity (K_r) is defined as the ratio between the K_{se} and the K_s. Eq. (1) and Eq. (2) have been derived by Peck and Watson (1979) based on heat transfer theory for a homogeneous medium containing non-porous spherical and cylindrical inclusions, respectively. Assuming that stones are non-porous and do not alter the porosity of the fine earth, Ravina and Magier (1984) approximated the K_r to the volumetric percentage of fine earth (Eq. (3)). ~~According to~~Based on empirical relations, Brakensiek et al. (1986) proposed a similar equation, but involving the mass fraction of the rock fragments instead of the volumetric fraction (Eq. (4)). On the basis of numerical simulations, Novák et al. (2011) proposed to describe the K_{se} of stony soils as a linear function of the R_v and a parameter that incorporates the hydraulic resistance of the stony fraction (Eq. (5)).

$K_r = \frac{2(1-R_v)}{2+R_v}$	$K_r = \frac{(1-R_v)}{1+R_v}$	$K_r = (1-R_v)$	$K_r = (1-R_w)$	$K_r = (1-aR_v)$
(1)	**(2)**	**(3)**	**(4)**	**(5)**
Peck and Watson for spherical stones (1979)	Peck and Watson for cylindrical stones (1979)	Ravina and Magier (1984)	Brakensiek et al. (1986)	Novák et al. (2011)

In which R_v is the volumetric stoniness [$L^3.L^{-3}$]; R_w is the mass fraction of the rock fragment (mass of stones divided by the total mass of the soil containing stones; the stone density is typically 2.5 g/cm^3 in this case) [$M.M^{-1}$]; a is an empirical parameter that incorporates the hydraulic resistance of the stony fraction considering shape, size and orientation of inclusions (the recommended value is 1.32 for clay soils according to Novák et al. (2011)).

Two major characteristics are widely used to describe the hydraulic properties of ~~water in the~~unsaturated soil: the water retention curve $\theta(h)$ and the hydraulic conductivity curve $K(h)$. These are both non-linear functions of the pressure head h. One of the most commonly used analytical models has been introduced by van Genuchten (1980), based on the pore~~ size distribution~~ bundle model of Mualem (1976), and given by:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \begin{cases} (1 + |\alpha h|^n)^{-m} \; if \; h < 0 \\ 1 \; if \; h \geq 0 \end{cases} \quad (6)$$

$$K(S_e) = \begin{cases} K_s \, S_e{}^l \left[1 - (1 - S_e{}^{1/m})^m\right]^2 \; if \; h < 0 \\ K(S_e) = K_s \; if \; h \geq 0 \end{cases} \quad (7)$$

In which h is the pressure head [L]; $S_e(h)$ is the saturation state [$L^3.L^{-3}$]; $\theta(h)$ is the volumetric water content [$L^3.L^{-3}$]; θ_r and θ_s respectively represent the residual and saturated water content [$L^3.L^{-3}$]; K_s is the saturated hydraulic conductivity [$L.T^{-1}$]; n [-], l [-], α [L^{-1}] are empirical shape parameters ($m = 1 - 1/n, n > 1$). ~~If the shape parameters of the van Genuchten/Mualem (VGM) equations (α, n and l) would be independent of R_v (Hlaváčiková and Novák, 2014), one could extend the hydraulic conductivity curves to stony soils using one of the models for K_{se} introduced earlier (Eq. (1) to Eq. (5)).~~ To extend the hydraulic conductivity curves to stony soils, Hlaváčiková and Novák (2014) propose a simple method considering that the shape parameters of the van Genuchten/Mualem (VGM) equations (α, n and l) are independent of R_v. However, this model relies on assumptions that have not been verified. It might be noteworthy to mention that there are currently no extensive empirical studies available dealing with the influence of porous inclusions under unsaturated conditions. This gap in existing literature is probably due to experimental issues linked with this kind of study: while measuring the potential and the water content of fine earth has become a standard procedure, the opposite is true for rock fragments, especially under transient infiltration processes.

2.2. Laboratory Experiments

2.2.1. Sample Preparation

We performed laboratory experiments on disturbed samples (height: 65 mm, diameter: 142 mm) containing a mixture of fine earth and coarse inclusions. Two types of inclusions were used: rock fragments (granite) with a ~~mean~~ diameter between 1 and 2 cm (1) and spherical glass ~~spheres~~beads with a diameter of 1 cm (2) (see fig 1). The fine earth is classified as a clay (sand: 26%, silt: 19%, clay: 55%).

Before each measurement campaign, fine earth was first oven dried for 24 hours at 105°C and passed through a 2-mm sieve. To prepare a sample without any inclusion, fine earth was compacted layer-by-layer to get an overall bulk density of 1.51 g/cm^3 (equal to the mean bulk density of the fine earth measured in situ~~).~~ (Pichault, 2015)). For samples containing rock fragments, stones were divided ~~into 4~~over four layers of soil application and laid on the fine earth bed on their flattest side. The samples were then compacted layer-by-layer in a way that maintains the same bulk density of fine earth~~. A similar method~~ as for samples without inclusions. Even though the filling and compaction procedure was ~~applied~~conducted with precision, it is probably impossible to avoid local bulk density heterogeneity as stones can move and/or soil between stones can be less compacted due to difficult access of the area close to the stone during compaction. The same procedure was to prepare samples containing glass balls~~ and rock fragments.~~. Once the specimen was made, it was placed ~~during at least 24 hours~~ in a basket containing a thin layer of water during at least 24 hours in order to saturate the soil from below.

2.2.2. Unsaturated Hydraulic Conductivity

Setup Description

We used the evaporation method to determine the hydraulic conductivity and the retention curve of a soil sample. The principle of this method is to simultaneously measure the matric head at different depths and the water content of an initially saturated soil sample submitted to evaporation.

The experiments were performed ~~over~~using cylindrical Plexiglas samples of 1 L (height: 65 mm, diameter: 142 mm), perforated at the bottom to allow saturation from below and open to atmosphere on the upper side to allow evaporation of the soil moisture. Four ~~6~~24.9 mm-long and 6mm diameter ceramic tensiometers (SDEC230) were introduced at 10, 25, 40 and 55 mm in height, respectively denoted T1 to T4 (the reference level is located at the bottom of the sample). Tensiometers are introduced at saturation; a pin with similar dimensions is used to facilitate their insertion. In order to avoid preferential flow due to the introduction of the tensiometers on ~~a~~the same vertical ~~line~~axis, each ~~hole of the sample~~tensiometer was ~~horizontally shifted~~introduced with a horizontal shift of 12 degrees ~~vis-à-vis~~with respect to the center of the ~~tube~~column. The tensiometers are connected ~~through~~by a tube to a pressure transducer (DPT-100, DELTRAN). The setup was filled with ~~degased~~degassed water. The variation in pressure of the drying soil was recorded every 15 min by a CR800 logger (CAMPBELL SCIENTIFIC). Tensions beyond the ~~consolidation~~air entry point were not taken into account. The ~~consolidation~~air entry point refers to the state from which the measured pressure head starts to decrease as bubbles appear and water vapour accumulates (typically 68 kPa ~~cm~~ in this case).

The total water loss as a function of time was monitored by a balance (OHAUS) with a sensitivity of 0.2 g with an accuracy of $\pm$ 1 g with a time resolution of 15 min. A 50 W infrared lamp was positioned 1 m above the sample surface to slightly speed up the evaporation process. The light was turned off for the first 24 hours of every experiment, as the evaporation rate is already high in a saturated sample. A measuring campaign lasted until ~~3~~three of the ~~4~~four tensiometers ran dry (the tension sharply drops down to approximately a null value). At the end of the experiment, the sample was oven dried for 24 hours at 105°C to estimate the θ.

Data Processing

A simplified Wind's method (1968) was used to transform matric potential and total weight data over time into the hydraulic conductivity curve (Schindler, 1980 cited by Schindler and Müller, 2006; Schindler et al., 2010). The method is further adapted in order to take into account the data from ~~4~~four tensiometers~~ (data points for the hydraulic conductivity curve is made for every possible combination of two tensiometers).~~. The method assumes that the distribution of water tension and water content is linear through the soil column. It further linearizes the water tension and the mass changes over time. The time step chosen to process the data is one hour.

~~The water retention curve $\theta(h)$ is calculated using the mean tension and the weight measurements from the scale (for information purposes only). A first step to determine the hydraulic conductivity curve $K(h)$ is to calculate the rate of water flow q through the cross-section in between tensiometers j and k at time t^i, which is calculated as follows:~~

$$q^i_{jk} = \frac{z_j + z_k}{2L}\left(\frac{-\Delta M^i}{\Delta t^i \rho_w A}\right) \qquad (8)$$

~~In which q is the cross-sectional water flow [L.T^{-1}]; z_j and z_k respectively represent the height of tensiometer j and k [L] (the reference level is located at the bottom of the sample); L is the height of the tube [L]; ΔM^i is the mass difference measured by the scale [M]; $\Delta t^i = t^i - t^{i-1}$~~

is the time interval [T]; ρ_w is the density of water [M.L^{-3}] and A is the cross-section of the tube [L^2].

Afterwards, the hydraulic conductivity K at time t^i can be deduced from measurement in tensiometer j and k inverting the Darcy equation:

$$K_{jk}^{i} = \frac{q_{jk}^{i}}{\Delta h_{jk}^{i}/\Delta z_{jk} - 1} \quad (9)$$

In which K is the hydraulic conductivity [L.T-1]; $\Delta z_{jk} = z_k - z_j$ is the height difference between tensiometer z and j [L] and Δh_{jk}^{i} is the mean difference of water tension between tensiometer z and j in the middle of the time interval defined by t^{i-1} and t^i [L]:

$$\Delta h_{jk}^{i} = \frac{(h_k^{i-1} - h_j^{i-1}) + (h_k^{i} - h_j^{i})}{2} \quad (10)$$

The mean matric head corresponding to the two tensiometers used to evaluate conductivity is calculated as follows:

$$\overline{h_{jk}^{i}} = \frac{h_k^{i-1} + h_j^{i-1} + h_k^{i} + h_j^{i}}{4} \quad (11)$$

By calculating the hydraulic conductivity based on measurementmeasurements of two tensiometers j and k and linking it to the corresponding mean matric head, one can thus evaluate thea point of the hydraulic conductivity curve $K_{jk}^{i}(\overline{h_{jk}^{i}})$.. We used every possible combination of 2two tensiometers (6six here) to obtain data points for the hydraulic conductivity curve.

Points of the hydraulic conductivity curve obtained at very small hydraulic gradients (defined here as $\nabla K = \frac{\Delta|h|}{\Delta z} - 1$) were rejected, because large errors occur in the near-saturation zone due to uncertainties in estimating small hydraulic gradients (Peters and Durner, 2008; Wendroth, 1993). This highlights in its turn the necessity of reliable tensiometers to estimate the near-saturated hydraulic conductivity. In the current literature, acceptation limits of the hydraulic gradient vary between 5 and 0.2 cm/cm (Mohrath et al., 1997; Peters and Durner, 2008; Wendroth, 1993). Using the least restrictive filter criterion (hydraulic gradient > 0.2) requires fine calibration and outstanding performance of the tensiometers. Choosing a more restrictive criterion leads to a larger loss of conductivity points, but provides more reliable and robust data. We decided to use a filter criterion that does not consider hydraulic conductivity points higher than the evaporation rate (from 0.1 to 0.2 cm/day in this case), resulting in a lower limit of 1 cm/cm for the hydraulic gradient.

As pointed out by Wendroth (1993) and Peters and Durner (2008), the main drawback associated with the evaporation experiment is that no estimates of conductivity in the wet range can be obtained due to the typically small hydraulic gradients so that additional measurements of the K_{se} should be provided. To do so, we used constant-head ~~infiltration permeameter tests~~permeability experiments (see below).

Except for the K_{se} which is fixed using results from the constant-head ~~permeameter tests~~permeability experiments, the parameters of the VGM-model (1980) (Eq. (7)) are obtained by fitting evaluation points from each combination of tensiometers using the so-called "integral method" (Peters and Durner, 2006).

2.2.3. Saturated Hydraulic Conductivity

Constant-head permeability ~~tests~~experiments were used to determine the K_{se} of saturated cylindrical core samples. The flow through the sample is measured at a steady rate under a constant pressure difference. The K_{se} can thus be derived using the following equation:

$$K_{se} = \frac{VL}{A\Delta H\Delta t} \qquad (12)$$

In which V is the volume of discharge [L^3]; L is the length of the permeameter tube [L]; A is the cross-sectional area of the permeameter -[L^2]; ΔH is the hydraulic head difference across the length L [L] and Δt is the time for discharge [T].

The soil sample~~,~~ used for permeability tests has the same size as the one from the evaporation experiment~~, was extended on its upper side by a paper tape.~~ (height: 65mm, diameter: 142 mm). A 2 cm thick layer of water was maintained on top of the sample thanks to a ~~water reservoir with a beveled outlet~~Mariotte bottle. Water was collected through a funnel in a burette and the volume of discharge V was deduced from measurements after 30 and 210 min after the beginning of the experiment (Δt= 180 min).

2.3. Numerical ~~Experiments~~simulations

The HYDRUS-2D software was used to simulate water flow in variably saturated porous stony soils. HYDRUS-2D is a two-dimensional finite element model based on Richard's equation.

All the performed simulations assumed that rock fragments were non-porous so that "no-flux" boundaries conditions were specified along the stones limits. Rock fragments were supposed to be circular. The soil domain over which simulations were performed had the same dimensions as the longitudinal section of the sampling ring used in the laboratory experiments (14 x 6.5 cm). We considered the 2D fraction of stoniness equal to the volumetric fraction. The parameters of fine earth used in the simulations ~~were obtained by inversion using~~come from the fitting on the hydraulic conductivity and water retention curves obtained in our laboratory experiments on stone-free samples (Table 1).

As a general rule, the hydraulic conductivity of a heterogeneous medium tends to be higher for 3D than for 2D simulations (Dagan, 1993). Similarly, for a same level of heterogeneity, the flow will be more hampered using 1D rather than 2D simulations. In the present study, we performed 2D simulations: the quantitative and qualitative conclusions from these experiments can be only extended to the third dimension for their corresponding 3D form with an infinitely long axis.

2.3.1. Unsaturated Hydraulic Conductivity

We repeated the evaporation ~~test as virtual~~ experiment~~.~~ as numerical simulation. The top boundary of the ~~virtual~~simulated sample was submitted to an evaporation rate *q* of 0.1 cm/day during 14 days. No fluxes were allowed across other boundaries.

The calculation method applied to the output data was similar to the laboratory evaporation experiment, except that the conductivity and pressure head estimations resulted from ~~2~~two observation nodes placed at the top and the bottom of the profile~~ (the~~. We are aware that these choices can be discussed, because of numerical instability at the limits of the sample on the one hand, and because of the setup extension modelled here (see Peters et al., 2015) on the other hand. However, we chose to consider these points for different reasons. Indeed, we observed some numerical instability near stones, which makes it more complicated to insert nodes deeper in the sample, especially for increasing stone contents. Besides, we checked that pressure head was linearly distributed across the soil profile, which was the case. Finally, as we are studying clayey soils, and as we are considering a pressure head range between pF 1.5 ad 2.5 these assumptions are likely to be fair enough (Peters et al., 2015).

As ~~numerical errors occur in~~ the ~~near-saturation zone~~relative mass balance error was large at the beginning of the ~~virtual~~ simulations, we considered values when this relative error was lower than 5%. This validation criterion was set arbitrarily, based on the comparison between evaluation points from the simulation of the evaporation experiment, extra simulations were required to minimize the extrapolation error of the hydraulic conductivity curve from the evaporation experiment data to the near-saturation zone. Although the causes are different, both real on stone-free samples and virtual experiments require the expected values obtained from the additioninputs of data from permeameter tests. As for the laboratory experiment, thesimulation. The hydraulic conductivity curve was obtained fitting the discrete conductivity data plus the simulated saturated hydraulic conductivity using the so-called "integral method" (Peters and Durner, 2006).

, just like we did for the laboratory experiment.

2.3.2. Saturated Hydraulic Conductivity

The K_{se} was determined using a numerical constant-head permeability testsimulation. We simulated a steady-state water flow of a saturated soil profile, with a constant head of 10 cm applied on the upper boundary. The bottom boundary of the column was defined as a "seepage face", which means that water starts flowing out as soon as the soil at the boundary reaches saturation. The calculation method applied to the output data was identical to the laboratory constant head permeameterpermeability experiment.

2.4. Treatments

Table 2 presents a scheme of all the performed experiments. We first studied the effect of R_v on unsaturated hydraulic properties using laboratory experiments and numerical experimentssimulations. In the laboratory approach, we performed evaporation experiments on samples containing i) fine earth only and ii) on others with rock fragments (1) at a R_v of 20%. Two replications per treatment were performed (4four measurement campaigns in total). For the numerical approach, simulations of the evaporation experiment were done on homogeneous soil (without stones) and on soil with a R_v of 10, 20 and 30%. Having less time- and practical constraints in the virtual experimentnumerical simulation, we added an increasing R_v to observe the evolution of the hydraulic conductivity curve. Simulations were performed on soil samples containing 12 regularly distributed stones. The accuracy of the conductivity curve from the evaporation experiment in the near-saturated zone was improved by using real and virtual permeameter tests. One can notice that no investigations of the unsaturated properties with coarse fragments above 30% of R_v were performed. Indeed, given that small variations of the hydraulic gradient can lead to substantial changes in the hydraulic conductivity estimates, the tensiometers should be ideally positioned out of the direct influence of one particular stone in order to obtain generalizable results. This implies the need for relatively low stone contents (< 30% according to Zimmerman and Bodvarsson (1995)).

Then, to study the relationship between K_{se} and R_v, we tested 2two types of inclusions (rock fragments (1) and glass spheres (2)) and 4four volumetric fractions (0, 20, 40 and 60%). We did not perform any replications since the for glass sphere inclusions while five replications were performed for rock fragments. The first setup with rock fragments was totally artificially controlled. The only source of uncertainty isconcomitant with the one with glass spheres. Then, the homogeneous compaction offour supplementary replications with rock fragments were processed for the fine earth fraction. Virtual permeameter testsdifferent volumetric fractions altogether: between replications the soil was oven dried for 24 hours at 105°C and passed through a 2-mm sieve. Numerical permeability simulations were also performed involving 12 circular regularly distributed inclusions for the same R_v (0, 20, 40, 60%).

In addition, we used the virtual permeameter experimentsimulations to investigate the effect of the inclusion shape and size on K_{se}. To do so, simulations of the permeameterpermeability test were performed on soil containing stones of 5five different shapes: circular, upward equilateral triangle, downward equilateral triangle, rectangle on its shortest side (L x 1.5L) and rectangle on its longest side (1.5L x L)) with an R_v of 10, 20 and 30%. We first performed simulations on soil containing only one centered inclusion. We also performed permeameter testspermeability simulations on soil containing 12 and 27 regularly distributed inclusions (for each R_v).

3. Results and Discussion

In the following, results from real and virtuallaboratory experiments and numerical simulations will be compared to the predictions of the different models developed in Section 2.1. The K_{se} will be represented by the median value predicted by the 5five models linking the properties of fine earth to the ones of stony soil (Eq. (1) to Eq. (5)). The sameThis will be referred to as "results from the K_{se} predictive models" in the following and will be graphically represented by dotted lines. The same predictive models assume that the shape parameters of the VGM-equations, n, l and α, do not depend of the stoniness. This will be referred to as "results from the models" in the following and will be graphically represented by dotted lines., as suggested by Hlaváčiková and Novák (2014). As mentioned above, unsaturated functions of stony soils have been barely studied. We will compare results from unsaturated experiments and numerical simulations to predictive models results following this assumption.

3.1. Effect of Stones on Saturated Hydraulic Conductivity

Fig. ~~1~~2 shows the relationship between the ~~relative~~ saturated hydraulic conductivity (~~K_r~~K_{se}) and the volumetric stone content (R_v) obtained from the constant-head permeability tests for laboratory experiments and numerical ~~experiments.~~simulation (12 circular inclusions). The figure also ~~deptiets~~depicts the median ~~K_r~~K_{se} of the predictive models (dashed line) and the ~~error~~ bars show ~~its~~the 95% ~~confidence~~ intervals around the median predicted by these models.

The models predict a decreasing K_{se} for an increasing R_v. The numerical simulations show a decrease in K_{se} with an increasing R_v, similar to the predictive models. Looking at the average curve obtained with our five replications (fig 2), we observe an overall increase between a R_v of 0 and 60%, this global trend being observed for each replication individually (fig 3). Statistically speaking, there are significant differences between K_{se} at a R_v of 0 and 60% and between K_{se} at a R_v of 20 and 60%. However, at low stone content, we observe for some replications local decrease of K_{se}. For example, for the first replication (Gravels 1, fig 3) K_{se} decreases until a R_v of 20% and then K_{se} begins to increase. For the second replication (Gravels 2, fig 3), the K_{se} increases from a R_v of 0 to 20% and then decreases at a R_v of 40%. Analogous permeability tests conducted by Zhou et al. (2009) showed a similar behaviour: the K_{se} initially decreases at low rock content to a minimum value at R_v = 22% and then at higher R_v, K_{se} tends to increase with R_v. Other laboratory tests carried out by Ma et al. (2010) displayed a larger K_{se} at R_v = 8% than the one of the fine earth alone. While carrying out in situ infiltration tests, Sauer and Logsdon (2002) measured higher K_{se} with increasing R_v, but decreasing K with increasing R_v under unsaturated conditions (and particularly at h = -12 cm). These considerations suggest that the relationship between K_{se} and R_v proposed by the predictive models simplifies reality to a great extent. These contradictory results suggest that the variation of K_{se} depends on different factors that can counteract the reduction of the volume available for water flow. One possible explanation of our observations has been pointed out by Ravina and Magier (1984), who directly observed large voids by cutting across a stony clay soil sample after its compaction, presumably due to translational displacement of densely packed fragments. This compaction of a saturated sample creates voids near the stone surface and hence increases K_{se} with an increasing R_v. Our sampling procedure, demanding the compaction of the sample layer-by-layer, could lead to the same kind of phenomena observed by Ravina and Magier (1984). Besides, we have to keep in mind that these elements are very likely to have a different impact depending on soil texture, which was clay for both studies.

Glass beads were used to check the influence of rock characteristics on our conclusions about K_{se}. Since results with glass beads show a trend similar to the five replications with rock fragments, we infer that it is not the rock fragment itself that produces bigger K_{se}, but the presence of a certain volume of inclusions. Besides, the variation observed between the trends of theThe models predict a decreasing K_{se} for an increasing R_v. Numerical experiments also simulate a decrease in K_{se} with an increasing R_v similar to the models. Regarding the real experiments with samples containing rock fragments, we can observe that the measured K_{se} decreases in the same way as the models until a R_v of 20%. For higher R_v, the tendency is reversed and K_{se} begins to increase. This decreasing then increasing relationship with an increasing R_v supports the results of Beibei et al. (2009) and Ma et al. (2010). Other factors than the reduction of the volume available for water flow have therefore a significant effect on K_{se}. We hypothesize that, from a certain R_v onward, voids at the stone-fine earth interface create a more continuous macropore system that overcomes the other drivers reducing the effective K. This formation of macropores between the rock fragment surface and the fine earth fraction has already been pointed out by Beibei et al. (2009), Ravina and Magier (1984) and Sauer and Logsdon (2002) to explain results obtained in similar experiments.

Ravina and Magier (1984) mention that compaction of a saturated sample creates voids near the stone surface and hence increases K_{se} with an increasing R_v. Our experiments show a similar behavior for dry soils (the disturbed samples were build compacting dry fine earth). As soil compaction often occurs naturally in the field (especially through consolidation processes), its effect should not be neglected.

We observed the same complex behavior during the experiment with glass balls. Moreover, we observed a nearly linear upward trend directly from the beginning. The large variation between the trends of the two curves suggestswith rock fragments and glass beads could be due to the inner variation of the hydraulic properties of samples, but it could suggest as well that K_{se} also depends on the shape and the roughness of the inclusions. We hypothesize that the roughness of the inclusions could alter the K_{se} by changing the amount and the type of voids in the stone vicinity. Nevertheless, we can only see the combined effect of these two factors roughness and shape in this experiment.

This leavesThese considerations suggest that the relationship between K_{se} and R_v proposed by the models simplifies reality to a great extent. However, the understanding of the major drivers of the K_{se} and their relative importance remains unclear. The effect of the size and shape of stones as such can be explored through simulations, but the void effect is less easy to

~~determine. A solution to this problem could be the use of imaging techniques such as X-ray CT to observe the structure of the fine earth fraction.~~unclear. These elements are further investigated through numerical simulations.

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Besides the observed increase of K_{se} depending on rock content, we can also observe a decrease in K_{se} between replications (see fig 3). In fact, as mentioned above, the global trend of increasing K_{se} is observed for each replication individually, but sampling procedure seems to have a large impact on results too. There are significant differences ($p<0.05$) between replication 2 and replication 5, the last one presenting lower K_{se} . The drying and wetting cycles and/or the sieving influence the hydrodynamic behavior of soil fraction since the effect decreases when R_v increases. This underlines the effect of soil texture and is an important aspect to take into account in future studies.

3.2. Effect of the ~~Stones'~~Stone Size and Shape on the Saturated Hydraulic Conductivity

To investigate the effect of the size of the inclusions and their shape on K_{se} ~~,~~ separately from other factors of variation, we performed ~~virtual~~ constant-head ~~permeameter experiments~~permeabiltiy simulations on samples containing 1, 12 and 27 inclusions of various shapes, for a R_v of 10, 20 and 30%. Table 3 illustrates~~Fig. 2 to 4 illustrate~~ the tendency of the effects and their respective drivers~~. The complete set of results can be found in the extra material section~~.

Table 3 presents~~Fig. 2 represents~~ the K_r for different sizes of circular inclusions and increasing overall stone content (R_v). When the size of the inclusions decreases (when the number of inclusions increases for a same R_v), the K_r tends to decrease. An interaction between the R_v and the size of inclusion can be observed: the effect of size is more marked with a higher R_v. For example, the decrease in K_r between 1 and 27 circular inclusions is limited to 2% for a R_v of 10%, but rises up to 25% for a R_v of 30%. A similar behavior is observed with simulations for different shapes of inclusions. These statements support the findings of Novák et al. (2011): the smaller the stones, the higher the resistance to flow at a given stoniness. We suggest the decrease of K_{se} is due to a combination of the two following phenomena. The first one is the overlapping of the influence zone of each inclusion, causing further reduction of K_r. The concept of overlapping influence zones was first proposed by Peck and Watson (1979) to explain higher decrease of the hydraulic conductivity of stones very close to each other in comparison to isotropically distributed stones. The second phenomenon could be that, for a given R_v, the contact area between stones and fine earth is higher for small stones than for bigger ones. Hence, a higher tortuosity can be responsible for a lower flow rate.

The shape of the inclusions ~~has~~ also has a ~~significant~~visible impact on K_r. ~~Fig. 3 shows the K_r as a function of R_v for different inclusion shapes in a profile containing 12 inclusions.~~ For a fixed number of inclusions, the K_r is higher with rectangular inclusions on their shortest side and smaller with rectangular inclusions on their longest side. Circular inclusions provoke a smaller reduction than triangular inclusions. The orientation of the triangles does not have a pronounced effect on K_r. Here again, we observe a stronger effect of the size for higher stoniness. As an illustration, the decrease in K_r between circular and triangular inclusions is limited to 5% for a R_v of 10% but rises up to 14% for a R_v of 30%. A similar behavior is observed with simulations including either 1 or 27 fragments.

Considering~~Fig. 4 displays the K_r for different inclusions shape and size, for~~ a fixed R_v of 20~~%. The~~% (see Table 3), the effect of the shape of the inclusions depends on their size. ~~E.g.,~~For example, the decrease in K_r between rectangular inclusions positioned on their longest and shortest sides is limited to 13% for samples containing one inclusion only while it is as high as 21% for samples containing 27 inclusions. Inversely, the effect of the size of inclusions also depends on their shape. This effect is higher for triangular and rectangular inclusions positioned on their longest side, with a K_r decrease between 1 and 27 inclusions of 23 and 18% respectively. This effect is less significant for circular inclusions, and for rectangular inclusions positioned on their shortest sides. The associated K_r decrease between 1 and 27 inclusions is 11 and 10% respectively.

The median value of K_r predicted by the models for a R_v of 20% (0.73) is similar to the simulated K_r ~~measured on~~for samples containing only one spherical inclusion (~~Fig. 4~~Table 3). The K_r predicted by the models is always higher than the K_r determined by the simulations, except for soils containing one inclusion on its shortest side. ~~One~~This can ~~conclude~~be a side effect of 2D simulations versus 3D measurements. Nevertheless, the numerical simulations show that the shape and the size of inclusions may have ~~a significant~~an effect on K_{se}, which is usually neglected by the current predictive models. In general there is a concordance between models and simulations, whatever shape and orientation of stones. This strengthens our hypothesis that macropore creation or heterogeneity of bulk density close to the stones can occur and influence K_{se}. Indeed, numerical simulations cannot simulate the creation of voids, unless we create them manually and subjectively in the domain.

Eventually, we hypothesize that, from a certain R_v onwards – the exact R_v value depending on the sampling procedure, the shape and roughness of inclusions, as well as soil texture – stoniness is at the origin of a modification of pore size distributions and of a more continuous macropore system at the stone interface. This macropore system could overcome the other drivers reducing K_{se} .

3.3. Effect of Stones on Unsaturated Hydraulic Conductivity

Fig. ~~5~~4 represents the hydraulic conductivity curves obtained from the ~~virtual permeameter~~permeability and evaporation ~~experiments~~simulations for different stoniness (R_v = 0, 10, 20 and 30%) as well as results predicted by the models for the corresponding R_v. The hydraulic conductivity curves from the predictive models and from the numerical ~~experiments~~simulations match hydraulic conductivity decreases for increasing R_v. According to these ~~experiments~~simulations, hydraulic conductivity in the unsaturated zone is well defined using a correct K_{se} and shape parameters do not ~~dependent on the stoniness.~~depend on the stoniness. But this is not surprising since predictive models and numerical simulations rely on same assumptions, i.e imperviousness of stones and an identical porosity distribution of fine earth. As a result, these elements do not prove that shape parameters do not depend on the stoniness.

~~We have to keep in mind that both the models and the numerical experiments cannot simulate other possible impacts of stones like the creation of voids at the inclusion vicinity unless we create them manually in the domain. They also both assume that stones are non-porous. This explains the close concordance of results from models and numerical experiments.~~

Fig. ~~6~~5 represents the hydraulic conductivity curves obtained from laboratory experiments on stone-free samples and on samples with a R_v of 20% as well as the results predicted by the models for a R_v of 20%. Even though the data points are dispersed, those coming from the evaporation experiments measured on stony samples are globally lower and slightly more flattened than the ones measured on stone-free samples. This suggests that stones decrease unsaturated hydraulic conductivity~~, whatever~~. However, it must be noted that we do not have unsaturated K data for higher stone contents, whereas for K_{se} , the ~~suction may be.~~effect becomes more obvious for R_v > 20%. It might therefore be needed to find a way to conduct evaporation experiments for higher stone contents in order to draw final conclusions.

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~~The hydraulic conductivity curve predicted by the models is higher than the fitted hydraulic conductivity curve from the evaporation experiments on the stony samples. This is linked to the fact that the fitted curve has been "forced" by the additional K_{se} data point at zero tension. The K_{se} predicted by the models is 1,95 cm/day while the K_{se} measured with the permeameter is 1,55 cm/day. We can explain such a difference (20%) in K_{se} by the way stones are positioned in the sample: stones were laid on their flattest side for practical reasons. As confirmed by the numerical simulations, they could therefore have hampered the water flow more strongly than if they were positioned differently.~~

In the numerical ~~experiments~~simulations, the presence of stones ~~reduced~~reduces the hydraulic conductivity in the same way as predicted by the models, whatever the suction was. Similarly, the laboratory experiments ~~suggested~~suggest that stones reduce the unsaturated hydraulic conductivity ~~at high suction (pF > 2). Nevertheless,~~while laboratory experiments in saturated conditions indicated that ~~voids creation at the stone-fine earth interface~~stones content might increase the K_{se}. ~~According~~These elements support the hypothesis of the macropore creation: according to the well-~~know~~known law of Jurin (1717), pores through which water will flow depend both on the pore size distribution and the effective saturation ~~state. The~~. Consequently, flow in the macropore system will ~~be~~ only be "activated" in the near-saturation zone while small pores will ~~be~~ only be drained at high suction. Therefore, we ~~can~~could hypothesize that ~~even if it is not clear whether stones increase or decrease the near saturation hydraulic conductivity, they~~stones are always expected to decrease the hydraulic conductivity at low effective saturation states. ~~As a total saturation of the soil is rarely reached in practice (Gras 1994), considering a diminishing hydraulic conductivity with an increasing R_v seems appropriate.~~ However, under saturated conditions, ~~the macropores have a non-negligible effect so that understanding the~~ relationship between R_v and K_{se} seems to be less trivial and requires further investigations considering soil texture and stone characteristics.

4. Conclusion

Determining the effect of rock fragments on soil hydraulic properties is a major issue in soil physics and in the study of fluxes in soil-plant-atmosphere systems in general. Several models aim at linking the hydraulic properties of fine earth to those of stony soil. Many of them assume that the only effect of stones is to reduce the volume available for water flow. We tested the validity of such models with various complementary experiments.

Our results suggest that considering that stones only reduce the volume available for water flow ~~many~~may be ill-founded. ~~We~~First, we observed that, contradictory to the predictive models, the saturated hydraulic conductivity of the clayey soil of this study increases with stone content. Besides, we pointed out several other potential drivers influencing K_{se} ~~,~~ which are not considered by these K_{se} predictive models. We observed that, for a given stoniness, the resistance to flow is higher for smaller inclusions than for bigger ones. We explain this tendency by an overlapping of the influence zones of each stone combined with a higher tortuosity of the flow path. We also pointed out the shape of stones as a ~~major~~ factor affecting the hydraulic conductivity of the soil. We showed that the effect of the shape depends on the inclusion size and inversely that the effect of inclusion size depends on its shape. Finally, ~~we proposed~~our results converge to the assumption that ~~soil compaction, swelling and shrinking might strongly alter the~~ this contradictory variation of K_{se} ~~via~~ could find its origin at the creation of voids at the stone-fine earth interface as pointed out by Ravina and Magier (1984). Even if the very mechanisms behind ~~the creation of voids~~these observations remains unclear, ~~its effect seems~~they seem to strongly depend on ~~the~~ R_v, ~~the~~ shape and ~~the~~ roughness of inclusions. ~~We also hypothesize~~However, as we conducted these experiments on a specific clay soil only, and given the fact that ~~the fine earth texture plays a major role in the voids creation~~structural modifications are textural dependent, our results can't be extrapolated to other soil textures without similar experiments. Finally, as we worked with disturbed samples, our results do not include quantification of natural phenomenon such as swelling and shrinking that occurs naturally for clay soils.

These findings suggest that the aforementioned predictive models are not appropriate in all cases, particularly under saturated conditions. ~~However, under unsaturated conditions, this statement should be more nuanced, as both numerical and laboratory experiments corroborate the general trends from the models.~~ Models should ~~at least~~ take into account the ~~effect of the~~counteracting factors, notably size and ~~the~~ shape of stones~~ as well as the voids creation induced by stones. However, the mechanisms governing the creation of voids at the stone-fine earth interface still need to be explored.~~

~~Further~~. However, further investigations are ~~thus~~ required in order to explore the hydraulic properties of stony soils and to ~~define the conditions under which we can apply the models~~develop new models or adapt the existing ones. The direct observation of undisturbed stony samples porosity using X-ray computed tomography or magnetic resonance imaging ~~is a necessary next step to a~~could confirm - at first - and then help better ~~understanding~~understand the mechanism of the link between voidsupposed voids creation at the stone-fine earth interface and soil compaction. However, under unsaturated conditions, these considerations should be more nuanced, as both numerical simulations and laboratory experiments corroborate the general trends from the predictive models. Finally, similar analyses should be conducted in view of determining the effect of the fine earth texture on the drivers of hydraulic properties as pointed out throughout our research.

Appendix A: Extra Material

Table 3 – Results from the investigation of the inclusion size and shape on the saturated hydraulic conductivity by means of numerical simulations (n is the number of inclusions simulated in the profile for the corresponding R_v, H = Rectangle on its shortest side, O = Circle, ▵ = Upward triangle, v = Downward triangle, L = Rectangle on its longest side)

		Relative saturated hydraulic conductivity		
R_v	Shape	n = 1	n = 12	n = 27
	H	0.88	0.88	0.88
	O	0.84	0.83	0.82
	▵	0.80	0.79	0.78
	v	0.80	0.79	0.78
10%	L	0.84	0.83	0.82
	H	0.76	0.71	0.68
	O	0.73	0.69	0.65
	▵	0.67	0.63	0.54
	v	0.67	0.63	0.54
20%	L	0.66	0.61	0.54
	H	0.70	0.60	0.55
	O	0.64	0.58	0.48
	▵	0.59	0.50	0.46
	v	0.59	0.50	0.47
30%	L	0.56	0.48	0.31

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Table 1 – Parameters of the van Genuchten equations used in the numerical experiments

θ_r [-]	θ_s [-]	α [cm^{-1}]	n [-]	l [-]	K_{se} [cm/day]
0.185	0.442	0.0064	2.11	-0.135	2.686

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Table 2 – Schematic summary of the treatments ~~(H = Rectangle on its shortest side, O = Circle, Δ = Upward triangle, v = Downward triangle, L = Rectangle on its longest side)~~

Tableau mis en forme

	Effect of R_v on unsaturated hydraulic conductivity		Effect of R_v on saturated hydraulic conductivity			Effect of size and shape on saturated hydraulic conductivity				
Method	Evaporation experiment + Permeameter		Permeameter			Permeameter				
R_v [%]	0 - 10 - 20 - 30	0 - 20	0 - 20 - 40 - 60			0 - 10 - 20 - 30				
Approach	Numerical	Laboratory	Numerical	Laboratory		Numerical				
Inclusion type	~~O~~● (2D) n = 12	Rock fragments	~~O~~● (2D) n = 12	Glass spheres	Rock fragments	~~O~~● (2D) n = 1, 12, 27	~~Δ~~▲ (2D) n = 1, 12, 27	~~v~~▼ (2D) n = 1, 12, 27	~~H~~▌ (2D) n = 1, 12, 27	~~L~~▬ (2D) n = 1, 12, 27

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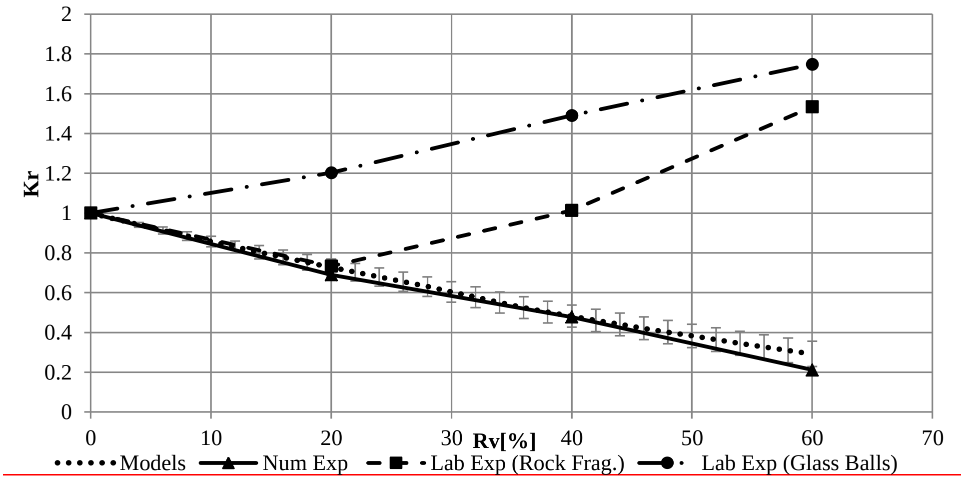

Fig. 1 – K_{se} depending on R_v obtained from laboratory experiments, numerical experiments and the models (the error bars show the 95% confidence intervals of median predicted by these models)

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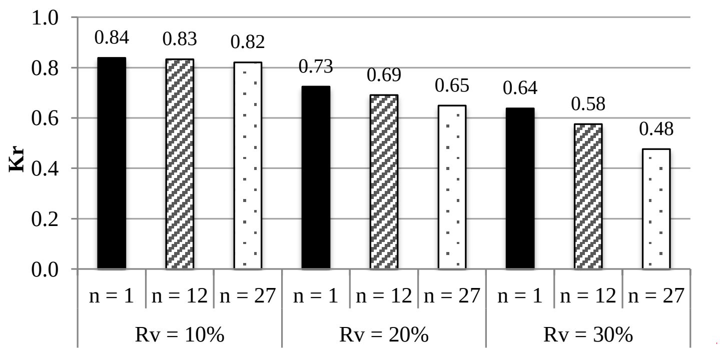

~~Fig. 2 – K_r depending~~Table 3 – Results from the investigation of the inclusion size and shape on ~~R_v for different sizes of circular inclusions~~the saturated hydraulic conductivity by means of numerical simulations (n is the number of inclusions simulated in the profile for the corresponding ~~R_v)~~ R_v)

R_v	Shape	Relative saturated hydraulic conductivity n = 1	 n = 12	 n = 27
	▮	0.88	0.88	0.88
	●	0.84	0.83	0.82
	▲	0.80	0.79	0.78
	▼	0.80	0.79	0.78
10%	▬	0.84	0.83	0.82
	▮	0.76	0.71	0.68
	●	0.73	0.69	0.65
	▲	0.67	0.63	0.54
	▼	0.67	0.63	0.54
20%	▬	0.66	0.61	0.54
	▮	0.70	0.60	0.55
	●	0.64	0.58	0.48
	▲	0.59	0.50	0.46
	▼	0.59	0.50	0.47
30%	▬	0.56	0.48	0.31

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Tableau mis en forme

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Fig. 1 – Preparation of disturbed samples containing glass balls (left) and gravels (right).

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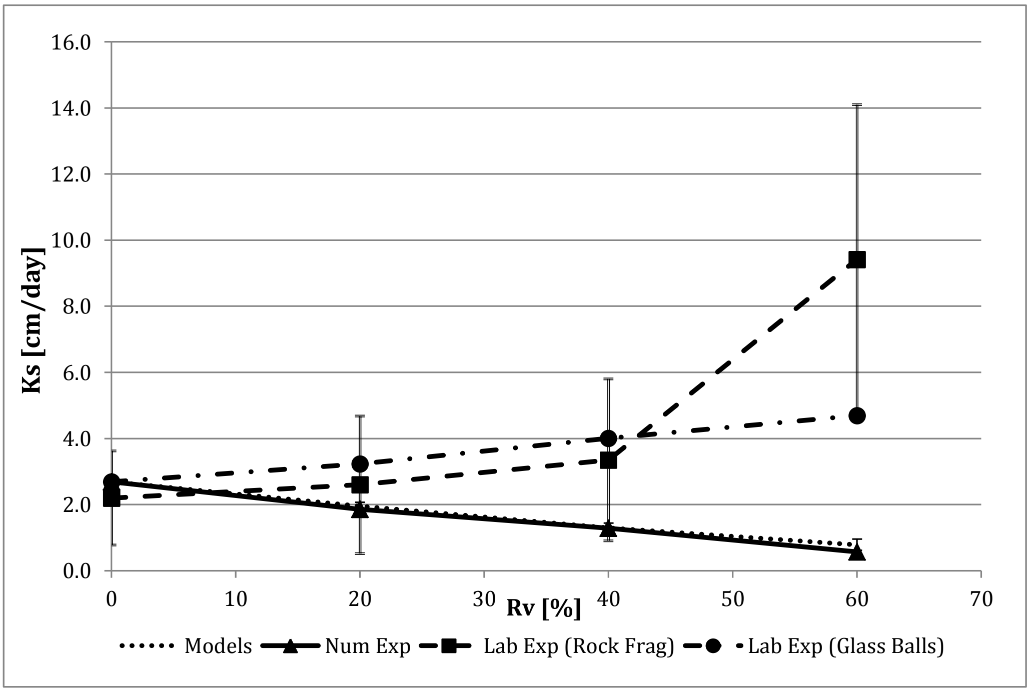

Fig. 2 – $\mathbf{K_{se}}$ depending on $\mathbf{R_v}$ obtained from laboratory experiments, numerical simulations with 12 circular inclusions and the predictive models (the bars show the 95% intervals around the median predicted by these models)

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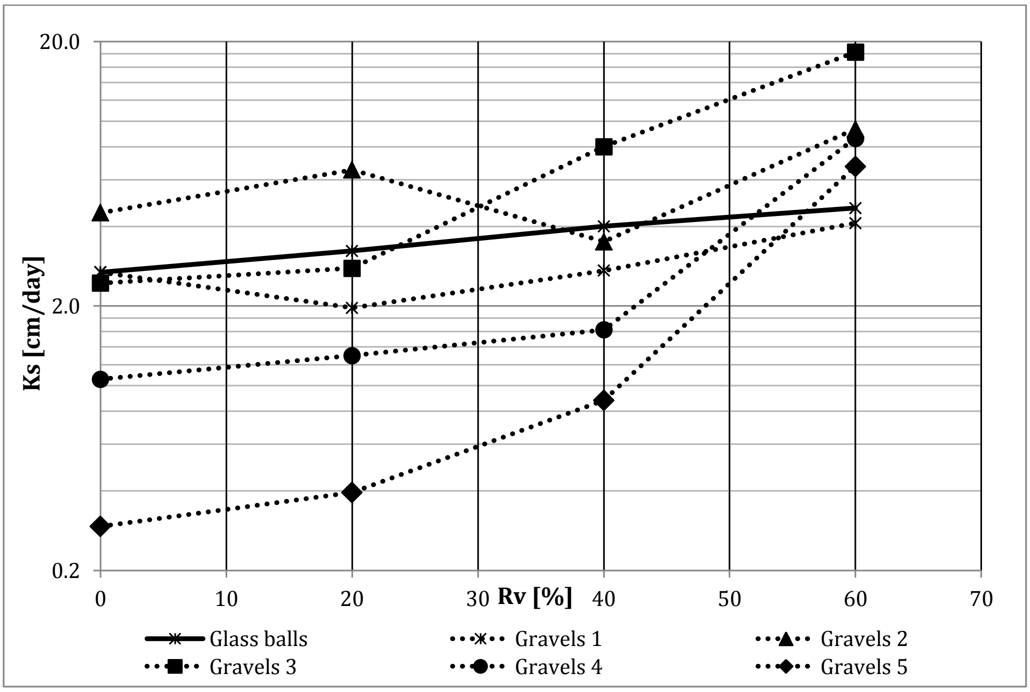

Fig. 3 – K_{se} depending on R_v obtained from laboratory experiments with gravels (5 replications) and glass balls (1 replication).

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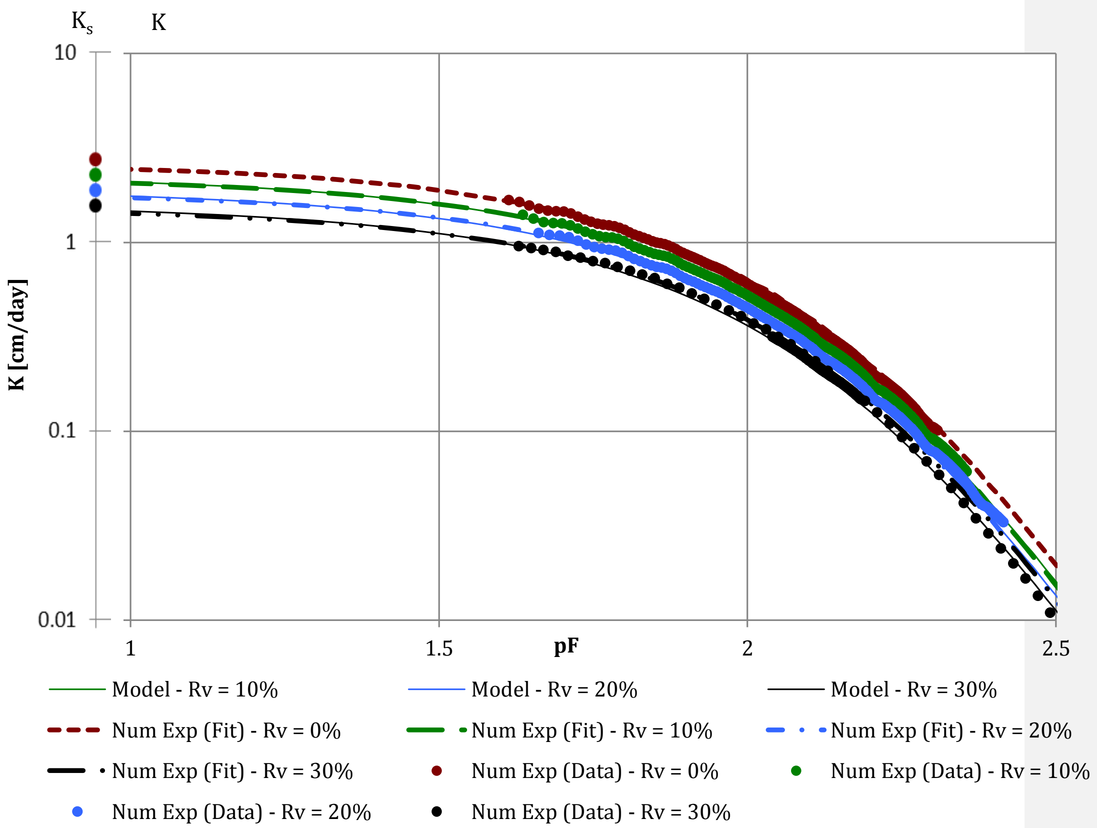

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2 Fig.

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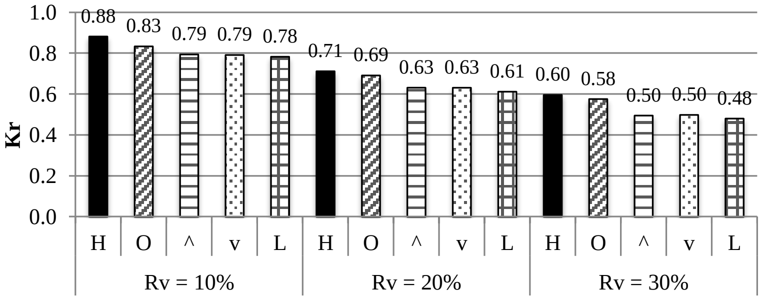

1 Fig. 3 – K_r depending on R_v for different inclusion shapes in a profile containing 12 inclusions regularly distributed (H = Rectangle on its shortest side, O = Circle, ^ = Upward triangle, v = Downward triangle, L = Rectangle on its longest side)

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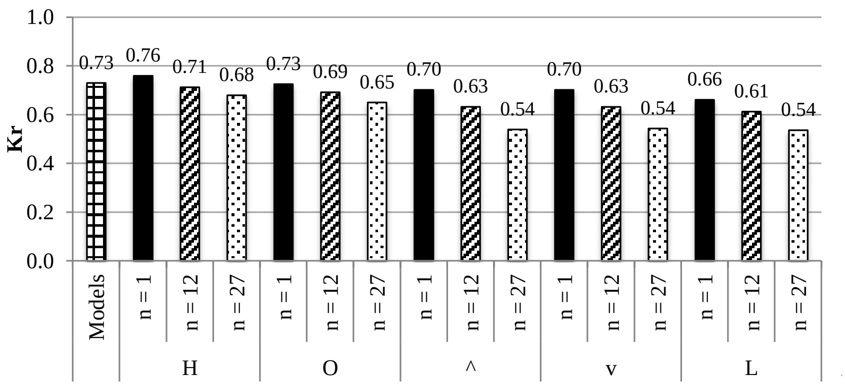

Fig. 4 – K_r for different inclusion shapes and sizes in a profile with a R_v of 20% (H = Rectangle on its shortest side, O = Circle, ^ = Upward triangle, v = Downward triangle, L = Rectangle on its longest side) and median K_r predicted by the models for the corresponding R_v.

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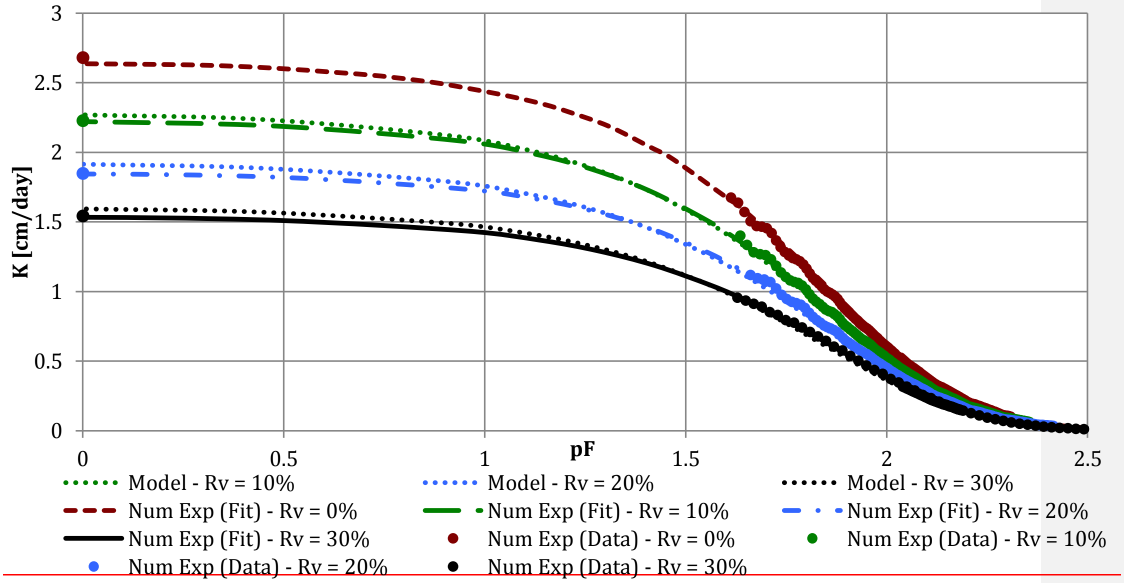

~~Fig. 5~~4 – Hydraulic conductivity curves obtained from numerical experiments (data and fit for $\mathbf{R_v}$ = 0, 10, 20, 30%) and results predicted by the models for the coresponding $\mathbf{R_v}$

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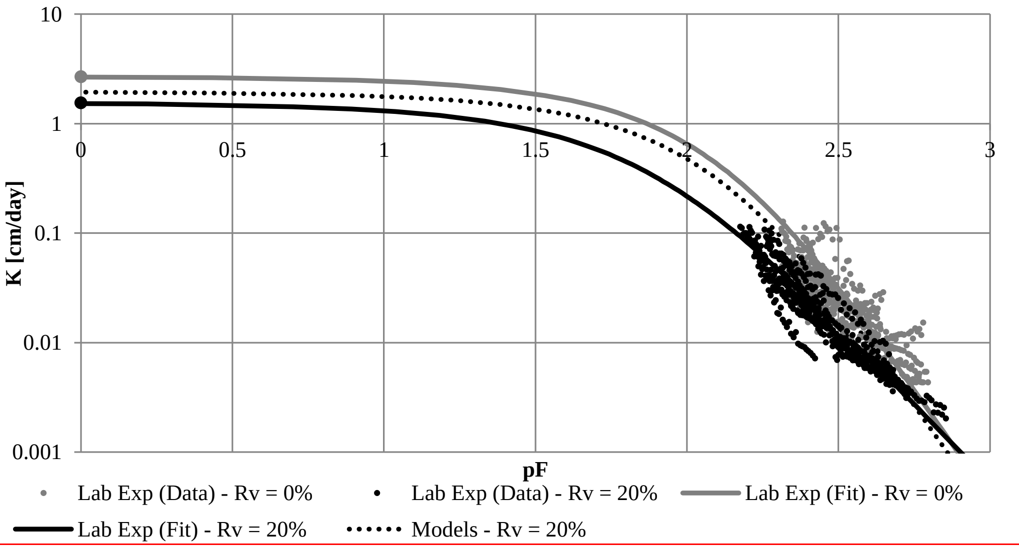

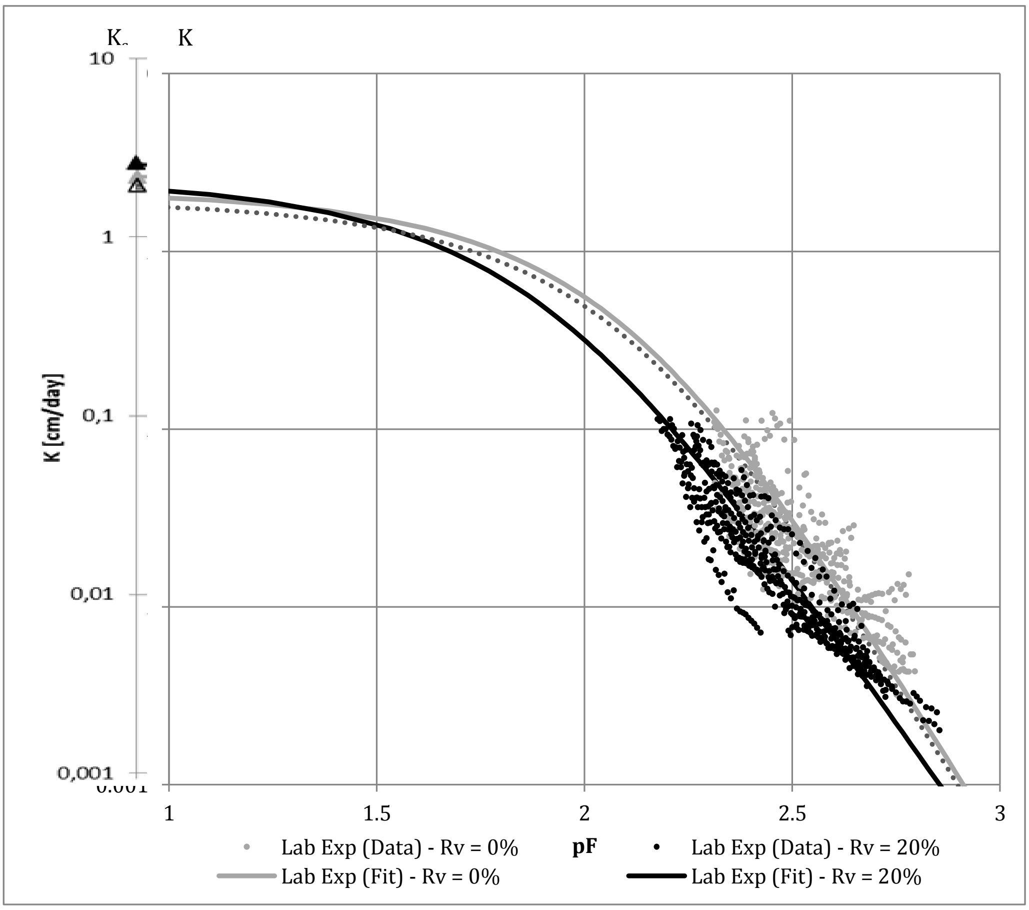

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Fig. ~~6~~5 – Hydraulic conductivity curves obtained from laboratory experiments (data and fit for ~~R_v~~R_v = 0 and 20%) and results predicted by the models for a ~~R_v~~R_v of 20%

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