AGH Journal of Mining and Geoengineering • Vol. 36 • No. 1 • 2012

*Lucyna Florkowska *, Jan Walaszczyk **, Agnieszka Maj **

DETERMINING MECHANICAL PROPERTIES AND MATERIAL MODELS OF SUBSOIL FOR BUILDINGS IN MINING AREAS

1. Introduction

Preventing mining damage buildings can sustain, entails above all determining correctly interactions in the soil (and consequently the load-bearing structure) caused by exploitation. Processes involved in deposit mining cause damage to a rock mass's structure around the excavation and cause deformation of surface layers. Under Polish conditions, underground mines are located almost exclusively in areas, where exploration has taken place for many years. Mining history of the Upper Silesian Coal Basin region dates back as far as 160 years. It comes as no surprise, than that rock mass's structure in those areas has been significantly affected. Repeatable mining influences leave their mark on mechanical properties of soil. Therefore it is important, not only to factor in at the stage of designing a building the direct impact of planned excavation, but also properties of soil have to correctly evaluated.

Investigation of geologic and geotechnical conditions of foundations should draw based on geological works[1] in case of mining areas. Applicable requirements are stipulated by relevant regulation and standards [16, 17, 19–25]. The impact of planned exploration work on surface and land development is normally determined over the course of forecasting mining influences [10, 11, 18]. In most cases, the so called *basic forecast* is sufficient for construction calculations.

* Polish Academy of Science, Strata Mechanics Research Institute, Kraków.
** Polish Academy of Science, Strata Mechanics Research Institute, Kraków; AGH University of Science and Technology, Faculty of Mining and Geoengineering, Kraków.

1 **Geological work** means the designing and conducting of investigations aimed at identification of the geology of the country, in particular prospecting for and exploration of mineral deposits and groundwater deposits, determination of geological-engineering conditions (own expression) and preparation of geological maps and documentation as well as designing and carrying out research for the purposes of the Earth heat exploitation or groundwater abstraction (the Act Geological and Mining Law, Journal of Laws from 9 June 2011, No. 163, item 981)

However, unconventional structures (either in terms of construction, geotechnics and intended use) require preparing a *detailed forecast* of mining influences. Optimum for this kind of analysis seems the ever-more popular numerical modelling. Employing such a tool involves designing and delivering a programme of field and laboratory research, which would consequently enable obtaining reliable data, demanded to an elaborate mathematical model of a given problem. Any material model of the subsoil, should be based on results of geologic-engineering investigation.

2. Mining deformation processes occurring in rock mass and on surface

Underground coal mining triggers multiple processes in rock mass. Most evident are decay and deformation processes of rock massif. The cavity left behind mining exploitation in the rock mass, disturb the natural geostatic equilibrium [12]. Some areas around excavation undergo relaxation, whereas other experience concentration of stress. The structure of superstratum cracks and decays thus causing blocks and fragments of rock to break off, which then fill the post-exploitation cavity. The excavation becomes filled to the brim with loose rock material (sometime additionally caulked), which is not strong enough a support for overlaying bed. Those layers are exposed to heavy deformations, causing crevices and cracks to appear. As distance from the excavation increases, those deformations become less intense and show continuous characteristics. On the surface, in general, a so called post-exploitation basin (mining basin) forms. If rock mass already affected by mining is again excaved for mineral deposits, the impact of new mining works overlaps with previous damage and deformation of rock structures [2].

Surface rock mass provides a base for buildings. They are normally composed of soil displaying viscoplastic behaviour. Depending on where mining panel's contour is relative to analysed area, the soil layers are either subject to evolving over time variable strains or they can remain in the permanent deformations zone (e.g. above the edges of mining panels). Subjecting soil to repeatable strain, interchangeably tensile and compressing, or leaving them in the permanent deformations zones, does influence its properties. Especially, because the additional aspect of mining influences is the alteration of the groundwater level, equally potent to changes in properties of the soil. In marginal cases the subsoil's structure can become significantly affected, causing irregular and discontinuous strains. These effects occur in areas considerably affected by mining and not only do they pose a serious threat to the nearby buildings, but also damage infrastructure — particularly underground networks and systems infrastructure.

3. Forecasting impact of mining exploitation on the surface and on buildings

Forecasting the impact of exploitation on surface and buildings is fundamental in preventing mining damage. Otherwise i.e. without knowing the magnitude and time-space distribution of mining influences, it is not possible to evaluate reliably the potential threat of mining induced events.

Preventative measures are two-faceted in this case. On one hand exploration work has to be designed to limit negative effects for the surface and buildings — so called *mining prevention* [10]. On the other hand, the bearing capacity of structures has to be verified as any protection designed to assure buildings to withstand mining influences — the so called *building prevention* [10].

Under Polish conditions, the forecasting the impact of underground mining on the surface is usually based on the Budryk-Knothe theory and definitions of related so called *deformation indexes* [7, 8]. Three deformation indexes: slope, radius of curvature and horizontal strain give grounds to attribute a given area with the so called *mining area category*. Those categories describe the probability of an area being in danger of surface deformations [18,10]. Experts distinguish three types of methods forecasting mining exploitation influences: approximate, basic and detailed [18]. They are normally prepared based on need and capabilities (i.e. availability of materials and documentation, a means to conduct given research). *Approximated forecast* is the most simple, as it gives expected subsidence and category of mining area. This forecast is sufficient only either when elaborating a more accurate one is not possible or it is intended for preliminary engineering works [18]. Usually, to design building the *basic forecast* is entirely sufficient. Such forecast should feature the following: maximum surface subsidence, maximum slope, minimum and maximum horizontal strains, minimum and maximum curvatures and time the deformations occurred as well as information about mining and geological situation in the region where the structure is planned [18]. In the case of special-purpose structures or large structures with unconventional load-bearing structure, *detailed forecast* of mining influences should be carried out. Its scope is established on an individual basis. Such a forecast is customised for a specific geological, mining and constructional situation of a structure. In order to factor it in, adequate data should be gathered. That data is prepared based on documentation, and completed field and laboratory research. Numerical modelling is a well-suited tool enabling such forecasting. Numerical simulation based on reliable data enables to determine optimum time-space distribution, strains and displacements caused by impact of planned exploitation [3].

As previously emphasised, such analysis has to be carried out using reliable data. An important element of analysed issue's mathematical model is material models, selected for particular subsoil and constructional members. Correctly conducted geologic-engineering investigation and a properly designed programme of laboratory experiments enable mechanical properties of subsoil to be determined, material model selected and its parameters identified.

4. Requirements towards investigating subsoil of structures located in mining areas

Determining geotechnical conditions of founding a building[2] is required for every construction project (Art. 34 p. 3.4 of the Act *Building Law* Journal of Laws from 7 July 1994,

2 Determination of geotechnical foundation conditions is understood as a set of activities undertaken to establish the usability of grounds for construction, involving especially field and laboratory work. (Regulation issued by the Minister of Internal Affairs and Administration from 24 September 1998 concerning determination of geotechnical conditions of founding buildings — Journal of Laws, No. 126, item 839).

No. 89, item 414) [19]. In case of buildings founded on areas affected by mining exploitation, this issue gains ground, because:

1) mining influences in form of deposit excavation induced subsoil deformation, are severe-load to the load-bearing structure;
2) in the areas repeatedly affected by mining influences structure of rock mass is changed as are properties of the subsoil.

According to regulation issued by the Minister of Infrastructure from 3 July 2003 *concerning detailed scope and form of construction projects* (Journal of Laws, No. 120, item 1133), the descriptive part of development project for a given building plot or area should include i.a. "data determining impact of mining exploitation on the building plot or area intended for construction, located within mining area (§ 8.6). Chapter 4 of that regulation stipulates clearly, that the technical description, part of architectural and building project, should specify i.a. "*geotechnical category of building, conditions and method of founding it and protection against mining exploitation influences*" (§ 11.3) [23]. Rules for determining geotechnical conditions are in turn given by the regulation issued by the Minister of Internal Affairs and Administration from 24 September 1998 *concerning determination of geotechnical conditions of founding buildings* (Journal of Laws, No. 126, item 839). According to that regulation, within the area of mining damage the so called *complicated foundation conditions occur*[3] (§ 5.3.3), thus qualifying an area as category three — the most unfavourable geotechnical category [24]. A similar definition is given by the Polish standard PN–B/02479 *Geotechnic. Geotechnical documenting. General rules.* Areas affected by mining damage have complicated foundation conditions and are attributed the III geotechnical category [21]. Also *Eurocode 7 Geotechnical design* specifies three geotechnical categories. Areas with long-term ground movement are listed as category III [17].

For III geotechnical category structures, required apart from geotechnical documentation is geologic-engineering documentation, whose scope is stipulated predominantly by: the Act *Mining and Geologic law* from 9 June 2011 (Journal of Laws, No. 163, item 981) and *Regulation issued by the Environment minister from 23 December 2011 concerning hydrogeological documentation and geologic-engineering documentation* (Journal of Laws, No. 291, item 16 988). Geologic-engineering documentation is based on geologic works which are subject to regulation provided by the Act *Geological and Mining Law (Part V: Geologic works)*. Art. 79 of the above-mentioned Act stipulates that "*Geological works involving geological operations may be carried out exclusively on the basis of a geological work programme*". Such a project is subject to the approval of an applicable body of geologic administration[4]. Having acquired a positive decision, it is necessary to file information about intending to commence field work, at least 14 days prior. Then, drawn up on basis of

3 **Complicated ground conditions** — occur when strata affected by negative geologic phenomena, especially landforms and phenomena related to karst, landslide, suffosion, and glacitectonism in areas of mining damage (own expression), with possible discontinuous rock mass deformation and in central areas of river deltas. (Regulation issued by the Minister of Internal Affairs and Administration from 24 September 1998 concerning determination of geotechnical conditions of founding buildings — Journal of Laws, No. 126, item 839).

4 "County administrators as the geological administration authorities of first instance is responsible for approving geologic works programmes and geological documentation concerning: (...) geologic-engineering research carried

completed works geologic-engineering documentation requires approval, which in turn becomes legally binding after subsequent two weeks [20]. Thus the completion date becomes considerably deferred in time due to required geologic-engineering documentation and the duration of legal procedures.

5. Subsoil investigation methods

The first stage of investigating foundation soil involves the gathering of information on geologic conditions within a given area. That data provides basic information on expected type of soil, structure of layers, level of groundwater or any possible tectonic faults. Geologic information about location for planned structure can also reveal any potential geotechnical problems. If the analysed structure is situated within a mining area, or area at risk of other type ground movement, it is important to gather detailed data on forecasted surface deformation and history of rock mass movement in that region. PN–B–02479. *Geotechnic. Geotechnical documenting. General rules*. specifies that archives used for drawing up geotechnical documentation should include i.a.:

- reference, master and detailed geologic maps of Poland,
- physiographic documentation,
- geological documentation and geotechnical documentation,
- archival exploration boreholes,
- data on initial level of groundwater.

The scope of geotechnical research for III geotechnical category should, according to the above-mentioned standard comprise "*apart from observation, open pits, exploration boreholes, static and dynamic probing, test loads (...) hydraulic conductivity testing, geophysical research (radar, electric resistance, seismic, gravimetric) and other types of tests as needed. It is advised, that both the scope and method of laboratory experiments on soil and water samples were strictly aimed at resolving issues concerning given project*". During the research, exact interactions which will occur during structure's life have to be reproduced, as consequently geotechnical parameters required for the design process can be determined [21]. Principles for designing works and investigations for individual geotechnical categories are enclosed in the above-mentioned *PN–B–02479 and Eurocode 7 PN–EN 1997-1 Geotechnical design. Part 1: General rules and PN–EN 1997-2 Geotechnical design. Part 2: Ground investigation and testing* [1]. According to the definition provided by the Act *Geological and Mining* "*a geological operation means carrying out, within the framework of geological works, any activities below the surface*" [20]. Hence, a great majority of research conducted as part of geotechnical investigation is in fact geologic works and in practice to a considerable extent they can overlap with tests carried out for purposes of creating geologic-engineering documentation [9]. Consequently, in order to correctly investigate soil, especially in

out for land development purposes of municipality and foundation conditions for buildings" (Art. 161 p.2.3 of Act Geological and Mining Law from 7 July 1994 - Journal of Laws, No. 89, item 981).

case of foundations located within mining areas, expert knowledge is indisposable, which allows one to evaluate the necessary scope of field research and design a programme of required laboratory tests. The analysis of results produced by those efforts, gives grounds to reliably determine mechanical parameters of soil. It would also provide the basis for selecting an applicable constitutive equation and determining its parameters in case a numerical model was to be developed for purposes of detailed forecast of mining influences.

6. Examples of selecting constitutive law and determining its parameters

Investigation of the subsoil leads to formulation of a material model, part of mathematical models representing holistically the interaction between foundations and the subsoil. Formulation of a material model in this case means assuming form of equations describing behaviour of either soil or rock under specific set of conditions and determining values of those equations' parameters [6]. This process has been illustrated with examples below. These examples were sourced from analyses carried out for purposes of determining impact of mining exploitation on buildings [3, 4].

6.1. Determining material model of sandstone

Sample sandstone subjected to analysis was taken from an exploration borehole drilled to investigate the subsoil of structure exposed to mining exploitation. In discussed case, the sandstone bed was encountered already at the depth of 6 m beneath the surface. Samples taken during an exploration borehole drilling were tested in laboratory experiments including: uniaxial and triaxial compression.

Based on results of uniaxial compression, mechanical parameters of the sandstone were determined: elastic modulus E, Poisson's ratio v and uniaxial compressive strength R_c [5, 14]. Results of three experiments of uniaxial compression have been presented in figure 1. Depicted charts show relation between axial stress (normal to surface parallel to sample's base in the direction of load axis) and axial strain (linear in the direction of generatrix and radius of sample's base). Results are clearly spread, which is characteristic for tests investigating geologic materials. Those discrepancies come primarily from natural material diversity and disturb material structure, caused by the process of extracting samples.

The results produced enabled determining basic material parameters within the elastic limit behaviour to material i.e. until the Hook's law applies. The elastic limit, plastic behaviour and failure point were determined on basis of triaxial compression experiments, carried out at different confining pressures. Figure 2 illustrates the relation between the Mises equivalent stress q and linear strain across the piston's axis ε_3.

Figure 3 illustrates the relation between the Mises equivalent stress q and volumetric strain ε_{vol} allowing to determine threshold of relative dilatancy, specific threshold of relative dilatancy and increase the volume. Compactional and dilational changes in volume have also been shown

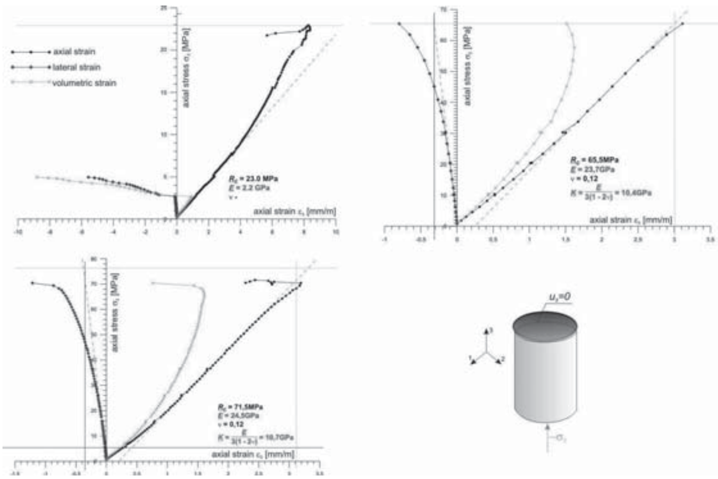

Fig. 1. Experiments results of uniaxial compression of sandstone

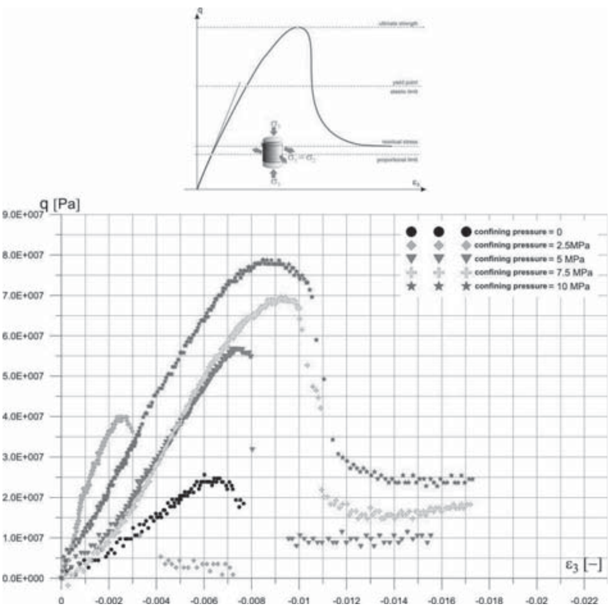

Fig. 2. Experiments results of triaxial compression of sandstone. The relation between the Mises equivalent stress *q* and linear strain in the direction of the piston's axis ε_3

in chart depicting the relation between volumetric strain ε_{vol} and axial strain ε_3 (Fig. 4). A segment of the plot reveals an increase in volume caused by failure processes of material structure.

It was assumed, that the inelastic behaviour of the discussed sandstone would be described using the Drucker-Prager model [13,3]. The model is formulated using yield surface in the stress space variables are invariants associated with state of stress: the equivalent pressure stress *p* and Mises equivalent stress *q*. Traces of material behaviour in the meridional *p*–*q*

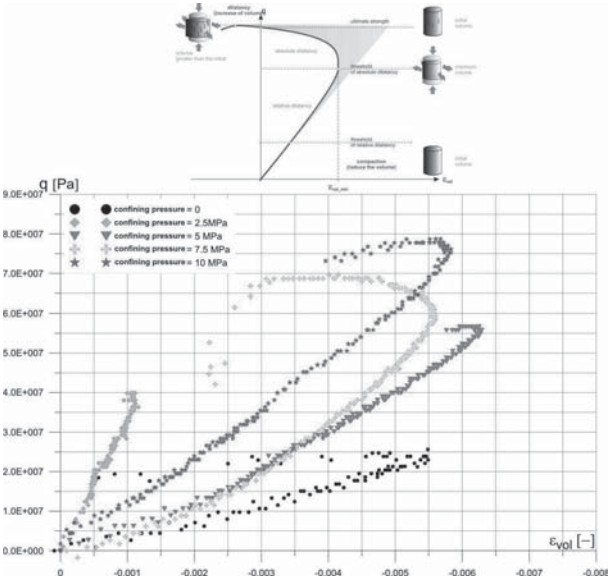

Fig. 3. The relation between Mises equivalent stress q and volumetric strain ε_{vol}

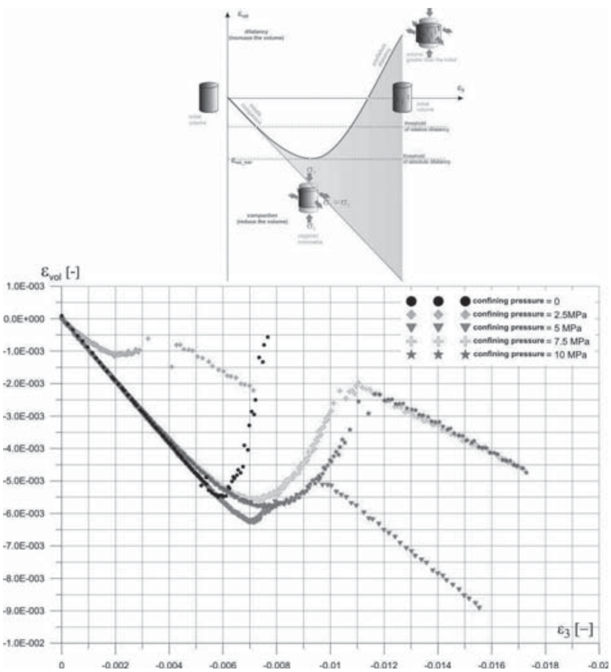

Fig. 4. The relation between volumetric strain ε_{vol}
and axis strain ε_3 for different confining pressures

invariants plane have been illustrated in figure 5. Determined based on those traces material's failure surface has been shown in figure 6.

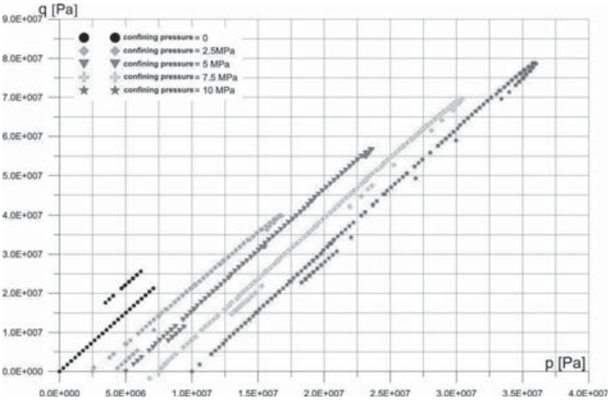

Fig. 5. The relation between Mises equivalent stress *q* and equivalent pressure stress *p*

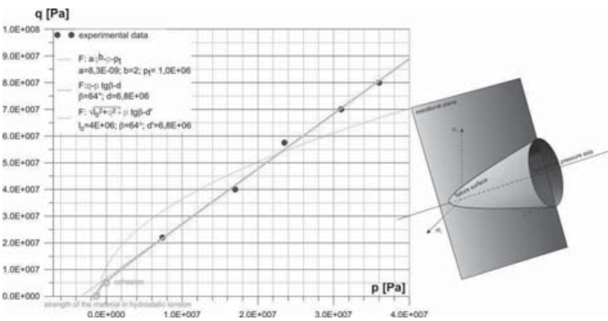

Fig. 6. Failure surface of the sandstone's in the meridional plane

From among three Drucker-Prager model forms, the one best describing investigated material was the hyperbolic form, where the plane section of the yield surface *F* in the *p*–*q* plane is given by the equation:

$$F\colon \sqrt{l_0^2 + q^2} - p \cdot tg\beta - d \tag{1}$$

Parameters of that equation are:

— angle of friction β (determined value $\beta = 64°$),

— cohesion *d* (determined value *d* = 6,8 MPa),

— $l_0 = d\big|_0 - p_t\big|_0 \cdot tg\beta$ (where: $d|_0$ — is initial cohesion, $p_t|_0$ is initial hydrostatic tensile strength); determined value l_0 = 4 MPa

The plastic flow law was formulated based on the uniaxial compression experiment. The parameter *d´* then becomes the parameter of plastic hardening/softening.

$$d' = \sqrt{l_0^2 + \sigma_3^2} - tg\beta \cdot \frac{\sigma_3}{3} \tag{2}$$

Plastic flow potential L has hyperbolic cross-section on the p–q plane:

$$L = \sqrt{(z \cdot \bar{\sigma}|_0 \cdot tg\psi)^2 + q^2} - tg\psi \cdot p \tag{3}$$

$$L: -\frac{p^2}{(z \cdot \bar{\sigma}|_0)^2} + \frac{q^2}{(z \cdot \bar{\sigma}|_0 \cdot tg\psi)^2} = 1 \tag{4}$$

where:

ψ — is the dilation angle measured across the p–q plane at the highest confining pressure (angle between hyperbola's asymptote and the p axis

$\bar{\sigma}|_0$ — stress corresponding to the beginning of the plasticising process (yield point); the initial yield stress;

z — is a parameter that defines the rate at which the function approaches the asymptote (the flow potential tends to a straight line as the eccentricity tends to zero).

In deviatoric plane the flow potential surface resembles in shape the Mises circle. The model was assumed with the associated plastic flow law.

6.2. Determining material model of sandy loam

Sandy loam was the foundation soil directly beneath the multi-family residential. It ran at a depth of 1.5–3.2 m and created two layers different in soil moisture (*mw* and *w*) and state (*tpl* and *pl*). Samples of soil were taken during drilling exploration boreholes, which then were tested in laboratory. Back at the laboratory, experiments involving triaxial compression were carried out for three different confining pressures. The boundary of Mohr's circle designating the material's failure surface was inscribed, taking account of principal stresses calculated for the moment of failure (Fig. 7) [14, 15].

Based on tests results it was assumed, that description of ground's plastic behaviour would be best given by the Mohr–Coulomb model. That model's parameters were determined as:

— angle of friction β = 26°,
— cohesion d = 0,75 kPa.

The model was assumed with the associated plastic flow law.

7. Impact analysis of basic mechanical parameters of subsoil on stress distribution beneath a wall footing

The discussed methods of formulating a material model of soil and rocks, and determining parameters of assumed constitutive equation are all used in the analysis of the structure — subsoil interaction. Correctly assumed constituting laws for the subsoil are crucial from perspective of determining the state of ground beneath given structure's foundations.

Specimen Details		
Specimen Reference	Effective Minor Principal Stress (σ_3')	Effective Major Principal Stress (σ_1')
A	42.3kPa	109.2kPa
B	65.6kPa	170.3kPa
C	100.8kPa	264.8kPa

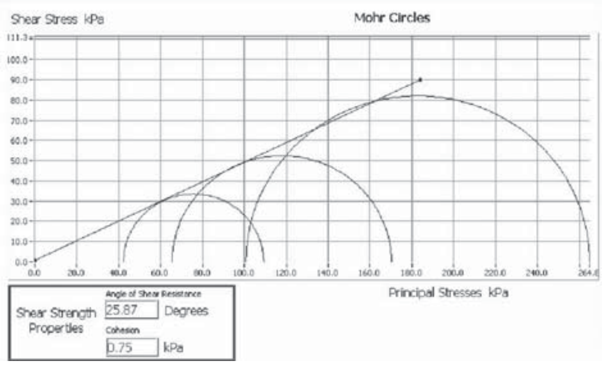

Fig. 7. Determining envelope of Mohr's circles for sandy loam based on triaxial compression experiments

A series of numerical experiments were carried out in order to illustrate the impact of material parameters on a calculated state of stress in the subsoil beneath a wall footing. During those experiments, modulus of elasticity E and Poisson's ratio v were altered while the form of material model remained constant. The elastic behavior of of the subsoil was described using Hook's law, whereas past the yield point — the Mohr-Coulomb model, which assumed an angle of friction $\beta = 36°$, cohesion $d = 1$ kPa and dilation angle $\psi = 30°$. The components of state of stress beneath the wall footing were calculated. The footing's horizontal width was 1.2 m. Calculations were done for plane state of strain. Simulation outcomes have been illustrated in Figure 8.

Results analysis leads to the conclusion, that a change in E and v parameters causes substantial differences in distribution and values of stresses calculated for the ground beneath the base of foundations. Particularly susceptible to change in the modulus of elasticity – for the assumed material properties — was normal stress in the horizontal direction (σ_{11}). Relatively low susceptibility to changes in Poisson's ratio was notable for normal stress in the vertical direction (σ_{22}).

8. Summary

This paper presented the issue of selecting a material model of subsoil, part of a numerical model describing the subsoil - structure interaction, which is normally developed to prepare a detailed forecast of impact of mining exploitation on a structure. The paper discussed primarily geologic-engineering investigation of soil and forecasting impact of planned mining work on a land surface.

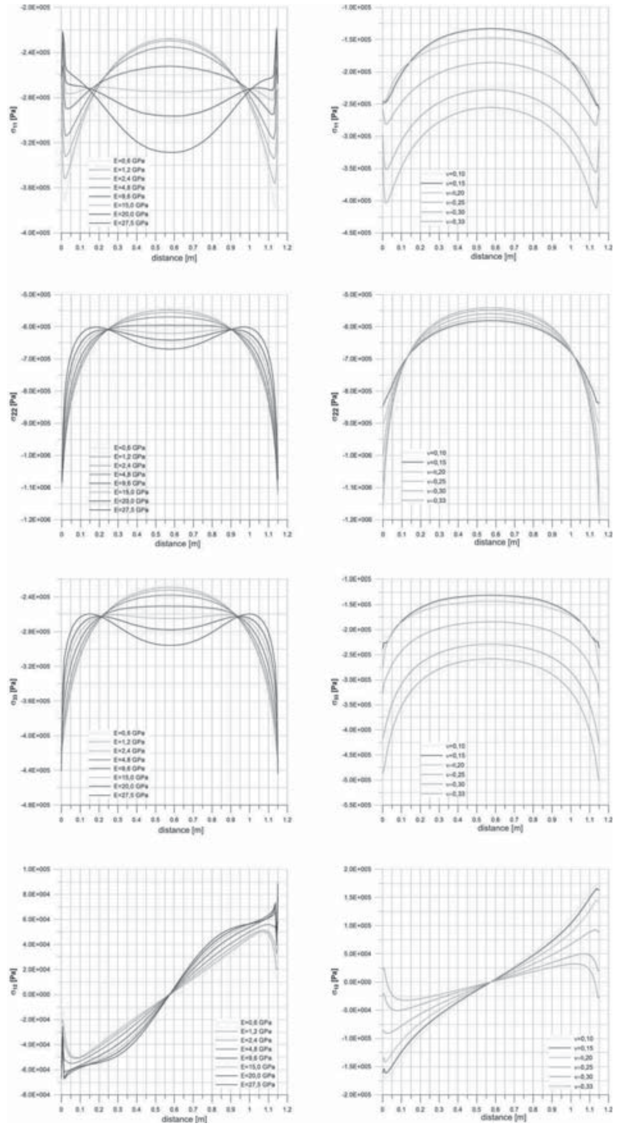

Fig. 8. Impact of change in material properties *E* and *v* on state of stress beneath wall footing. Numerical experiments were carried out for plane state of strain

In the light of current regulations, every building located in mining areas has complicated subsoil conditions, thus consequently is classified as third geotechnical category. This translates into the obligation to draw up a geologic-engineering documentation for a given structure, which requires a broader scope of geologic investigation. In practice, those requirements are usually ignored, due to high cost of drawing up such documentation and ensuing dilation of design process (geologic works require a project approved by applicable body of geologic administration). In the case of small, typical structures, such intentional negligence goes unnoticeable, however, a lack of proper geologic-engineering investigation in case of substantial investments e.g. buildings with complex load-bearing structures or buildings of particular importance, such a practice may have serious consequences. They require detailed forecasting of mining influences on their structure. As it has been proved, that numerical modelling is a perfect tool for those analyses. It enables factoring into calculations many factors, and in conjunction with field research and laboratory tests it becomes a tool allowing one to determine the impact of mining exploitation on the entire structure whilst keeping track of all conditions individual for a concrete case.

The process of numerically modelling impact of mining exploitation on a structure involves developing a material model of subsoil. In order for such model to best represent and describe reality, it is necessary to conduct research investigating the mechanical properties of geologic materials composing the subsoil. The samples taken during drilling exploration boreholes were tested in a laboratory. Analysis of results yielded by a completed research programme enables assuming correct for given material mathematical model and determines its parameters. Examples of selecting constitutive equations for rock and soil were also discussed in this paper.

Preventing mining damage buildings can sustain geotechnical issues, owing to the fact that surface deformations are the major threat to bearing capacity of a building and comfort of its residents. To correctly determine mining influences is a tall order requiring adequate knowledge, both in design engineering and geologic-engineering as well as about processes related to mining exploitation.

REFERENCES

[1] Bagińska I.: *Rozpoznanie i badanie podłoża gruntowego metodami polowymi w ujęciu Eurokodu 7* [Field Methods of Investigating and Testing Subsoil from Perspective of Eurocode 7]. Górnictwo i Geoinżynieria. [Mining and Geoengineering]. 2009, R. 33, z. 1, p. 39–46.

[2] Florkowska L.: *Land subsidence due to Mining Operations in Disturbed Rock Mass, on the Example of Ruda Śląska (Poland).* Archives of Mining Sciences. Volume 55. Kraków 2010. p. 691–701.

[3] Florkowska L.: *Zastosowanie numerycznej mechaniki nieliniowej w zagadnieniach ochrony budynków na terenach górniczych* [Non-linear Numerical Mechanics in Issues of Protecting Buildings Located in Mining Areas]. Archives of Mining Sciences. Monografia. Nr 11. Kraków, 2010.

[4] Florkowska L., Walaszczyk J., Cygan J., Maj A.: *Dobór i kalibracja praw konstytutywnych dla podłoża obiektów budowlanych* [Selection and Calibration of Constituting Laws for Subsoil]. Prace IMG PAN. [Transactions of the Strata Mechanics Research Institute]. Kraków 2011 (in press).

[5] Gustkiewicz J., Nowakowski A.: *Deformacje i pękanie skał w warunkach laboratoryjnych* [Deformation and Cracking of Rock under Laboratory Conditions]. Archives of Mining Sciences. Vol. 49 spec.

[6] Izbicki R., Łydżba D.: *Podstawy teoretyczne w geotechnice* [Theoretical Foundations of Geotechnical Engineering]. Inżynieria Morska i Geotechnika [Hydraulic Engineering and Geotechnical Engineering]. 2004, nr 1, p. 28–37.

[7] Knothe S. (A): *Równanie profilu ostatecznie wykształconej niecki osiadania* [Equation of Subsiding trough's Curvature]. Archiwum Górnictwa i Hutnictwa [Archives of Mining and Metallurgy Sciences] Tom 1, Zeszyt 1, 1953.

[8] Knothe S. (B): *Wpływ czasu na kształtowanie się niecki osiadania* [Time Influence on Formation of a Subsidence Through]. Archiwum Górnictwa i Hutnictwa [Archives of Mining and Metallurgy Sciences]. Tom 1, Zeszyt 1, 1953, p. 128–139.

[9] Koszela J., Koszela-Marek E.: *Engineering Geology and Geotechnics in Civil Engineering.* Studia Geotechnica et Mechanica. 2009, vol. 31, nr 4, p. 17–23.

[10] Kwiatek J. (red.): *Ochrona obiektów budowlanych na terenach górniczych* [Protection of Buildings in Mining Areas]. Wydawnictwo GIG. 1997.

[11] Popiołek E.: *Ochrona terenów górniczych* [Protection of Mining Areas]. Kraków. Wyd. AGH. 2009.

[12] Sałustowicz A.: *Mechanika górotworu. Górnictwo tom III: Mechanika Górotworu, Część I*, [Mechanics of Rock Mass]. Stalinogród, Wydawnictwo Górniczo–Hutnicze, 1955.

[13] *Theory Manual.* ABAQUS by Karlsson & Sorensen, Inc. Hibbitt (1998).

[14] Thiel K.: *Mechanika skał w inżynierii wodnej* [Rock Mechanics in Hydraulic Engineering]. PWN. Warszawa 1980.

[15] Wiłun Z.: *Mechanika gruntów i gruntoznawstwo drogowe* [Soil Mechanics and Soil Science of Roads]. Wydawnictwa Komunikacji i Łączności. Warszawa 1969.

[16] Eurokod PN-EN 1990: *Podstawy projektowania konstrukcji* [Eurocode PN-EN 1990: Basis of structural design].

[17] Eurokod 7 PN-EN 1997-1: *Projektowanie geotechniczne. Zasady ogólne* [Eurocode 7 PN-EN 1997-1: Geotechnical design General rules].

[18] Instrukcja ITB nr 416/2006: *Projektowanie budynków na terenach górniczych*. ITB, Warszawa 2006 [ITB manual No. 416/2006: Desinging buildings in mining areas ITB, Warsaw 2006].

[19] Ustawa z dnia 7 lipca 1994 r. *Prawo budowlane* (Dz.U. nr 89, poz. 414) [Act from 7 July 1994 Act Building Law (Journal of Laws, No. 89, item 414)].

[20] Ustawa z dnia 9 czerwca 2011 r. *Prawo geologiczne i górnicze* (Dz.U. nr 163, poz. 981) [Act from 9 June 2011 Geological and Mining Law (Journal of Laws, No. 163, item 981)].

[21] PN-B-02479:1998: *Geotechnika. Dokumentowanie geotechniczne. Zasady ogólne* [PN-B-02479: 1998 Geotechnic. Geotechnical documenting. General rules].

[22] Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. *w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie* (Dz.U. nr 75, poz. 690 z późn. zm.) [Regulation issued by the Minister of Infrastructure from 12 April 2002 concerning technical requirements, with which buildings and their location should comply (Journal of Laws, No. 75, item 690 and further amendments)].

[23] Rozporządzenie Ministra Infrastruktury z dnia 3 lipca 2003 *w sprawie szczegółowego zakresu i formy projektu budowlanego* (Dz.U. nr 120 poz. 1133) [Regulation issued by the Minister of Infrastructure from 3 July 2003 concerning detailed scope and form of construction projects (Journal of Laws, No. 120, item 1133)].

[24] Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 24 września 1998 r. *w sprawie ustalania geotechnicznych warunków posadowienia obiektów budowlanych* (Dz.U. nr 126, poz. 839) [Regulation of Minister of Internal Affairs and Administration from 24 September 1998 concerning determination of geotechnical conditions of founding buildings (Journal of Laws, No. 126, item 839)].

[25] Rozporządzenie Ministra Środowiska z dnia 23 grudnia 2011 r. *w sprawie dokumentacji hydrogeologicznej i dokumentacji geologiczno-inżynierskiej* (Dz.U. nr 291, poz. 16 988) [Regulation issued by the Environment minister from 23 December 2011 concerning hydrogeological documentation and geologic-engineering documentation (Journal of Laws, No. 291, item 16 988)].