Dynamics of crack opening in a one-dimensional desiccation experiment

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Abstract

We used a simple one-dimensional experiment to investigate the dynamical aspects of crack opening that occurs in clay exposed to shrinkage induced by desiccation. The opening rate of single cracks is obtained. A simple model is introduced to account for the observed behavior. Interaction between adjacent cracks is put into evidence and a collective behavior is observed. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Mud and clay can produce very typical fracture patterns when they dry. This phenomenon is well known and can arise in many materials [1]. From a general point of view, when two adjacent layers of materials are subjected to different variations of length during a physical process, tension occurs and builds up in both layers and may eventually lead to rupture or folding of the least resistant layer of the two. In this paper, we study experimentally the fractures that appear due to the shrinkage of a drying layer of clay on a stable substrate.

As in Ref. [2] we use a long narrow line of clay in order to obtain cracks only in the direction perpendicular to the line. Since fractures occur only in one direction, dividing the line of clay in smaller segments, we call our system one-dimensional. This is in contrast with other drying experiments involving a wide surface layer of

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clay where cracks can form complex bidimensional networks [3–6]. This allows for an easier study of many aspects of the cracking induced by desiccation phenomenon.

We start this article with a description of our experimental setup in Section 2. Then we explain the image analysis process and detail our observations in Section 3. The discussion in Section 4 is divided into three parts. First, the individual behavior of one crack is discussed and a simple model is introduced. Secondly, we investigate the collective behavior of cracks. Thirdly, specific examples of interaction between cracks are presented. Finally, we conclude this article in Section 5. But before going further, let us mention some theoretical/numerical studies of the cracking induced by desiccation phenomenon [7–9].

2. Experimental setup

The wet material was disposed in a rectangular polyhedral line (width = 7 mm, height = 5 mm, length = 200 mm) on an horizontal glass plate. The only face of this rectangular polyhedra which was not in contact with air was the bottom one. This line was then left to dry at room air while pictures where automatically taken at regular intervals (2 min) during several hours with a CCD camera (lens 12/120 mm F5.6) placed 30 cm above the sample (see Fig. 1). During this process only a central portion of the line (1.5–6 cm wide) was recorded on the pictures to avoid considering end effects. We call this central portion the window of observation. The camera was computer controlled and pictures were recorded on the computer for further image processing and analysis. For better shadow definition of the cracks, we used a side lighting.

The clay used comes from natural clay mass material (Tournai, Belgium). It was selected against other types of clay because of its strong shrinkage during drying process. This ensures that clear fractures separate well-defined clay segments. This clay has been studied from a geological perspective in Ref. [10].

Fig. 1. The acquisition setup. During the drying process, a picture is taken every minute by the CCD camera in order to follow the apparition and evolution of cracks.
3. Image analysis and observations

A good way to visualize the evolution of the line of clay is to build a spatiotemporal diagram. Every picture of the line of clay is averaged on a single pixel wide line image. This line image contains all the one-dimensional information of the sample at the time the picture was taken. Then all of these line images are glued successively below each other. This gives us the spatiotemporal diagram shown in Fig. 2 that represents the time evolution of the drying line of clay. The horizontal axis represents the distance along the line of clay while the vertical axis represents time (time increases towards the bottom of the picture). The dark vertical stripes that appear and widen as time goes on are the cracks. Thin long vertical stripes correspond to small irregularities of the surface of the drying clay. These irregularities are underlined by the inclined light rays of the lighting we used.

In order to measure the width of each crack every minute, we convert the image of Fig. 2 to black and white using a threshold function of an image processing software. We wrote a plugin for ImageJ (free Java image processing software) that allows us to count the number of black pixels in each crack for every horizontal line of the picture.

![Image of spatiotemporal diagram](image)

Fig. 2. Spatiotemporal diagram for a drying line of clay. Successive horizontal lines of this picture correspond to successive images of the same line of clay at regular intervals (1 min). Total acquisition time (vertical axis) on this picture is 700 min and the length of the line (horizontal axis) is 4 cm. The apparition and evolution of the cracks can be seen on this kind of diagram. Cracks are numbered according to their order of apparition.
In this way we obtain the data represented in Fig. 3. Each thin curve (either dotted or solid) corresponds to an individual crack of Fig. 2. The wide solid curve represents the sum of the widths of all cracks.

Several observations can be made from this graph. (i) The cumulated opening rate for all cracks is nearly constant (20 \( \mu \text{m/min} \)) during a long period of evolution of the clay, then it vanishes progressively. The cumulated opening rate of all cracks is equivalent to the retraction rate of the line of clay in the window of observation. Notice that when the first crack appears, the retraction rate goes abruptly from zero to its constant value. (ii) Considering the opening rate of individual cracks, one can see that all the cracks display approximately the same behavior. The opening rate decreases progressively from its initial maximal value (when the crack appears) to zero when the clay is dry. Typical opening rate for a growing crack is around 5 \( \mu \text{m/min} \) in our experiment. (iii) The later a crack appears, the smaller its final width. This has been reported in Ref. [2] where a linear decrease of the final width of a crack as a function of its time of apparition has been proposed. (iv) Let us mention finally that no definite trend was observed in Ref. [2] for the evolution of the rate of apparition of new cracks and that measures therein allow to consider it as roughly constant during the period of cracks formation. In Fig. 2, we can see that a new crack appears on average roughly every 50 min.

Then we look at what happens when a crack appears. In Fig. 4 we can see a detail of Fig. 2 showing the apparition of the first and third cracks. The vertical lines that make this picture look like a bar code are due to the irregularities and imperfections of the clay surface. Those lines allow to visualize the trajectories of different points of the surface of the line of clay. We make two additional observations. (v) From those trajectories we see the strong influence that a crack has on the evolution of the clay line in its neighborhood. The range of this influence can be estimated by the distance of
disturbed trajectory lines. For the first crack, the range of influence extends to a distance of the order of 8 mm, the distance at which the third crack will form. (vi) Moreover, we can see that the influence of a crack propagates fast compared to the characteristic time of opening of cracks. Indeed the perturbation induced by the apparition of the first crack extends to its maximal range in a delay corresponding to less than one horizontal line of pixel on the picture, i.e., less than 1 min. (This propagation is visualized by the discontinuity of the trajectory lines at the same horizontal position than the tip of the first crack, shown by the arrow in Fig. 4).

4. Discussion

4.1. Individual crack behavior

Cracks appear and grow in order to release the stress induced by the shrinkage of the clay on a rigid substrate. Indeed when clay dries, its natural tendency is to shrink. We can say that the natural length of a line of clay decreases as it dries. But the rigid substrate on which the line rests does not retract. Because of friction between the clay and the substrate (sticky contact), the line of clay cannot shrink at first. This leads to the apparition of a growing tension in the line of clay. At some point, this tension exceeds the cohesive force in the clay and the line of clay breaks. This fracture will grow under the effect of the tension in the clay. A slip front appears and propagates away from each side of the crack (see Fig. 5). The dynamics of such slip front was studied by Baumberger et al. [11] in an experiment involving a block of gel sliding on glass due to an external driving velocity. They found that this front propagates in their experiment with an approximately constant velocity of 8 mm/s, independent of the driving velocity. If we admit the same order of magnitude for the velocity of the slip front in our experiment, we can understand our observation that the influence of the apparition of a crack propagates fast. It can be considered as instantaneous in comparison with the opening velocity of cracks (around 5 μm/min). Then the line of clay can retract in the slippy region and release the stress there in that way.

In relation with the slip front, we note that [6,9] obtain at the end of the desiccation, in bidimensional experiments or simulations, circular central sticky regions that attach the clay cells to the substrate. The perimeter of these regions is the limit of the propagation of the slip front.

We now present a simple model for crack opening. We will admit that the sliding velocity \( v \) leads to a frictional shear stress \( F \) at the interface that is described by a
linear viscous friction law:

\[ F = \eta v \]  

(1)

with \( \eta \) being the viscous friction coefficient. This has been done by Brener and Marchenko in a theoretical study [12] of the above-mentioned experiment [11]. Moreover, since the sliding velocity is observed to be very low (maximum 20 \( \mu \)m/min), we will assume that the motion is quasi-static, i.e., the frictional shear stress \( F \) is always equal to the tension in the clay \( T \)

\[ F = T \]  

(2)

The tension in the clay comes from the fact that the line of clay is longer than its natural length. Let us assume that the tension in clay follows a hookean law:

\[ T = k \Delta x \]  

(3)

where \( \Delta x \) is the difference between the actual length of the clay and its natural length, while \( k \) is the elasticity modulus. The system we consider is a quasi-static form of the damped oscillations problem. It is represented in Fig. 6.

With Eqs. (1)–(3) we get

\[ v = \frac{dx}{dt} = \frac{k}{\eta} \Delta x \]  

(4)

where \( x \) is the horizontal position of the moving border of the crack. Solving this differential equation gives

\[ x(t) = x_{\infty}(1 - e^{-(k/\eta)(t_0-t)}) \]  

(5)

with \( x_{\infty} \), the final position of the border of the crack \( (\Delta x = x_{\infty} - x) \), and \( t_0 \), the time of apparition of the crack.
When a crack forms, both of its borders start to move in opposite directions. So we should apply Eq. (5) to both borders. Finally, under the three assumptions we made, we can write the evolution of the width $\ell$ of a crack as

$$\ell(t) = \ell_\infty (1 - e^{-(k/\nu)(t_0 - t)})$$

for $t > t_0$,  \hspace{1cm} (6)

with $\ell_\infty$ the final width of the crack.

Fig. 7 shows the fits of the evolution of the width of cracks 2–4 of Fig. 2. Large, medium and small squares are, respectively, data points of crack 2–4. The fit is fairly good in all three cases. Note that the slopes of the three fits are close. We find values of $\nu/k$ equal to 147, 176 and 166 min, respectively, for cracks 2, 3 and 4. Values of $\ell_\infty$ obtained by the fit are slightly over the measured final values. Values of $t_0$ obtained by the fit are slightly below the values observed in Fig. 3.

Of course the basic theory we presented is a very simplistic picture of the phenomenon. Such important factors as the shrinking of the natural length of the clay during the opening of the crack have not been introduced. The fact that the velocity and the tension are not homogeneous in the whole slippy region of the line of clay should also be taken into account. Moreover, one has to keep in mind that the elasticity modulus $k$, the friction coefficient $\nu$ and the limit of rupture of the clay are probably varying functions of the water content of the clay. As water content changes during drying, characteristics of the material evolve. However our basic considerations give us a good grasp of the phenomenon and a fair agreement with the experiment in most cases. The model only intend to give us a clue of what kind of behavior can be expected when a crack forms.
Here we should mention that we have observed cracks that show deviations from Eq. (6). In some cases, the beginning of the crack is slightly better fit by a square root function. This corresponds to the case of diffusive processes. However the asymptotic behavior cannot be obtained with a square root function. Our experiment presents some similarities with the above-mentioned sliding block of gel experiment [11]. The opening profiles we obtain for cracks are similar to the displacement profiles observed in that experiment. In Ref. [11], the displacement stops due to a resticking of the gel on the glass when the sliding velocity falls below a finite critical value ($\approx 100 \mu m/s$). This leads to a quasi-discontinuity of the slip velocity. We do not observe this kind of discontinuity. We should also underline that our sliding velocities are much smaller ($\sim 10^{-3}$) than in the case of the gel experiment.

In Ref. [2], we observed that the distribution of the final width of cracks was approximately uniform. This and the observation that the apparition rate of cracks was approximately constant lead to think that crack opening could be linear with time. Although in some case we observed a roughly linear behavior, these cases are exceptions. In Section 4.3, we will see how the apparition of a new crack can influence the opening rate of an existing crack. Interaction between cracks affects the opening profile and deviations from the behavior predicted by Eq. (6) are observed.

4.2. Collective behavior

As mentioned above, Fig. 3 and similar experiments show us that the retraction rate of the line of clay—due to the apparition and opening of cracks—is nearly constant during the whole period of time during which cracks appear.

We can conclude that, on a scale large enough, singularities of the retraction rate due to the apparition of new cracks tend to smooth out. Moreover, the lowering of the opening rate of existing cracks with time is counterbalanced by the apparition of new cracks.

If we consider the linear decrease of $\ell_\infty$ with the time of apparition of the crack, as reported in observation (iii) of Section 3 above, we can use Eq. (6) in order to graph the evolution of the cumulated width for several cracks. This is done in Fig. 8 for six cracks with parameters close to the ones of Fig. 3. The width $\ell_m(t)$ of crack $m$ follows:

$$\ell_m(t) = 0.2(10 - m)(1 - e^{(50m-t)/100}).$$

(7)

Obviously the sum represented in Fig. 8 considers only positive values of crack opening.

Similarity with Fig. 3 is good but not perfect as can be seen when considering cumulated widths. The profile was more linear in Fig. 3. Small differences like that one come from the fact that in Fig. 8, all the cracks were considered independent. We will see in next section that this is not the case in experiments. A precise understanding of collective behavior of cracks cannot be achieved with a simple model such as the one presented in Section 4.1. However Eq. (6) is compatible with the observed collective behavior.
Fig. 8. Six cracks following Eq. (7) and the cumulated width (top curve).

Fig. 9. The apparition of a new crack close to an existing crack (7 mm apart) can alter significantly the opening rate of the existing crack.

4.3. Interaction between cracks

Cracks are not independent of each other. This was shown in Ref. [2] where different spatial correlation coefficients were discussed. Fig. 9 shows the strong influence that the apparition of a new crack close to an existing crack can have on the opening rate of the existing crack. As soon as the second crack appears, the opening rate of the first crack falls by half. The second crack has a typical opening profile, well described by
Eq. (6). After the second crack has appeared, the opening rate of the first crack rises slightly again.

A similar case of influence can be seen in Fig. 3 between crack 1 and cracks 3 and 4 that appear on each side of crack 1. Because of the influences of cracks 3 and 4, crack 1 does not present a typical opening profile.

In both cases, we can say that new cracks that appear in the vicinity of an existing crack release part of the tension that was driving the opening of the existing crack. As a consequence, the opening rate of the existing crack falls down quite markedly. On the other side, new cracks follow a quite typical opening profile (Eq. (6)) since they do not encounter strong external variations of the tension.

The late rise of the opening rate of the initial crack after new cracks have appeared is not explained. In some way, the tension has to increase close to the old crack while it is diminishing close to the new cracks. Local resticking of the clay between the old and the new cracks when drying could explain this. This resticking would screen the influence of the new cracks, so the tension in the neighborhood of the old crack would increase more with the drying of the clay. Further experiments could enlighten this point.

Another interesting point to investigate is whether or not the presence of a substrate do influence the retraction rate. This question arises only if we consider a system large enough. Indeed, on a small scale, the retraction rate is just the opening rate of the local crack. On a larger scale, however, the influence of a single crack is no longer perceived as we saw that the retraction rate of the clay remains constant even when additional cracks appear. If the retraction rate depends only on such factors as the temperature and the humidity but not on substrate friction, it would mean that clay produces more or less cracks, depending on substrate friction, in order to maintain a definite retraction rate. Groisman and Kaplan have shown [3] that the final number of cracks obtained in a desiccation experiment decreases if substrate friction is lowered. In this case the width of the cracks increases. In our case, with a final retraction of about 18%, we can note that a 2 mm wide crack can assume the relaxation of stress in a clay segment of length 11 mm. Finally, note that if the retraction rate is not dependent on the presence of a substrate, the free contraction of the clay (without a substrate) due to drying should be at least approximately linear.

5. Conclusion

This work comes as a continuation of Ref. [2]. Using a similar experimental setup we investigated the details of the dynamics of crack opening in a one-dimensional desiccation experiment. Main observations were that the opening rate of cracks was a varying (diminishing) function of time that could be described in most case by the simple model presented. On the contrary, the cumulated opening rate of neighboring cracks was observed to be quite constant for a long period of the evolution of the drying clay. Finally, the interaction between cracks was put into evidence by the fact that the apparition of a new crack close to an existing one causes a significant drop in the retraction rate of the existing crack.
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References