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SAFETY ASSESSMENT OF LINEAR STRUCTURES IN AREAS AT RISK OF LARGE MINING DEFORMITIES

1. Introduction

By joining the numerical analysis of such complex issues as the evaluation of structures cooperation with the subsoil exposed to the influence of mining deformation in conditions where the top layer of the subsoil was subjected to strengthening treatment, which modifies its structure (Fig. 1 — Protections in the hazard area influenced by the discontinuous deformation), the question must be asked:

"How reliably can we create a numerical description of reality, consistent with the expected or observed in situ behavior?"

Fig. 1. Protections in the hazard area of the A1 motorway influenced by the discontinuous deformation (Bytom Bobrek, 2011, own photos)

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The threat to the safety of structure on the mining area generally follows the displacements and strains of the substrate forced by the mining exploitation. This threat is also connected with the possibility of restarting the process of building subsidence caused by the change of soil state, as well as with locally emerging phenomenon to mobilize the maximum shear stress in the soil. Examples of loss of serviceability limit state by the structure and a threat to the safety situation are shown in figure 2.

Fig. 2. The loss serviceability characteristics of a structure with the threat to safety state (Bytom Bobrek, 2011, own photos)

With the growth of mining ground deformation- in a particular the formation phase on the surface of the mining basin — the relaxation state of the ground and reduction in the value of horizontal stress σ_h are observed. Reliable reconstruction of the mining subsoil behavior in the calculation model must combine description of the changes in state of stress with changes of volume. Using the critical state model — Modified Cam-Clay (MCC) — allows for representing a change of the ground state in the subsoil due to mining deformation as transition process of a ground from the preconsolidated state (OC) to the state of normal consolidation (NC).

Safety assessments of the system ‘building vs. ground’ results from the evaluation process of formation and areas range of changes in the ground state and local changes in stiffness of the subsoil [3, 4]. The paper presents, based on a constitutive model describing the behavior of soil Modified Cam-Clay (MCC), the following:

- transmission mechanism of mining deformation from substrate to linear structure which cooperates with a layer (or layers) protecting its failure-free work, while proposing
- how to create description of protection layers behavior in a critical state model (MCC).

2. Numerical response of the ground constitutive models to load paths — estimation of the critical value ε_x

Using a numerical model for assessing the safety of the building structure (B) cooperating with the mining subsoil (P_g) requires certain rigors of modeling, including:

1) very important (for the evaluation of subsystems cooperation) condition of the suitable numerical field representing the ground subsystem [2, 4],
2) implementation of the appropriate kinematic boundary conditions at the subsystem (P_g),
3) acceptance of the constitutive relations which allow reliable reproduction of the studied phenomenon.

The numerical analyses, field (P_g) must be treated as a subfield of the extensive mining area (G), in which exploitation activities are carried on.

Such activity generates deformations of the rock mass, top layers of the ground and deformations of terrain surface — determined factors for building needs are: ground horizontal strain ε_x, curvature radius R of ground surface and its inclination T.

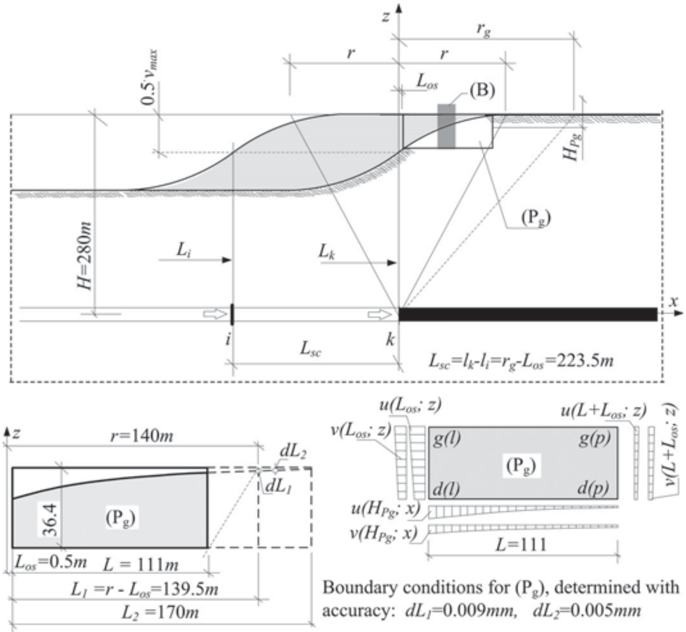

Fig. 3. Development of the subfield (P_g) deformation during relocation of the exploitation front

Separation of the subfield (P_g) from the mining field (G) requires determination of adequate boundary conditions. For example it can determine by the simplified method shown in figure 3 consistent with the Budryk-Knothe theory. Transition of the exploitation front in the interval form "*I*" to "*K*" (Fig. 3) causes the development of the deformation state in the field (P_g), which can be described by the displacement boundary conditions $\{u,v\}$; such approach does not consider changes of the ground state occurring during the subsoil deformation.

The choice of the relevant constitutive model for the subsoil representing the field (P_g), is the next step of the discussed analysis. As the basic engineering criterion of evaluation of ground behavior is to consider the Coulomb-Mohr criterion. Knowledge possessed from the experimental investigation and in situ tests show the real complexity of stress-strain relations.

Namely, if at some point of the subsoil, with the proper state of stress, the pure state of deviatoric flow is formed then volumetric strain at the same time leans towards a critical, stabilizing value. Formation of such state is very probable in analyzed problems.

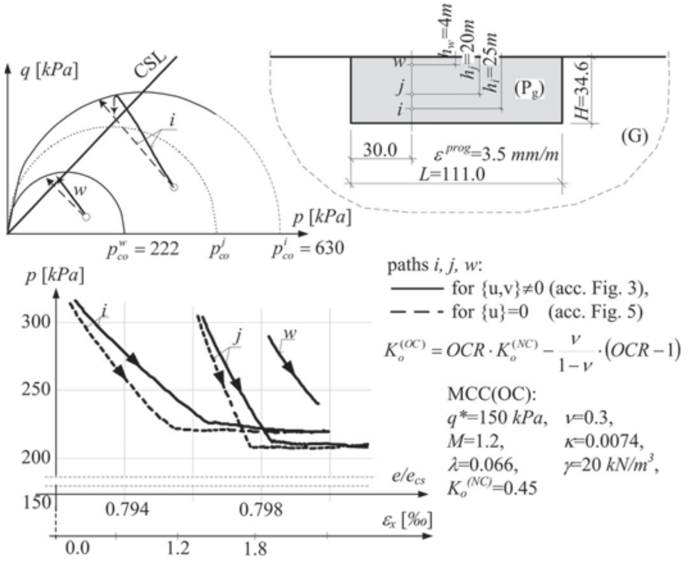

Fig. 4. Stress and strains paths in the field (P_g) described by the MCC (OC) model

In the models of critical state, coupling of ground strength assessment because of stresses together with registration of changes in volumetric strains in the space (p, q, e), state of stress invariants (p, q) and the axis changes of porosity coefficient (e) is recognized.

This property has been used in realized investigations. Initial figure 4 shows the essence of the description of ground behavior in the field (P_g) with application of the MCC model. For the boundary conditions implemented incrementally (determined for the stopped exploitation front at the point „*J*" — according to Fig. 3) stress paths are determined for assigned points *i*, *j*, *k* of cross-section α–α.

For continuous paths representing the actual state of stress, accompanying the full boundary conditions ($\{u,v\} \neq 0$), the background as discontinuous paths are made out. These paths accompany pure ground relaxation.

The discontinuous paths were developed during forced uniform deformations ($\{u\} \neq 0$) in the field (P_g), which generate specified values of strain ε_x. Such values correspond to maximum value of strains formed in the investigated field (P_g) together with real boundary conditions.

During the deformation process, the change of the original state of stress in the subsoil is recognized. Investigated paths seen during the implementation of successive increments of deformation ($\{u,v\} \neq 0$ for continuous lines, $\{u\} \neq 0$ for discontinuous lines) tend to the state of pure deviatoric flow — Fig. 4.

Note that discontinues paths, corresponding to a relaxation state, run in a fixed manner in relation to the continuous paths for the full boundary conditions. The average stress at a given point can thus be expressed with satisfactory accuracy as a function of the forced deformations: $p = f(\varepsilon_x)$ — Fig. 4b. This confirms the phenomenon observed in the behavior of mining subsoil – a dominant influence of horizontal stresses to changes in average stresses values [6]. This phenomenon is used in the presented work for the safety assessment of linear structures.

In the investigated system, the state of forced deformation ε_x was used in order to evaluate areas at risk of weakening the material at the change of initial stress state — see turns of paths in Figure 4.

It can be stated that, the running in such a manner of analysis of changes of initial stresses (in situ, or in situ plus the state which results from loading of structure) gives the safe evaluation for limiting the investigated states "from the top".

Based on above, let us assume the following course of interpretation:

— knowing value of forecasted strain ε_x in the area of mining activity, we would like to evaluate what part of caused deformation will be transformed on the linear structure or on the protection installed under such structure, simultaneously,
— to ensure the safety (stability) of a system linear structure — subsoil, we do not allow to create at the top layer (of ground or protection under the structure) any tensile stresses $\{\sigma_x\}$.

Let us compare the results of some of the analyses. Figure 5 shows the behavior of two different kinds of loose subsoil (P_g) with known histories of load, shaping their geological profile: 1) subsoil which is recognized as homogeneous (Fig. 5a), 2) subsoil with weak top layer (Fig. 5b). Profiles Ko are given; these profiles characterize the ground preconsolidation state in Upper Silesia region.

During incrementally the forced displacements of boundaries the following was observed — strain values $\varepsilon_x = \varepsilon_0$ which cause a decrease of initial horizontal stresses at the top layer of subsoil to a value close to zero ($\varepsilon_x \approx \varepsilon_0$); and the layer was called the 'critical layer' (CL).

We observe the forming of the limit state in subsoil during the strain values ε_x increase up to the forecasted value ε_x^{prog}.

The 'critical layer' is created at the certain value ε_x ($\varepsilon_x = \varepsilon_0$), in which every point of layer is representing the ground behavior under the state boundary surface in the critical state models. To ensure the safety (stability) of a system linear structure — mining subsoil for a given forecasted value of ε_x^{prog}, the following should be satisfied:

$$\varepsilon_x \leq \varepsilon_x^{prog} \leq \varepsilon_0 \tag{1}$$

3. Parametric evaluation of the protective layer. Summary

Let us now introduce a controlled protective top layer forming correct, failure-free work of a linear structure.

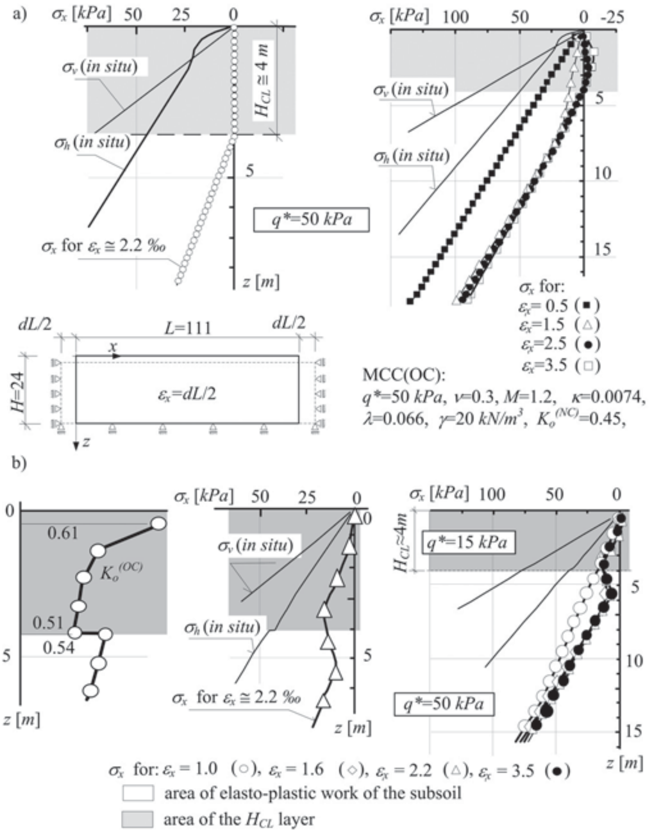

Fig. 5. Formation of a 'critical layer' in the subsoil a) homogeneous (q^* = 50 kPa), b) with weak layer (q^* = 15 kPa)

The evaluation of equivalent parameters of the protective layer — formed from one or two layers of geo-mattresses, in which dense aggregates cooperate with geo-grids with suitable characteristics σ–ε — is based on the proposed description of composite work in the model MCC (OC); Figure 6 and equations (2) and (3).

Let us write the initial stress state in the protective, composite layer analogous to the condition prevailing in preconsolidated subsoil, but by introducing a two-component horizontal stress, depending on: 1) the degree of compaction of aggregate, and 2) stress state in initially strained geo-grids.

$$\sigma_v = h \cdot \gamma^{agg} \tag{2}$$

$$\sigma_h = \sigma_v \cdot K_o^{CL} = \left(\sigma_v \cdot K_o^{agg} + \sigma_h^S\right) \tag{3}$$

To determine the equivalent value of the coefficient of lateral pressure — K_o^{CL} the following must be defined:

1) K_o^{agg} — coefficient of lateral pressure in compacted layers of aggregate, taken in the analysis as: $K_o^{agg} = 0{,}8$,
2) σ_h^s – equivalent stress of strained geo-grids, averaged over the height of the previously designated 'critical layer' ($H = H_{CL}$); assuming in the analysis value (constant at the height of the layer), determined according to interpretation given in Figure 6a.

To evaluate the value σ_h^s may be use for example inequality (4). It requires evaluating shear force T in contact subsoil — protective layer according to [5].

$$\frac{\sigma_h^S + (\sigma_h^S + \sigma_v \cdot K_o^{agg})}{2} \cdot H_{CL} \geq T \tag{4}$$

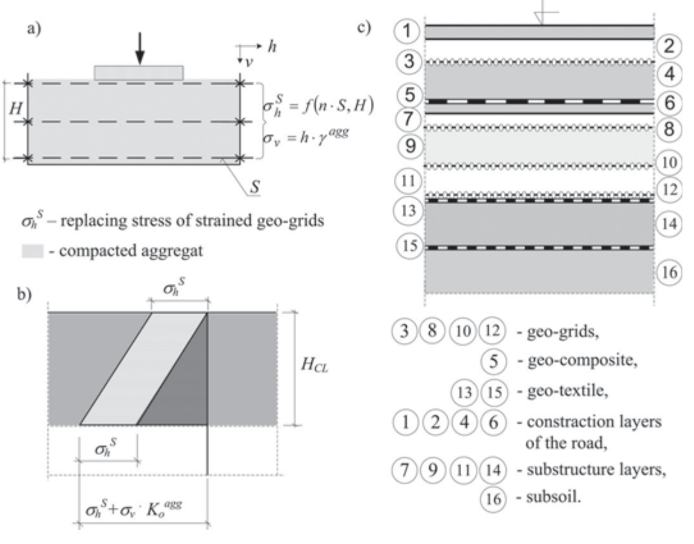

Fig. 6. a) b) Drawing interpretation of the work of 'composite' layer which protects a linear construction, c) road-protection for IV category of mining deformations [1]

Figure 6b presents the real road-protection for the IV category of mining deformations based on engineering experience [1].

Figure 7 shows the "philosophy" of analyses and the obtained results.

Appropriate for the protected structure state of stresses and strains was obtained for the subsoil (with determined preconsolidation) and for the protective layer (with parameters given in Fig. 7), by fulfilling the equation (1) with the critical strain $\varepsilon_x = \varepsilon_0 = 2{,}2$ ‰.

It is a condition accompanied by stress state, neglecting tension in the material of the protective layer (with the reserve of stresses provided for grids "strapping").

In the MCC model, such phenomenon is "interpreted" by the initial state of stress, in which horizontal stresses in the preconsolidated ground (or in the compacted and horizontally prestressed protective layer) are responsible for subsidence state of loaded structure.

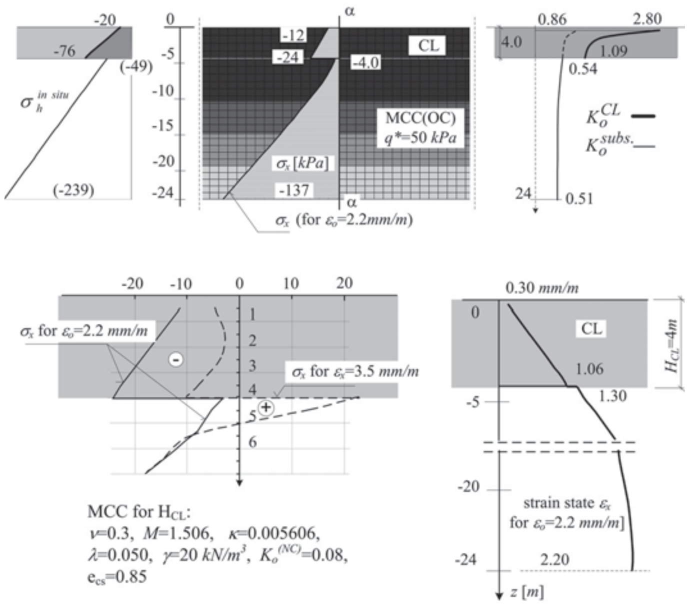

Fig. 7. Results of the test for subsoil with protective layer against the effects of mining deformations

An important conclusion is that:

— the thickness (H_{CL}) of critical layer (in which we do not allow tensioning) is determined due to preconsolidation state of the subsoil, and not by the state (stiffness) of the top layer, and that,

— the predicted strain state of protective layer in the model (Fig. 7) does not provide any hazard for the work of the linear structure.

For the effective use of critical state models in a global behavior evaluation of systems (B)-(P_g), it would be required to include laboratory tests (and even better, the in situ tests) in the assessment of the "elements" forming dependence (4).

Acknowledgements

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