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NUMERICAL CALCULATIONS OF THE CONSOLIDATION OF FLOTATION WASTE LANDFILL "ŻELAZNY MOST" BASED ON BIOT'S MODEL WITH THE KELVIN - VOIGHT RHEOLOGICAL SKELETON

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consolidation process, poroelasticity theory, rheology, Kelvin - Voight rheological skeleton, Biot theory, flotation waste landfill, Żelazny Most

konsolidacja, teoria porosprężystości, reologia, ciało Kelvina-Voigta, teoria Biota, składowisko odpadów poflotacyjnych, Żelazny Most

This paper presents simulation results of the consolidation process of the flotation waste landfill "Żelazny Most". The mathematical model used in presented research is based on Biot's model of consolidation and is extended with rheological skeleton. The load is the mass pressure of the landfill itself. The initial point selected for calculations was based on the ground water level calculated in a landfill. The creeping process in this waste landfill was analyzed along the north – south section. The solution is therefore 2D with the assumption of a plane strain state. Effective model parameters data were obtained in laboratory tests on the material from the waste landfill. Results obtained for a stress state in a storage state can help to determine whether the adopted linear model of visco-elastic medium does not lead to changes in the Coulomb – Mohr potential yield, showing the emergence of plasticity of material storage areas.

1. Introduction

As a valuable example of the application of Biot's model, taking into account the characteristics of the viscosity of the rheological Kelvin-Voigt skeleton in the process of consolidation of flotation waste landfill We have taken a set of measurement data made accessible by the "Żelazny Most" Department of Hydrotechnic and material collected from the flotation waste landfill. This material is a mixture of waste of the desulfurization installation, sludges created during the neutralization of liquid industrial wastes and acid dusts from the collection plants. Laboratory tests of this material allowed us to define the effective parameters of Biot model of consolidation with rheological skeleton. The obtained results of measurements allowed us the construction of the numerical model of "Żelazny Most" waste landfill and analysis of the creeping process in time. The results of calculations can be used to analyze the state of stress and compressive strain of the sediment trap under its own weight and the water filtration process. The analysis of potential yield of plasticity can be a starting point for a many analyses of stability of this important, European largest hydrological structure.

1.1. Geographical location of the flotation waste landfill

Administratively flotation waste landfill "Żelazny Most" is located in Lower Silesia in the Legnicko – Glogowski Copper District (LGOM), in two districts: Lubin and Polkowice. This flotation waste landfill was built in 1974, and its operation and the simultaneous expansion begun in 1977. The total length of barriers surrounding the landfill is 14.3 km and the total area – 1394 ha. The annual volume of waste deposited to the flotation ranged from 20 to 26 million tones, of which almost 75% is to further the superstructure and only 25% is in the process of disposal. Location and view the landfill in the form a satellite, based on information from the KGHM Polish Copper SA [11] if shown in Fig. 1.

Fig. 1. Satellite image of area occupied by the "Żelazny Most".
Rys. 1. Satelitarne zdjęcia obszaru zajmowanego przez Żelazny Most

1.2. The creation of landfill

For the construction of earthen structure unconventional materials are being used increasingly. The group of such materials includes mining wastes. The problem of the use of mine waste is of particular importance if the hydrotechnical construction through its impressive size and the influence on the environment. The "Żelazny Most" is an example of this kind of engineering design and also one of the largest hydraulic engineering facilities in the world. KGHM Mine production rate at this time, and thus the rate of landfill grow, requires ongoing assessment of many crucial parameters such as: strength parameters, deformation characteristics of waste built into the embankments and the control of the static water level inside the embankments. Thus, the current development and exploitation of the "Żelazny Most" site even just in the geotechnical meaning is a very complex issue. According to information provided on the KGHM website [11],"Żelazny Most" is one of the most important part of the company. One of the key issues of operation the hydrological building is the safety of the dam site, water management and environmental-friendly activities. KGHM appointed experts of numerous scientific institutions in Poland to cooperate in this regard. Since 1992, KGHM also cooperate with an international team of international experts in the field of geotechnics (ZEM). The basic tasks are related to the water and sludge economy of three *Ore Enrichment Division(OED)* which carry out the enrichment of mining muck copper ores by flotation method. The copper concentrate recovered from the enrichment process represents only about 4-6% of the weight of the extracted ore. The flotation process requires usage of large amounts of water – 4-5 m3/t of ore sent to flotation. The wastes generated by this process are in the form of a liquid slime, in which solids represent 6.5-8.7% by volume. From 1980 These wastes are transported by pipeline to the Żelazny Most tailings pond. There follows particulate solids sedimentation, the water from the surface is re-directed to the *Ore Enrichment Division (OED)*of all mines. Undoubtedly, "Żelazny Most" is a specific project. Drainage system which is applied there is dewatering the whole area surrounds this landfill. This tank has a circumference of about 15 km. It is constantly being augmented by superstructure (increase) around the successive "terraces". The consequence of this is the need for a permanent extension of drainage system, and care for resistance to groundwater operation through the constant monitoring of the area. The most important elements of landfill: dams and water intake and outlet are under constant geotechnical monitoring. Measured data are analyzed on an ongoing basis, and the decision about the extension of superstructure is taken after a thorough examination by the expert team. Therefore, analysis preparation and forecasts of the state of stress and strain of the site is an important element of prevention in the creep of the landfill and surrounding area.

2. Filtration process in the landfill

Data referred in the preceding paragraph together with the full geotechnical documentation provided an excellent base for the research and gave us the opportunity to verify the measurements through numerical calculations based on large-scale three-dimensional model of geotechnical processes. One of these models has been proposed by Nowak et al [6] and became part of a larger study made at the request of the Research and Development Center KGHM Cuprum Ltd. [5]. The primary goal of the presented numerical model of filtration flow was to determine three-dimensional shape of water-surface and by using the calibration of numerical model to obtain maximal resemblance of filtration flow model and the piezometric measurements. In the paper [5] authors have showed how the assumptions on infiltration affects the three-dimensional model of groundwater flow. The authors have showed also how the groundwater filtration may affect the security threats of this object and the surrounding areas. The filtration balance during design and maintenance of engineering facilities are extremely important element in modeling flow through porous medium (Whitaker, [9] and the Strzelecki and others [8]). The authors used the information of the geometry of the studied area, and proposed a three-dimensional model of groundwater flow in the context of filtration. This numerical model of the geological structure is geometrically mapping aquifers, geological strata and faults. Modern software allowed authors to generate a numerical model of calculated free surface of water in the form of scalar field of hydraulic head, and to determine the vector velocity field of filtration, and the flow through the drainage system. It allowed also the calculation of the filtration stability for the assumed boundary conditions of flow, which is one of the most important result obtained. A comparison of the shape of water free surface obtained from the calculations and piezometric levels measurements was used for the assessment of the numerical model quality.

Nowak and others in the work [7] noted, that the filtration characteristics depend to a large extent on the storage technology in “Żelazny Most”, i.e. “from outside to inside”. The wastes are deposited from the barriers surrounding the landfill, thus bigger grains are sedimenting closer to the shaft, and smaller within the lowest level. Geometric data for filtration calculation were taken from piezometric measurements from the wells and drainages. Authors divided the area into 7 regions, assuming for each different value of the average filtration coefficient. The spatial mesh of finite element for the tank is shown in Fig. 2.

2.1. Results of numerical calculations of filtration

The result of computer simulation is hydraulic head function H (x, y, z), which is limited from the top by surface of free surface of water. Calculations made repeatedly to obtain model, which will simulate real shape of free surface of water obtained from

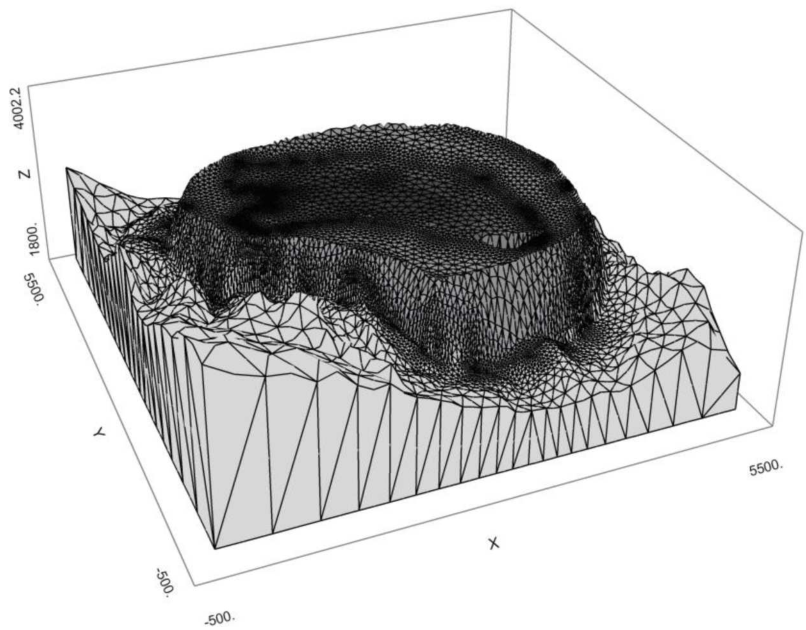

Fig. 2. View of spatial finite element mesh for the "Żelazny Most" landfill.
Rys. 2. Widok przestrzennej siatki elementów skończonych dla zbiornika Żelazny Most

piezometric measurements in best way. Two previously mentioned criteria, important in the process of calibration of the model, were adopted:

1. Comparison of the underground water shape, calculated from the model with the shape of free water surface obtained from piezometric measurements.
2. Comparison of discharge from wells and horizontal drainage systems, with the measured value of discharge of wells

Export of calculation results to a text file in the form of a mesh, allowed the transfer of the resulting free water surface to MicroStation and generation, using the InRoads, the numerical model of water free surface. An undoubted advantage of this method is the possibility of comparison with the numerical model of free surface of water generated on the basis of piezometric measurements for the same moment in time, for which calculations were made with Flex PDE v.6 program [10]. Using the numerical model the values of the discharge were also calculated in each type of drainage for a comparison with measured values for these wells. Figure 3 shows the location of the two surfaces (measured and calculated) obtained for the generated model. Figure 4 shows additionally the N-S section through these surfaces.

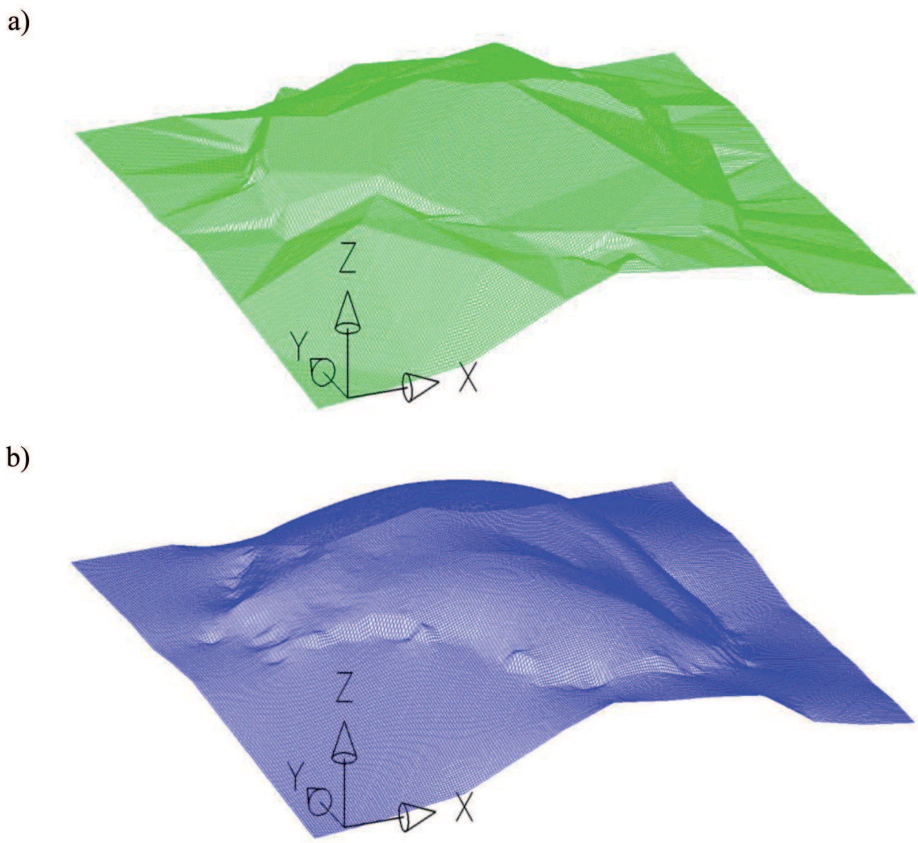

Fig. 3. Water level generated:
a) from piezometric measurements, b) with a numerical model of filtration.
Rys. 3. Zwierciadła wody wygenerowane w MicroStation z:
a) pomiarów piezometrycznych, b) modelu numerycznego filtracji

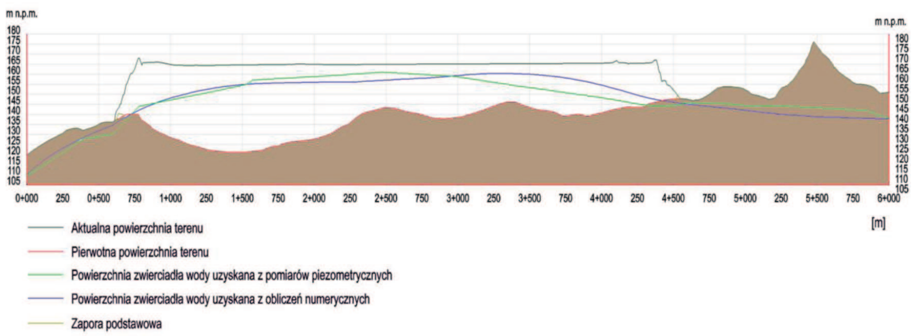

Fig. 4. Cross-section along the N-S line.
Rys. 4. Przekrój pionowy wzdłuż linii N-S

3. LABORATORY GEOTECHNICAL TESTING OF THE MATERIAL FROM ŻELAZNY MOST LANDFILL

To generate 2D numerical model of consolidation of Żelazny Most flotation waste landfill and surrounding area, physical and strength parameters were used. These parameters were obtained with laboratory tests, presented in following paragraphs of this paper.

3.1. MEASUREMENT OF BASIC PHYSICAL PARAMETERS

Basic measurements consisted on the standard analyses of material in accordance with the methodology presented in publications [1,2]. In this case, also microscopic images of soil samples prepared in a manner similar to the clay samples were used. Obtained microscope images are shown in Fig. 5. Most of the grains is larger than 10 μm, but there are also grains which are larger than 40 microns. Sharp edges of grains confirm anthropogenic origin of the test material.

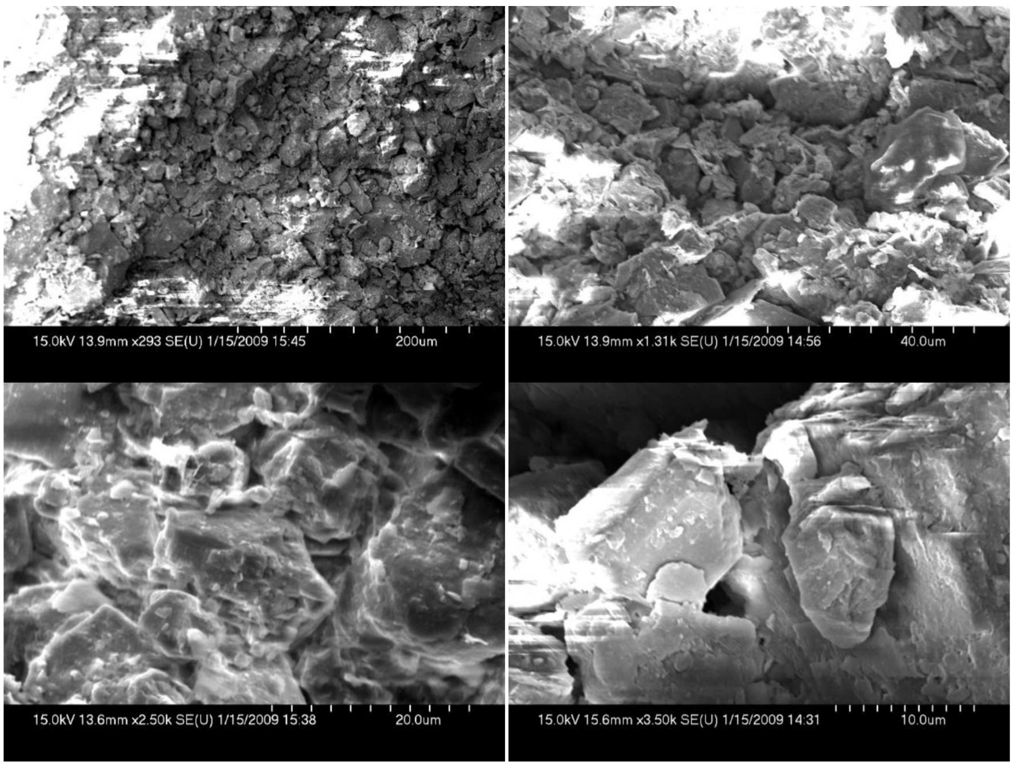

Fig. 5. Microscopic view of the test soil.
Rys. 5. Widok mikroskopowy badanego gruntu

3.2. Edometric test and measurement of strength parameters of the material from Żelazny Most landfill

To determine the consolidation-modulus of compressibility the edometric test was performed for four external loads. The value of primary consolidation-modulus of compressibility can be defined as Mo= 1662.9 KPa. Strength parameters obtained from direct shear testes and have been presented in [1].For calibration of other parameters; statistical methods presented in [1] were used. Preliminary analysis of equations of the Biot model with the rheological Kelvin-Voigt skeleton revealed, that three parameters should be a subject of calibration.

4. Calculation of Consolidation of Żelazny Most flotation waste landfill

Based on the three-dimensional numerical model of the geological structure and the filtration flow which is described in details in study [1], numerical model of creeping of Żelazny Most waste landfill using FEM software – FlexPDE 6 [10] was built. Numerical model of consolidation was created for the vertical section along the north-south line through the geometric center of the landfill.

4.1. Mathematical Model of Biot's consolidation with rheological skeleton

According to Bartlewska [1] the constitutive relations for Biot model with the rheological Kelvin-Voigt skeleton, where the pore space is not filled with Newtonian fluid in isothermal process take the form:

$$\begin{aligned} \sigma_{ij}^{p} &= 2N\varepsilon_{ij}^{p} + 2\eta^{p}\dot{\varepsilon}_{ij}^{p} + A\varepsilon^{p} + \eta^{o}\dot{\varepsilon} \\ \sigma &= Q\varepsilon + R\theta \end{aligned} \tag{4.1}$$

In the Biot-Willis paper [3], constant occurring the constitutive relations were interpreted as follows:

- N is the module of the form viscosity of skeleton,
- A is module of volume viscosity of skeleton filled with a liquid,
- Q is a factor of influence the volume strain of liquid on the stress in the skeleton or conversely: factor of influence of the volume strain of skeleton on the stress in the liquid,
- $R$is module of volume strain of liquid filling pores in Biot's medium,
- parameter M is given by:

$$M = A - \frac{Q^2}{R}$$

Compound (1.1a) can be represented as:

$$\sigma_{ij} = 2N\Psi_k\varepsilon_{ij} + M\Psi_l\varepsilon\delta_{ij} \tag{4.2}$$

$\Psi_k = 1 + T\partial/\partial t$ – the differential operator $T = \eta^p/N$, $T = \eta^o/N$ – the viscosity parameter; η^p – the form viscosity of skeleton, η^o the volume viscosity of skeleton.

The constitutive relations for Biot's model with rheological Kelvin-Voigt skeleton for isothermal process take the form:

$$\begin{cases} \sigma_{ij} = 2N\Psi_k\varepsilon_{ij} + (A\Psi_l\varepsilon + Q\theta)\,\delta_{ij} \\ \sigma = Q\varepsilon + R\theta \end{cases} \tag{4.3}$$

Taking into account the constitutive relations for the Biot medium with rheological Kelvin-Voigt skeleton in equations for the movement of liquid and solid medium phase we obtain the equations of consolidation in the form:

(4.4)

$$\begin{cases} N\Psi_k\nabla^2 u_i + (M + N\Psi_l)\,\varepsilon_{,j} = -\frac{H}{R}\sigma_{,j} + \rho_{11}\frac{D^s v_i^s}{Dt} + \rho_{12}\frac{D^s v_i^l}{Dt} + \rho_{12}\frac{D^l v_i^s}{Dt} + \rho_{22}\frac{D^l v_i^l}{Dt} \\ \frac{k}{f}\nabla^2\sigma = \frac{1}{R}\dot{\sigma} - \frac{H}{R}\dot{\varepsilon} + \rho_{12}\frac{D^l v_i^s}{Dt} + \rho_{22}\frac{D^l v_i^l}{Dt} \end{cases}$$

For quasistatic processes, with the use of the Einstein index notation, equation (4.4) might be written in the form of:

$$\begin{cases} N\Psi_K\nabla^2 u_i + (\Psi_l M + N\Psi_k)\,\varepsilon_{,i} = -\frac{H}{R}\sigma_{,i} \\ \frac{k}{f^2}\nabla^2\sigma = \frac{1}{R}\dot{\sigma} - \frac{H}{R}\dot{\varepsilon} \end{cases} \tag{4.5}$$

After numerical differentiation on the time, substituting $\frac{k}{f^2} = K$ into flow equation we obtain the form of:

$$\begin{cases} N\nabla^2 u_i + (M + N)\,\varepsilon_{,i} + \eta^s\nabla^2\dot{u}_i + (\eta^s + \eta^o)\,\dot{\varepsilon}_{,j} = -\frac{H}{R}\sigma_{,i} \\ K\nabla^2\sigma = \frac{1}{R}\dot{\sigma} - \frac{H}{R}\dot{\varepsilon} \end{cases} \tag{4.6}$$

The above set of equations describe the process of consolidation caused by filtration flow of viscous Newtonian liquid passing through the pores of the Kelvin-Voigt skeleton, being subjected to external load. Solutions of this set were given on study [1].

The whole area that was the subject to a computer simulation of consolidation process consists of areas with different parameters of stored sediments. Therefore, the whole domain was were divided into smaller areas with known and approximately constant parameters. In this way, 22 sub-regions were established (shown schematically in Fig. 6).

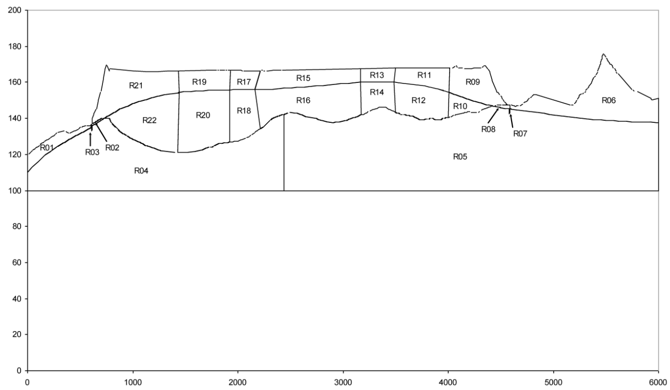

Fig. 6. Breakdown of the landfill area in the 2D regions.
Rys. 6. Podział obszaru składowiska na regiony 2D

4.2. Results of numerical calculations for one dimensional model

Results of numerical calculations with finite element method and Flex PDE 6 software [10] for a two-dimensional model when $t \to \infty$, in the form of 2D graphs are shown on Fig. 7-12.

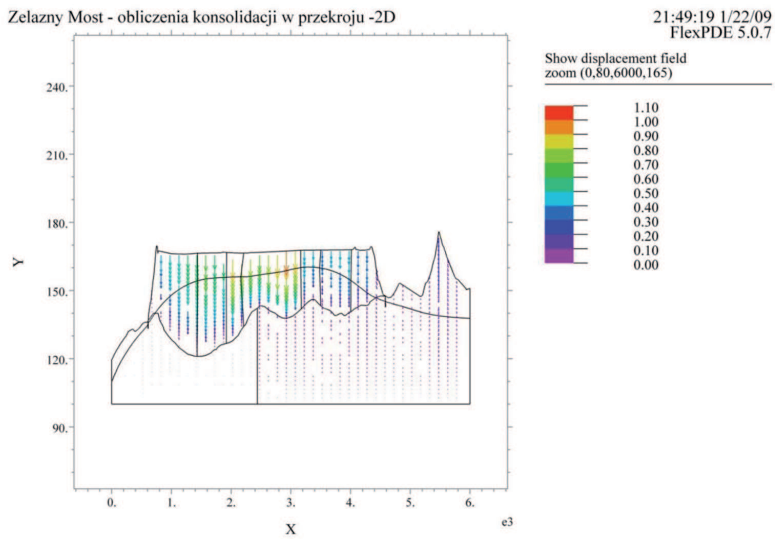

Fig. 7. Vector field of movements of material from the landfill.
Rys. 7. Pole wektorowe przemieszczeń materiału składowiska

Fig. 7 shows the vector field of displacement of material from landfill and the landfill substrate. The maximum value of settlement over time to 30 years is in a central part of the landfill and is about 1.1 m. This quantity is slightly smaller than the size obtained from surveying measurements.

Figure 8 shows a graphical representation of horizontal displacement after 30 years of consolidation. As shown on this chart, maximum horizontal displacement quantities are in the slopes area. Simulated values are of the order of 0.10 m while from the geodetic studies result gave the maximum amount of horizontal displacement of the order of 0.16 m. This quantity has it in a different section than the calculated . In the south direction maximum horizontal displacement quantity was of the order of 0.09 m which is consistent with the results of numerical calculations.

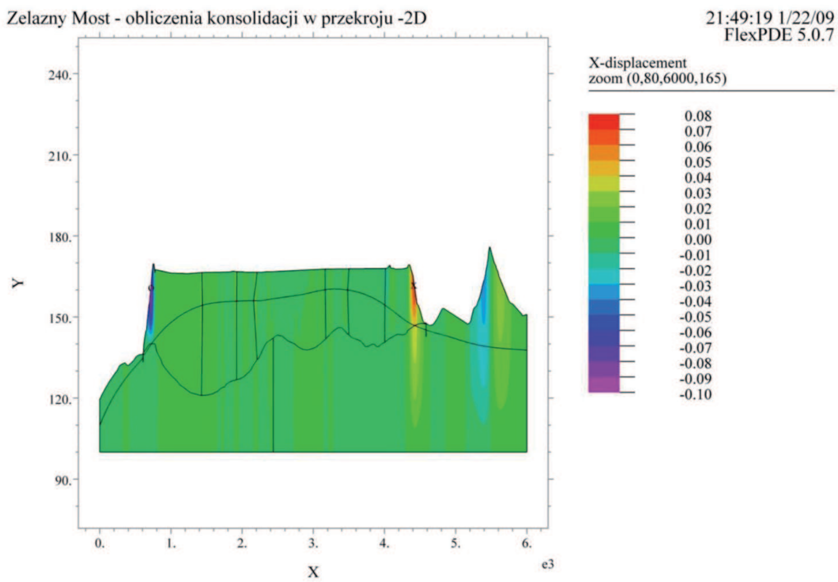

Fig. 8. Graph of horizontal displacement.
Rys. 8. Wykres przemieszczeń poziomych

Vertical displacements graph is shown in Figure 9. This figure shows that the largest vertical displacement occurred in the central part of the landfill, which is consistent with the observations in the field. The maximum calculated vertical displacement is of the order of 1.10 m. The observed maximum displacement is larger, but there are in other section than the cross section used for calculation.

Figure 10 contains a chart showing the behavior of the filtration stability potential that is expressed by the formula:

$$\Phi = \frac{\partial H}{\partial y} + \frac{(\gamma_s - \gamma_w)}{\gamma_w}$$

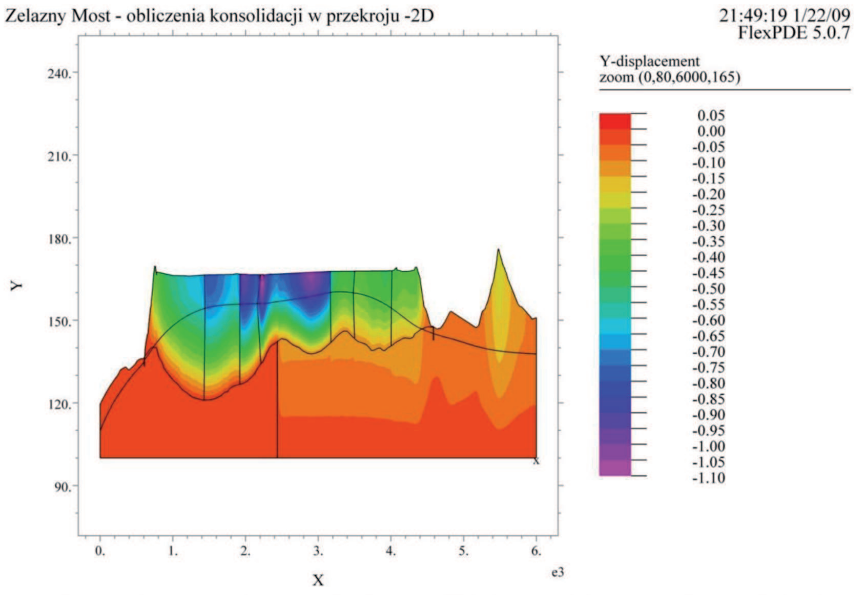

Fig. 9. Graph of the movements in the vertical direction.
Rys. 9. Wykres przemieszczeń pionowych

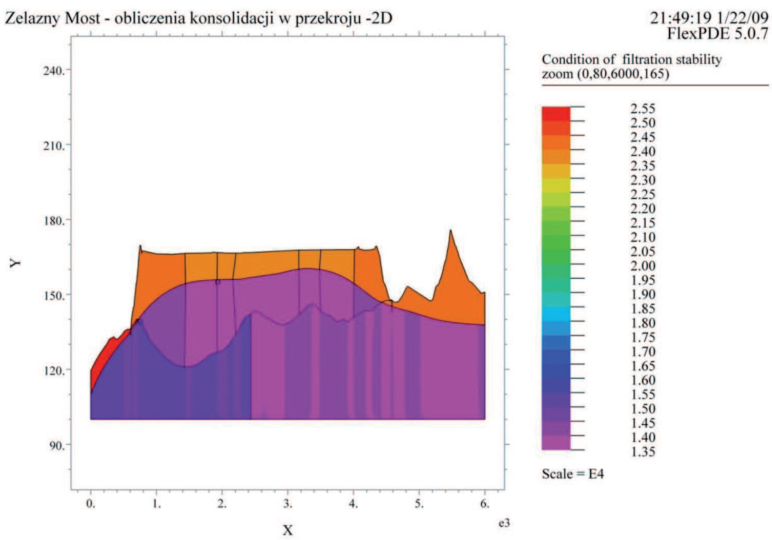

Fig. 10. Graph of Φ potential.
Rys. 10. Wykres potencjału Φ

When the Φ value is positive there is no loss of filtration stability. As it can be seen from the graph, there is no lost of filtration stability in selected test section.

Figure 11 shows the distribution of stresses in the fluid (pore strain) after completion of the consolidation process. The adopted boundary condition was, that the stress on the water free surface of and above that level are $-f p_a$ to where f denotes the porosity, and p_a barometric pressure. The greatest pressure in the liquid has occurred in the soil underneath the landfill.

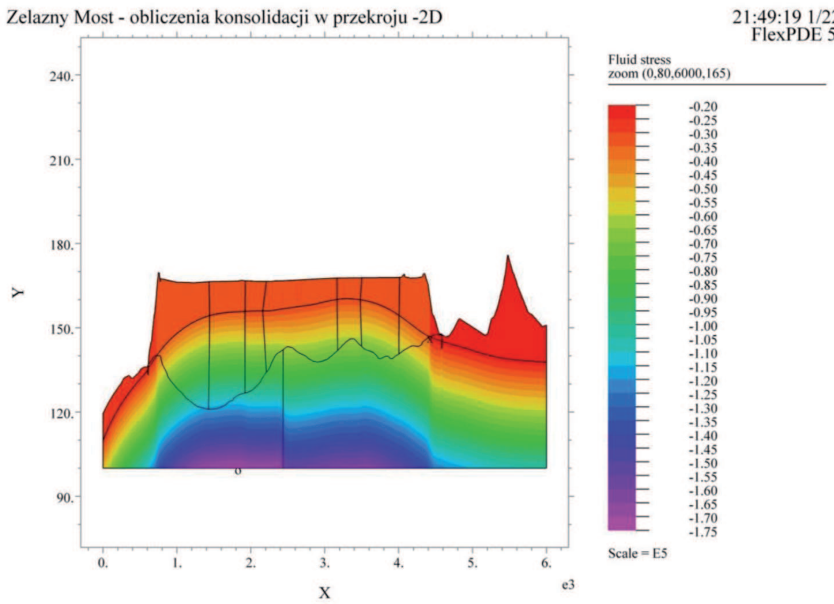

Fig. 11. Stresses in the liquid.
Rys. 11. Wykres naprężeń σ w cieczy

The calculated stress state allowed us to determine the quantity of the Coulomb Mohr potential, to see if the tested area is located in the elasticity zone of of the material of which the landfill is built. Results of Coulomb-Mohr potential calculation are presented in Fig.12. A negative value of potential specifies the areas which are in the range of elasticity. Where the potential takes a positive value the shear strength was exceeded (with adopted parameters for the angle of internal friction and cohesion). The chart shows that there are areas in which the soil may be in plasticized state. This result should be a signal to the representatives of KGHM to make detailed research on the stability of the landfill.

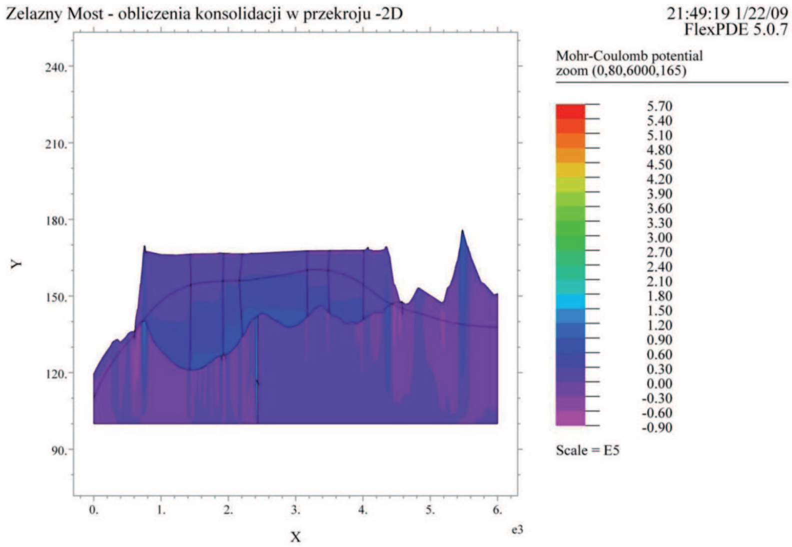

Fig. 12. Results for 2D model – Mohr-Coulomb potential.
Rys. 12. Wykres potencjału Coulomba-Mohra

5. CONCLUSIONS

Presented solution of creeping issues of " Żelazny Most" - flotation waste landfill is an example of the possibility of use of a Biot's mathematical model of consolidation with rheological skeleton for practical applications. Despite the complexity of the model and the complex procedure of determining the elastic and viscous parameters of material from the site a numerical model of consolidation of the landfill was built and the process of deformation was simulated in time.

The presented example shows that at the present stage of knowledge more complex models of process stress – deformation of porous media can be used in engineering calculations. In the given in this paper example, the calculation process included a significant variation of mechanical and hydrogeological parameters of simulated space and its anisotropy. Thus, it is possible and one can try to solve complex engineering problems with the use of mathematical models more and more close to the reality.

This article brings an example of how to use geomatics tools such as numerical terrain model for practical applications in geotechnics. Comparison of the calculated shape of free surface of water and displacements with measurements made on the real object shows the extent to which we obtained the accuracy of our engineering solution.

REFERENCES

1. M. BARTLEWSKA, Określenie parametrów efektywnych modeli reologicznych gruntów spoistych, praca doktorska, Wydział Goinżynierii, Górnictwa i Geologii, Instytut Górnictwa, Politechnika Wrocławska, Wrocław (2009).
2. M. BARTLEWSKA, T. STRZELECKI, *Metodyka określania parametrów efektywnych ciała Biota*, VI Konf. Nauk. Dokt.. Szklarska Poręba, 23-25 marca 2006, Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej 116, Seria konferencje 47 (2006).
3. M.A. BIOT, D.G. WILLIS, The Elastic Coefficients of the Theory of Consolidations, J. Appl. Mech., 24, (1957).
4. O. COUSSY, *Mechanics of Porous Continue*, John Wiley & Sons (1995).
5. J. NOWAK, J. BUTRA, J. PYRA, T. STRZELCKI, D. KONSENCJUSZ, J. NOWAK, M. STRZELECKI, A. BARAŃSKA-BUSLIK, Z. KISIELEWICZ, M. NIEDBAŁ, *Badania skuteczności procesu uszczelniania dna składowiska Żelazny Most.* Raport roczny za okres 01.07.2007 – 30.06.2008.
6. J. NOWAK, M. STRZELECKI, T. STRZELECKI, *Numeryczny model przepływu filtracyjnego w obrębie składowiska odpadów poflotacyjnych, Cuprum – czasopismo naukowo – techniczne górnictwa rud*, Wydawnictwo i Drukarnia AKCYDENS, zesz. 4 [49] 2008, str. 63 do 87 (2008).
7. J. NOWAK, T. STRZELECKI, M. STRZELECKI, *Praktyczne wykorzystanie metody identyfikacji zagrożeń geotechnicznych na podstawie obliczeń przestrzennego modelu zwierciadła wody*, Międzynarodowy Kongre Górnictwa Rud Miedzi,tom 2, str. 56-66 (2009).
8. T. STRZELECKI (red.), S. KOSTECKI, S. ŻAK, *Modelowanie przepływów przez ośrodki porowate*, DWE. Wrocław (2008).
9. S. WHITAKER, *Flow in Porous Media. I: A Theorical Derivation of Darcy's Law*, Transport in Porous Media, zesz. 1 (1986).
10. Flex PDE 6, Ver. 6, *www.pdesolution.com*, PDE Solutions Inc. (2009).
11. Strona internetowa KGHM Polska Miedź S.A. – *www.kghm.pl*.

Streszczenie

W pracy przedstawiono wyniki symulacji procesu konsolidacji składowiska odpadów poflotacyjnych Żelazny Most w oparciu o model matematyczny konsolidacji Biota ze szkieletem reologicznym pod działaniem ciężaru własnego składowiska. Punktem wyjścia do obliczeń było obliczone zwierciadło wód podziemnych w składowisku. Zagadnienie pełzania składowiska wykonano w przekroju północ - południe przez składowisko. Rozwiązanie jest więc typu 2D przy założeniu płaskiego stanu odkształcenia. Dane dotyczące parametrów efektywnych modelu uzyskano w badaniach laboratoryjnych na materiale uzyskanym na składowisku. Uzyskane wyniki stanu naprężenia w składowisku pozwalają określić, czy przyjęty liniowy model ośrodka lepko sprężystego nie prowadzi do pojawienia się zmian znaku wartości potencjału plastyczności Coulomba - Mohra, co świadczyłoby o pojawianiu się obszarów uplastycznienia materiału składowiska.

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