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Analysis of climate change impacts on the shrinkage-swelling phenomenon of clayey soils to adapt infrastructures

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Abstract. As a tendency in France, the well-known shrinkage-swelling phenomenon of clayey soils intensifies naturally and durably under climate change effects after the severe droughts happened post 2015. More than 10.4 million houses are highly exposed to this phenomenon and the new national zoning shows that high or medium exposure now concerns 48% of the metropolitan soils. Roads are also severely impacted by the shrinkage-swelling phenomenon through damage characterized most often by longitudinal cracks close to the edges and very significant deformations that can be a danger for the safety of users. The aim of this research is first to understand how the natural unsaturated clay soils shrink and swell under numerous drying-wetting cycles using several devices at the laboratory scale. The second approach consist of several in situ experimentations of different techniques to reduce the shrinkage-swelling impact on unsaturated clay soils. The first results show that at the laboratory scale, the unsaturated clay soils can be significantly affected after some drying-wetting cycles. In the other hand, in situ monitoring results show that some techniques allow clay soils to save their hydromechanical properties at a hydric equilibrium state which can reduce settlement deformations. The main goal of these research works is to better understand how the shrinkage-swelling phenomenon of clayey soils evolves under climate change in order to develop the new solutions allowing the adaptation of the infrastructures.

1 Introduction

Climate change is disrupting the hydric cycles of drought and precipitation to which soils are accustomed. The precocity, recurrence and intensity of these increasingly unpredictable hydric solicitations affect the hydromechanical properties of unsaturated soils with complex mechanisms of desiccation cracking. For example, this can induce more damages on the slight infrastructures built on the clay soils subjected to the shrinkage-swelling phenomenon, named "RGA" in France. In 2022, France faced for the 6th time in the last 10 years a severe drought. Since 2016, the combination of high temperatures and low precipitations, particularly during the June to September period, has indeed frequently recurred. 6 of the 9 most affected years in terms of drought damage compensation are post 2015. By applying the damage indicators to the number of exposed houses, the MRN (Mission Risques Naturels) estimates the cost of the 2022 drought between €1.9 and €2.8 billion [1].

Longer and more intense droughts will lead to deeper desiccation in the soils, which are becoming increasingly desaturated. The effect of this desiccation is now estimated to be the first two meters depth from the surface exposed to evapotranspiration. This high exposure to drought increases the vulnerability of these soils, which are cracked by desiccation, making them less resistant. Desiccation cracking has been the subject of much previous research [2, 3, 4, 5] and more recently [6, 7]. These works approached the phenomenon of cracks by various aspects, for example: by the research of the mechanisms of initiation and propagation of cracks under hydric and mechanical solicitations (or coupled), by the influence of the initial suction of the ground, by the analysis of the anisotropy of the variations of volume during the shrinkage. [8] proposed a paper that describes a synthesis of research conducted to date on the behaviour and cracking mechanisms related to desiccation of unsaturated soils.

This research work is mainly focused on unsaturated and natural clay soils. The purpose is to carry out a multi-criteria analysis based on soil/atmosphere interactions, in order to study the influence of the evolution of hydric cycles, under climate change, on the hydromechanical soil properties and the initiation and propagation mechanisms of desiccation cracking. This experimental analysis is performed both in the laboratory, through a series of hydric tests, and in situ by testing some techniques. This may significantly help us to understand how climate change can deteriorate the properties of clay soils and induce structural damages.

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2 Materials and methods

2.1 Material properties and sample preparation

2.1.1 Laboratory tests

Samples used in the laboratory tests are prepared from natural clay soils collected in situ using a mechanical shovel, where roads are damaged by droughts and the RGA phenomenon. Three boreholes were performed in situ on roadside: SPM1, SPM2 and SPM3 according to different depths from 0.5m to 2.5m. The physical properties of three samples cut at 1.0m depth from each borehole are summarized in Table 1.

Table 1. Physical properties of the tested clay soils at 1.0m.

Physical properties	SPM1	SPM2	SPM3
Natural water content w_n (%)	27.6	19.8	15.3
Liquid limit w_L (%)	86.5	63.0	50.0
Plastic limit w_P (%)	47.0	28.0	26.0
Plastic index I_P (%)	40.0	35.0	24.0
NF P11-300 classification	A3	A3	A3

2.1.2 In situ tests

For the in situ tests, a part of road was comforted using an innovative experimental technique which consists of horizontal sealing similarly the roadsides on their width. Using a mechanical shovel, two boreholes were performed in situ on both the two roadsides: PM1 and PM2 according to different depths from 0.5m to 2.0m.

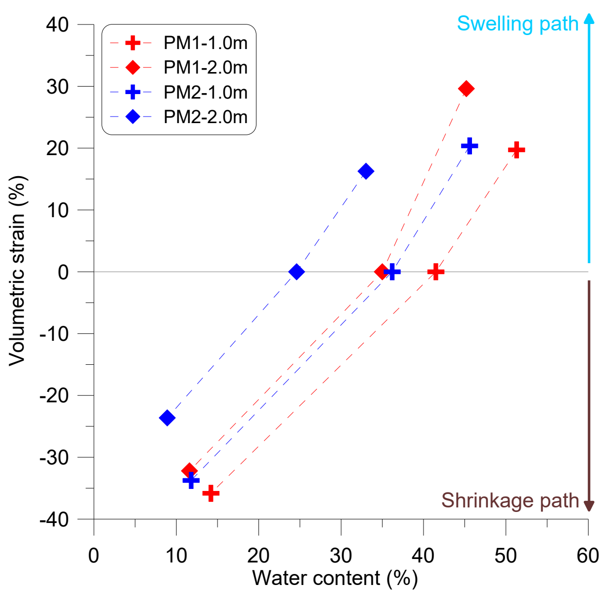

Fig. 1. Volumetric strain during shrinkage and swelling.

Figure 1 shows some results of the simplified shrinkage-swelling tests performed on samples cut from PM1 and PM2 clays soils, which are very plastic (plastic index, I_p varies between 34 and 53 starting at 1.0m depth). Results are here expressed by maximum amplitude of shrinkage and swelling as a function of water content. It can be seen that globally considering mean values, the maximum shrinkage amplitude is higher that the maximum swelling amplitude. The simplified shrinkage-swelling tests are performed according to the Australian standard AS 1289.7.1-2003 “Method of testing soils for engineering purposes. Method 7.1.1: soil reactivity tests– Determination of the shrinkage index of a soil – Shrink-swell index”.

2.2 Experimental tests equipment and program

2.2.1 Dynamic Vapor Sorption (DVS)

Laboratory tests are carried out using the Vsorp Plus DVS, an instrument for moisture sorption analysis using the gravimetric method for determination of moisture sorption/desorption. Each of 11 soil samples is placed in a sample pan inside a sealed chamber (Figure 2). The DVS measurement is a technique in which a sample is subjected to humidity and temperature variations. This to analyse its hygrometric behaviour and its response to imposed and controlled hydric solicitations, which can be cyclic with constant laminar flow and continuous tray rotation for similar conditions at all sample positions.

Fig. 2. Sample tray inserted inside the sealed chamber.

The 11 soil samples used in this DVS test are cut from different depths of SPM1, SPM2 and SPM3 clay soil of the laboratory tests. In this study, we focus the analysis on 6 soil samples cut at 1.0m depth with 2 samples from each borehole:

- SPM1-1.0m-a (sample pan n°2 on Figure 2) and SPM1-1.0m-b (sample pan n°3 on Figure 2) from SPM1;
- SPM2-1.0m-a (sample pan n°7 on Figure 2) and SPM2-1.0m-b (sample pan n°8 on Figure 2) from SPM2;

- SPM3-1.0m-a (sample pan n°10 on Figure 2) and SPM3-1.0m-b (sample pan n°11 on Figure 2) from SPM3.

The purpose here is first to analyse the repeatability of the hydromechanical response of the two samples from the same clay soil and secondly to characterize the influence of initial water content (given in Table 1). Hydric conditions imposed inside the sealed chamber of the DVS are described in Table 2 with a constant air temperature of 20°C and a step of 10% in terms of relative humidity (*RH*) variation.

Table 2. Details of experimental protocol of the DVS test.

Hydric paths	Imposed *RH* (%)	Duration (hours)	Cycles
Preconditioning	40.0	48.0	
Drying path	40.0 to 0.0	108.5	
Plateau	0.0	48.0	Cycle repeated 3 times
Wetting path	0.0 to 80.0	184.0	
Plateau	80.0	48.0	
Drying path	80.0 to 0.0	195.0	
Plateau	0.0	48.0	

2.2.2 Horizontal sealing of roadsides technique

Figure 3 shows how horizontal sealing technique can be applied on a half of road affected by drought and the RGA phenomenon. The treatment of 0.3m thickness consists of 4 layers, described in Fig.3, in order to guarantee sealing of the soil under roadside by reducing its evapotranspiration and water content change. This in situ test was monitored using 10 soil suction probes placed at different depth values between 0.5m and 4.0m and numbered from S11 to S20. The instrumentation is in use since September 2019.

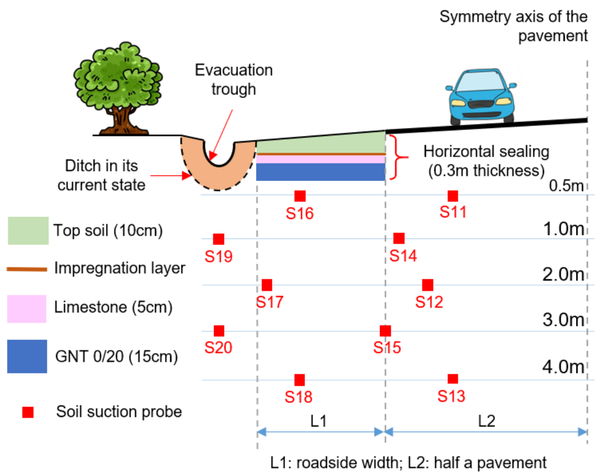

Fig. 3. Horizontal sealing on a half of road and monitoring.

The aim of this in situ experience is to analyse the efficacity of horizontal sealing technique to adapt the pavement built on clay soils and subjected to severe and repeated drought. At the same time, this allows observing how soil desiccation evolves under climate change conditions in order to predict in fine how desiccation cracking initiate and propagate.

3 Results and discussion

3.1 Hydromechanical soil properties evolution under laboratory drying-wetting cycles

Results issued from the DVS test performed on the SPM1, SPM2 and SPM3 clay soils are given as a function of imposed relative humidity. In order to analyse the hydromechanical properties evolution during drying-wetting cycles, an estimated soil suction can be calculated using the Kelvin's law below:

$$u_a\text{-}u_w=RT/(gM_w)\ ln(RH\%) \quad (1)$$

Where u_a and u_w (MPa) are air and water pressures, respectively. R (= 8.3143 J.mol^{-1}.K^{-1}) is the molar gas constant, T (°C) is temperature, g (= 9.81 m.s^{-2}) is the Earth's gravity, M_w (=18.016 g.mol^{-1}) is the molar mass, and RH (%) is relative humidity. When T = 20°C, the constant $RT/(gM_w)$ equals 137.837 MPa. Thus, equation (2) given by [9] allows to determine the imposed global suction s_{glob} (MPa) as a function of RH and T:

$$s_{glob}=-(\rho_w RT/M_w)\ ln(RH\%/100) \quad (2)$$

Where ρ_w (kg.m^{-3}) is the water density. To estimate soil suction, noted s, we assumed here that it is close to the imposed global suction because of the small size of DVS samples. Thus, Figure 4 summarize the results of change in mass based on lowest net weight of soil samples as a function of their estimated suction. Each curve shows how sample mass evolves during drying-wetting cycles where soil suction increases and decreases respectively.

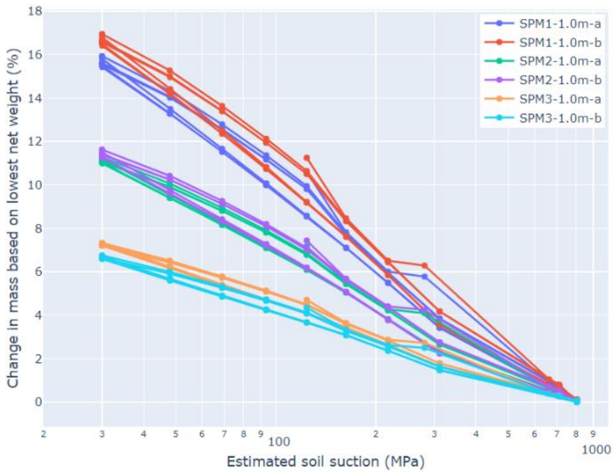

Fig. 4. Change in mass as a function of soil suction.

It can be seen that the repeatability is verified for each borehole soils between (a) and (b) samples. The gap at maximum wetting path (RH=80% and s=30MPa) is around 1.0% for SPM1, 0.3% for SPM2 and 0.6% for

SPM3. Considering how soil water content of tested samples changes according to change in mass under drying-wetting cycles by shrinking and swelling respectively, it shown that hydromechanical response of soil changes. The mean total change in mass is about 16.2% for SPM1 samples, 11.3% for SPM2 samples and 7.0% for SPM3 samples. This means that initial state of the material has an influence on its water content change during drying-wetting cycles.

3.2 In situ horizontal sealing first results

Figure 5 summarize original measurement of soil suction during 2020, 2021 and 2022 (until 9th, December) given by the 10 suction probes (S11 to S20, Fig.3) used to evaluate the horizontal sealing technique.

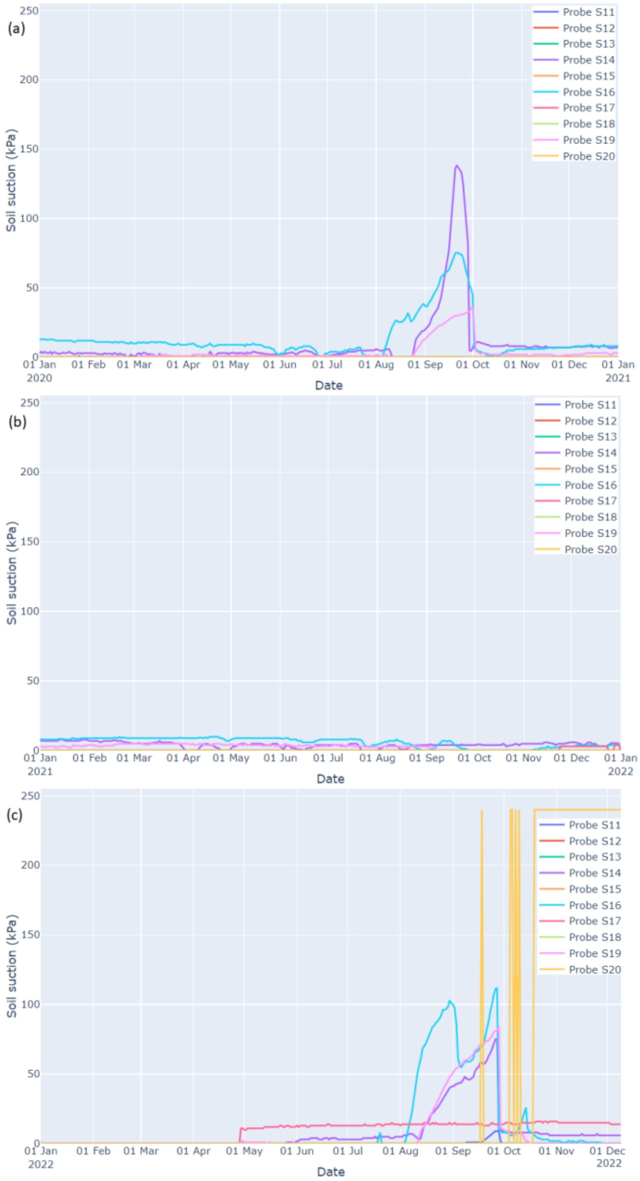

Fig. 5. Soil suction as a function of time during: (a) 2020, (b) 2021 and (c) 2022.

Considering the drought period from June to October, in 2020 (Figure 5a) 3 probes have reacted to the dry state of soil: first probe was S16 at 0.5m depth that reached a pic of 75.5kPa in 21th, September, then S19 at 1.0m depth that reached a pic of 36.5kPa in 1st, October and finally S14 also at 1.0m depth that reached a pic of 138.5kPa in 21th, September. In 2021 (Figure 5b), it can be seen that there is no suction probe that measured significant values of soil suction including the drought period. Finally, in 2022 (Figure 5c), some probes started to measure soil suction since the end of April (like S17 at 2.0m depth) and continued to save data until the end of October such as: S16 at 0.5m depth that reached a first pic of 103.0kPa in 30th, August then a second pic of 112.0kPa in 27th, September; S19 at 1.0m depth that reached a pic of 84.0kPa in 28th, September; S14 at 1.0m depth that reached a pic of 75.0kPa in 27th, September; S20 at 3.0m depth which has repeatedly reached the value of 240kPa since 28th, September.

Since September 2019, when the horizontal sealing of roadsides technique was carried out on a section of road of 300m long, there is no damage or any deformation to report despite a severe drought in 2020 and 2022 in France. Figure 6 is a photo taken on December 9, 2022 showing the section of road that was reinforced.

Fig. 6. Photo of adapted road by sealing its sides on December 9, 2022.

3.3 Global behaviour soil characteristics: effect of the initial soil properties

Experimental results of the laboratory tests showed that initial state of the tested soil has an influence on its water content change during drying-wetting cycles. In this case, the natural water content of borehole soils (Table 1) is the property of soil samples that influenced their hydromechanical response. Thus, the mean total change in mass (Figure 4) increases with the increase of natural water content.

Indeed, the effect of the initial soil properties has a significant impact both on its hydromechanical properties and their evolution under drying-wetting cycles and also on desiccation cracking phenomenon during drying. [10] used 2D digital image correlation (DIC) method to show the effect of initial suction on the mode I cracking mechanism. To do this, the authors performed indirect bending tensile tests to impose extensional opening of the lower fiber of clay beams, which are themselves under controlled initial suction.

Among the results of this research was the characterization of the significant effect of the initially imposed suction level on the tensile strength at failure. Thus, it is important to analyse the hydric conditions to which soils are subjected on the initiation of desiccation cracking.

3.4 Soil desiccation propagation under climate change conditions

One of the consequences of climate change is the propagation of soil desiccation, which is now estimated at the first two meters of depth. The result of the in situ horizontal sealing tests (Figure 5) allows us to observe this propagation of soil desiccation. In France, the 2020 and 2022 droughts were severe and long as they have been since 2015. Figure 7 show that soil desiccation was developed essentially under the roadside until 1.0m depth in 2020 but it propagated more until 3.0m depth in 2022.

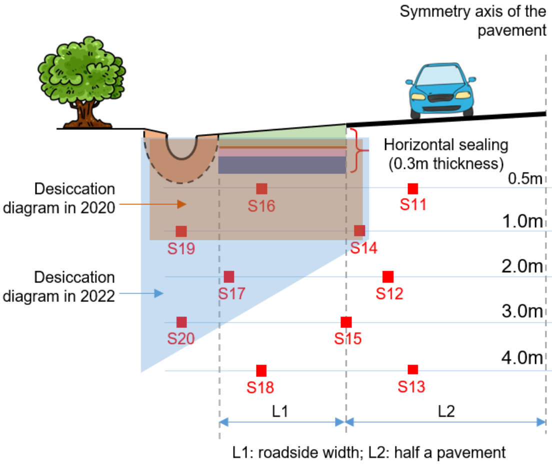

Fig. 7. Desiccation propagation diagram between 2020 and 2022.

Thus, it can be seen that in the context of a road, soil desiccation begins under its sides with a tendency to decrease by going towards its center. This is similar to what [11] presented in his works. In the other hand, these results show that soil desiccation will continue to propagate in depth under climate change conditions. This will require more expensive work to adapt infrastructures exposed to drought and the RGA phenomenon.

3.5 Soil-atmosphere interactions analysis

In parallel to the research work presented above, additional work is currently in progress and concerns an in situ instrumentation equipped with a weather station coupled with a soil suction sensor. The goal is to complete the laboratory and in situ analysis with a better knowledge of soil-atmosphere interactions under the effect of climate change.

First measurement data are saved during 2022/2023 period and summarized in Figure 8 in terms of mean rainfall during 24 hours and mean volumetric water content (*VWC*) as a function of time.

It can be seen how 2022 drought is severe with very low levels of rainfall and *VWC*=5% from July to October. In the other hand, Figure 8 shows that during 32 consecutive days in 2023 winter (January to March), it was an impressive drought without precipitation and a *VWC* gap of 15% which habitually observed in April/May. This is another consequence of climate change.

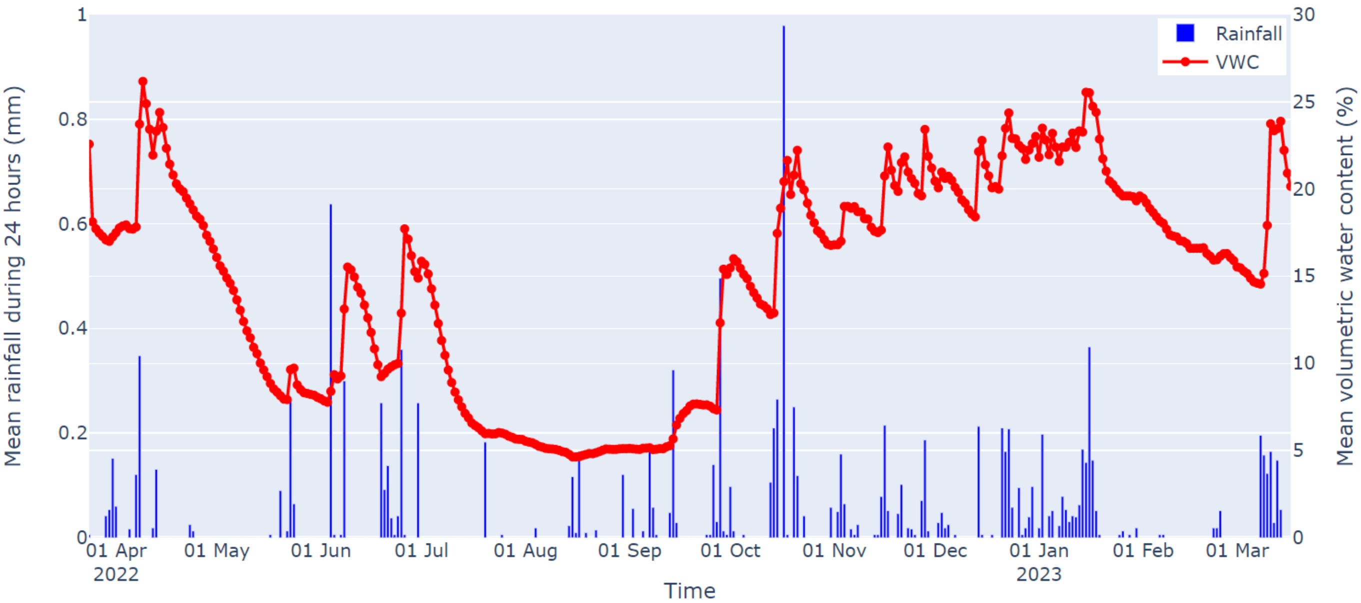

Fig. 8. Mean rainfall and volumetric water content change as a function of time in 2022/2023.

4 Conclusions and perspectives

In the current context of climate change and the recurrence of extreme climatic events, there is an urgent need to understand how the shrinkage-swelling phenomenon of clayey soils evolves in order to develop new solutions to limit the vulnerabilities of infrastructures.

In order to study the climate change effects on the hydromechanical behaviour of clay soils, it is necessary to perform both laboratory and in situ tests and several techniques. In this research, first series of analysis was carried out on natural clay soils:

- Laboratory tests showed the importance of the soil initial properties like natural water content on its hydromechanical response during drying-wetting cycles. Additional laboratory tests are in progress by imposing irregular drying-wetting cycles in the DVS in order to simulate climate change effects.
- In situ tests performed to analyse the efficacity and the durability of the horizontal sealing of roadsides technique showed a very interesting first results. There is no damage or any deformation to report despite a severe drought in 2020 and 2022 in France. In the other hand, soil desiccation was developed essentially under the roadside until 1.0m depth in 2020 but it propagated more until 3.0m depth in 2022. Other in situ tests are also in progress in different sites to test several innovative solutions to adapt road and houses subjected to drought and the RGA phenomenon.

In parallel, new laboratory investigations will soon begin to analyse desiccation cracking phenomenon in unsaturated soils subjected to climate change conditions. Especially, the 3D digital correlation images (DIC) will be used to characterize the initiation and propagation of cracks. At the same time, other in situ instrumentations will be installed in different locations of clay soils in France to collect more data in order to use data science methods; machine learning and deep learning to identify correlations between hydromechanical soil properties and try to predict its desiccation cracking.

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