Efficiency of mitigation measures for structures subjected to ground movement

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EFFICIENCY OF MITIGATION MEASURES FOR STRUCTURES SUBJECTED TO GROUND MOVEMENT

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ABSTRACT: *Surface subsidence resulting from the collapse of underground cavities, whether natural or man-made can interact with existing buildings on the surface. One of the mitigation measures used is to dig a peripheral trench at a certain distance from the structure, filled with a soft material, like peat, or artificial material. This is thought to reduce the horizontal strain applied to the structure. The 3D numerical analysis presented in this paper is a first step towards evaluating the efficiency of this type of mitigation technique. The numerical model developed using Abaqus allows the effect of various parameters such as the width or depth of the peripheral trench, its distance from the building and/or the stiffness and strength of the filling material to be clearly determined.*

INTRODUCTION

The collapse of underground cavities, both natural and man-made, causes many accidents at the surface. This can cause human and material damage. Various types of ground movement can be observed, such as subsidence and sinkholes.

INERIS[1] is in charge of a research project aimed at assessing the consequences of this type of ground movement on buildings and infrastructures, proposing and evaluating mitigation measures and defining design recommendations. The most affected zones in France are the Lorraine iron-ore basin, the Northern coal field and the Paris basin. The latter is particularly vulnerable due to its dense urbanization.

The present study is a contribution to this research project and deals with 3D numerical modelling of the effect of ground movement on buildings protected by a peripheral trench. This mitigation method has been proposed, for example in France, by CSTB (Deck, 2002, CSTB[2] 2004) and already implemented in some planning documents (PPRM[3] at Auboué, 2007 and Hayange 2005). Caudron (2007) studied the effect of the collapse of underground cavities using physical and numerical modeling without any mitigation measures. The first 2D numerical model was developed by Al Heib (2008) to evaluate the effect of structure and trenches. In this paper, we use a 3D numerical model to evaluate the mechanical response and to propose design recommendations. In particular, the influence of the different geometrical and mechanical characteristics of the trench must be assessed: stiffness and strength of the

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[1] INERIS : Institut National de l'Environnement industriel et des Risques

[2] CSTB : Centre Scientifique et Technique des Bâtiments

[3] PPRM stands for Plan for the Prevention of Mining Risks.

filling material of the trench (one of possible materials is peat), distance to the building, depth and width of the trench.

Ground movement induced by the collapse of an underground cavity is generally complex. A combination of horizontal and vertical displacement is observed at ground level under greenfield conditions (i.e. with no existing buildings or structures). It is alternatively described through horizontal strains (compression and extension), curvature (sagging and hogging) and slope (Al Heib, 2008). The consequences on the structures embedded in the subsurface can therefore be of various types: translation, tilt, horizontal strain (compression or extension) and bending; the structures are generally impacted by a combination of these different types. Unfortunately, the numerical of displacement fields in soil requires an explicit description of the cavity and its failure process. The resulting computing cost is excessive and not acceptable in the proposed parametric study which focuses on the building and surrounding trench.

According to many observations and back-analyzed case studies (Deck, 2002), horizontal strains appear to be the most important source of damage in buildings: it generates cracks in the corners of apertures, friction in the lower parts of the structure, bending the embedded walls and other complex reactions of the building. Therefore, the proposed numerical model focuses on this loading process alone. The problem can thus be split: the horizontal stress field generated by underground cavity failure can be directly calculated (with reference to the greenfield case) and applied to a 3D model that explicitly includes the structure, trench and volume of soil necessary to avoid boundary effects.

1 THE PROPOSED NUMERICAL MODEL

The numerical model described in Figure 1 has been implemented in Abaqus v6.7: a virtual square slab (10 m wide and 0.25 m thick) installed on a 50 m x 50 m wide, 10 m thick volume of soil. The surrounding trench is further introduced at a distance *D* from the structure, with depth *H* and width *W*. Reference values are first considered: *D*=1 m, *H*=1 m and *W*=0.5 m.

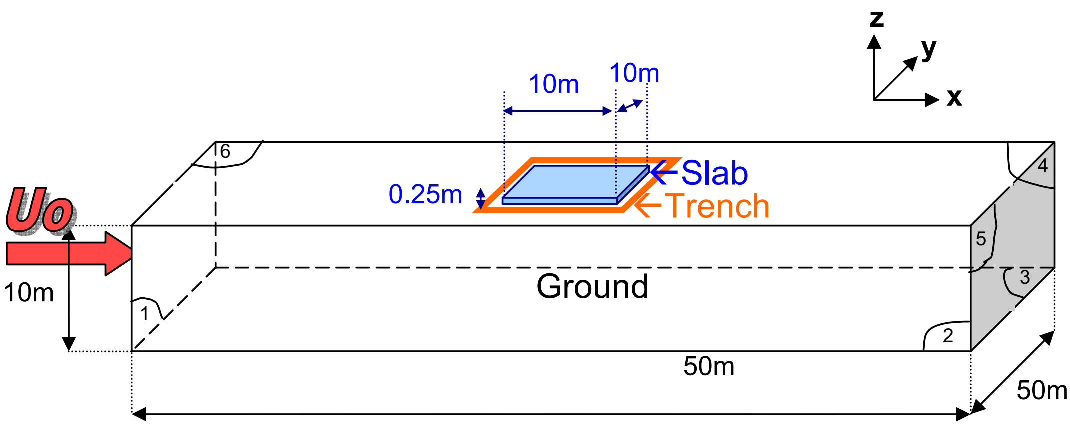

Fig. 1. Geometry of the model, U_0 is the uniform horizontal displacement applied to the left boundary of the model

Compressional horizontal displacement U_o=0.30 m is applied at boundary 1 of the model (Fig.1). This displacement value was chosen with reference to the greenfield case to induce 0.6 % compressive stress in the ground and, with the soil strength parameters under consideration, to produce plastic deformation in the vicinity of the ground surface. According to Burland (1995), horizontal stress ε_{xx} of this magnitude in a building can be responsible for Category 4 or 5 ('severe' or 'very severe') damage due to hogging, whatever the deflection ratio. In addition to the soil-structure interaction resulting from the difference in stiffness, the proposed numerical model will consider frictional interfaces between soil and slab. Therefore stresses transferred to the slab will be less than 0.6 % but will still correspond to possibly severe damage.

On boundaries 2, 3, 4 and 5, rotational displacement is restrained in the direction perpendicular to the boundaries. Boundary 6 is considered free.

Linear elastic isotropic is considered for the structure, with stiffness parameters corresponding to reinforced concrete (Table 1). Soil and trench material is linear elastic – perfectly plastic materials using the Mohr-Coulomb criterion and non-associated flow rule. Reference values for the trench material correspond to peat soil (Table 1).

Table 1. Properties of the ground and structure

	Density (kg/m^3)	**Young's modulus E (MPa)**	**Poisson's modulus ν**	**Friction angle φ (°)**	**Dilatation angle ψ (°)**	**Cohesion c (MPa)**
Ground	**2000**	**100**	**0.3**	**30°**	**15°**	**0.1**
Slab	**10,000**	**30,000**	**0.3**	**-**	**-**	**-**
Trench filling material	**1500**	**5**	**0.4**	**35°**	**15°**	**0.04**

The density of the virtual slab is actually used to represent the weight of a concrete structure with four walls and a 0.25 m thick roof. The soil characteristics considered correspond to compact cohesive soil. The difference in soil-structure stiffness can be estimated, according to Potts *et al.* (1997), by relative bending stiffness $\rho^{*}=EI/E_sH^4$ and relative axial stiffness $\alpha^{*}=EA/E_sH$, with EA and EI axial and bending stiffness of the structure, E_s soil Young's modulus and H half the length of the building. In the present case, ρ^{*}= 6.25x10^{-4} m^{-1} and α^{*}=15. Potts et al. (1997) showed that in the case of a tunnel excavation beneath a centered building, for these values of ρ^{*} and α^{*}, the behavior (in particular horizontal displacements and strains) at the ground surface is affected by the presence of the slab. Although they also showed that for α^{*} greater than 4.86 and any value of ρ^{*}, there is approximately no horizontal displacement in the soil under the slab (with rough interaction between soil and slab), the proposed numerical model will consider frictional interfaces between soil and slab.

For the trench, CSTB (2004) recommended the use of peat soil for filling the trench, therefore the mechanical parameters considered, listed in Table 1, correspond to this type of material. In the PPRM for Auboué (2007) and Hayange (2005), it is proposed to use an alternative material with Young's modulus E less than 10 MPa.

The interface between the soil and the slab or the trench uses a simplified normal interaction (hard contact option in Abaqus) and a frictional tangential interaction ("penalty" type in Abaqus) with the parameters given in Table 2.

Table 2. Properties of the ground/ trench and ground/slab interfaces

Ground/Trench	**Friction coefficient μ**	**Friction angle φ (°)**	**d (m)**
	0.4	**22°**	**0.01**
Ground/Slab	**Friction coefficient μ**	**Friction angle φ (°)**	**d (m)**
	0.58	**30°**	**3.9^{E}-5**

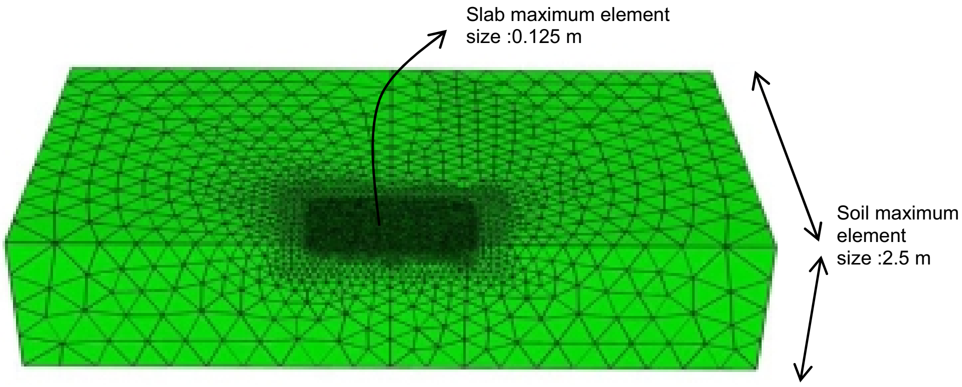

Fig. 2. Mesh used in the numerical simulations

The mesh corresponds to 4 node tetrahedral elements for the soil and 8 node hexahedral elements for the slab (Fig. 2). Due to the symmetry, only half of the problem is shown.

2 ANALYSIS OF THE REFERENCE CASE WITH TRENCH

The reference case considers a peripheral trench with distance to the slab D=1 m, depth H=0.5 m and width W=0.5 m. It is compared to the greenfield case and the case with the slab but no peripheral trench. The results are analyzed along three profiles (Figure 3): profile 1 in the direction of ground level loading (longitudinal direction), profile 2 in the transverse direction at ground level and corresponding to the edge of the slab, and profile 3 is a vertical profile in the plane of symmetry. The horizontal strains ε_{xx} and stresses σ_{xx} are considered as well as horizontal displacements U_x.

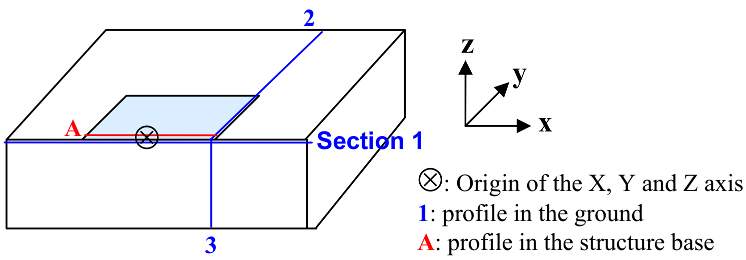

Fig. 3. Profiles localization used for the analysis

Figure 4a shows that, in the longitudinal direction, horizontal strains at ground surface are modified by the presence of the slab compared to the greenfield case. Without the peripheral trench, horizontal strains decrease under the edge of the structure and are greater than the strains in the greenfield case. With the trench, a drastic decrease of ε_{xx} is observed under the slab, in particular at its edge, and in the vicinity of the trench (on both sides of the trench). On the other hand, strain concentration is observed within the trench on each side of the building: ε_{xx} reaches average values of 4.3 % and 4.2 % respectively in the left and right trench (Fig.4a), i.e. 7 times the greenfield strain value.

Horizontal strain ε_{xx} determined along section A (along the slab) which coincides with section 1 but refers to the slab, are very small in both cases with or without trench (approximately 10^{-3} %) due to the axial stiffness of the slab and to the soil-slab interface that experiences slippage along most of its length. Nevertheless, the presence of the trench reduces the value of the maximum relative horizontal longitudinal displacement from 26.0 to 21.0 mm

To evaluate the efficiency of the trench, an average horizontal strain $\underline{\varepsilon}_{xx}$ can be determined on the part of section 1 limited by the left and right trenches (i.e. between x=-6 and x=6 m). With the trench, $\underline{\varepsilon}_{xx}$ = 0.41 % whereas without the trench, $\underline{\varepsilon}_{xx}$ = 0.56% (the effect of the slab can also be evaluated by comparing this latter value to the greenfield 0.6 % constant strain. The presence of the trench thus reduces the average strain by 27%.

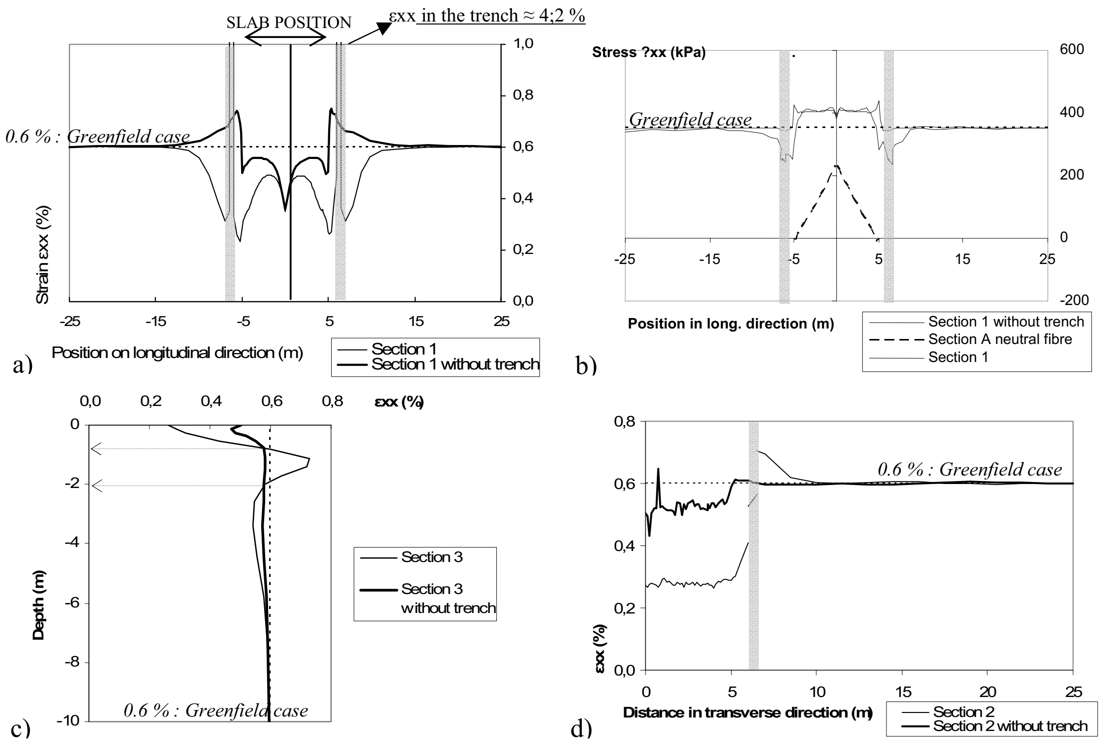

Fig. 4. Horizontal strain and stress profiles along sections 1, 2 and 3: greenfield case, without and with the trench (trenches appear as grayed areas)

Horizontal stress distribution σ_{xx} is also modified by the presence of the trench (Fig.4b): in particular a decrease of σ_{xx} is noticeable in the soil close to the trench. However, this decrease of stress from 351 kPa to 250 kPa is very local and in particular the stress distribution under the slab is quite similar with or without the peripheral trench. Under the slab, an average value $\underline{\sigma}_{xx}$ = 397 kPa is obtained whereas it is 408kPa without any mitigation measures. The horizontal stress transferred to the slab is smaller due to the slippage occurring at the soil-slab interface (Fig.4b).

In the transverse and vertical directions, strain profiles are also modified. For example, in section 2, horizontal strain is almost uniformly decreased under the slab (Fig.4d): $\underline{\varepsilon}_{xx}$ falls from 0.53 % without the trench to 0.28 % with the use of this mitigation measure. It is also noteworthy that the trench induces an increase of ε_{xx} on the outer boundary of the trench whereas without the trench, strains in this area are very close to the greenfield values. In a vertical direction (for example section 3, see Fig.4c), ε_{xx} is also reduced in the close vicinity of the structure's base (between 0 and 0.78 m below ground level). A corresponding sharp increase of ε_{xx} is observed between -0.78 m and -2.1 m. A clear effect of the trench can be noticed up to -6 m.

3 INFLUENCE OF THE TRENCH ON MECHANICAL PARAMETERS

3.1 Influence of cohesion c

In the reference case, the trench fill materia has cohesion c = 40 kPa. In this part, in order to analyze the effect of material strength, a cohesionless material is considered by introducing c = 0.01 kPa (for computational reasons). The resulting horizontal strains in sections 1 and 2 are reported in Figure 5. Only a slight change is observed, confirming that the trench material remains essentially in an elastic regime during loading (whereas this part of the ground surface would experience plastic behavior without the trench). ε_{xx} is 0.38 % compared with 0.41 % with c = 40 kPa and 0.56 % without the trench. The average strains in the trench are nevertheless more affected: 5.7% and 4.7% respectively in the left and right trench (compared to 4.3 and 4.2 %).

Considering horizontal stress variation along section 1, although σ_{xx} close to the trenches is reduced to 80 kPa, the influence of this reduction is only local. Horizontal stress below the slab retains almost constant values.

In the transverse and vertical directions, very slight differences are reported between the two cases of material cohesion (see for example Fig.5b).

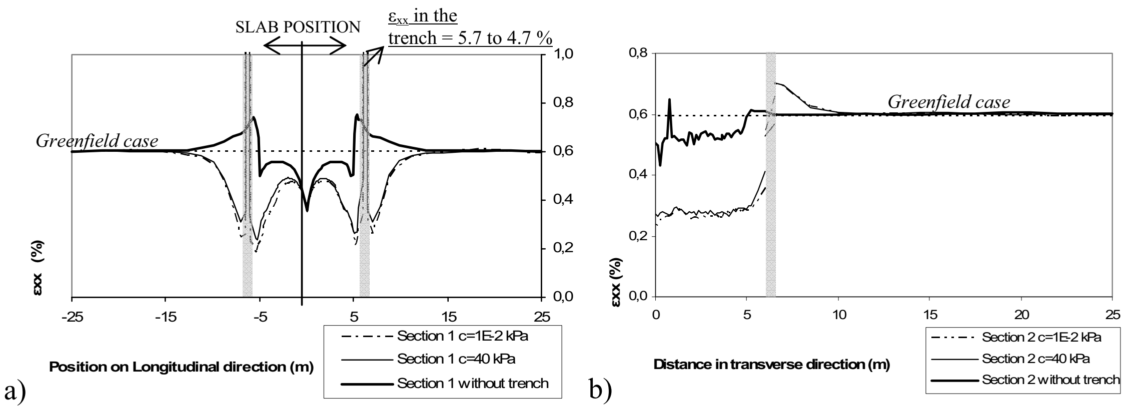

Fig. 5. Strain ε_{xx} in section 1 and 2 with different levels of cohesion *c (trenches appear in grayed areas)*

3.2 Influence of Young's modulus E

The influence of the stiffness of the trench filling material is analyzed by considering E = 10 MPa instead of 5 MPa in the reference case (note that 10 MPa is the value recommended by Auboué and Hayange PPRM), cohesion is kept constant at c=40 kPa.

It appears that the efficiency of the trench is directly related to the elastic modulus of the filling material: the average strain within the trench is reduced to 2.9 and 2.7% respectively in

the left and right trenches. In the meantime, the average horizontal strain ε_{xx} below the slab is equal to 0.46 %, thus representing 18 % of reduction compared to the case without trench.
The same phenomenon is observed along section 2, where the computed average horizontal strain is 0.35 % beneath the slab (compared to 0.27% in the reference case). The same conclusion can be drawn from the analysis of results in section 3 in the first layer of soil below the slab. The extent of this layer is slightly increased by the stiffening of Young's modulus (-0.95m instead of -0.78m). Between -0.95 m and - 2 m deep, the strain is still greater than the greenfield value but smaller than that computed for the reference case. Stresses σ_{xx} are not affected by the change in elastic modulus.

The results of this parametric study are summarized in Table 3. The case of an empty trench has also been analyzed. Trench efficiency is increased when its stiffness and strength are reduced (within the considered range of values). It also appears that for an empty trench, the efficiency of the surrounding trench is greater than for any combination of material properties considered , but in practice, the trench must be filled.

Table 3. Comparison of the efficiency of the filling material

	Empty trench		**c=40 kPa E=5 MPa**		**c=0.01 kPa E=5 MPa**		**c=40 kPa E=10 MPa**	
	Left Trench	**Right Trench**	**L**	**R**	**L**	**R**	**L**	**R**
Trench closure (cm)	**3.75**	**3.60**	**2.13**	**2.08**	**2.86**	**2.36**	**1.45**	**1.35**
Average strain within the trench (%)	**7.5**	**7.2**	**4.3**	**4.2**	**5.7**	**4.7**	**2.9**	**2.7**
Average ε_{xx} in section 1 between trenches (%)	**0.28**		**0.41**		**0.38**		**0.46**	
Reduction of ε_{xx} (x=-6 m and +6 m) due to the trench*	**50 %**		**27 %**		**32 %**		**18 %**	

*without any trench, the average ε_{xx} between the trenches is 0.56 %. ε_{xx} : horizontal strain L : left, R right

4 INFLUENCE OF THE GEOMETRICAL PARAMETERS OF THE TRENCH

4.1 Influence of distance D from trench to structure

In the reference case, the distance *D* between the trench and the structure is 1.0 m. To determine the influence of this distance on strain and stress distribution, the case of *D*=1.5 m is analyzed (all other parameters remaining constant, in particular *c*=40 kPa and *E*=5 MPa).

Along section 1, the average horizontal strain ε_{xx} between the trenches is 0.43%. Without the peripheral trench, ε_{xx} is slightly higher than that of the reference case at 0.57 % (the average is calculated between x=-6.5 and 6.5 m). Thus the presence of the trench is responsible for a 25% reduction in strain. The distance D does not therefore have a great impact on this reduction, even though in the reference case, this value was slightly higher (27%).

In the transverse direction (section 2), increasing the distance between the trench and the structure induces a noticeable increase in average strain, ε_{xx} increases from 0.28% with D=1m under the slab to 0.36 %.

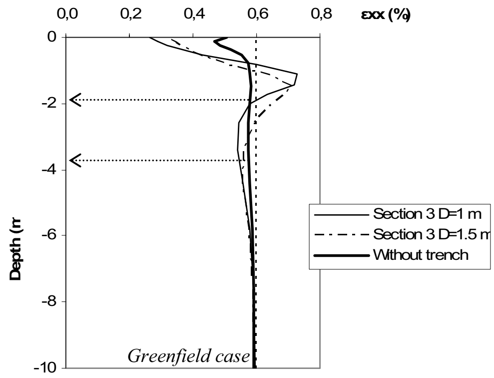

Fig.6. Effect of the distance D on the distribution of εxx in a vertical direction (section 3)

Finally in the vertical direction (section 3), it can be concluded from Figure 6 that an increase in D leads to a deepening of the zone where strains less than the greenfield values are experienced (from -0.78 m to -1 m) and also of the zone where higher values are observed (from -2 m to -2.8 m). In addition, in each of these zones the difference in strain between the greenfield case and the case without a trench is reduced.

4.2 Influence of the depth of the trench

Based on the geometry of the reference case, the depth of the trench is now decreased to H=0.5 m. It appears that the average horizontal strain $\underline{\varepsilon}_{xx}$, along section 1 between the trenches, is greater than that observed with a deeper trench (0.46 % compared to 0.41 % with H = 1.0 m and 0.56 % without the trench). In the transverse direction (Fig. 7), the horizontal strain under the slab is uniformly reduced compared to the deeper trench: ε_{xx} is approximately equal to 0.42% instead of 0.28% with H = 1.0 m. Along section 3, the influence of the trench is qualitatively the same as for deeper trenches but the thickness of the fringe of soil concerned by strain reduction is now reduced to 0.40 m instead of 0.78 m when H = 1 m.

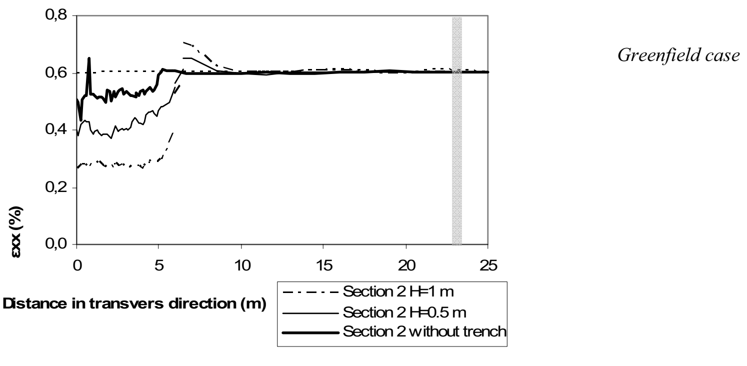

Fig.7. Effect of depth H on the distribution of ε_{xx} in the transverse direction

4.3 Influence of the width of the trench

All others parameters remaining identical to the reference case, when trench width W is increased from 0.5 m to 0.8 m, it is observed that the average strain $\underline{\varepsilon}_{xx}$ along section 1 between the trenches is reduced to 0.37 % compared to 0.41 % with W = 0.5 m and 0.56 % without the trench. Simultaneously, the average strain along section 2, below the slab, decreases from 0.28 % to 0.23 % and the thickness of the soil layer experiencing strain reduction below the slab increases to 0.9 m from 0.78 m.

The results of this parametric study are summarized in Table 4. The case of an empty trench with D = 1 m, H = 1 m and W = 0.5 m has also been analyzed. The efficiency of the trench is increased when its depth and width are increased and/or its distance from the structure reduced (within the considered range of values). It also appears that for an empty trench, the efficiency is greater than for any considered geometry of a trench filled with a material where E = 5 MPa.

Table 4. Comparison of the different trench configurations

	Empty trench		**D=1 m H=1 m W=0.5 m**		**D=1.5 m H=1 m W=0.5 m**		**D=1 m H=0.5 m W=0.5 m**		**D=1 m H=1 m W=0.8 m**	
	Left Trench	**Right Trench**	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**
Closure (cm)	**3.75**	**3.60**	**2.13**	**2.08**	**2.12**	**2.15**	**1.59**	**1.69**	**2.79**	**2.80**
Average strain within the trench (%)	**7.5**	**7.2**	**4.3**	**4.2**	**4.25**	**4.3**	**3.2**	**3.4**	**3.5**	**3.5**
Average ε_{xx} in section 1 between trenches (%)	**0.28**		**0.41**		**0.43**		**0.46**		**0.37**	
Reduction of ε_{xx} due to the trench*	**50 %**		**27 %**		**25%**		**18%**		**34%**	

*as a percentage of the average strain obtained without any trench (i.e. ε_{xx} between the trenches is 0.56% between -6 m and +6 m and 0.57% between -6.5 m and +6.5 m).

CONCLUSION

The main objective of this study is to analyse the efficiency of mitigation measures in the case of ground movement induced by the collapse of underground cavities. The peripheral trench was considered using simplified numerical modeling. The proposed 3D, numerical model, taking soil-structure interaction into account, is used to analyze the effect of a peripheral trench around buildings qualitatively and quantitatively, in order to reduce possible damage caused by ground movement (for example due to failure of underground cavities). Only compression horizontal strains have been studied. From these preliminary numerical results, it appears that the main effect of the trench is to reduce the horizontal strain transferred to the structure.

This parametric study focused on the impact of mechanical properties (both strength and stiffness) of the material used to fill the trench and the geometry of the trench, mainly its width, depth and distance from the structure.

It appears that most of the horizontal strain is absorbed by the trench and that its efficiency as a mitigation measure mainly depends on the stiffness of the material used to fill it. In that sense, maximum efficiency seems to be obtained for the limiting case of an empty trench, but in practice, the trench must be filled.

In addition, the efficiency is increased when the trench is wider, deeper and closer to the structure.

The main limitation of the proposed analysis is that it considers a plain slab as representing an entire structure. Only the total weight of a true structure was included. The actual stiffness and heterogeneity of the structure was neglected.

Further analysis will consider a more detailed model of a simple structure (with walls, roof and apertures) resting on shallow foundations (square or strip foundations) embedded in the soil (the depth of the trench being in that case based on the depth of the foundation).

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