Three-Dimensional Printing of Macropore Networks of an Undisturbed Soil Sample

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Macropore systems predominantly determine rapid water flow and solute transport in undisturbed soils. Repeated experiments are needed to investigate the relationship between the nature of the macropore network and the resulting water and solute transport under different hydraulic initial and boundary conditions. However, the large heterogeneity in soil macropore network structures renders each soil sample unique and multiple identical samples impossible. In addition, the fragile nature of soil strongly limits the possible number of repeated experiments on one individual sample. Micromodels that mimic the precise shape and location of the macropores in undisturbed soil are therefore necessary to allow repeated experiments. In this study we investigated whether such micromodels can be obtained using contemporary three-dimensional (3-D) printing techniques and materials. We used X-ray computed tomography to digitize the 3-D macropore structure of an undisturbed soil sample. We printed a subsection of this macropore system in five different materials. Four out of the five investigated materials had essential parts of their macropore system clogged with residual printing or printing-aid material. Only one reprint, namely the prime-gray sample that was printed using stereo lithography, exhibited no pore clogging and had the largest hydraulic conductivity of all investigated reprints. Prime gray showed subcritical water repellency with a medium contact angle of approximately 65°, which is similar to contact angles found in natural soil. We conclude that the 3-D printing of undisturbed soil macropore systems is in principle possible with contemporary 3-D printing systems.

Abbreviations: ABS, acrylonitrile butadiene styrene; AL, alumide; HD, high-detail resin; PA, polyamide; PG, prime gray; 3-D, three-dimensional; μCT, computed microtomography.

The flow of water and solutes through soil is largely determined by the size and connectivity of the largest water-filled pores (Jarvis, 2007). Often the size of the largest soil pores considerably exceeds the size of the soil textural pores. This is the case for soil with sufficiently large clay content that enables the formation and maintenance of soil macropores (Horn et al., 1994), which Luxmoore (1981) defined as pores with a low tortuosity and a radius \( r > 0.5 \) mm. Water and solutes may be rapidly leached below the root zone through the macropore system, bypassing large fractions of the soil matrix (Bouma and Dekker, 1978; Thomas and Phillips, 1979). This is commonly referred to as preferential macropore flow, which has been identified as a main transport pathway of agrochemicals into ground and surface water bodies (Flury, 1996; Jarvis, 2007).

Two main challenges are posed when investigating the hydraulic properties of natural soils. One is that the flow-determining soil properties exhibit a strong spatial variability (Netto et al., 1999). This renders exact replicates impossible for soil samples. The other challenge is that soil hydraulic properties are subject to temporal changes (Mesting and Jarvis, 1993; Schwen et al., 2011) and are often altered by the measurement itself. For instance, the inverse estimation of hydraulic properties by multistep outflow experiments (van Dam et al., 1994) or tension disk infiltrometry (Angulo-Jaramillo et al., 2000) requires a certain amount of water to flow through the investigated soil, which may lead to either consolidation of the pore space of loose soils (Or et al., 2000) or internal soil erosion (Bonelli...
The assembly of more realistic soil micromodels requires copies of the pore structure of undisturbed soil samples. An alternative to experiments on real soil may be experiments on artificial macropores (Karadimitriou et al., 2013). Despite the large potential of the 3-D printing methodology, many challenges still need to be overcome. Karadimitriou et al. (2013) stressed that requirements for the printing material are a high durability to water, waterproofness, and a constant degree of water repellency. Especially the latter has not been tested yet. Another problem inherent in some of the printing materials is the removal of the powder that supports the printing process. If it is not removed, it might clog the pore system.

The objective of this study was to investigate the suitability of different 3-D printing techniques and materials for reproducing micromodels of undisturbed soil macropore systems that are usable for water and solute transport experiments. We used µCT to digitize the macropore structure of an undisturbed soil sample and printed it in five different materials, using four different 3-D printing techniques. The potential and limitations of the different printing materials and methods were assessed with respect to the reprint resolution, reproducibility of the original pore network, hydraulic conductivity, and degree of water repellency.

**Material and Methods**

**Soil Sampling and X-ray Imaging**

An undisturbed soil sample was collected from the topsoil of an arable field in Säby (59°50′ N, 17°42′ E), 3 km south of Uppsala, Sweden. The sample was taken in November 2012 at the 10-cm depth from a bare field under long-term reduced tillage. The soil column had a diameter of 6.82 cm and a height of 3.80 cm. The soil was characterized by a silty clay loam texture (21.0% clay, 47.3% silt, 31.7% sand) and had developed in post-glacial lake sediments. More information on the soil was provided by Larsbo et al. (2009).

The soil column was scanned by a GE phoenix v|tome|x m cone-beam X-ray computed tomography system (GE Sensing &
The spatial resolution was 51 μm. The X-ray radiographs were acquired with a cathode voltage of 170 kV and an electron flux corresponding to a current of 300 mA. Two thousand radiographs were recorded for 3-D image reconstruction. The 3-D image reconstruction was performed by the GE phoenix datos|x software package (GE Sensing & Inspection Technologies GmbH, Germany), which is based on the Feldkamp algorithm (Feldkamp et al., 1984).

Image Post-processing and Segmentation

The Fiji software package (Schindelin et al., 2012) was used for all image post-processing and analyses steps. The 3-D image of the soil column was prepared for 3-D printing by segmentation and noise reduction. First, we applied a relatively large 3-D median filter with a radius of seven voxels. The large radius was chosen to remove structures smaller than the 3-D printing resolution (see below). This filtering step resulted in a reduced image complexity and in widened bottlenecks in the imaged macropore system. The segmentation of the soil column into two phases corresponding to the air- and water-filled pores and the solid material was accomplished by using a global threshold, which was selected on visual inspection. This approach provided better results than off-the-shelf thresholding algorithms that were also tested, among them the algorithms of Otsu (1979) and Li and Tam (1998) and the method of entropy maximization proposed by Kapur et al. (1985). Because it was merely our goal to create a 3-D template of a percolating soil macropore system without bottlenecks at or below the printing resolution, we abstained from applying a more sophisticated local thresholding approach, which otherwise would have been preferable (e.g., Iassonov et al., 2009; Schlüter et al., 2014).

A cubic subsection of the 3-D soil pore-space image was selected for 3-D printing (see Fig. 1). This subsection was chosen because it contained two continuous macropores. The edge lengths of the cubic subsection were 400 voxels corresponding to 2.03 cm. To reduce the number of isolated voxels, a morphological opening was applied to the binary image. Finally, the segmented image of the cubic sub-sample was saved in a vector image format for 3-D printing.

Creating Artificial Soil Samples by Three-Dimensional Printing

The vector image of the soil subsection was printed by i.materialise (www.i.materialise.com) using five different printing materials (Table 1). The first tested material was acrylonitrile butadiene styrene (ABS, Stratasys Inc., 2013). Acrylonitrile butadiene styrene is a thermoplastic material that is widely used for 3-D printing. The printing process with ABS is accomplished by fused deposition modeling (McCullough and Yadavalli, 2013). The raw material is molten and applied layerwise by a nozzle that presses the material out. This process creates a porous, water-permeable matrix (McCullough and Yadavalli, 2013). A support material is commonly applied to stabilize overhanging features by filling gaps to the underlying layer. It has to be removed after printing.

We also tested reprints made of polyamide (PA) and alumide (AL), a powder blend of polyamide and aluminum. Both materials are thermoplastic powders (EOS GmbH, 2010, 2012; Zhou et al., 2008). The printing technique is identical for both materials and is referred to as selective laser sintering. The 3-D object is created by applying fine polyamide (or alumide) powder layerwise, which is locally solidified (sintered) by a laser. The unconsolidated powder remains in place and is removed by mechanical means in a post-processing step.

Prime gray (PG) was the fourth material considered in our study. Prime gray is an epoxy resin photo polymer (3D Systems Inc., 2008, 2011) and is printed by stereo lithography. The liquid resin is applied in thin layers by a wiper. The produced platform is lowered after curing, and a subsequent layer is formed (Chua et al., 2010, p. 35–136). Uncured resin is removed after the printing process.

Fig. 1. Computed microtomography scan of the original soil sample (left) and the pore morphology of the subsection that was used for reprinting (right).
The last reprint consisted of high-detail resin (HD), which is a photopolymer that is based on an acrylic monomer (Stratasys Inc., 2011, 2014). High-detail resin reprints are produced by using the PolyJet technology (Stratasys Inc., 2014). During the printing process, liquid photopolymer, along with a support material, is applied in the same way as in inkjet printing. The printing material is cured (solidified) by ultraviolet light (Chua et al., 2010, p. 35–136). Uncured raw material has to remain in place until the printing process is finished.

According to the i.materialise company, residual or printing-aid materials are flushed away from freshly printed objects using a high-pressure water jet. In this study, we did not try to dislodge residual or printing-aid material that the printing provider did not succeed in removing.

### X-ray Imaging of the Three-Dimensional Reprints

The five reprints were scanned with μCT at the same resolution as the original soil sample (51 μm). The reprints were scanned simultaneously to ensure a similar brightness and contrast. In contrast to the X-ray image of the original soil, which had been filtered with a very large median filter to ensure a good connectivity of the macropore system, we kept the amount of noise filtering for the X-ray images of the reprints at a minimum, providing a good comparability to the smoothed image of the original soil that had served as a printing template. The images of the reprints were prepared for segmentation by applying a median filter with a radius of three voxels to reduce the image noise. Subsequently, an unsharp mask with a radius of 1.5 and mask weight of 0.6 was applied to improve the contrast between different density phases. We used statistical region merging (Nock and Nielsen, 2004) to reduce the number of different gray values of the image. The Q parameter in the statistical region merging algorithm determines the number of regions left after merging. Setting Q to 2 resulted in the optimal case of three final regions corresponding to the number of density phases present in each reprint (air, printed solidified material, and unsolidified printing-support material). In cases where the statistical region merging yielded more than three classes, we merged the classes on visual inspection.

Two binary 3-D images were created for each of the five reprints. The first one segmented each image into solidified printing material and macropores, regardless of whether the latter were air filled or filled with unconsolidated printing or printing-aid material. These binary images were used to determine the morphology of the actually printed macropore system. They represent the theoretically best performance of each printing technique and material combination, assuming that it was possible to remove the unconsolidated printing and printing-aid materials from the pore system by investing more effort than we did in our study. The second 3-D binary image depicted the air-filled macropores as one phase and the unconsolidated and consolidated printing material as the other phase. This image corresponds to the unlogged printed macropore system as it was in our study.

### Determination of Physical and Hydraulic Properties of the Artificial Soils

Segmented images of the reprints were analyzed using the Fiji software package (Schindelin et al., 2012) and the plug-in BoneJ (Doube et al., 2010). The mean pore diameters in each sample were determined by the thickness algorithm adapted from Dougherty and Kunzelmann (2007). It was defined as the diameter of the largest sphere that fitted into the macropore. The bottleneck of a connected macropore system was defined as the diameter of the largest sphere that fitted through the macropore system along the entire path from top to bottom. The properties of individual macropores were determined using the Particle Analyzer plug-in, which is based on the 3-D Object counter (Bolte and Cordelières, 2006). The macropore surface was calculated using the Isosurface plug-in, which triangulates surfaces from the binary voxels contained in the images. The average length and average tortuosity of the pore network was calculated with the help of the Skeletonize3D plug-in (Lee et al., 1994; Arganda-Carreras et al., 2010). The specific tortuosity of the macropores connecting the top and bottom of the cubic subsection was calculated by the path length of the shortest top-to-bottom connection of the skeletonized macropore system divided by the Euclidean distance between the entry and exit points of the connection.

The degree of water repellency of the tested materials was assessed by means of the contact angle between the solid surface and a water

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**Table 1. Physical data about the tested printing materials. The product indicates the brand name; wall thickness and detail are indicators for the minimal printing resolution.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Product</th>
<th>Technique</th>
<th>Min. detail</th>
<th>Min. wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile butadiene styrene (ABS)</td>
<td>ABplus P430/M30</td>
<td>fused deposition modeling</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Alumide (AL)</td>
<td>EOS PA12-MD(Al)</td>
<td>selective laser sintering</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>High-detail resin (HD)</td>
<td>VeroWhitePlus RGD835</td>
<td>PolyJet technology</td>
<td>0.02–0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Polyamide (PA)</td>
<td>PA2200 Balance 1.0</td>
<td>selective laser sintering</td>
<td>0.03</td>
<td>0.08–0.1</td>
</tr>
<tr>
<td>Prime gray (PG)</td>
<td>Accura Xtreme</td>
<td>stereo lithography</td>
<td>0.03</td>
<td>0.1</td>
</tr>
</tbody>
</table>
We used the sessile drop method described by Bachmann et al. (2000). A water drop was put on the upper surface of a reprint by a pipette. The contact angle was then captured by a Nikon D3200 digital SLR camera equipped with an AF-S DX NIKKOR 35 mm f/1.8G lens on a tripod. Subsequently, the material was wiped with a paper towel to prepare the reprint for a repetition of the measurement. Ten repetitions were performed at random positions on the surface of each material. The contact angle between the sample surface and the water drop was determined manually using the Fiji software (Schindelin et al., 2012). Contact angles <90° are considered subcritical and easily wettable, while angles >90° are considered critical, indicating a severe degree of water repellency (Bachmann et al., 2000).

The saturated hydraulic conductivity, \( K_s \), was measured on the artificial reprint samples using the constant-head method (Hillel, 2003). Duct tape enclosed the top of the sample, forming a funnel, and the gaps between the sample and the duct-tape-funnel walls were sealed with silicon sealant. The sample was fixed on a holder, and the bottom boundary was open to the atmosphere (seepage face). A constant head of 2 cm was maintained on the soil surface until the flow rate had stabilized for a measurement. We repeated this procedure 10 times for the fast-conducting PG material and five times for the less conductive ABS material. For comparison, we calculated equivalent hydraulic conductivities using the Hagen–Poiseuille law, which we parameterized with the help of the binary \( \mu \)CT images of the unclogged macropore system, using the length and average pore diameter of the largest macropore connecting the top and bottom of the reprint, ignoring dead-end branches.

Results and Discussion

The pore morphology of the soil subsample was dominated by two large, continuous macropores and some smaller isolated pores (Fig. 1). The cubic subsection exhibited an X-ray resolvable macroporosity of approximately 3%, which is typical for undisturbed soils (e.g., Kim et al., 2010; Luo et al., 2010).

Images of the five reprints are shown in Fig. 2. Figure 3 shows the \( \mu \)CT-derived interior macropore structure of the five reprints as well as the original subsection of the soil sample. The macropores in Fig. 3 are filled with either air or residual printing-support material. The outlines of the larger of the two connected macropore systems (Fig. 3f) were printed in all five materials, although this is only visible in four of the five isosurfaces shown in Fig. 3, namely for AL, PA, PG, and HD (Fig. 3b–3e). In contrast, the ABS material (Fig. 3a) showed a regular mesh of interconnected, smaller macropores. These printing artifacts were probably related to the applied fused-deposition printing technique. Consequently, the ABS material exhibited a six times higher macroporosity and >20 times larger macropore surface area than the original soil sample (Table 2). As already stated, the main macropore features were also reproduced by the ABS reprint, but in Fig. 3a these are hidden by the printing artifacts. Similar artifacts were also present in the AL reprint (Fig. 3b), but they were smaller and not interconnected. Only two materials (PA and HD; Fig. 3c and 3e) also contained the smaller of the two continuous macropores. This pore connected the top and bottom of the sample but was not connected to the larger macropore (Fig. 3f). The numerous smaller isolated macropores in the original soil sample were only sporadically printed in all reprints because their size was often close to the 3D printers’ resolution.

Due to the absence of small and isolated pores, the macroporosity and macropore surface area in the reprints were smaller than in the original soil sample (Table 2). With respect to macroporosity and macropore surface area, the PA and HD materials were most similar to the original soil sample (Table 2). The good agreement in macropore surface area of the HD material was probably due to the overly rough representation of the macropore walls, which were smoother in the original soil sample (compare Fig. 3e and 3f).
PG and AL materials slightly underestimated the macroporosity and macropore surface area.

We compared some morphological properties of the largest well-connected macropore in each material and the original soil sample. The mean pore diameter in the PA and PG reprints deviated <1% from the estimate obtained from the original soil sample, while HD and AL underestimated the mean pore diameter by >10 and 20%, respectively (Table 3). For ABS the underestimation of the mean pore diameter was even larger due to the spuriously printed, mesh-like pore network. The diameter of the bottleneck in the shortest connecting path was best represented in the PG reprint. For the PA reprint, it was still comparable to the bottleneck for the soil, with an underestimation of 8.2% (Table 3). In contrast, the bottlenecks in the AL and HD materials were less than half the size of the estimate for the original soil. We abstained from determining the bottleneck size of the ABS reprint because the spuriously printed mesh-like structure made this impossible (Fig. 3a).

More than 83 and 63% of the printed macropores in the AL and PA materials, respectively, were clogged by residual printing-support material (Table 2; Fig. 4). These two reprints were created by selective laser sintering. It seems that the AL and PA reprints (Fig. 4b and 4c) are not suitable to investigate the hydraulic and solute transport properties of an undisturbed macropore system at the original scale—unless a way of removing the printing aid material can be found. A small fraction (5%) of the macropores was also clogged in the HD reprint (Table 2), including the secondary connected macropore (compare Fig. 3e and 4e). The other two reprints showed comparatively little pore

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Table 2. Characteristics of the pore system of the tested reprints and the original soil sample. Macroporosity relates to the porous fraction in relation to the volume without pores. Surface denotes the pore surface. The average tortuosity is the average ratio between the skeleton branch length and the corresponding Euclidean distance. The percentage of clogged macropores indicates the clogging level by printing-support materials.

<table>
<thead>
<tr>
<th>Material†</th>
<th>Macropore volume</th>
<th>X-ray detectable macroporosity</th>
<th>Macropore surface area</th>
<th>Average tortuosity</th>
<th>Clogged macroporosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm³</td>
<td>cm²</td>
<td>%</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>ABS</td>
<td>1.607</td>
<td>0.195</td>
<td>130.13</td>
<td>1.22</td>
<td>1.3</td>
</tr>
<tr>
<td>AL</td>
<td>0.155</td>
<td>0.019</td>
<td>3.12</td>
<td>1.17</td>
<td>83.7</td>
</tr>
<tr>
<td>HD</td>
<td>0.197</td>
<td>0.024</td>
<td>5.67</td>
<td>1.26</td>
<td>5.2</td>
</tr>
<tr>
<td>PA</td>
<td>0.204</td>
<td>0.025</td>
<td>4.78</td>
<td>1.22</td>
<td>63.0</td>
</tr>
<tr>
<td>PG</td>
<td>0.176</td>
<td>0.021</td>
<td>4.07</td>
<td>1.20</td>
<td>0.7</td>
</tr>
<tr>
<td>Soil</td>
<td>0.261</td>
<td>0.031</td>
<td>5.51</td>
<td>1.25</td>
<td></td>
</tr>
</tbody>
</table>

† ABS, acrylonitrile butadiene styrene; AL, alumide; HD, high-detail resin; PA, polyamide; PG, prime gray.
The fused-deposition technique used for the ABS reprint (Fig. 4) posed two problems for data processing. First, it used a support material with a similar density as the printing material, and second, the mesh-like artificial pore structure (Fig. 3a) was connected to the printed macropores. Finally, the printing technique of stereo lithography with which the PG reprint was created (Fig. 4d) uses a gel-like casting material, which was obviously easier to remove after printing.

The mean contact angle for water of the reprint materials varied in a range between 53 and 84° (Fig. 5). Prime gray and ABS showed a slight decreasing trend in contact angle after repeated wettings, while HD showed a rather constant wettability. Polyamide showed a highly wettable behavior after repeated wettings, with occasional immediate and complete diffusivity of water drops. This suggests a spatially and temporally variable contact angle for this material. Polyamide materials are therefore not recommended if a spatially constant wetting behavior of the soil facsimile is desired (Karadimitriou and Hassanizadeh, 2012). Alumide exhibited the highest water repellency but showed a large variance between repeated measurements compared with the other materials.

Only two reprints, PG and ABS, conducted water during the infiltration tests. For PG, we found $K_s = 1044$ (standard deviation 24.5) cm h$^{-1}$. This agreed quite well with the $K_s$ value calculated by the Hagen–Poiseuille equation for a circular pipe with a pore bottleneck diameter of 0.165 cm of the large macropore in the PG reprint (Table 4), which was 2109 cm h$^{-1}$. The somewhat lower hydraulic conductivity in the reprint was probably related to sub-critical water repellency, tortuosity, and deviations from circularity. The $K_s$ of the ABS reprint was 4.3 (standard deviation 4.1) cm h$^{-1}$, which is more than two orders of magnitude smaller than

<table>
<thead>
<tr>
<th>Material†</th>
<th>Mean pore diameter</th>
<th>Bottleneck diameter</th>
<th>Macropore volume</th>
<th>Surface/volume ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>0.048</td>
<td>1.567</td>
<td>0.423</td>
<td>0.423</td>
</tr>
<tr>
<td>AL</td>
<td>0.135</td>
<td>0.073</td>
<td>0.107</td>
<td>0.149</td>
</tr>
<tr>
<td>HD</td>
<td>0.148</td>
<td>0.073</td>
<td>0.187</td>
<td>0.139</td>
</tr>
<tr>
<td>PA</td>
<td>0.172</td>
<td>0.156</td>
<td>0.195</td>
<td>0.114</td>
</tr>
<tr>
<td>PG</td>
<td>0.167</td>
<td>0.165</td>
<td>0.175</td>
<td>0.119</td>
</tr>
<tr>
<td>Soil</td>
<td>0.172</td>
<td>0.170</td>
<td>0.219</td>
<td>0.113</td>
</tr>
</tbody>
</table>

† ABS, acrylonitrile butadiene styrene; AL, alumide; HD, high-detail resin; PA, polyamide; PG, prime gray.
that of the PG reprint. A pipe with the average pore diameter (average local thickness) of the ABS reprint would have a theoretical $K_s$ value of 15.5 cm h$^{-1}$. Even though the HD reprint contained a connected macro pore, no water percolated through the sample during the infiltration experiments. We created two additional 3-D images of the HD sample after the infiltration experiment under both dry and saturated conditions to investigate why this was the case. From these images, it became obvious that the roughly printed HD pore walls (Fig. 4e) had partly disintegrated during the infiltration experiments. From a visual inspection, it appeared that this debris did not completely clog the macro pore. However, numerous air bubbles were visible in the macro pore under water saturation, which blocked the pore together with the debris from the pore wall. The PA and AL reprints showed no water conductance during the experiment. This finding was in line with the morphological analysis that revealed clogged macro pores.

**Conclusion**

In this study, we assessed the potential and limitations of five different 3-D printing technologies and corresponding printing materials for the reproduction of undisturbed soil macro pore systems. All tested printing technologies were able to reproduce the main macro pore features of the original soil sample. However, only PA and HD were able to resolve the outlines of a second well-connected but smaller macro pore with a bottleneck diameter of 0.046 cm.

The reprints created with selective laser sintering (AL and PA) as well as the one created with the Polylet technology (HD) exhibited problems with printing-materi al residues or printing-aid material that clogged substantial (AL and PA) or minor (HD) fractions of the pore space. This finding is critical considering the relatively small size of the reprints and the relatively large size of the well-connected macro pore compared with the printing resolution. For reprints of larger soil samples than the ones considered in our study, more bottlenecks in more remote locations from the reprint surfaces are to be expected, which will make it more difficult to remove the residual printing material. If the problem of removal of residual printing-support material cannot be resolved, printing of soil macro pore systems for hydraulic or solute transport experiments is not recommended for these materials. We consider it worthwhile to study the question of whether pore clogging occurs regularly for the tested printing techniques and materials in a future study, including replicated reprints of one soil sample with the same material. Future studies may also focus on the development of better methods for removing residual printing or printing-aid material from reprints of pore systems.

A fourth tested material, ABS, exhibited large printing artifacts in the form of a mesh-like interconnected pore network, which was hydraulically connected to the printed macro pores found in the original sample. However, it is conceivable that such an artifact may be welcome in some cases, since it would allow printing macro pore systems that are connected to a relatively homogenous pore matrix. An ABS reprint could therefore work as a soil model containing macro pores alongside a porous matrix domain.

The PG material produced by stereo lithography provided a reasonable reprint accuracy and an unclogged macro pore system. The removal of residual printing material was probably assisted by...
the fact that stereo lithography assembles reprints in a liquid raw material. Prime gray also exhibited a favorable, subcritical wetting behavior and a measured hydraulic conductivity that was similar to that of the original sample. Thus stereo lithography appears to be the method of choice for printing soil macropore networks.

Recent scientific studies on optical lithography techniques have demonstrated that the current 3-D printer prototypes provide 3-D reprints with a sub-100-nm resolution and a root mean square surface roughness below 10 nm (Malinauskas et al., 2013). A capillary with a radius of 100 nm drains approximately at the permanent wilting point, which is commonly defined by a matrix potential of \(-15\) m. In this light, it seems that the precision with which a macropore network can be printed will very soon be of minor importance because the expected error margins will be well below the pore diameter of even the smallest macropores (75–100 \(\mu\)m). Note that state-of-the-art synchrotron X-ray facilities provide a similar, sub-micrometer image resolution as the 3-D printer prototypes (e.g., Keyes et al., 2013). On this basis it appears that even 3-D imaging and printing of undisturbed soil meso- and micropore networks is already feasible at the original scale, albeit for relatively small sample sizes not larger than some millimeters. It follows that the 3-D printing of artificial soil samples that are usable for hydraulic and solute transport experiments is possible even at the scale of micropores, provided that the residual printing or printing-aid material can be removed from the finished reprint. The future success of combining high-resolution 3-D imaging and 3-D printing to investigate the hydraulic and solute transport properties of soil macropore systems will ultimately depend on the availability of suitable 3-D printing hardware.

Acknowledgments

We are thankful to Mats Larsbo and Nick Jarvis for helpful discussions during the onset of this study and, in the latter case, also for improving the language of this manuscript.

References


