Accurate measurement of radius evolution as a function of direction in 3D images

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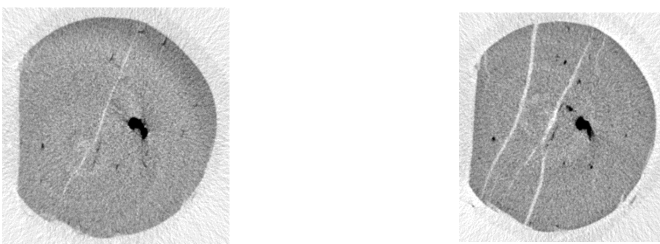
Aims

Very often the reason for using of X-Ray tomography in a research project is to measure the evolution of some geometrical characteristic. The sought characteristic may be explained in simple words like size, shape, or distance, but in practice measures based on these notions can have a complex implementation.
We present a simple problem, measuring the evolution of radius in a cylindrical sample (a common shape for sample preparation for tomography) and how this value differs according the direction in which we look, when such evolution is known to be anisotropic.
The solution is not unique, but we show that a naïve manual approach are not accurate enough, and how even a simple geometric notion such as radius needs a thorough definition in relation to its applicability to 3D image analysis. We extend the argument to how a good understanding of the notions and algorithms used in the quantification of geometrical characteristics can directly affect the pertinence and representativity of the results.

Method

Convective drying experiments were conducted on Boom clays from the region of Mol, as part of a nuclear waste deep geological storage project, an application that requires a stable and low-permeability rock formation like clay. Clay is a laminar material exhibiting anisotropy in shrinkage during dessication. The objective is to develop a predictive model to simulate the thermo-hydro-mechanical behavior of the clay formation during waste storage, including this anisotropic aspect. Obviously in order to validate the model, experimental data must be collected, i.e. the degree of anisotropy must be measured.

X-ray microtomography scans were performed using a Skyscan 1172/G every hour during the drying, and a series of 3D images of the cylindrical samples were obtained. As shown in figure 1, fractures can be observed, they are all parallel and correspond to the bedding direction of the clay. It is this direction that plays a crucial role in the anisotropy of the drying behaviour.



a) b)

Figure 1: Cross-sections of a clay sample around 13 mm in initial diameter before and after complete dessication. The noise level is high because the experiment was not made in-situ so the sample had to spend the least amount of time out of the drier. In this sample a nick was made on the left side to adjust its position for the scan.

A prior measurement method consisted in manually drawing two lines over a cross-section of the reconstructed 3D image, near the center height of the sample and across its diameter, one parallel to the visible fractures and the other perpendicular, and recording their lengths. This method presented a wide spread of values across different samples, especially in the direction of highest shrinkage, perpendicular to the bedding. This variation made it a hard sell for validating the model. But the reasons for the inaccuracies in this method is not difficult to grasp.

There are two main factors that contribute to rethink the radius measurement methodology. The first is that in the 3D reconstruction the cylindrical sample is never perfectly vertical. Since samples are mostly prepared and placed on the holder by hand, it is impossible to be more accurate to within a few degrees of deviation from the vertical. A horizontal cross-section of a slanted cylinder produces an ellipse and not a circle, so when measuring radii in different directions, we measure the result of this slanting. Even though in practical cases this effect is small, it can strongly influence the result if the shrinkage is itself small. The second factor is that the cylindrical sample is never perfectly cylindrical. Surface roughness and overall topography leads to measurements that are highly dependent on the exact position where they are made.

The solution to these shortcomings is to pay closer attention to what should be measured, and examine in detail how geometrical notions translate into an image processing algorithm. In this case, a radius is sought, i.e. the segment joining the center to the edge. This is applied on a cross-section of the sample that should be perpendicular to the axis of the sample, which should be a perfect disc were it a cylinder. This means the first step of the solution is to position this axis, thus giving center and orientation of the plane on which to examine the cross-section. This first step would solve the first flaw mentioned above. To handle the second, surface variations, a wide enough area should be used to measure the radius, instead of just one point. When the edge and sample axis are defined, it become simple to automatically average over a given angular interval and a given height along the axis.

In practice, the images are first segmented (in this case, using a watershed approach on the image gradient). The edge points are then extracted, simply to speed up the computation. For historical reasons[2] (mainly due to memory limitation on workstations ten years ago), the identification of the cylinder axis is decomposed as follows: on each cross-section, the smallest enclosing circle is found that surrounds the sample edge points, and a linear regression is performed on the set of circles centers to find the cylinder axis (an iterative approach has been implemented in order to remove outliers for the final regression).
The coordinates of the edge points, (x, y, z) in the Cartesian system, can then be converted to cylindrical coordinates (r, θ, h), or orthogonal distance from the axis, angle around it, and height along it. The arbitrarily chosen point on the axis such that $h = 0$ has no influence on the measurement. The angle $\theta = 0$ can be set as the bedding direction in the case of the clays, defined manually.

It then becomes a simple process of examining the values of r in the cylindrical coordinate system, and defining the proper areas over which to average these values. We initially wanted the radius at the center height, therefore knowing the range $[h_b; h_t]$ of values that comprise all sample edge points, we selected all the points that have a height value around the center height, i.e. in the interval $[\frac{h_b+h_t}{2} \pm \delta]$, with $\delta = 1.5\, mm$ chosen so as to have a large enough area. We also use a certain angular range by defining a wedge of $\frac{\pi}{4}$ over which to average. Therefore, to measure the radius parallel to the bedding direction, we average all values of r for the edge points having a height in the range $[\frac{h_b+h_t}{2} \pm \delta]$ and an angle in the ranges $[0 \pm \frac{\pi}{4}]$ and $[\pi \pm \frac{\pi}{4}]$.

Results

Figure 2 summarises the main steps in the application of this radius measurement method. Figure 2a shows a photograph of a clay sample roughly the same diameter as the one in figure 1, in its paraffin coating to insulate all but the top portion from the air flow during the drying. A fracture can clearly be seen, from left to right and slightly downwards. Figure 2b is a volume rendering of the tomographic reconstruction from the same point of view, a blue line overlayed to show the chosen bedding direction, in correspondence with the fractures. Figure 2c shows the set of points that define the edge of the sample, after segmentation, with the subsets used for measuring the parallel and perpendicular radii in blue and red respectively. The green line represents the cylinder axis used to define the cylindrical coordinates. Figure 2d shows these edge points coloured according to their value of r. The redder the point the farther from the axis. These data are from the image of the dried sample, and we can already observe that parallel to the bedding direction the radius is greater than perpendicular to it. We also see strong irregularities on the surface, especially in the perpendicular direction, justifying the need to average the measurement over a representative area. The final results for this sample are plotted in figure 2e, where the blue points are parallel measurements, and the red are the perpendicular one. The X axis is drying time, and a point on the curve represents a tomographic scan and radius measurement. The values are normalized with the initial radius measure, and the last points are the measurements made after complete drying, which was after 72 hours.

Perpendicular shrinkage was measured for all samples to be in between 7% and 9%. The developed numerical mechanical model produces shrinkages of 8%, which is in good agreement with the experiment. The application of this more robust measurement method allows to have better confidence in the validity of the numerical model.

Conclusion

The necessity to precisely define the notions behind the measures that are sought in 3D images is argued. X-ray tomography has an enormous potential for studying the evolution of geometric characteristics in heterogeneous materials, but there is hardly ever a unique or optimal method for extracting a given characteristic. Typically the first problem to deal with is finding a rigourous definition of the characteristic. The second is implementation.

We illustrate these difficulties with a simple example of measuring the radius in cylindrical samples in different directions, as the sample does not shrink isotropically. We show that a naïve approach to measuring this leads to results too spread out to provide strong conclusions, and that a proper quantification of this characteristic is not so straightforward, but after accurately defining what is sought and constructing a robust algorithm, the results are in much better accordance with the physical phenomena involved and have higher value for numerical model validation.

References:

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2. E. Plougonven, and D. Bernard A rigid registration method for the study of microgeometry evolution of limestone during dissolution by acidic water Advances in X-ray tomography for geomaterials, 2006, 349-354

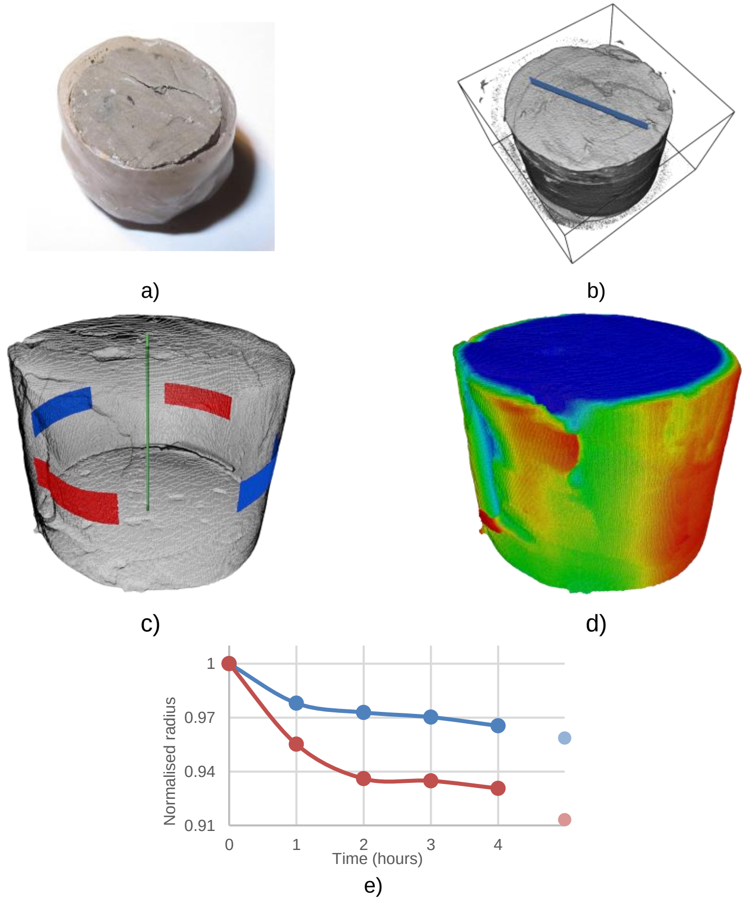

Figure 2: Illustration of the measurement methodology: a) is a photograph of the sample once dried, b) is a volume rendering of the tomographic reconstruction along with the direction of the bedding represented by a blue line. c) shows the edge points, with the ones used for measuring parallel and perpendicular radii in blue and red respectively. Radii are defined as the distance of the points to the axis, shown in green. d) shows the points coloured according to this distance, redder meaning farther from the axis. e) plots the normalised shrinkage values obtained during the drying, the last points being after complete drying, after 72 hours.