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Using 3D Printing Techniques to Build Artificial Porous Media

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Abstract. Technology has been a great ally to scientists over the last decades. In fact, some of the most important breakthroughs in soil sciences have been accompanied by technological advances. Either by enhancing experimental apparatus or by using more powerful computers, physical modelling has greatly benefited from technology. So far, the focus has been on better characterizing natural porous media. Less attention has been payed to creating artificial media. Understanding and controlling the geometry of the porous matrix is of great importance, as not only experimental studies but also numerical simulations demand a considerable knowledge of the porous matrix involved. In the present paper, 3D printing techniques are studied as means to produce artificial porous media. At first, an artificial digital model for the soil is chosen. In the present paper, 3D cellular automata are considered. Then, in order to bring digital models to the real-world, the artificial porous media are 3D printed. The dimensional accuracy of the printings is checked by performing a metrological analysis, revealing that the deviations between the digital and printed models are within the accuracy of the printer. This validates the usage of 3D prints as valuable tools to build real artificial porous media. Future works may consider other 3D printing techniques. Printing in flexible materials, for example, could provide samples for consolidation analyses.

Keywords. 3D printing, artificial porous media.

1. Introduction

In general, the experimental methodology and apparatus needed to validate the theories and numerical routines are quite complex. In fact, due to the randomness of some natural porous media, it is hard to isolate a given phenomenon and perform tests to specifically model the latter. Influences of other phenomena are common and lead scientists to work on solutions to avoid the interferences [1].

When one has the complete control of the geometry of the porous medium, it is possible to isolate the study of a given phenomenon of interest. Artificial porous media are alternatives to natural ones as the latter are hard to map and fully mathematically represent.

Different techniques have been used to create artificial porous media. Glass spheres packings, for example, have been used as artificial porous media for a long time. In general, this type of porous media is considerably controlled, as the grain size distribution

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is known, as well as the physical-chemical properties of the glass spheres [1]. One of the main drawbacks of this methodology is that the porous network is not necessarily preserved, only the grain size distribution. Thus, studying how pore sizes and shapes influence properties such as permeability is not achievable by this methodology as real soils are more complex in both geometry and composition [1].

Other approaches, which increase the similarity between real and artificial porous media, are available. Combining tomographical images and digital models of the porous matrix is a promising approach [1]. In these models, the researcher obtains information about real media and then mimic it with digital models. Besides, if one wants to study a given phenomena separately, digital models can have its pore space shaped as desired. This also enables researchers to study the porous medium structural features in a more isolated way, as the inherent complexity of natural media can be substantially reduced in an artificial medium [1]. In the present paper, a series of steps in the process of artificially modelling of porous media are investigated.

2. The generation of artificial digital porous media

The most relevant problems the scientific community face nowadays are linked to Soil sciences, namely: food security, and ecological threats brought about by global climate change [2].

As discussed in [2], further development in soil sciences depend on facing three main issues, namely: characterization of the spatial heterogeneity of soil properties at the micrometric scale, trying to understand experimentally how microorganisms relate to their physical environment at that scale, and developing models that encapsulate this information and make predictions of future trends possible. This way, correctly modelling the porous matrix is crucial to assure the success of numerical simulations performed inside the computationally built model.

Different techniques to build artificial digital porous media are presented in the literature. Most of such techniques essentially distribute two dimensional (2D) or three dimensional (3D) geometric shapes in a given area (or volume) until a given porosity is achieved. For example, in [3] squares and circles have been used to generate the medium. Also, in [4] an arrangement of rectangles has been used to build an artificial porous medium.

Although the techniques have been extensively used, they tend to capture only macroscopic features of the real media. Microscopic features, such as pore network complexity, are neglected.

Novel approaches such as fractal geometry and cellular automata modelling have emerged as candidates to capture such micro-scale features [1]. Fractal geometry has been increasingly used to model porous media. A complete and robust approach to simulate soil structure based on fractal geometry may be found in the works of [5]. A complete survey may be found in [6]. On the other hand, in [7,8] bidimensional cellular automata have been applied to generate a 2D porous matrix.

Regarding 3D porous media, in [9] the Settle3D algorithm has been used to generate tridimensional media by distributing spheres, spheroids and prismoids in a given volume. On the other hand, in [10] an algorithm has been used to distribute sphero-cylinders and generate a porous matrix. In [11], an artificial porous medium has been generated by the deposition of cylinders.

Even though the artificial soils discussed are quite easy to understand and to implement, such media fail to effectively represent soils. In the latter, as opposed to other natural porous media (aquifer materials for example), there is a heterogeneous solid phase, organized to constitute a well-defined structure [1].

In the works of [7] and [8], the usage of cellular automata (CA) to generate 2D porous media has been illustrated. Besides the easiness of generation of the cellular automata, this type of computational entity has been increasingly applied to the modelling of naturally chaotic systems. The intricate structure of CA turn these types of systems of interest to be applied to the modelling of porous media. In the present paper, 3D cellular automata are investigated as mathematical models to the porous matrix.

Cellular automata, as their name suggests, are computational systems based on the evolution of states of entities named cells by means of predetermined rules. This evolution occurs uniformly (all the cells follow the same rule), synchronously (the evolution from one state to the other is obtained by applying a given rule to all the cells at the same time) and locally (only a given neighborhood influences on the evolution of each cell [12].

Since the focus of the present paper is to describe 3D printing as a tool to create artificial porous media from digital models, the creation process of the 3D totalistic cellular automata with Neumann neighborhood models will not be presented. The reader may find the whole process precisely described in [13].

3. 3D Printing

The processes and techniques of 3D printing have their roots in medical studies. On the other hand, applying knowledge from other areas to soil sciences has shown to be an effective approach, as in the case of tomographies [1].

By definition, 3D printing is the process by which a given computational model is transformed into a solid by means of a great variety of techniques. Among the most common are the fused deposition modelling (FDM) and the laser sintering (LS). [14,15].

Regarding soil mechanics applications, in [14], 3D printing techniques have been used to generate porous matrix substrates for the growth of fungus. Those authors used tomographies to generate a porous medium similar to the soil, as seen on Figure 1.

On the other hand, the creation of experimental equipment for soil sciences has been addressed in [15]. Those authors created a permeameter by means of 3D printing a computational model developed in their research. Besides 3D printings, the authors used plastic and metallic components to build the equipment. Figure 2 presents their results. Also, in [16] the role of 3D printing in geosciences has been briefly discussed.

In the present paper, the laser sintering 3D printing technique is considered. This is used to build 3D models from a printing material. This material can have various chemical compositions. In the present paper, polyamide has been chosen as the building material.

The printing procedure is performed layer by layer by building the shape of the cross section of the model in a thin layer of polyamide. When in contact with the polyamide powder, the laser melts and binds it, in order to form a thin layer of the model. After a layer has been built, a new thin layer of powder is positioned at the top of the model by means of a small rolling pin. In the case of this printing procedure, the printer has a heated chamber whose temperature is slightly below the melting point of the powder, such that the laser provides the exact energy to melt the powder and build the model's layer. By the end of the printing process, the result is a portion of heated polyamide powder with a solid model in its interior [17].

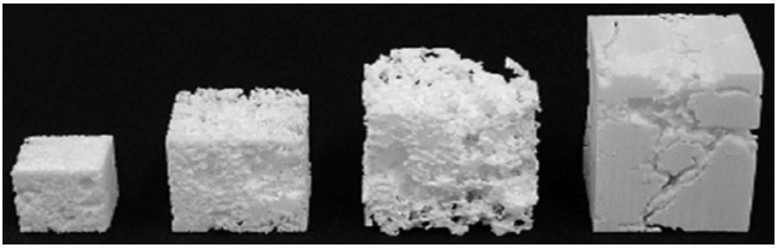

Figure 1. 3D printed substrate for fungus growth [14].

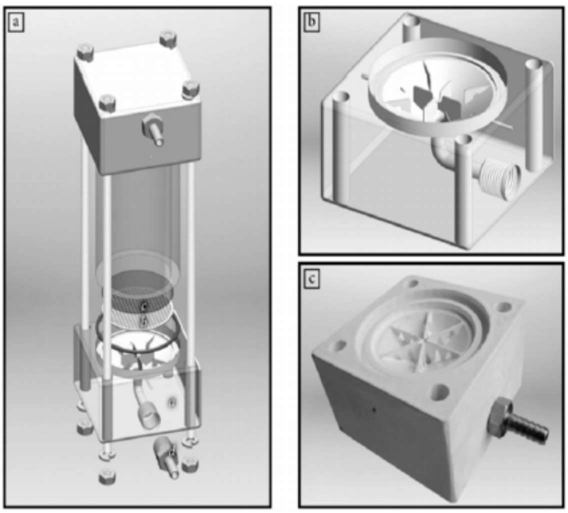

Figure 2. Permeameter built by means of 3D printing: (a) basic configuration of the permeameter to be built; (b) computational design of bottom and top of the permeameter and (c) 3D printed result [15].

The main limitations of 3D printing techniques are the minimum wall thickness, minimum buildable detail and maximum dimensions of the model. In the case considered in the present paper, the printer used is able of delivering a minimum wall thickness of 0.8 to 1 mm, while the minimum buildable detail is of about 0.3 mm. Besides, for the printer considered, the maximum dimensions of the printed model are of 650 x 330 x 560 mm [17]. For the level of details considered in the present paper, this resolution is appropriate. This comes from the fact that both the smallest details of CA models and the printer resolution are approximately equal. On the other hand, if smaller or more detailed samples are needed, one would need to look for other printing techniques.

4. Materials & Methods

In the present section, the materials used in the present paper as well as the methodology proposed to validate 3D printing as a tool to create artificial porous media are described. For further information, one may refer to [1].

The material by means of which the 3D solids are printed is the polyamide. This material is made on the basis of Nylon 12, which is a polymer with the formula $[(CH_2)_{11} C(O)NH]_n$. Further information about this material may be found in [17].

On the other hand, regarding the methodology considered in the present paper, it consists of three steps: generation of the digital file to be printed, the printing process itself and the metrological analysis of the printed samples.

Regarding the first step, the 3D CA are generated by means of the software Mathematica. The generation schemes allow one to obtain the layers which form the 3D volume of the CA, similarly to a tomography. In forthcoming stages, impervious walls are added to the CA generated in order to orientate the fluid flow through the model. By means of the software Avizo Fire, the stacked representation of the 3D CA can be imported and its surface can be extracted. The latter is then exported in form of *.stl* format in order to be compatible with the 3D printer used.

Now, the second step consists of the printing process. The *.stl* files are sent to *i.materialise* in order to be printed by means of the laser sintering technique. The authors chose to consider professional 3D printers in order to benefit from their expertise on printing complex geometrical volumes. It is worth noticing that this does not invalidate the methodology and conclusions of the present paper, as 3D printing techniques themselves are being checked.

Finally, the validation of the 3D printing technique is performed by means of a metrological analysis. In order to do so, the printed samples will be tomographed and their tomographic images shall be compared to the computational models. The tomographies have been done by means of the X-ray tomograph Metrotom 1500. Due to the simplicity of the samples considered in the present paper, the sample preparation procedures are quite straightforward [1].

Regarding the metrological analysis, the software VGStudio Max v.2.2 has been used to compare the tomographic and computational models of the printed porous medium. In short, this software allows one to obtain the linear differences heat map as well as the histogram of deviations, showing the differences between the real (obtained from the tomography) and virtual (*.stl* file sent for printing) objects [1].

5. Results

At first, it is worth noticing that the model sent for printing is a *.stl* file, which is basically a triangular mesh correspondent to the surface of the sample to be printed. Factors as the number of triangles used as well as the triangulation algorithm may result in differences of permeability of the printed and the original automaton model. Thus, it is important to check the consistency of the *.stl* generated [1].

Figures 3 and 4 present the printed and correspondent computational samples. It is possible to see on Figure 3 that each sample has been identified by a number. This has been done by adding impervious layers of polyamide to the sides of the samples and, over those layers, the numbers have been marked. The model sent for printing already contained such markings. The whole generation and numbering process has been carried out by the aid of a routine in the Mathematica software.

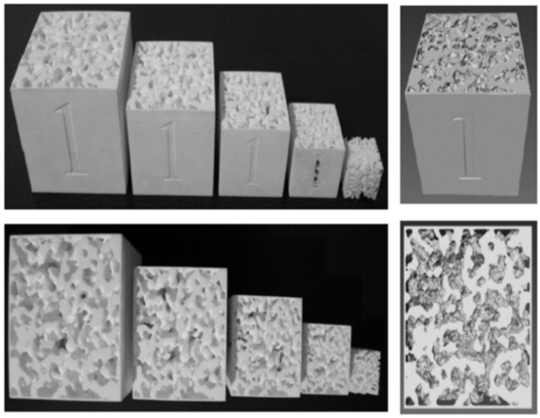

Figure 3. 3D prints and computational models for sample 1 in different scales (from left to right, with 6 cm, 5 cm, 4 cm, 3 cm and 2 cm side lengths [1].

From the analysis of Figure 3, it is possible to be seen that some flaws occurred while printing the impervious side layer. This is due to the considerably small thickness of such layers. Other water blocking methods could be considered for those cases. For example, by wrapping the model with an impervious adhesive tape, the same blocking would occur. In Figure 4, more printed samples are shown side by side with their computational models.

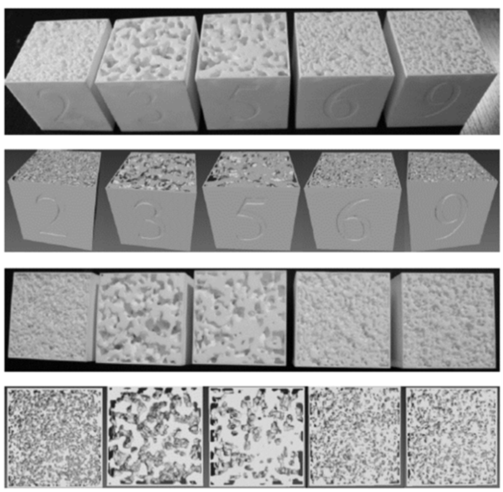

Figure 4. 3D prints and computational models for samples 2, 3, 5, 6 and 9 [1].

For simplicity, the visual comparison regarding the other samples considered in the present research is suppressed. For some samples, full pore clogging was observed. These are the cases with the lower porosities considered (approximately from 35% to 24%). When clogging occurs, some unclogging techniques must be used [1,14]. For the present paper, immersion of the sample in commercial acetone, 99% acetone (2-propanone) and 99% ethyl acetate have been considered. None of the techniques cited was able to fully unclog the pores of such samples. Only the high porosity samples were unclogged. A permeability test [1] was performed to check the clogging of the sample by.

A major issue which arises when considering 3D printing in Soil Sciences is whether or not this prototyping technique affects the porous network of the medium. In order to verify the effectiveness of 3D printing, a metrological analysis of deviations has been carried out. The latter consists of performing a tomographic analysis on the printed samples and then comparing the tomographic and computational model sent for printing.

The linear deviations between the digital and printed samples are presented in Table 1. The probability of a deviation to be lower than 0.3 mm (which is the precision of the printer used) is presented. This reveals a good agreement between the computational and printed models.

Table 1. Deviations for CA rules without clogging [1].

Samples	Porosity (%)	P(δ<0.3 mm)	Approx. Max. Deviation
1_{3cm}	61.51	98.31	0.42 mm
1_{4cm}	61.51	98.70	0.46 mm
1_{6cm}	61.51	97.37	0.51 mm
1_{5cm}	61.51	98.49	0.46 mm
1_{2cm}	61.51	99.92	0.35 mm
2	61.91	95.51	0.65 mm
3	62.80	97.65	0.42 mm

From Table 1, it can be seen that for all the rules which did not present pore clogging, the 3D printing technique is quite precise in representing the computational model, with most deviations (at least 95.51%) being less than the precision of the printer.

Table 1 also shows that the maximum deviance does not exceed 0.65 mm for any of the samples studied. In fact, except for sample 2, the maximum deviance is less than 0.5mm. This corroborates to demonstrate the correctness of representation of digital medium. Besides, regarding permeability evaluations, as the maximum deviance is not considerably greater than the printer precision, no important macropores have been created during the printing process. This is crucial as the permeability does not change considerably from its value on the digital medium [1].

Special attention has to be paid to the sample 1_{2cm}. In this case, the 3D printer was not able to print the water blocking wall, as can be seen on Figure 3. This is not a problem since the wall thickness in this case is less than the printer precision.

6. Conclusions

Alternative prototyping techniques need to be considered by Geotechnical engineers. In the present paper, laser sintering 3D printing technique has been studied as a tool to generate artificial porous media. Digital models were printed and a metrological analysis has been carried out to check the accuracy of the printed models.

For all the cases analyzed, more than 95 % of the deviations between the computational and printed models are less than the precision of the printer used (which is of 0.3 mm). Thus, 3D printing techniques have been validated as a prototyping tool to build real porous media from computational models. Some points which deserve more attention and must be studied separately are: using other 3D printing techniques in order to check their validity and using flexible printing materials to enable one to study consolidation-related themes.

The proposed 3D-printing-based methodology enables researchers to better analyze transport in porous media. Besides, the effects of pore throat sizes, tortuosity and other characteristics of the porous matrix can be directly related to its permeability by properly shaping the digital (and real, after printing techniques are applied) media.

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