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UNDERSTANDING SINKHOLE CONSEQUENCES ON MASONRY STRUCTURES USING LARGE SMALL-SCALE PHYSICAL MODELING

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ABSTRACT

Subsidence and sinkhole are one of important geological risk due to the collapse of underground cavities either natural cavities or due to the human activities (such as mines). The impact of the subsidence and sinkhole on the existing structures can be sever and dramatic. The prediction of the level of damage depends on the characteristics of the sinkhole and the characteristics of the structures. A large small-scale physical model is developed by the INERIS in order to improve the understanding of the behavior of individual masonry structures subjected to ground subsidence or the collapse of underground cavities. The masonry structure is simulated by using small pieces of wood or sugar pieces, the foundations by polycarbonate or silicon slab. The displacements and strains of the soil and the structure are measured using an imagery technique called DIC (Digital Image Correlation). The results highlighted the influence of the soil-structure interaction on the subsidence.

The silicon slab is less stiff allowing more displacement transfer to the structure. The experimental study pointed out the advantages of using wood and sugar material to represent a masonry structure, the using of sugar and wood is easy to deal and economic compared to real large scale test.

The study showed that the damage of the masonry structure depends on its position on the subsidence area and it's stiffness. The experimental analysis has pointed out the importance of the soil/structure interaction.

INTRODUCTION

Withdrawal-swelling clays, water pumping, mining activities and the collapse of natural cavities can induce the subsidence of surface. The formation of subsidence on the ground surface can be very damaging to structures and infrastructures and to the safety of the populations. Damages depend on two main components: the subsidence (intensity, extension, etc…) and the structure (position and characteristics, materials, shape, age and design). Several research works have been focused on the study of the ground-structure interaction phenomena due to ground movements induced by tunnel and mining excavations (Potts & Addenbrooke, 1997, Franzius & Potts, 2006, Caudron et al. 2007).

Since many years, we developed several actions to take into account the interaction between soil and structures using numerical and physical models (Deck, 2002, Abbass-Fayad, 2003, Caudron, 2007 et al., Hor et al, 2011).

In this paper, we will focus on the influence of movements due to mine activities on existing structures such as individual house. The paper presents the main results of the small-scale physical model designed to study the consequences of subsidence on structures. We present the transfer of movements from the soil to the structure. The objective is to understand and then to predict the real behavior and the damage of structures on subsidence areas.

SUBSIDENCE CHARACTERISTICS AND STRUCTURE DAMAGES

Subsidence description

The deformation undergone by the ground surface following a progressive subsidence breaks up classically into a vertical movement of the ground, called subsidence, and a horizontal displacement (Standing, 2008, Al Heib, 2008). The derivative of the vertical and horizontal displacements gives the strain and the tilt curves. Figure 1 presents the theoretical curves of vertical displacement, horizontal displacement, tilt, horizontal strain and curvature. Traditionally, only the vertical displacements are obtained by direct survey measurements, the others parameters are estimated using empirical and analytical approaches (Deck et al., 2003).

The subsidence characteristics depend on the underground void characteristics (depth, surface, etc.). The influencing area for structures and infrastructures, under the cavities, is delimited by influence angles γ. The vertical direction and the line that connects negligible subsidence point to the edge of the underground voids form this angle. The maximum damages observed on structures are located in the zone of maximum horizontal extension strain defined by the angle of break θ (Figure 1). The value of the angle of break is largely lower than the angle of influence.

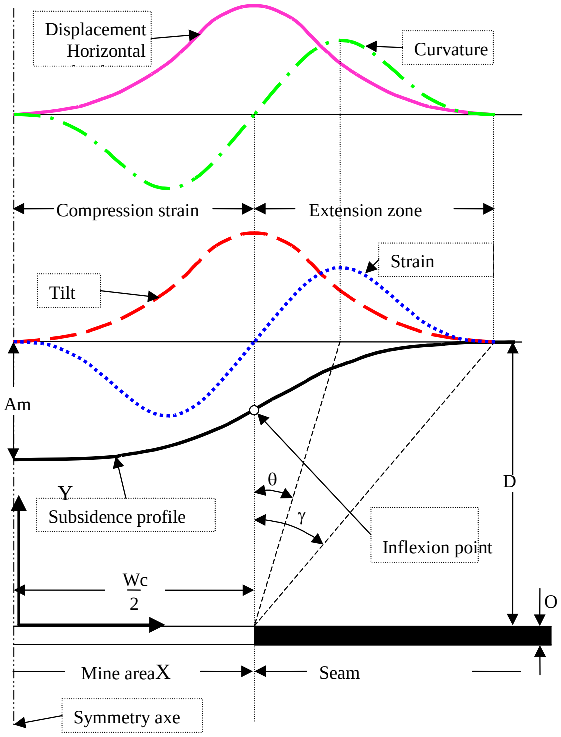


Figure 1. Subsidence Parameters (O: layer open, Am: maximal subsidence, γ and θ: influence angle and failure angle, D: depth, Wc: critical width)

Damages of structures

The influence of subsidence on buildings and infrastructures has become an important and costly environmental issue during mining and after the closure of mines (ISRM, 2008, Abla et al. 2012, Figure 2). The figure 3 describes very simply the different movements that can affecte on the structure due to surface subsidence. The vertical component of ground movements (subsidence) causes changes in ground gradient, which can adversely affect, for example, drainage, tall buildings and machinery in factories.

Figure 2. Example of serious structure damages due to subsidence – Iron mine – Lorraine – France

The horizontal strains (extension and compression) are the causes of the most commonly observed type of subsidence damage. Extension is characterized by the pulled open joints in masonry (Figure 2). The compression strain results in the squeezing-in of voids: such as doors and windows and the horizontal movements of masonry blocks. The intensity of the horizontal strain gives the level of damages (from light to very severe). The occurrence of damage in flexible structures corresponds to 2 mm/m. The horizontal strain of 6 mm/m horizontal strain induces serious damages and sometimes the collapse of a structure (Figure 2). The way soil movements affect the structure depends on the stiffness of the structure, its age and the type of foundations. Potts and others declare that the transfer of soil strains decreases with the increasing relative stiffness. The soil-structure interaction influences the transfer of strains to buildings and other types of structures. The nature of the subsoil can play a major role on the transfer of underground movement to the structures. If the subsoil is soft enough, the soil can compress against the structure and foundations, applying significant horizontal stresses on the superstructures.

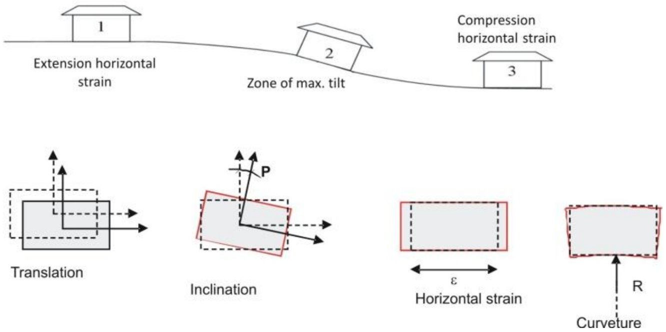


Figure 3. Different types of movement affecting a structure due to subsidence influence (Deck et al., 2003)

LARGE SMALL SCALE PHYSICAL MODEL

Different types of physical models have been developed for studying geotechnical problems (Hor et al, 2012). The first physical model was presented by Knoth in 1950. The progress of numerical modeling and computer capacity has reduced the use of physical models. The INERIS physical model is designed to be used in 1g environment (earth gravity). The objective of the physical model is to simulate the surface ground movements due to mining and underground cavities. The large small-scale model has to be able to hold a soil block of 3 x 2 x 1 m^3 with a maximum geometric scale of 1/50 (ratio between the physical model and the prototype).

The main hypothesis of the physical model is the abstraction of the cavity collapse, thus it only focuses on the phenomena at surface level is focused. The movements at ground surface are achieved by vertical downwards movements “electric jacks” placed at the bottom of the model downwards. The control of the velocity and the magnitude of the vertical movement are both realized using computer and a commercial software.

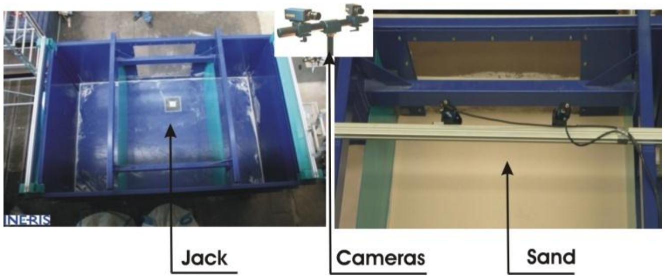


Figure 4: Large small scale physical model for modeling surface subsidence and damage structures

In this paper, we consider a mining case study of 20 m depth with 10 x 10 m^2 area of underground mining extraction. The extraction area corresponds to the application of vertical displacements. In the model scale, this is equivalent to an overburden of 0.5 m and a jack section of 0.25 x 0.25 m^2 for a geometric scale of 1/40. The chosen geometric scale makes it possible to use the Fontainebleau sand to model the soil. The diameter of the grain varies from 0.1 to 0.3 mm with D50 approximately 0.2 mm. The estimated properties of the soil mass model are presented in the Table 1.

Table 1. Characteristics of Fontainebleau Sand

Parameter	Soil (Fontainebleau sand)
Unit weight (kNm^3)	16
Elasticity Modulus (MPa)	5-20
Cohesion (kN/m^2)	0-2
Friction angle (°)	32-36

The building model

A building model was created to investigate the impact of ground movements on the surface structure. The chosen geometry for the building was inspired from the existing database of individual buildings damaged by mining subsidence in the east of France. A typical 10 m x 10 m two-floor house of constituted by masonry walls, reinforced concrete slabs and shallow foundations were considered. This realistic but complex 3D prototype scale model was simplified for defining the small-scale model. The prototype structure is first reduced to a simple equivalent slab. Two materials are used to represent the slab in the small-scale physical model: polycarbonate and silicon. The main difference between the two materials is the mechanical properties (Young modulus). Secondly, we modeled the upper masonry structures by using wood and sugar pieces. Table 2 represents the characteristics of the building and the scaling ratio. The structure is consisted of 4 exterior and 2 interior walls (Figure 6 and Figure 8).

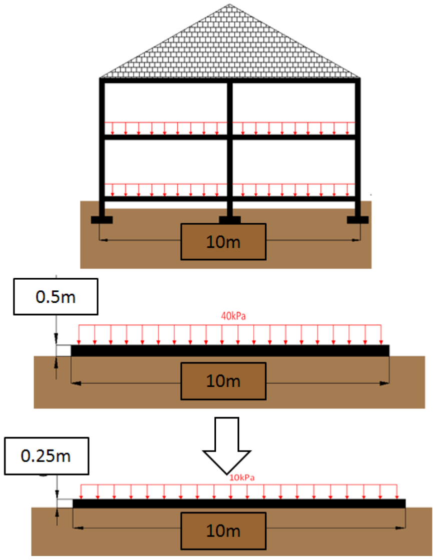


Figure 5. Procedure of the simplification of the structure to a slab

Table 2. Characteristics of the model and prototype structure

Characteristics	Model	Scaling factor	Equivalent prototype
Width (m)	0.25	40	10
Length (m)	0.25	40	10
Total Height (m)	5.5E-3	40	0.22

A polycarbonate slab

To obtain a deformable structure, the bending stiffness (EI) of and the axial stiffness (EA) of the polycarbonate slab are reduced by half in both directions to exacerbate the strain in the structure.

The polycarbonate small scale model is square with 25 cm length and 5 mm height; the slab respects the factors of the scaling laws. The structure model presented in Figure 6 is indeed a U-section slab made of polycarbonate, the interior part of which is composed of lead powder in plastic bags. This allows the model to represent stiffness and a stress transmitted to the ground approximately equivalent to those of the prototype. The 5 mm width of the edge is designed to be visible to the camera for measurement during the test.

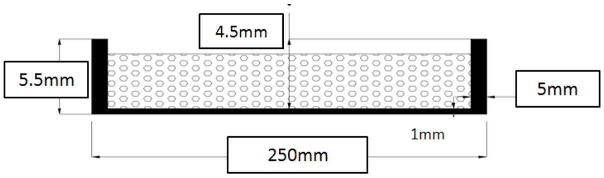


Figure 6-a. Polycarbonate small-scale structure model dimensions

Figure 6-b. Polycarbonate small-scale structure model composed of a hollow slab and small bags of lead powder representing the load.

A silicon slab

The silicon model has a simple geometry and initially identical to the polycarbonate slab, the height of the edges is 40 mm and the height of the inside of the model is 18 mm (Figure 7):

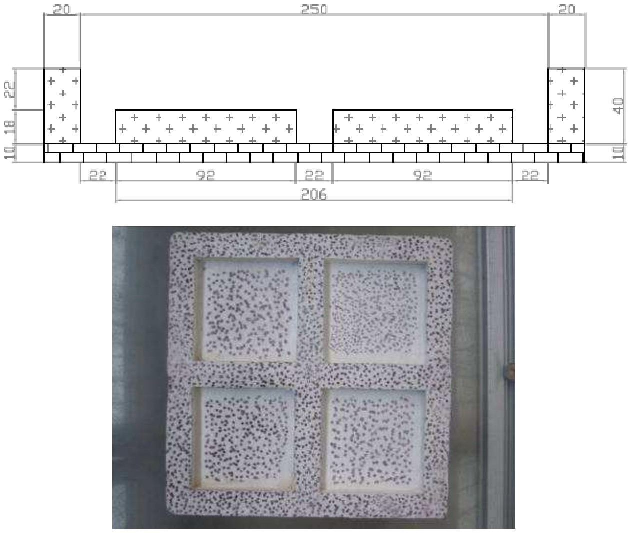


Figure 7. Silicon small-scale structure model composed of a hollow slab

The Table 3 summarizes the principal characteristics of the two small scales models of the slab (polycarbonate and silicon). The polycarbonate structure is stiffer than the silicon one. The silicon structure has a smaller axial stiffness (- 95%)

and a greater bending stiffness (+ 17%).

Table 3. Characteristics of small scale structure models

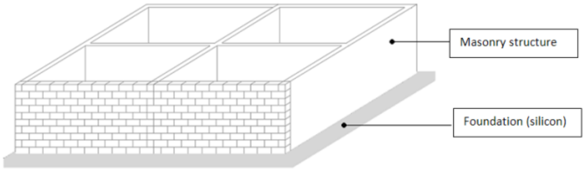
Parameter	Polycarbonate	Silicon
Height (mm)	4.5	40
Elasticity modulus (MPa)	2200-2500	5
Density (N/m^3)	1.12	1.13
Mass (kg)	1.56	2.15
EA (MN)	0.67	0.036
EI (N.m)	2.81	3.3

EA : Axial stiffness and EI Bending stiffness

Table 4 presents the characteristics of equivalent masonry materials (sugar and wood). The difference between the wood and the sugar concern bloc dimensions (Table 4), sugar blocks are two to three times larger than the wood pieces. The wood pieces are cut to represent real masonry blocks. The wood type used herein is Azoba, a very dense wood associated with high compression strength. The mechanical parameters of sugar and wood are not determined for this study. There is no mortar considered between blocks and the friction ensures the transfer of displacements and stresses between them. The building of the structure model is build manually.

Table 4. Characteristics of masonry blocks

Parameter	Sugar	wood
Dimension (mm)	27*18*12	7*7*14
Elasticity Modulus (MPa)	?	16000-19000
Density (N/m^3)	1.59	1.03
Friction angle (°)	?	30±9



a- Presentation of masonry structure

b- Physical model using wood blocks

c Physical model using sugar blocks

Figure 8. Small-scale structure of masonry (wood and sugar) and foundation (silicon)

The measurement technique

Digital Image Correlation (DIC) technique was adopted to determine the displacements and the deformations of the ground surface and of the building model. Two high-resolution digital cameras whose relative position is very precisely known allows the determining of the 3D deformations of the specimen's surfaces using correlation software Vic3D (Figure 9). In addition, this method provides an accurate result with a small error on the Fontainebleau sand (about 0.03 mm for a whole test).

RESULTS ANALYSIS

To induce the vertical movement on the surface, a vertical movement of the jack, is applied with constant velocity of the jack of 0.15 mm/sec. The total vertical movement (displacement) is 30 mm corresponding to 1.2 m in the reality, due to the adopted scale (1/40). Two categories of test were done: green field tests and soil-structure interaction tests in the presence of the masonry structure on the surface.

The results analysis consists:

- The formation and the characteristics of the subsidence (vertical displacement, horizontal displacement, maximum tilt and horizontal strain) in the case of green field (with the absence of surface structure) and when a structure is placed on the surface;
- The deformation of structure (horizontal strain, tilt) due to

the subsidence, we compare the amount of structure deformation to soil subsidence. The transfer ratio between the soil and the structure deformations will be responsible for the damage of the structure.

- The identification and the characterization of the masonry cracks (open joints due to the underground movements).

Figure 9 presents the model (sand, polycarbonate slab) and the position of the cameras. Thanks to cameras, we obtain the 3D subsidence, horizontal displacement… at each time steps of the experiment.

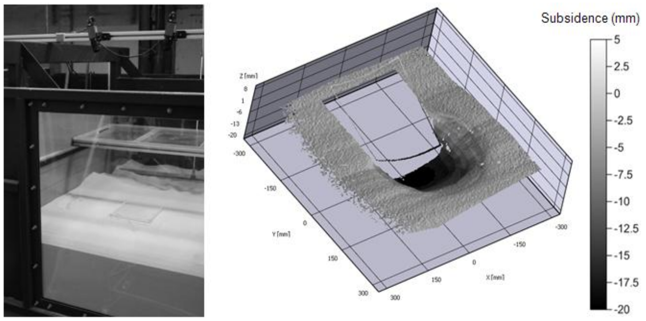


Figure 9. Monitoring of the physical model: (a) Two digital cameras capturing the surface of soil and building model; (b) Example of the 3D shape of the soil and building model determined (only the edges of the structure can be analyzed)

<u>Simulation of foundations (silicon and polycarbonate slabs)</u>

The Figure 10 presents an example of the vertical surface displacement (subsidence) corresponding to 30 mm of the vertical jack displacement. The maximum subsidence is equal to 26 mm. The difference between the jack vertical movement and the surface subsidence is not very important (4 mm); the reason of this small difference is the use of the Fontainebleau sand. It is a very homogenous and uniform soil limiting the effect of buckling. The subsidence magnitude decreases from the centre to the exterior corresponding to the theoretical profile (Figure 1). Different profiles can be realized. We will compare them with and without the structure (green field).

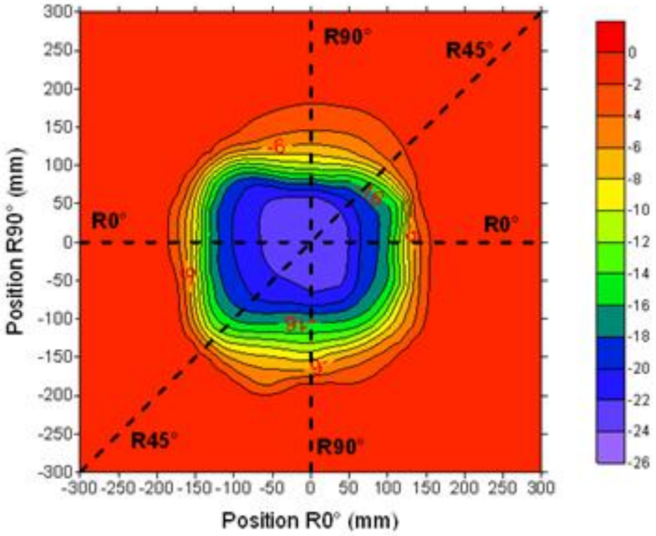


Figure 10. Subsidence through due to a vertical displacement of the jack equal to 30 mm

The figure 11, presents the curves of vertical and horizontal displacement of the soil and the structure. The influence of the presence of the structure on the vertical displacement is not very important. The structure does not follow the ground displacement (for the direction considered in Figure 11, the structure loses the contact with the soil and therefore a presents a cantilever-like behavior.

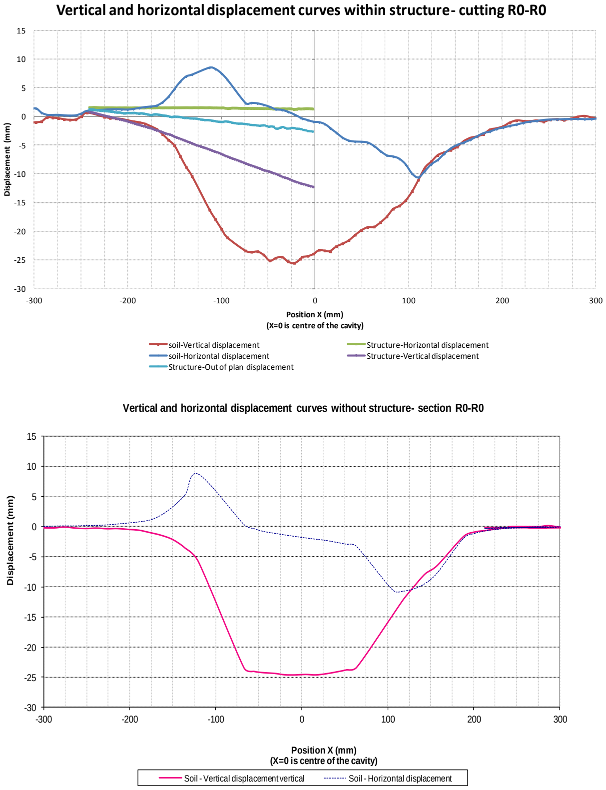


Figure 11. Vertical and horizontal displacement curves for two configurations (within and without structure)

Table 4 presents the main results of green field subsidence and those with the presence of polycarbonate slab. One can observe the reduction of the amplitude of vertical, horizontal displacements and the maximum tilt. The effect of the structure is clearly observed but the reduction of the parameters is still not very important. The reason is the nature of soil and the interface between the structure and the soil. The Table 6 presents the maximal deformation of the structure. One can observe that the vertical displacement of the structure is less than the vertical soil displacement. The ratio between soil and structure displacement varies as a function of the material characteristics. The silicon slab follows the soil movement. The polycarbonate slab behaves as the cantilever beam and the silicon slab behaves as flexible solid due to their characteristics and the strong contact with soil. The collapse of the structure depends on the strength of the material. Polycarbonate and silicon still behave as elastic materials.

Table 4. Subsidence characteristics for two configurations: green field without the structure and with the presence of the structure

Parameter	Green field	Soil-structure interaction
Svsoil, max (mm)	-26	-23.9
Shsoil,max (mm)	12,4	11,1
T soil max (%)	-45,0	-30,4
ε soil hc,max (%)	-8,2	-
ε soil ht,max (%)	14,4	-

Sv soil, max: maximal vertical subsidence (displacement)
Sh soil, max: maximal horizontal displacement
T soil max: maximal tilt
ε soil hc max.: maximal compression horizontal strain
ε soil hc max.: maximal tension horizontal strain

Table 5 presents the structure deformation due to the vertical displacement of the soil. The main difference between the two types of slab behavior (foundation) is the magnitude of the compression horizontal strain; it is 8 times more sensitive for the silicon slab than the polycarbonate slab. This result confirms the importance of the stiffness, in particular the axial stiffness. The damage of the structure depends on the horizontal strain of the structure than that of the soil.

Table 5. Characteristics of the structure deformation for two different materials (polycarbonate and silicon slabs)

Parameter	Polycarbonate	Silicon
Sv, max (mm)	11	20.1
Sh, max (mm)	1.93	3.84
pmax (%)	6.4	5.13
εhc,max (%)	0.08	0.61

Sv structure, max: maximal vertical displacement
Sh structure, max: maximal horizontal displacement
P structure max: maximal tilt
ε hc max.: horizontal maximal compression horizontal strain

Results for the masonry structure

The masonry structure was located on the ground surface in the maximum tilt zone (Figure 1 and Figure 12). The result of test on the masonry structure using the sugar and the wood pieces are respectively presented by Figures 11 and 12. The maximum vertical displacement is 30 mm. The first opened joint between sugar blocks is observed for a vertical displacement of 6 mm and only one or two blocks are concerned. The number of opened joints increases with the vertical displacement of the jack. The magnitude of the crack width (normal distance between two pieces) increases up to 0.375 mm corresponding to very severe damages of the structure. Vertical cracks develop across the structure from the bottom to the top. The localization of vertical cracks corresponds to the limit of the contact between the soil and the structure.
The use of the wood pieces to present the masonry structure allowing obtaining opening cracks. The localization of cracks in the wood structure corresponds to sugar structure. This results headlight the importance of the structure position in the development of cracks and damage in the masonry structure.

The pieces of the wood are smaller, so the localization of cracks is different and concerns large zone compared to sugar structure. This result can help to understand the role of block dimensions of masonry structures in subsidence zones

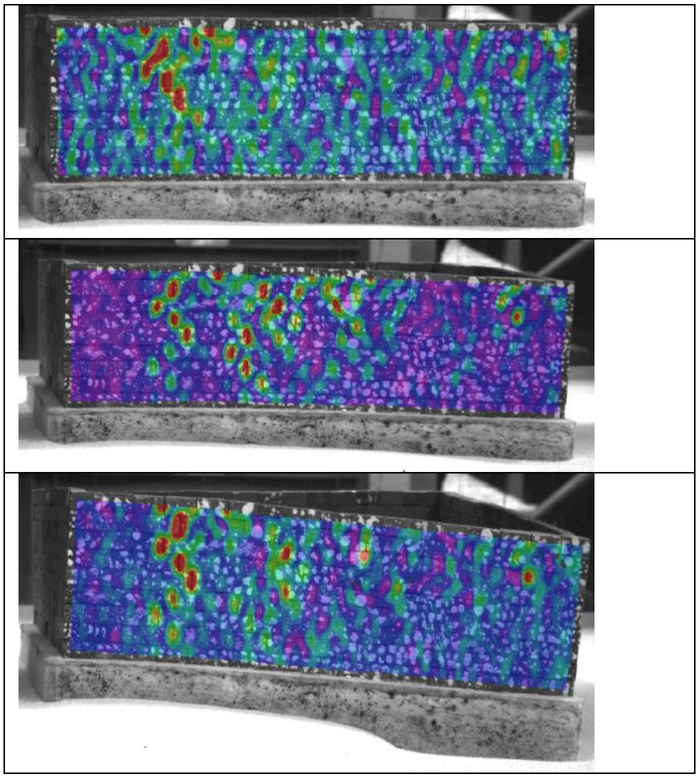


Figure 12. Progress of the masonry structure (wood pieces) behavior due the increasing of the vertical displacement of the soil

CONCLUSION

The stability of surface structures due to underground excavation was studied using a large small-scale physical model. The physical model simulated also a masonry structure. It appears to be a very useful tool for studying the soil-interaction phenomena. A stiff structure behaves like a cantilever beam and ground displacements transferred to the structure are smaller than for a flexible structure. The masonry structure was modeled by sugar and wood blocks. The damages of the structure were located clearly in the zone of maximum of tilt. The open cracks of the sugar physical modeled structure are more located than those of the wood structure due to the dimension of blocks. Using woods or sugar blocks allows localizing and quantifying damages of masonry structures.

The original and encouraging results presented in ths paper shall not hide the limitations and simplifications of the considered cases compared to real situations. This research should be pursued to improve the physical modeling of the soil and masonry structures.

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