Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

The ground movement simulator: An interesting facility for the study of the behavior of buildings submitted to ground subsidence

M. Caudron, M. Al Heib & B. Hor
National Institute for Industrial Facilities and Risks (INERIS), Verneuil en Halatte, France

F. Emeriault
CNRS UMR 5521, 3SR Lab, Grenoble, France

ABSTRACT: Soil subsidence of various extend and amplitude can result from the failure of underground cavities, whether natural (for example caused by the dissolution of rocks by underground water flow) or man-made (such as mines and quarries). The impact of the movements of the ground on existing structures (houses, buildings, bridges, etc…) is generally dramatic. A large small-scale physical model is developed in order to improve our understanding of the behaviour of the building subjected to ground subsidence or collapse. We focus on the soil-structure interaction and on the mitigation techniques allowing reducing the vulnerability of the stakes.

1 INTRODUCTION

INERIS is working for many years on the "ground movements" risk caused by underground cavities (mines, quarries and tunnels). Several research tasks are followed concerning the stability of the cavities, the prediction of the ground movements reaching the ground surface, the behaviour of the building subjected to this hazard and mitigation techniques.

A large small-scale physical model is developed in order to improve our understanding of the behaviour of the building subjected to ground subsidence or collapse. We focus on the soil-structure interaction and on the mitigation techniques allowing reducing the vulnerability of the stakes.

This article is composed in a first part on the presentation of the physical model, the measurement facilities and the basic hypothesis. Secondly a corresponding building model is detailed. We develop then two similar tests, the first one presenting the case of a ground subsidence in greenfield condition while the second one uses the building model: a slab with his loading. We detail the influence of the position of the structure with respect to the cavity.

2 BIBLIOGRAPHY

2.1 *Mining subsidence & soil-structure interaction*

The subsidence is generally caused by convergence or collapse of anthropic or natural underground cavities. This phenomenon can be very prejudicial for the structures and infrastructures on the surface and for the population. Empirical rules exist for the estimation of the building damages caused by such ground movements (…). But they are limited by the context of their definition. There is very few relationships to determine the damages caused to a building by ground movements and taking into account the soil-structure interactions. These are mainly based on numerical studies (Potts & Addenbrook 1997, Dimmock & Mair 2008, Deck & Anirudth 2010).

Several research projects are focused on the study of the ground-structure interactions phenomena under the effect of the soil movements (Standing 2008, Lee et al. 2007, Sung et al. 2006, Abbass 2004, Deck 2002, Burd et al. 2000, Nakai et al. 1997).

While previous works (Caudron 2007) had allowed shedding some light on the interest of taking into account the soil-structure interaction, this paper will focus on the conception of a new small-scale physical model intended for the study of mining subsidence and the consequences on building on the ground surface. Previously, a bidimensional small-scale physical model was used (Caudron et al. 2006). However, the 2D nature of this model was a too important limit for the expected results preventing any transposal to the reality.

2.2 *Physical model for mining subsidence*

Very few physical models have been used to study the effects of ground movements caused by the mining process or by the collapse of old mine or quarries. We can mention a block caving small-scale physical model: Castro et al. (2007) and Trueman et al. (2008). This model is dedicated to the study of block caving exploitation method and not to the ground movement rising to the surface. Few models are focusing on the phenomena corresponding to the formation of a subsidence trough. Genis et al. (2008) studied the effect of an earthquake on the stability of an old coal mine located in Japan. They showed that depending on the geometry, the failure may happen in the pillars or at the mine ceiling. Dyne (1998) conceived a model, trap door type, in order to represent the happening of sinkholes in an ancient coal mine in Pennsylvania. The model was a very simple one with a trap door of four different widths and a single layer of sand as overburden.

Ren et al. (2010) achieved several tests with 1 g smal-scale physical model concerning subsidence characters of ground and wall rock due to underground mining. Few details are reported in literature on the parameters and the hypothesis to model it.

For these different works, none consider the potential damages caused by the rising subsidence on the surrounding buildings.

On this particular subject, several small-scale physical models have been realized in the field of tunnels. For example, Nakai et al. (1997) and Shahin et al. (2004) use a bidimensionnal physical model for the study of the influence of the position and nature of the foundation of a building subjected to settlements caused by a tunnel boring.

Tests have been performed in the context of EU research project "QUAKER" to study the influence of several buildings, considering different geometries, weight and foundation systems, on the path followed by a fault activated by the Kocaeli earthquake (Bransby et al. 2008a and 2008b). Very interesting results are obtained, showing a more or less important bifurcation of the fault when a building is located close the path obtained in Greenfield condition. The bifurcation can even become very important in the case of heavy building or when a deep foundation system is used.

3 THE APPARATUS

3.1 *Hypothesis and conception*

The first part of the hypothesis comes from the rules of similarity. It is very difficult, if not impossible to achieve a perfect similarity with a small-scale model. As we are not using a centrifuge, the gravity in the model will be normal gravity. Results would be only qualitative one and not quantitative.

The geometry scale factor may range up to 1/50. With a size of 2 m by 3 m in the horizontal plan for a thickness up to 1 m, we would be able to represent a soil block as large as 100 m by 150 m with a height of 50 m. With the 1 g gravity, the main consequence is that for high scale factor values, the difference between the achieved values of stresses and the normally scaled ones become very large and might cause some important differences.

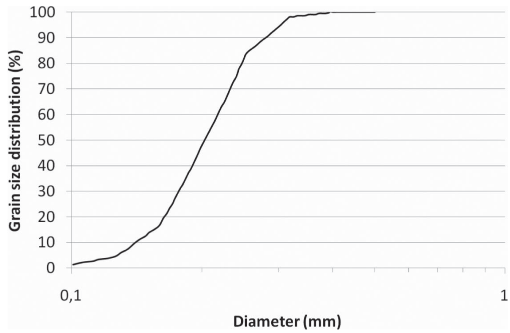

Figure 1. Grain size distribution of the Fontainebleau sand.

To take into account the high magnitude of subsidence, mines and quarries as cavities being at the origin of the ground movements caused by their collapse, the maximal depth of 50 m may appear like a serious limit for this model. However, we choose not to model the cavity itself but only the equivalent void raising to the ground surface. This is achieved by the use of electric jacks with a vertical moving trap-door. The apparatus is designed to be equipped with 48 jacks at most, in a configuration of 6 rows of 8.

The model is still being in an early stage of development, only one jack is installed. The cross-section of the actuator is limited to 250×250 mm², corresponding to up to 12.5×12.5 m². The apparatus is indeed limited to localized phenomena: sinkhole or collapse/subsidence of small-extent. When more jacks would be installed, various shapes of collapse/subsidence would be able to be modeled.

Up to 48 jacks may be installed on the apparatus. The purpose is to be able to model, for example, a chosen area from a subsidence trough observed in a mining basin and then to study the effects of this particular trough on the buildings and the protection potential of several mitigation techniques.

3.2 *Material*

The soil used is the Fontainebleau sand, category N34. The grain size distribution and the mechanical properties are reported in Figure 1 and Table 1 respectively.

3.3 *Monitoring*

Measurement of surface displacements is achieved by the mean of stereo digital imagery. This allows

Table 1. Mechanical characteristics of the sand.

	Density	E (MPa)	φ (°)	c (kPa)
Sand	1.6	5–20	35–37	0–2

monitoring the whole top surface of the ground and more especially where ground movements happen. A commercial product is chosen, Vic3D from Limess Gmbh, being very effective in the task of computing the movements with the grains of sand showing very low contrast on the photos.

Two cameras, 4 MP each, are used. They allow a maximal frequency capture of 8 images/second at full resolution, with the possibility to reach 30 images/second with a 1 MP resolution. They have to be calibrated before the start of a test by the use of a test pattern. A good calibration allows obtaining very precise measurements with an error of 1/100 of a pixel in good conditions: that's 10 μm when 1 pixel is equal to 1 mm. In the tests presented later in this paper, we have a ratio close to 2 pixels per millimeter. But, due to the nature of the sand, constituted of small particles and so not a continuous media, the corresponding maximal error is around 0.10 pixel giving 0.05 mm: this is quite a good performance (White et al. 2003).

One disadvantage of this method of monitoring is the huge volume of data created by a single test. With a volume of 8 Mo per capture (two images of 4 Mo each) and considering the full speed frequency of capture, it represents near 2 Go of raw data to be stored each minute. For a full test and with the exploitation files for the digital correlation process, this corresponds to a total between 30 and 40 Go.

3.4 *The building model*

A building model corresponding to an individual house had to be created to be used in the tests in order to study the effects of the soil-structure interactions during the happening of a subsidence trough and after what the effects of this ground movement on the structure.

Geometry was chosen for this building. Inspired from the database existing on the building damaged by mine subsidence in the east of France, like Lorraine basin, a house is considered, whose characteristics are shown in Figure 2 (Deck et al. 2003).

While it is not possible to make in a direct way a 3D realistic small-scale model of this structure, we have to simplify it. For the first campaign of tests, we chose to consider only an elastic behavior and to use an equivalent slab. The followed process to simplify the building and to obtain the small-scale model is presented on Figure 2.

Three steps compose it: first, the equivalent slab is determined such as the bending stiffness and the axial stiffness of this slab are quite equivalent to the 3D structure. Then we choose to reduce the stiffness, in both directions, in order to exacerbate the strains in the structure. Both stiffnesses are approximately halved. From this very simple structure at prototype scale, a small scale model is conceived by applying the scale factors.

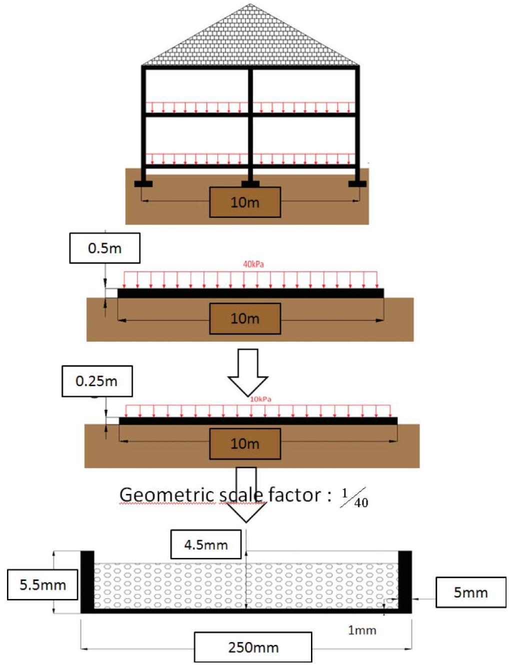

Figure 2. Simplification procedure of the 3D building to an equivalent small-scale slab.

Figure 3. The resulting small-scale structure model composed of a hollow slab and small bags of lead powder representing the load.

As shown on Figure 3, two parts are used for the structure model. The first one is a hollow slab while the second one is composed of lead powder in a plastic bag. This allows the model to present a stiffness and a stress transmitted to the ground equivalent to the prototype's ones.

This small scale model is laying on the ground without taking into account any foundation parts. This is limiting the interaction between the soil and the structure. However, this procedure makes it very simple to reproduce on several tests. The next small-scale building model should emphasize a foundation system so as to respect a configuration closer from the reality.

3.5 *Achievement of a test*

The sand is manually put in the apparatus by layers if 15 cm thick. Each layer is compacted by a compacting tool equipped with 15 cm long needles in order to ensure a certain level of density, repeatable for each different test. This is repeated until the total height of the soil layer is reached, in our case, 30 cm. Afterwards a 130 cm wide rule is used to obtain the right level on the whole ground surface.

A snapshot is then taken by both cameras to insure that the ground surface is flat enough with a difference less than 5 mm in altitude between the points the highest and the lowest. The building model is then placed delicately on the ground surface, its position depending from the modeled case (see part 4 of this paper).

The acquisition by the two cameras is then started with a frequency of 0.5 Hz. The motion program of the jack is launched at the same time a snapshot is taken by the camera. The jack is moved down at a speed of 0.125 mm/second for a total of 30 mm.

At the end of the test, the displacements of the ground and the structure are computed by the DIC program.

4 RESULTS OF THE TESTS CAMPAIGN

This campaign is dedicated to the study of the influence of the building position relative to a subsidence trough. After the presentation of the reference result, the subsidence trough in greenfield condition, the results from the parametric study are presented.

4.1 *Greenfield condition*

Four identical tests were performed in order to ensure a good level of repeatability. As shown on Figure 4, the greenfield trough is symmetric. The average global characteristics are summarized in Table 2, which S_{max}, i, R_{max}, α and ε_h are respectively the maximum settlement, the distance to the point of inflexion, the maximal horizontal displacement, the maximal slope and the maximal horizontal strain). The indicated values are in prototype scale (1/40 geometric scale). Differences from one test to another are not very important, but cannot be neglected; it is less than 15% of variation.

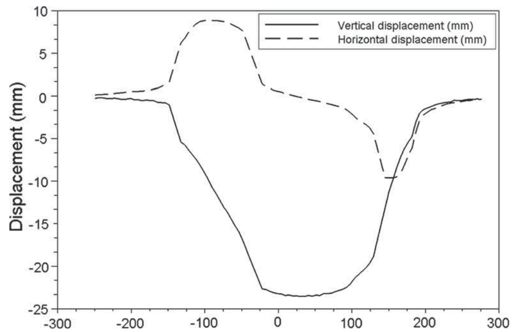

Figure 4. Displacements in Greenfield condition.

Table 2. Geometric characteristics of the surface ground displacement.

Characteristics	Average
S_{max}	96 cm
i	4 m
R_{max}	44 cm
α	21.6%
ε_h	−10.5%

4.2 *Parametric study*

Three positions are used for the building model. They are defined with respect to the main component of the subsidence trough. Position n°1 is where the slope is the greatest, position n°2 correspond to the building being on the extension area and position n°3 puts the building completely in the compression area. Figure 5 presents these three different positions. Three particular axes are then defined for the exploitation of the results. They are chosen so that they go from the center of the building to the center of the subsidence trough.

Four tests are performed for each position of the building, as for the greenfield condition. Results are then presented for two points of view. First the displacement measured at ground surface will be compared in order to identify the effect of the building on the ground behavior. Secondly some light will be shed on the strains in the building model.

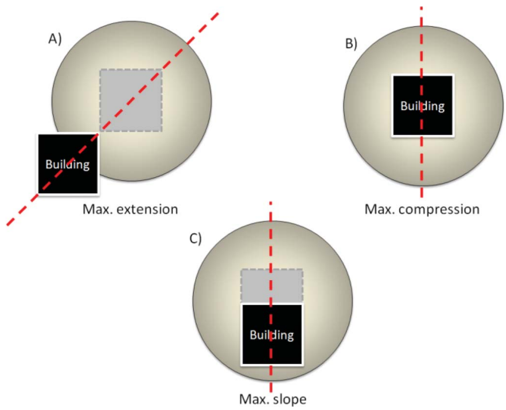

Figure 5. Building position for the parametric study.

4.2.1 *Ground behavior*

The building engenders some important differences in the soil displacement at ground surface. The trough, formerly symmetric in greenfield condition, shows clearly some dissymmetry. However, the building being in B position, centered in the subsidence trough, does not break the symmetry. Two examples of ground displacement curves are shown on Figure 6, corresponding to the axis plotted for the positions A & C of the building.

It appears that the soil movements are reduced due to the effect of the soil-structure interaction. Different areas may be distinguished, depending on the relative displacement of the ground to the building model. In the center part of the trough, the ground falls off the building due to a more important displacement, while on the other side of the building, its rotation causes another detachment.

4.2.2 *Consequences on the building*

The optical measurement setting allows catching the movements and the strains of the building. Those measures are synthesized in Table 3 concerning the main strain modes for a building. It can be seen that the measured strains are very small. Several reasons are identified:

- The elastic behavior chosen for the building model;
- The fact that the building is just laying on the ground surface;
- The stiffness of the building being too important.

The soil-structure interaction is thus clearly identifiable: the behavior of the soil is modified in an important manner due to the presence of the building, and consequently the strains measured in the structure are different from those calculated using the ground displacement in Greenfield condition.

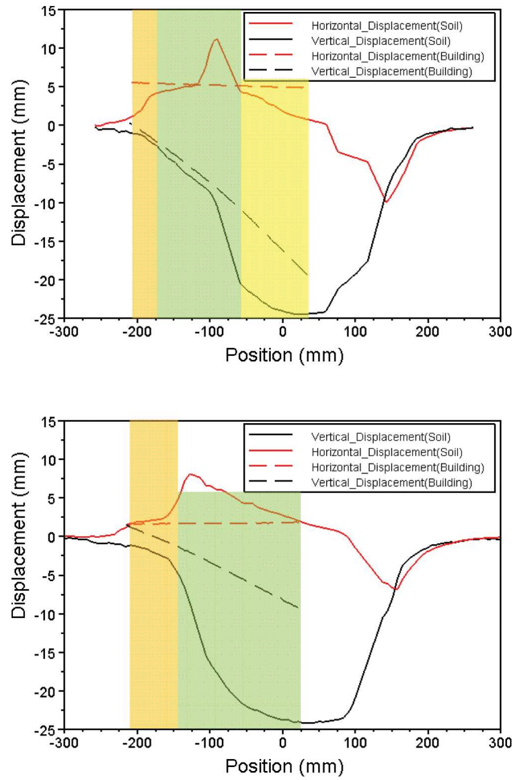

Figure 6. Behavior of the ground for two different positions of the building (top: pos. A; down: pos. C).

Table 3. Comparison between the strains determined in greenfield and ISS conditions.

Case	Horiz. strain	Bending radius	Slope
	(%)	(m)	(%)
Greenfield (pos. A)	–5	–	21.6
ISS (pos. A)	–0.21	–	6.4
Greenfield (pos. C)	–10.5	–1.67	21.6
ISS (pos. C)	–0.24	–9.42	11.1

5 CONCLUSIONS AND PROSPECTS

This study presents a new apparatus allowing to model ground movements caused by the collapse of underground cavities. A simple structure model, conceived in order to stand for a personal housing, is used with two purposes: observe the evolution of the ground movements in presence of the building and its behavior; highlight the importance of the soil-structure interaction.

As a conclusion for this study, we would like to emphasize the fact that these tests represent the first step of a more global research for the consequences of ground movements on building, by taking into account the soil-structure interactions. It was established than the soil-structure phenomenon must not be neglected and that it depends greatly of the relative position of the building in the subsidence trough.

Still, many technical improvements must be brought to the small-scale physical model. The initial state of the sandy soil must be clarified and several jacks will be set up to increase the variety of subsidence trough geometry that the apparatus is able to achieve.

However, in parallel, the structure model should be improved in order to represent in a more realistic way a building. The main points are the design of the foundation system and of the upper part of the structure. Afterwards a new test campaign may be set up with the final objectives to study the performance of mitigation techniques.

ACKNOWLEDGEMENT

The authors would like to thank the French Ministry for Environment, Sustainable Development and the Sea for the partial founding of this research program.

BIBLIOGRAPHY

Abbass-Fayad, A. 2004. Modélisation numérique et analytique de la montée de cloche des carrières à faible profondeur. Etude de l'interaction sol-structure due aux mouvements du terrain induits par des fontis. *Institut National Polytechnique de Lorraine. PhD Thesis*.

Burd H.J., Houlby G., Augarde C., Liu G. 2000. Modelling tunneling-induced settlement of masonry building. *Proc. Inst. Civ. Eng. Geotech. Engng*, 143:17–29

Bransby M., Davies M. and Nahas A. 2008. Centrifuge modelling of normal fault-foundation interaction. *Bull. Earthquake Eng*. 6:585–605.

Bransby M., Davies M., Nahas A. and Nagaoka S. 2008. Centrifuge modelling of reverse fault-foundation interaction. *Bull. Earthquake Eng*. 6:607–628.

Castro R, Trueman R, Halim A. 2007. A study of isolated draw zones in block caving mines by means of a large 3D physical model. *Int J Rock Mech Min Sci 2007*;44:860–70.

Caudron M., Emeriault F., Kastner R. & Al Heib M. 2006a. Sinkhole and soil-structure interactions: Development of an experimental model. *Int. Conf. on Physical Modeling in Geotechnics, Hong-Kong*, 04–06 Aug. 2006, pp 1261–1267.

Caudron M., Emeriault F. & Al Heib M. 2007. Contribution of the experimental and numerical modeling to the understanding of the soil-structure interaction during the event of a sinkhole. *ECSMGE 2007, Madrid*.

Deck O., Al Heib M., and Homand F. 2003. Taking the soil-structure interaction into account in assessing the loading of a structure in a mining area. *Engineering Structure* 25:435–448.

Deck O. and Anirudth 2010. Numerical study of the soil-structure interaction within mining subsidence areas. Computers and Geotechnics. Article in Presse.

Dimmock P. and Mair R. 2008. Effect of building stiffness on tunnelling-induced ground movement. *Tunnelling and Underground Space Technology* 23 (2008) 438–450.

Dyne L. 1998. The prediction and occurence of chimney subsidence in southwestern Pennsylvania. *Master Thesis from Virginia Polytechnic Institute and State Faculty*.

Genis M. & Aydan O. 2008. Assessment of dynamic response and stability of an abandoned room and pillar underground lignite mine. *12th IACMAG, Goa, India*, pp 3899–3906.

Lee, Y. & Bassett, R. 2007. Influence zones for 2D pile-soil-tunnelling interaction based on model test and numerical analysis. *Tunnelling and Underground Space Technology*, 22, 325–342.

Nakai, T.; Xu, L. & Yamazaki, H. 1997. 3D and 2D model tests and numerical analyses of settlements and earth pressures due to tunnel excavation. *Soils and Foundations*, 37, 31–42.

Potts D. and Addenbrook T. 1997. A structure's influence on tunnelling induced ground movements. *Proc. Inst. Civ. Eng. Geotech. Eng*. 125 (2), 109–125.

Ren W., Guo C., Peng Z. and Wang Y. 2010. Model experimental research on deformation and subsidence characteristics of ground and wall rock due to mining under thick overlying terrane. *Int. J. Rock Mec. & Mining Sc*. 47 (2010) 614–624.

Shahin, H., Nakai, T. Hinokio, M. Kurimoto, T. and Sada, T. 2004. Influence of surface loads and construction sequence on ground response due to tunnelling. *Soils and Foundations*, 44:71–84.

Standing J. 2008. Impact of underground works on existing infrastructure. *Post-Mining'08, Nancy (France)*. Invited Lecture.

Sung, E.; Shahin, H.; Nakai, T.; Hinokio, M. & Makoto, Y. 2006. Ground behavior due to tunnel excavation with existing foundation. *Soils and Foundations,* 2:189–207.

Trueman R., Castro R, & Halim A. 2008. Study of multiple draw-zone interaction in block caving mines y means of a large 3D physical model. *Int. J. of Rock Mechanics and Mining Sciences* 45 (2008) 1044–1051.

White D., Take W. and Bolton M. 2003. Soil de formation measurement using particle image velocimetry (PIV) and photogrammetry. *Geotechnique*, 53:619–631.