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Excavation induced building damage

Evaluation du risque de dommage des bâtiments provoqué par des excavations

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ABSTRACT

Ground decompression is usually associated to underground excavation, generally leading to subsidence of the surface. Consequences of such movements on existing buildings must be evaluated especially in urban areas. In this paper a Building Risk Assessment (BRA) method of the type proposed by Burland is presented. Initially, surface movement induced by excavations is analysed. Possible consequences on neighbouring structures are then outlined using classifications of damages. Typical damage categories are related to serviceability parameters, past performance of buildings, namely, structural type and behaviour, and its position towards excavation works. Past performance and data behaviour of buildings are used to correct serviceability parameters in order to predict risk of damage. Protective measures for each risk category are established. The method for risk assessment is then presented and exemplified. The paper concludes with a discussion on its usefulness and consequences on monitoring activities and plans.

RÉSUMÉ

La décompression est un phénomène associé à l'exécution d'ouvrages en souterrain, conduisant en général au développement de bassins de subsidence à la surface du terrain. Les conséquences de ces mouvements sur les bâtiments, surtout en milieu urbain, devront être analysées. On présente dans cette communication une méthode d'Evaluation du Risque de Dommage sur Bâtiments du type proposé par Burland. D'abord, on analyse les mouvements de surface induits par les excavations. Eventuelles conséquences sur les structures environnantes sont alors abordées sur la base des classifications de dommage. Les catégories typiques de dommage sont associées aux paramètres d'utilization, à la performance précédente des bâtiments, notamment le type et le comportement structural, et à leur position par rapport aux travaux d'excavation. Les données sur la performance antérieure et le comportement des bâtiments sont utilisées pour la correction des paramètres d'utilization en vue de prédire le risque de dommage. Des mesures de protection de chaque catégorie de risque sont établies. Par la suite on présente et exemplifie la méthode d'évaluation de risque. Finalement, on aborde la question de l'utilité et les conséquences sur les activités d'observation et d'auscultation.

1 INTRODUCTION

Excavation induced building damage might be assessed in a systematic way by means of a sequential approach based on a method proposed by Burland (Burland and Wroth, 1974). Hereafter we present the main analytical background (items 2 and 3) of such method, followed by a detailed presentation of the phases in which it can be divided (item 4). A brief description of two examples illustrates the proposed approach (item 5).

2 EXCAVATION INDUCED SETTLEMENT

The first phase of BRA is the calculation of both vertical and horizontal ground displacements. These subsidence profiles depend on the excavation type and must be assessed at foundation elevations of the building under analysis. The complexity of the structural behaviour of tunnel excavations makes it difficult to predict subsidence profiles with simple methods. It is therefore current that such predictions are done by specific numerical analyses, that must take into account namely the construction sequence and the soil-structure interaction. It is however possible, for excavations with relatively simple shapes, to use empirical simplified methods for the prediction of induced displacements. Such methods being of significant practical interest, they are hereafter presented for the cases of tunnel and between vertical walls excavations.

The method for estimation of soil-induced displacements due to tunnel excavation is based on the empirical model proposed by Schmidt and Peck (1969), which validity is widely confirmed by scientific and relevant literature. An exponential law gives the settlement profile with a maximum at the vertical of the tunnel. The adopted curve is:

$$S(y) = S\max e^{\left(\frac{-y^2}{2i^2}\right)} \quad (1)$$

where: y – horizontal distance measured from the tunnel axis; S(y) – ground vertical displacement; Smax – maximum ground vertical displacement; i – inflexion point abscissa.

For the horizontal displacement (Sh), the adopted curve is:

$$Sh(y) = \frac{y}{H - z} S(y) \quad (2)$$

where: H – tunnel axis depth; z – foundation level depth.

For the case of excavations between vertical walls induced ground subsidence depends on the walls deformation modes. According to Hsieh and Ou (1998) there are two possible types of subsidence profiles: i) When the wall behaves mainly as a cantilever, i.e., with maximum horizontal displacements at the top, settlement is given by a parabolic law, the maximum adjacent to the wall – spandrel curve; ii) When the wall behaves mainly as a beam, i.e., with maximum horizontal displacements at the span, settlement is given by an exponential law such as the one presented for tunnels, the maximum displacement occurring at a distance from the wall – concave curve.

For the selection of the curve type the criterion proposed by Hsieh and Ou (1998) is adopted. Once the curve type is chosen settlement quantification must be done. For the spandrel curve the equation proposed by Bowles (1990) is adopted:

$$S(y) = S\max\left(\frac{D - y}{D}\right)^2 \quad (3)$$

where D is the subsidence area length in the direction perpendicular to the wall. For the horizontal displacement the following law is assumed:

$$Sh(y) = \frac{Sh\max}{S\max} S(y) \tag{4}$$

For the concave curve case the method proposed by Hsieh and Ou (1998) is adopted:

$$S(y) = S\max\, e^{\frac{-\left(y - \frac{He}{2}\right)^2}{2 i^2}} \tag{5}$$

where, He is the elevation difference between the building foundations and the excavation bottom. Horizontal displacement is given by equation (4).

3 MOVEMENTS AND EFFECTS ON BUILDINGS

3.1 *Definition of foundation movements*

The approach of damages to buildings requires the establishment of parameters able to describe thoroughly and consistently eventual movements and deformations of foundations (Burland and Wroth, 1974). Fig. 1 presents the parameters initially proposed by Burland to describe the overall movements of the foundation considering a plane state.

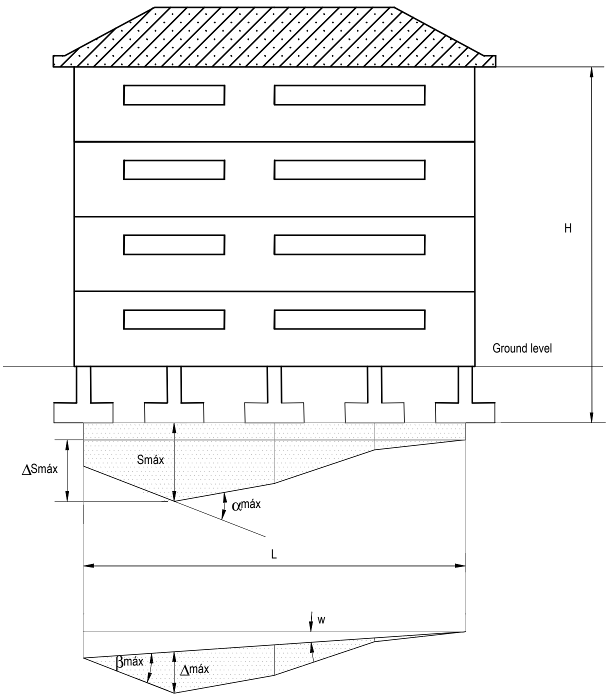

Figure 1. Symbology adopted for movements at the foundation level (Burland, 1997)

Thus the following symbology is adopted (Fig. 1): S - settlement; ΔS - relative settlement; w - tilt; α - angular strain; Δ - relative deflection; Δ/L - deflection ratio; β - angular distortion, the maximum value of the respective (i.e., ΔS_{max} – maximum relative settlement) corresponding to "max".

When the subsidence curves are known and the buildings are characterized it is possible to assess the risk itself. This assessment consists of the estimation of a number of control parameters, that are compared with limit values to which established risk categories are associated. The risk category to be applied depends on the characteristics of the building under analysis. Two alternatives are placed:

- Burland Classification (Burland et al., 1977) – applicable to structures in granite masonry or brickwork and to reinforced concrete structures founded on strip foundations. This classification is also suitable to reinforced concrete structures founded on pile groups.

- Rankin (1988) Classification – applicable to reinforced concrete structures founded on isolated footings or single piles.

Rankin classification uses as control parameters (Fig. 1) the maximum angular distortion undergone by the building (β_{max}) and the maximum settlement (S_{max}). These parameters can be calculated only when the structural typology is rigorously known, namely the location and the depth of footings. Burland classification uses as control parameter the maximum tensile strain (ε_{max}) induced to the building by the under laying ground displacement. This parameter (ε_{max}) depends mainly on the maximum deflection ratio ($[\Delta/L]_{max}$).

The methods used for the calculation of the control parameters (β_{max} and S_{max} or ε_{max}) are based on two fundamental assumptions: i) the building is treated as an ideal linear elastic beam with length L and height H (Fig. 1); ii) this beam adapts perfectly to the ground settlement profile, i.e., there are no relative displacements between the foundations and the ground.

These assumptions lead to conservative results as the ground/structure interaction, that tends to attenuate the movements undergone by the buildings, is disregarded.

3.2 *Maximum tensile strain*

When applying Burland's Classification it is necessary to calculate the maximum tensile strain (ε_{max}) induced in the building. The method of analysis of ε_{max} is that presented by Burland and Wroth (1974).

For each section under analysis and taking into account the corresponding ground deformation, the maximum deflection ratio Δ_i/L_i will be estimated between each pair of the reference points of the straight segment line L. The reference points define the zones to analyse and are placed at the ends and at the eventual inflexion points of the settlements curve (Fig. 2). In general when length L covers an inflexion point of the settlements curve, a part of the building will be under tension (L_T – zone 1) and another will be under compression (L_C – zone 2). Should the building be located in a zone submitted to the influence of more than one excavation, the respective effects will overlap.

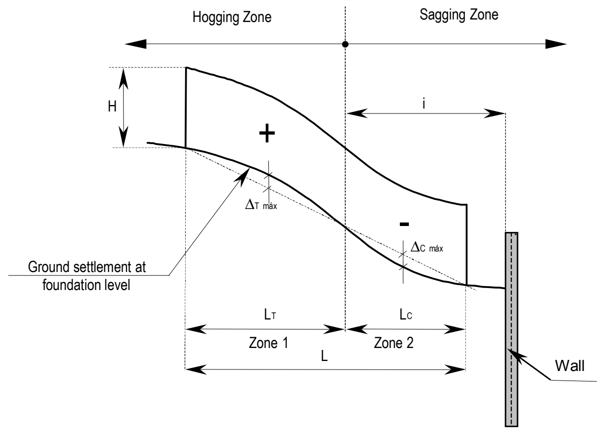

Figure 2. Building deformations induced by the subsidence profile

3.3 *Maximum settlement and angular distortion*

When applying Rankin Classification, the control parameters (Fig. 1) used are β_{max} and S_{max}. The calculation of these parameters is done through simple geometric considerations as shown in Fig. 1, and it can only be performed upon thorough knowledge of the detailed location of the foundation slabs.

4 ASSESSMENT OF RISK OF DAMAGE TO BUILDINGS

4.1 *Buildings vulnerability*

Building damages are usually classified in three large categories (Burland, 1997): i) *aesthetic damages*; ii) *serviceability damages* and, iii) *stability damages*. The definition of this classification takes into account not only the type of damage but also the nature of works necessary to remedy the situation.

Burland and Rankin's risk classifications assume that buildings are in good maintenance state, i.e., no damage affected them before the execution of excavations. As a matter of fact, all buildings are subject to deformations, at least to those resulting from foundation settlements induced by self-weight and by the service loads. Thus, the deformations eventually created by the execution of the underground excavation represent additional deformations to existing ones. In the event of previous high deformations, a small increase originated by the excavation may produce drastic effects that are not proportional to its size and that are not expressed in the risk classifications. Therefore, it seems appropriate to quantify the previous condition of the buildings under analysis. This quantification is subjective and it is essentially empiric. One of the ways to do it is through the *Vulnerability Index* (Geodata, 2000), which is intended to be an intrinsic characteristic of the building (maintenance state, damages recorded, etc., however independent from external factors that contribute to the ground movements). The Vulnerability Index (I_V) expresses the way in which the building under analysis is far from the ideal maintenance condition, i.e., its vulnerability. The greater is the building vulnerability the lesser is its capacity to support deformation induced by external factors. Based on the vulnerability index it is possible to correct the damage risk classifications (Geodata, 2000). Geodata's suggestion to quantify the vulnerability index consists of an empirical processing of data collected during the survey of the buildings condition. Relevant characteristics to determine the buildings sensibility to eventual settlements are: i) structural characteristics (type of structure, nature of eventual rehabilitation actions and number of underground storeys); ii) serviceability characteristics (typology of the building functional uses); iii) aesthetics characteristics (patrimonial typology; nature of the interior walls and exterior linings); iv) maintenance characteristics (judgement on the overall conservation state of the building, signs of eventual settlements and pattern of eventual cracks) and; v) characterisation of the building orientation and position towards the excavation works. A numeric value and a weight factor are ascribed to each one of these characteristics. The value of I_V is the sum of the factored numeric values and ranges between 0 and 100.

4.2 *Risk classifications correction to account for vulnerability*

Based on the value of I_V the limit control parameters of the original risk classifications are corrected. This correction is made by dividing the original limit control parameters by a factor ($F_R > 1$), which depends on the I_V value.

The purpose of these corrections is to explicitly quantify that in the risk classifications the same deformation induced at the foundation level causes more serious damages to a more vulnerable building (high I_V) than to a lesser vulnerable building (low I_V). Thus, in terms of risk classification, this leads to the fact that, on equal terms, the risk factor ascribed to a more vulnerable building (high I_V) is higher than that ascribed to a less vulnerable building (low I_V).

4.3 *Assessment of risk of damage to buildings*

The above risk classifications can be used to establish a method for the assessment of risk of damage to buildings due to excavation. The proposed method (Burland, 1997) consists of the determination of the risk category of each building neighbouring the excavation. It must be noted that, in both classifications, up to category 2, the damages are of aesthetic nature, that is, the structural integrity is not jeopardized and the damages can be easily and economically repaired. Thus, in both classifications, the limit between categories 2 and 3 is of the utmost importance as, in the excavation design and construction, one of the goals is to maintain the risk level of buildings below this limit.

Given the high number of buildings to analyse, the method for BRA proposed by Burland (1997) includes the following phases:

i) Phase 1 – *Preliminary analysis*;
ii) Phase 2 – *Risk assessment*;
iii) Phase 3 – *Detailed risk assessment*.

Phase 1 – *Preliminary analysis* – in order to reduce the number of risk analyses to a minimum, a simplified and conservative method is adopted, that makes the distinction between the buildings subject to significant movements from those subject to insignificant movements. For this purpose isolines of the total settlement (S) and angular distortion (β) are drawn, which are obtained by the methods described in 2, or using the available design calculations. As per Rankin (1988) a building subject to an angular distortion β below 1/500 and to a total settlement S below 10 mm presents a negligible risk of undergoing damage. If as conservative limits are adopted, for example, values $S = 5$ mm and $\beta = 1/750$, the most serious combinations of those two isolines allows to limit an area, called the control strip, in which there is damage risk. This way it will be possible to clearly distinguish two zones: one susceptible of being affected by the excavations ($S > 5$ mm; $\beta > 1/750$) and another where damage risk to buildings (outside the control strip) is not significant, therefore not requiring an explicit risk assessment in the next phase of studies. It must be noted that this is a conservative approach, as it considers surface movements and not building foundation movements and the soil/structure interaction is disregarded.

This way, from the preliminary analysis, the buildings needing an explicit risk assessment are identified. Phase 2 – *Risk assessment* is conducted according to the above assumptions and methods (3). Based on the structural characteristics of the buildings located in the control strip (structure and foundation typology), risk assessment is conducted according to Burland or Rankin classification, as the application fields may be. In this phase the control parameters are calculated at the building foundation elevations. As a result of the BRA, a risk category is obtained for each building inside the control strip. Although this result is much more worked out it is still very conservative. As a matter of fact, in most of practical cases, the damages actually identified are much lesser serious than those pertaining to the risk categories obtained. This is due to the design assumptions (item 3.1).

Thus, a *Detailed risk assessment* (Phase 3) of all buildings whose risk category obtained in Phase 2 is equal or above 3 has to be made. In this third phase the control parameters calculations obtained in Phase 2 shall be refined with the introduction of the detailed characteristics of the building under analysis and of the excavation method. The way of improving the calculation varies from case to case. Often, in this phase, sensitivity analyses based on design assumptions variations (ground properties, construction method, etc.) are made in order to identify their influence on the risk level. In the case of important buildings (historic or aesthetic heritage, for example) specific numerical analyses may be deemed necessary in order to explicit the influence of the excavation sequence and methods, the ground/structure interaction, the buildings orientation, and others. On the other hand, in this case, the buildings maintenance state has to be taken into account. The building may have experienced damages prior to the excavation works, and these reduce its tolerance to subsequent movements. Clearly, often one cannot rigorously consider most of the factors influencing the results of the analysis intended to be improved, and, for this reason, the final risk category always requires a subjective reasoning.

4.4 *Actions to undertake according to the risk of damage*

Once BRA has the purpose of predicting the type of damages undergone by buildings as a result of the excavations, a direct consequence is the definition of the measures to be applied during construction to the buildings whose situation such requires.

Firstly, buildings pertaining to risk categories 0 to 1 do not require any type of preventive measures. For buildings included in risk categories above 1 the measures that can be anticipated belong to three major types: i) strengthening of monitoring; other eventual measures shall be proposed in the construction phase (risk categories equal or above 2); ii) repair and/or strengthening works (risk categories equal or above 3); iii) modification of the solution adopted for the excavation execution (risk categories equal or above 3).

In any case, the results of the BRA should be considered to establish alert levels for the observation system as they allow to correlate the evolution of the monitored parameters during the works with the associated level of risk. This fact allows to analyse in anticipation worse evolution scenarios, and, immediately, to recommend countermeasures, to be followed in the event those scenarios are confirmed during the execution of works. It is, thus, of the utmost usefulness to update the risk assessment according to the observation system results during works, allowing at all times the adoption of remedial actions.

5 EXAMPLES OF RISK ASSESSMENT

The application of the above described risk assessment method is illustrated through the presentation of two examples, that only show the type of calculations to be made in Phase 2 (buildings inside the control strip). Although these examples are virtual, they correspond to adaptations of some calculations undertaken for the risk assessment of buildings, affected by the construction of an underground station in a European city (Figs. 3 to 6).

GROUND SETTLEMENT (S) AND HORIZONTAL DISPLACEMENT (Sh)

$S_{máx}$ = 0.016012 m   ν = 0.30

i = 3.000   Iv = 78

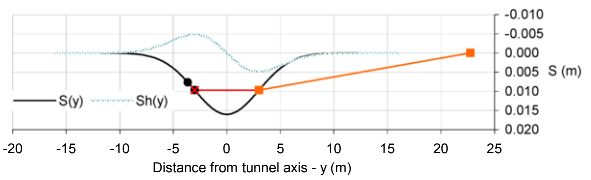

Figure 3. Ground movements due to tunnel - building 1

STRAIN EVALUATION

Zone	1	2	3	
L	0.650	6.00	19.75	
Δ	0.00001	-0.00630	0.00681	
Δ/L	0.00181%	-0.10500%	0.03447%	hogging (+)
ε_h	0.03218%	-0.16186%	0.02459%	sagging (-)
	Hogging	Sagging	Hogging	
I	914.67	228.67	914.67	
ε_b	0.00006%	0.06612%	0.03317%	
ε_d	0.00181%	0.10028%	0.03057%	
$\varepsilon_{b,t}$	0.0322%	-0.0957%	0.0578%	
$\varepsilon_{d,t}$	0.03225%	0.08870%	0.04310%	
$\varepsilon_{máx}$	0.0323%	0.0887%	0.0578%	

ε_{lim} = **0.089%**

F_R = 1.75

$\varepsilon_{lim,cor}$ = **0.155%**

Category of damage: **3**   **- Aesthetic/Serviceability**

Type of damage: **Moderate**

Figure 4. Damage classification for building 1 (tunnel)

The first example (Figs. 3 and 4) deals with a building (H = 14 m; L = 26.4 m) affected by the construction of a 6 m diameter tunnel. The foundation level is some 2 m (z = 2 m) deep. The building presents a structure in stone masonry load-bearing walls, founded on continuous footings. The corresponding I_V has been evaluated by the method proposed by Geodata (2000).

The second example concerns a building of the same type (H = 20 m; L = 14 m) neighbouring a 6 m wide excavation and with an I_V equal to 49 (Figs. 5 and 6). The excavation depth to the foundation level is about 7.5 m (He = 7.5 m).

GROUND SETTLEMENT (S) AND HORIZONTAL DISPLACEMENT (Sh)

Ac = 0.03 m^2

Type: **Concave**

$S_{h,máx}$ = 0.005 m

$S_{máx}$ = 0.004 m

i = 3.185

ν = 0.30

Iv = 49

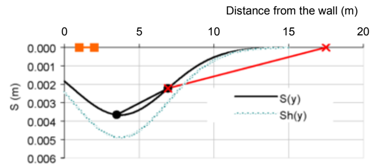

Figure 5. Ground movements due to diaphragm wall - building 2

STRAIN EVALUATION

Zone	1	2	3	
L	3.435	10.57	NE	
Δ	-0.00036	0.00109	NE	
Δ/L	-0.01062%	0.01036%	NE	hogging (+)
ε_h	0.05558%	0.02807%	NE	sagging (-)
	Sagging	Hogging	NE	
I	666.67	2666.67	NE	
ε_b	0.00278%	0.00414%	NE	
ε_d	0.01054%	0.01018%	NE	
$\varepsilon_{b,t}$	0.0584%	0.0322%	NE	
$\varepsilon_{d,t}$	0.05708%	0.03072%	NE	
$\varepsilon_{máx}$	0.0584%	0.0322%	NE	

ε_{lim} = **0.058%**

F_R = 1.50

$\varepsilon_{lim,cor}$ = **0.088%**

Category of damage: **2**   **- Aesthetic**

Type of damage: **Slight**

Figure 6. Damage classification for building 2 (diaphragm wall)

6 CONCLUSIONS

A systematic and simplified method, for the assessment of risk of damage to buildings affected by the construction of neighbouring excavations, is established. Its major result is the explicit identification of cases where the risk of damage is higher, providing an important help in the decision about the preventive, selective and appropriate actions to be applied to each one of the affected structures. A first approach to this result can be obtained during the design phase, with double advantages: on the one hand, all involved staff will draw their attention to the potential problematic areas and, on the other hand, monitoring systems can be set up in those areas.

In addition, the results of risk assessment can/should be used to establish alert limits for the observation systems, as they enable to correlate the evolution of the monitored parameters during the works with the associated level of risk. This way it is possible to analyse in anticipation the worse evolution scenarios and to recommend countermeasures to be followed, in the event those scenarios are confirmed during the execution of works.

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