EFFECT OF SPATIAL VARIATION OF SPOIL MATERIAL PROPERTIES ON SLOPE DISPLACEMENTS UNDER RAPID DRAWDOWN OF PIT LAKES

WPŁYW PRZESTRZENNEGO ZRÓŻNICOWANIA WŁAŚCIWOŚCI MATERIAŁU ZWAŁOWEGO NA PRZEMIESZCZENIA ZBOCZY W WARUNKACH GWAŁTOWNEGO SPIĘTRZENIA WÓD ZBIORNIKÓW POEKSPLOATACYJNYCH

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In many European countries, lignite or brown coal is used as a fuel source in steam-electric power generation. Upon completion of mining activities, a reclamation plan is imperative to ensure environmental and social prosperity of local areas. Abandoned mine pits are often reclaimed by creating a pit lake. Reclamation of large lignite open pit mine sites may use large amounts of previous overburden materials or "spoils" to create the slopes of the pit lake. Spoils are anthropogenic materials with large spatial variation in properties, hence, considering mean values of shear strength and hydraulic parameters to assess stability and seasonal displacements will not fully simulate actual field conditions. This paper considers the effect of spatial variation on slope stability and ground movements during rapid drawdown events (a critical case) using coupled flow-deformation 2D finite element analyses, incorporating unsaturated soil suctions above the phreatic surface. Effects of heterogeneity and randomness of spoils on the response of the slope are considered through random field modelling and the Monte-Carlo simulation technique. Four lognormally distributed random variables (spoil cohesion, friction angle, void ratio, and permeability coefficient) are examined. The effect of spatial variability of spoils is shown to be important; a significant number of the random field analyses resulted in larger displacements compared to a benchmark deterministic analysis adopting uniform mean parameter values.

Keywords: *slope stability, spoil, spatial variation, numerical modelling*

W wielu krajach europejskich węgiel brunatny jest wykorzystywany jako źródło paliwa w energetyce parowo-elektrycznej. Po zakończeniu działalności górniczej konieczne jest opracowanie planu rekultywacji w celu zapewnienia środowiskowego i społecznego dobrostanu okolicznych obszarów. Opuszczone wyrobiska górnicze są często rekultywowane poprzez utworzenie w nich zbiorników wodnych. W rekultywacji dużych kopalni odkrywkowych węgla brunatnego do tworzenia zboczy zbiornika można wykorzystać duże ilości wcześniejszych materiałów nadkładowych lub „odpadowych". Materiał zwałowy jest materiałem antropogenicznym o dużej przestrzennej zmienności właściwości, dlatego też przyjęcie średnich wartości wytrzymałości na ścinanie i parametrów hydraulicznych w celu oceny stabilności i sezonowych przemieszczeń nie będzie w pełni odzwierciedlać rzeczywistych warunków terenowych. W niniejszej pracy rozważano wpływ zmienności przestrzennej na stabilność zboczy i przemieszczenia gruntu podczas gwałtownego obniżenia poziomu wody (przypadek krytyczny), stosując sprzężone analizy 2D metodą elementów skończonych typu przepływ-deformacja, z uwzględnieniem ssania gruntów nienasyconych powyżej powierzchni freatycznej. Wpływ heterogeniczności i losowości materiału na zachowanie zbocza rozważany jest poprzez modelowanie pola losowego i technikę symulacji Monte-Carlo. Badane są cztery zmienne losowe (kohezja materiału, kąt tarcia, wskaźnik porowatości i współczynnik przepuszczalności) w rozkładach log-normalnych. Wykazano, że wpływ przestrzennej zmienności materiału zwałowego jest istotny; znaczna liczba analiz z wykorzystaniem pola losowego skutkowała większymi przemieszczeniami w porównaniu z wzorcową analizą deterministyczną, w której przyjęto jednolite średnie wartości parametrów.

Słowa kluczowe: *stateczność zboczy, zwałowisko, zmienność przestrzenna, modelowanie numeryczne*

Introduction

In many European countries, lignite or brown coal is used as a fuel source in steam-electric power generation. Although reducing, a considerable amount of lignite is still consumed in the European Union. According to the latest report on lignite utilization for power sector (EU, 2020), EU countries use more than 250 million tonnes of lignite per year. Lignite is extracted from the earth by surface mining with the creation of an open pit. These mining activities, which can last for many decades, can have detrimental effects on the environment. Economic and social prosperity of local communities surrounding a mine site is closely related with mining activities. With the closure of mining activities, the lifestyle and economic prosperity of surrounding communities are also affected. Therefore, proper use of abandoned mine sites is very important. At the same time, it must be kept in mind that reclamation of mine pits should satisfy the expectations of local communities while following the principles of sustainable development.

Abandoned mine pits are often reclaimed by flooding. Pit lakes enhance the recreational or ecological benefits by re-landscaping and re-vegetating the shoreline, by creating aquatic life, and maintaining water quality. The performance of pit lake slopes is dependent upon several factors such as topography, geotechnical and hydrogeological characteristics. Sometimes, in cases of reclamation of large lignite mine sites, previous overburden materials or spoils are used to fill up the slope side. During extraction of lignite mines, spoils or overburden mine wastes are excavated first and then dumped to a nearby location of the mine site. Spoils are anthropogenic materials with large spatial variation in properties (Masoudian et al. 2019a, Zevgolis et al. 2021). Therefore, considering mean values of shear strength and hydraulic parameters throughout the problem domain does not fully simulate actual field conditions. Being a highly heterogeneous material, the use of spoil materials increases the chances of slope instability. With varying climatic conditions, there can be sudden drawdown of reservoir water, especially during summer periods.

The purpose of this paper is to present results of a numerical modelling study that focused on evaluating two key aspects related to slope stability and soil movements: (1) the effect of unsaturated soil, and (2) the effect of material heterogeneity. Alterations of the ground water regime, resulting from changes to the water elevation inside a pit reservoir, both on steady-state and transient conditions, were investigated for their influence on the stability and movements of flooded pit slopes. The effect of spatial variation on slope stability and ground movements during rapid drawdown events (a critical case) is obtained using coupled flow-deformation 2D finite element analyses conducted using Abaqus, incorporating unsaturated soil suctions above the phreatic surface. Effects of heterogeneity and randomness of spoils on the response of the slope are considered through random field modelling and the Monte-Carlo simulation technique. Four lognormally distributed random variables (spoil cohesion, friction angle, void ratio, and permeability coefficient) are examined, with results compared against a benchmark deterministic analysis adopting uniform mean parameter values. In this paper, for brevity, the focus is placed on vertical displacements occurring at key locations within the slope.

Problem statement

Figure 1 shows the two-dimensional plane strain problem domain of the slope considered in the analysis. The slope is inclined at an angle of 24° from horizontal, taken as a critical section in the North-South direction of Lake Most of the CSA open pit mine in the Czech Republic. The slope height is 12.87 m, a foundation spoil of height 20.13 m is considered below the slope, and the slope is extended horizontally to a length of 30 m from its crest to the model boundary. Vertical and horizontal extensions of the problem domain were decided after ensuring there were negligible effects of boundaries on the results for a reasonable computational time. Two initial positions of the ground water table at the left (crest) side boundary were considered (measured from the model base): WT_{ia} = 29 m and WT_{ib} = 23 m. The initial water table within the slope was assumed to be horizontal, hence the initial reservoir level was also 29 m and 23 m from the bottom of the problem domain.

Two cases of reservoir water drawdown were considered: (i) from 29 m to 21 m, and (ii) 23 m to 21 m. The latter reservoir water drawdown case closely represents water level monitoring data at the Lake Most site. During drawdown, the water table on the left side boundary was kept constant. Reservoir drawdown was simulated stage-wise depending upon drawdown velocities. Four drawdown velocities representing slow to fast drawdowns were considered. Pore pressure was monitored at three different locations near the crest ('p'), middle ('q'), and toe ('r') within the slope, as shown in Figure 1.

Material properties

The dry density of the spoil was assumed to be 14.56 kN/ m³. Spoil stiffness (E) and saturated permeability coefficient (k_{sat}) which influence the deformation and pore water response of the slope under reservoir water drawdown were varied. Three values of spoil stiffness (E = 10 MPa, 100 MPa, 500 MPa) and permeability coefficient (k_{sat} = 1.11 m/day, 0.11 m/day, and 0.011 m/day) were considered. Deterministic values of spoil shear strength parameters (c', ϕ') were used according to lab test data obtained from samples of spoil from the CSA open pit mine, conducted at the University of Nottingham. Unsaturated spoil parameters were obtained from Masoudian et al. (2019b). Table 1 details all data required for the deterministic analyses.

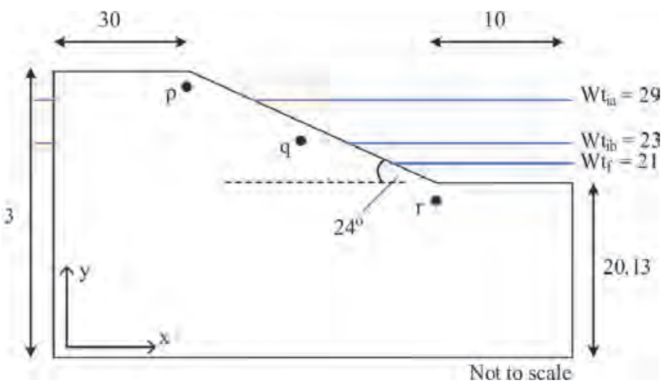

Fig. 1. Problem domain considered in the present study (units in m).
Rys. 1. Domena problemowa rozpatrywana w niniejszej pracy (jednostki w m)

Tab. 1 Spoil parameters used in the present study (after Masoudian et al. 2019b and lab test results)
Tab. 1 Parametry materiału zwałowego zastosowane w niniejszej pracy (na podstawie Masoudian et al. 2019b i wyników badań laboratoryjnych)

Mean cohesion (kPa)	10
Mean friction angle (°)	22
Dilation angle (°)	5
Mean elastic stiffness (MPa)	100
Dry unit weight (kN/m^3)	14.56
Mean initial void ratio	0.94
Permeability coefficient (m/day)	0.11
Residual degree of suction	0.27
Suction constant (/ kPa)	0.167
Tortuosity coefficient	-4
SWCC exponent	1.7

Results

Benchmark deterministic analyses

Effect of rate of drawdown

Four drawdown velocities (D_v = 0.01, 0.5, 1, and 2 m/day) representing slow to fast drawdowns were considered, while keeping other parameters constant (refer to Table 1). The reservoir level was lowered from WT_{ia} = 29 m to WT_f = 21 m.

Figure 2 shows slope displacements at the crest in the (a) horizontal (positive to the right) and (b) vertical (negative downwards) directions with time for different drawdown rates. The slope crest displaces to a greater amount and at a faster rate when drawdown rate is relatively high. After completion of drawdown (marked by black dots), the settlement rate of the slope becomes almost constant with time.

Effect of drawdown depth

Two drawdown depths are considered: (i) 29 m to 21 m, and (ii) 23 m to 21 m. In order to compare the effect of drawdown depth, the drawdown rate was kept constant at 1 m/day. Other parameters were also kept constant (refer to Table 1).

Figure 3 shows slope displacements measured at the crest and toe in the (a) horizontal and (b) vertical directions for the two drawdown depths. For the lower water drawdown depth, slope deformations at the crest, which is relatively far from the location of the lake water elevation, are a result of global effects of soil self-weight changes and ground movements. Slope deformation at the toe in the horizontal direction is due to both self-weight changes of the slope and localised mechanisms from the removal of external support from the lake water drawdown. For that reason, the magnitude of slope deformations at the toe is more pronounced than at the crest, though in both cases the displacements are small (<2mm).

Effect of spoil permeability

Three values of spoil permeability (k_{sat} = 1.11 m/day, 0.11 m/day, and 0.011 m/day) are considered. For this comparison, the drawdown rate was 0.11 m/day and drawdown depth was from 29 m to 21 m. Other parameters were also kept constant (refer to Table 1).

Figure 4 shows that slope displacements at slope crest are greatest for the less permeable spoil.

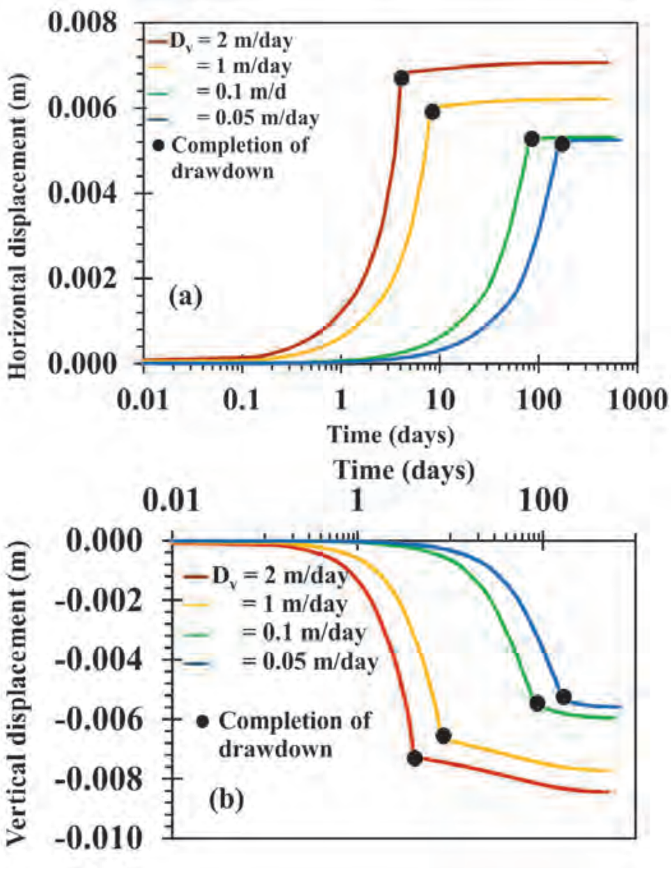

Fig. 2. Displacement at crest of slope for different drawdown velocities: (a) horizontal and (b) vertical
Rys. 2. Przemieszczenia w koronie zbocza dla różnych prędkości obniżania poziomu wody: a) poziome i b) pionowe

Effect of spoil stiffness

The effect of spoil stiffness on slope displacements was investigated by considering E = 10, 100, and 500 MPa. For these comparisons the drawdown rate was 0.11 m/day and drawdown depth was from 29 m to 21 m Other parameters were also kept constant (refer to Table 1).

Slope displacements at the crest in the (a) horizontal and (b) vertical directions are shown in Figure 5. Displacements are shown to be greatest for the spoil with the lowest stiffness E = 10 MPa.

Random field probabilistic analyses

For the random field probabilistic analyses, the (i) cohesion (c'), (ii) friction angle (ϕ'), (iii) elastic stiffness (E), and (iv) void ratio (e) of the spoil were considered as Lognormally distributed random fields. It should be noted that the spoil permeability coefficient (k) also varies spatially as it is related to the void ratio by Kozeny's equation (Le et al., 2015). Parameters (coefficient of variation, auto-correlation lengths in both horizontal θ_x and vertical θ_y directions) required to generate random fields are in accordance with Phoon and Kulhaway (1999 a-b) and Zevgolis et al. (2021). Coefficient of variation (CoV) denotes the randomness of spoil properties. Auto-correlation lengths in the horizontal (θ_x) and vertical (θ_y) direction express how spoil parameters are correlated with each other at two spatial locations (x_1, y_1) and (x_2, y_2). A higher value of CoV indicates that the spoil is highly

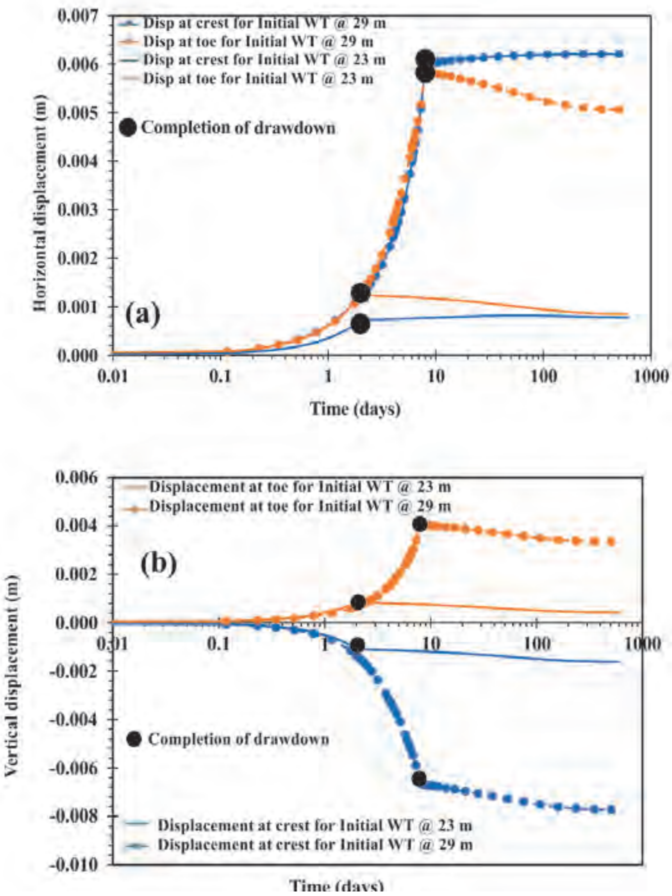

Fig. 3. Displacement at crest and toe of slope for different drawdown depths: (a) horizontal and (b) vertical

Rys. 3. Przemieszczenia w koronie i u podnóża zbocza dla różnych głębokości obniżenia poziomu wody: (a) poziome i (b) pionowe

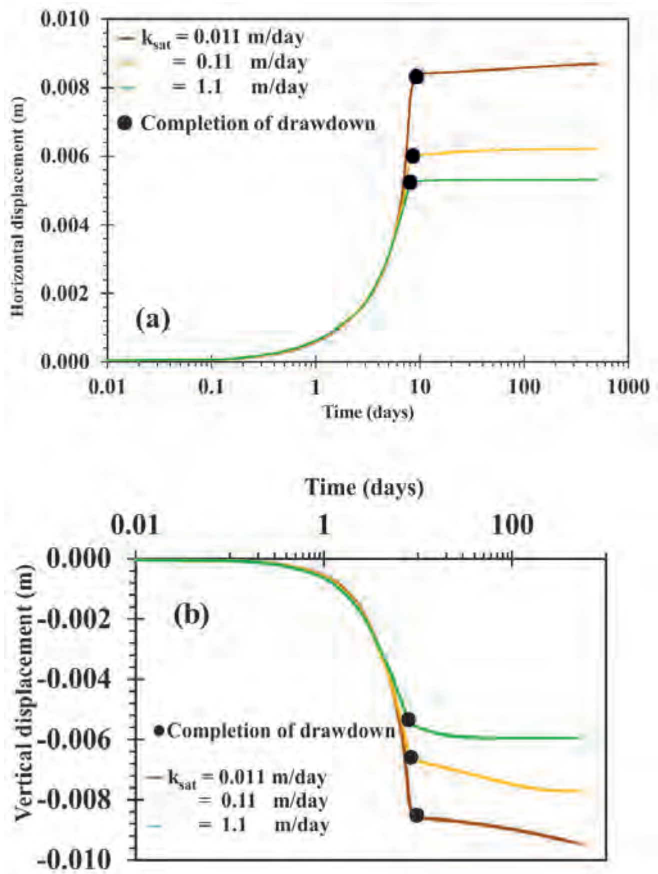

Fig. 4. Effect of spoil permeability on displacements at slope crest: (a) horizontal and (b) vertical

Rys. 4. Wpływ przepuszczalności materiału zwałowego na przemieszczenia w koronie zbocza: a) poziome i b) pionowe

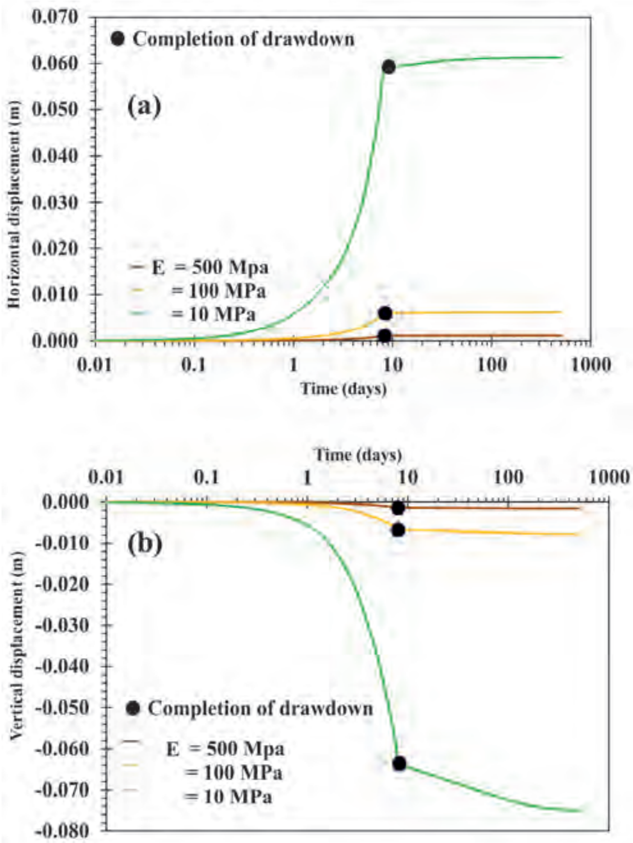

Fig. 5. Effect of spoil stiffness on displacements at slope crest: (a) horizontal and (b) vertical

Rys.5. Wpływ sztywności materiału zwałowego na przemieszczenia w koronie zbocza: (a) poziome i (b) pionowe.

random, whereas a lower values of θ_x and θ_y indicate that the spoil is highly heterogeneous. Figure 6 shows and example of isotropic random fields generated for friction angle with $\theta_x = \theta_y = 1$ and 10. As the values of correlation length increase, larger patches of similar spoil parameters are generated. A Python based computer code was developed to incorporate the effects of spoil spatial variability in the numerical simulations.

This section will focus on results obtained from analyses using the higher reservoir drawdown case, i.e. from 29 m to 21 m. The effect of spatial variability was found to be more significant for greater drawdown depths as the range of variation in the influenced zone of the slope was greater than that for the lower drawdown case. Figure 7 presents a typical result of vertical displacement at the slope crest from 400 Monte--Carlo simulations for a combination of $\theta_x = \theta_y = 1$, CoVc = 20%, CoVϕ = 5%, CoVE = 10%, CoVe = 15%. Mean values of other parameters were used (refer to Table 1). The slope is subjected to stagewise drawdown at a rate of 1 m/day. The deterministic analysis result is also provided (red line), which is noted to demonstrate significantly less displacement than many of the probabilistic results; 235 out of the 400 (59%) results were greater than the deterministic analysis.

Effect of correlation length θ for isotropic random fields

Figure 8 compares deterministic results of vertical displacement with mean probabilistic values (i.e. the mean from the 400 Monte Carlo analyses) obtained at the slope crest, middle, and toe for random fields with isotropic correlation lengths

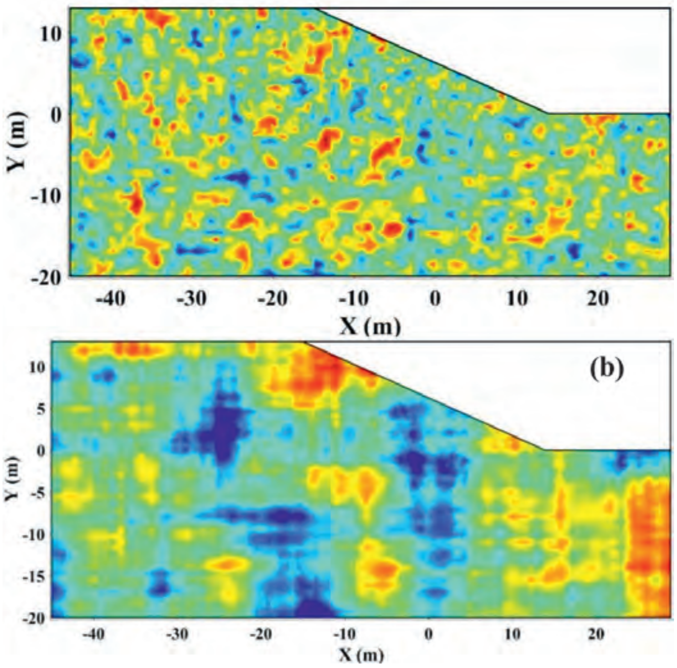

Fig. 6. Random fields of friction angle of spoil for (a) $\theta_x = \theta_y = 1$ and (b) $\theta_x = \theta_y = 10$

Rys.6. Pola losowe kąta tarcia materiału zwałowego dla (a) $\theta_x = \theta_y = 1$ i (b) $\theta_x = \theta_y = 10$

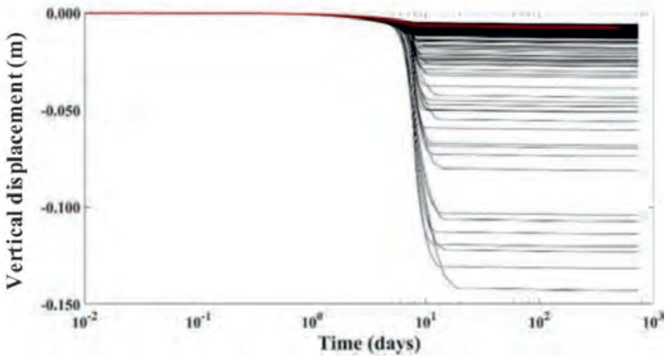

Fig. 7. Random field probabilistic results of vertical displacement of slope crest for a typical analysis with $\theta_x = \theta_y = 1$

Rys. 7. Wyniki probabilistyczne pól losowych przemieszczenia pionowego korony zbocza dla typowej analizy z $\theta_x = \theta_y = 1$

of $\theta_x = \theta_y = 1$, 5, and 10. The highest settlement at the toe is obtained for higher correlation lengths ($\theta_x = \theta_y = 10$).

With increasing correlation lengths, the deviation between deterministic and mean probabilistic values increases. This outcome is contradictory to initial expectations which was that the deviation between deterministic and mean probabilistic settlements should be higher for lower auto-correlation lengths (heterogeneity is greatest for lower correlation lengths).

This may be explained by considering the size of the "influence zone" dictating the overall movement of the slope, which is mainly at a shallow depth, near the slope face, as indicated by Figure 9, alongside the random fields of spoil parameters corresponding to lower and higher correlation lengths (Figure 6 a and b). For low correlation lengths, spoil properties are highly heterogeneous with a more distributed mix, whereas for the higher correlation lengths, the influence zone may be dominated by a more uniform region of soil properties. The result is that, overall, the more heterogeneous mix of high and low soil parameters for the lower correlation length cases results in smaller ground movements around the slope compared to the higher correlation length cases.

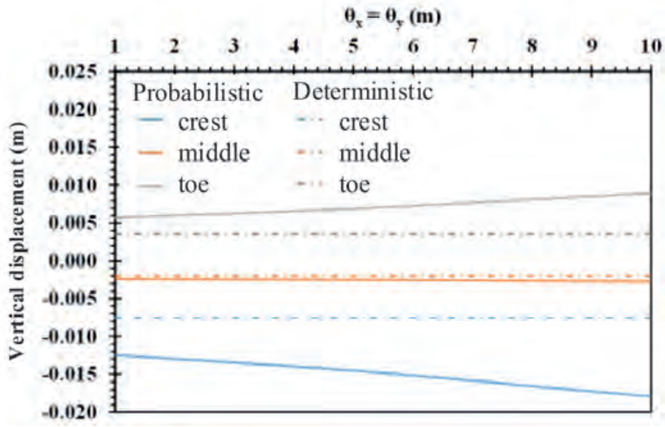

Fig. 8. Variation between mean probabilistic vertical displacements with correlation length

Rys. 8. Zróżnicowanie pomiędzy średnimi probabilistycznymi przemieszczeniami pionowymi w zależności od długości korelacji

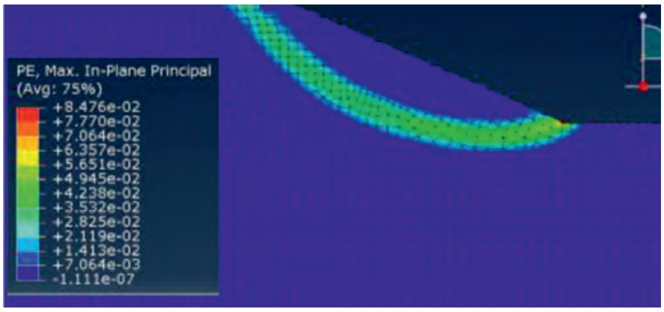

Fig. 9. Plastic strain contours for $\theta_x = \theta_y = 10$

Rys. 9. Kontury odkształcenia plastycznego dla $\theta_x = \theta_y = 10$

Figure 10 shows the proportion of probabilistic outcomes that gave a larger value of displacement at the slope crest than the deterministic result. The proportion is obtained by counting the number of times the probabilistic result exceeds the deterministic result (Count ($\delta_{MC} > \delta_{det}$)) and dividing by the total number of simulations (i.e. Total Count = 400). For the lower correlation lengths, where there is more heterogeneity, it is more likely that the probabilistic outcome will be greater than the deterministic result, though these results are shown not to be very sensitive to correlation length. As an example, the percentage of outcomes of the vertical displacement at the crest that exceed the deterministic result reduces slightly from 59% to 56% with the change in correlation lengths from 1 to 10.

Effect of anisotropic correlation lengths

Figure 11 shows the variation between the mean probabilistic vertical displacement of the slope at different locations for anisotropic correlation lengths: (a) for a varying correlation length in the horizontal direction θ_x with a fixed correlation length in the vertical direction ($\theta_y = 1$ m), and (b) for a varying correlation length in the vertical direction θ_y with a fixed correlation length in the horizontal direction ($\theta_x = 1$ m). Deterministic analysis results are also provided for comparison. Results in Figure 11 demonstrate that increasing variability in the vertical direction mainly affects the vertical displacements; horizontal displacements were not sensitive to this change. Results of horizontal displacements (not shown here) indicated that increasing variability in the horizontal direction mainly affects the horizontal displacements, with vertical displacements are less sensitive to this change. Overall, however, the impact of the anisotropic correlation lengths on displacements was not significant.

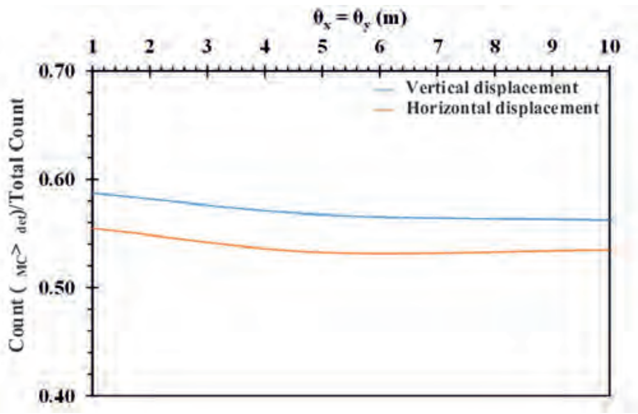

Fig. 10. Variation of proportion of probabilistic outcomes of slope crest displacements that were larger than deterministic results with correlation length

Rys. 10. Zmienność udziału probabilistycznych wyników przemieszczeń korony zbocza, które były większe od wyników deterministycznych w zależności od długości korelacji

Tab. 2. Values of mean probabilistic vertical displacements (in m) at different slope positions for varying magnitudes of coefficient of variation of spoil parameters.

Tab. 2. Wartości średnich probabilistycznych przemieszczeń pionowych (w m) w różnych położeniach na zboczu dla zmieniających się wielkości współczynnika zmienności parametrów materiału zwałowego.

Details	Crest	Middle	Toe
Low CoV: CoV_c = 20%, CoV_ϕ = 5%, CoV_E = 10%, CoV_e = 15%	-0.013	-0.003	0.006
Medium CoV: CoV_c = 30%, CoV_ϕ = 10%, CoV_E = 15%, CoV_e = 20%	-0.033	-0.004	0.019
High CoV: CoV_c = 40%, CoV_ϕ = 15%, CoV_E = 20%, CoV_e = 25%	-0.071	-0.006	0.049

Effect of coefficient of variation

The effect of the coefficient of variation of different spoil parameters on the measured mean vertical and horizontal displacements at the slope crest, middle, and toe were examined by considering three combinations corresponding to low, medium, and high levels of CoV, as detailed in Table 2. With increasing values of coefficient of variation, the upper and lower bound values of the range increases, which causes an increase in the mean probabilistic vertical displacements at all locations increases.

Conclusions

This paper investigated the response of spoil made slopes under the action of reservoir drawdown. Coupled flow-deformation analyses were carried out using the 2D finite element software Abaqus. Spoil suctions above the water table were considered. Effects of (i) drawdown velocity, (ii) depth of drawdown, (iii) spoil permeability, and (iv) spoil stiffness on the vertical displa-

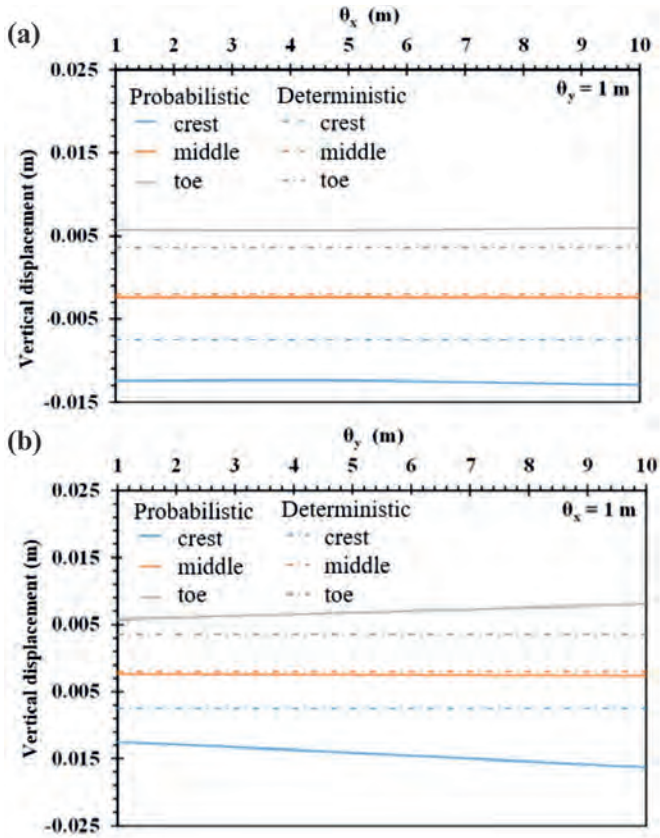

Fig.11. Variation between mean probabilistic and deterministic vertical settlements measured at different slope locations with varying correlation lengths: (a) varying θ_x and (b) varying θ_y

Rys. 11. Zróżnicowanie pomiędzy średnimi probabilistycznymi i deterministycznymi osiadaniami pionowymi zmierzonymi w różnych miejscach zbocza przy różniących się długościach korelacji: (a) zmieniającej się θ_x i (b) zmieniającej się θ_y

cements of the slope were investigated first by considering mean shear strength and hydraulic properties of spoil (deterministic analyses). Effects of heterogeneity and randomness of spoils on the response of the slope were then considered through random field modelling and the Monte-Carlo simulation technique (random field probabilistic analyses). Four lognormally distributed random variables (spoil cohesion, friction angle, void ratio, and permeability coefficient) were considered.

Vertical displacements of the slope at the crest and toe were higher for relatively high rates of drawdown. Drawdown depth had a significant effect on the slope displacements; slope displacements at the crest and toe were greater for the larger depth of drawdown (from 29 m to 21 m) compared to the lower drawdown depth (from 23 m to 21 m). Relatively low permeability spoils caused greater slope displacements than more permeable spoils, and slope displacements reduced with increasing spoil stiffness.

The effect of spatial variability of spoils on slope displacements was found to be significant. Outcomes demonstrated that slope displacements in many probabilistic analyses were greater than the deterministic analyses where spoil shear strength and hydraulic parameters were assumed constant (using the mean values from the probabilistic analyses). For isotropic random fields (i.e. correlation lengths $\theta_x = \theta_y$), slope displacements increase with the magnitude of correlation length, i.e. displacements increase as the heterogeneity decreases. With increasing correlation lengths, the deviation between deterministic and mean probabilistic values increases. This outcome was explained by considering the "influence zone" near the slope surface in conjunction with the spatial distribution, where the "influence zone" can be dominated by a more uniform region of soil with properties that lead to larger displacements. The effect of spatial variability was found to be more significant for greater drawdown depths as the range of variation in the "influence zone" of the slope was greater than that for the lower drawdown case. The anisotropy of the random fields (i.e. correlation lengths $\theta_x \neq \theta_y$) was shown to mainly affect displacements in the direction where the anisotropy existed (e.g. vertical anisotropy affected vertical displacements but not horizontal), however the overall effect was minimal. Increasing values of coefficient of variations of spoil parameters increased mean probabilistic vertical displacements at all locations within the slope.

Acknowledgements

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References

[1] EU (2020) *Production of lignite in the EU statistics (2020)*- https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Production_of_lignite_in_the_EU_-_statistics. Eurostat. Accessed June 2022.

[2] Le, T. M. H., Gallipoli, D., Sánchez, M., & Wheeler, S. (2015). *Stability and failure mass of unsaturated heterogeneous slopes. Canadian Geotechnical Journal,* 52(11), 1747-1761.

[3] Masoudian, M. S., Zevgolis, I. E., Deliveris, A. V., Marshall, A. M., Heron, C. M., & Koukouzas, N. C. (2019a). *Stability and characterisation of spoil heaps in European surface lignite mines: a state-of-the-art review in light of new data.* Environmental Earth Sciences, 78(16), 1-18.

[4] Masoudian, M. S., Afrapoli, M. A. H., Tasalloti, A., & Marshall, A. M. (2019b). *A general framework for coupled hydro--mechanical modelling of rainfall-induced instability in unsaturated slopes with multivariate random fields.* Computers and Geotechnics, 115, 103162.

[5] Phoon, K. K., & Kulhawy, F. H. (1999a). *Characterization of geotechnical variability.* Canadian geotechnical journal, 36(4), 612-624.

[6] Phoon, K. K., & Kulhawy, F. H. (1999b). *Evaluation of geotechnical property variability.* Canadian Geotechnical Journal, 36(4), 625-639.

[7] Zevgolis, I. E., Theocharis, A. I., Deliveris, A. V., Koukouzas, N. C., Roumpos, C., & Marshall, A. M. (2021). *Geotechnical characterization of fine-grained spoil material from surface coal mines.* Journal of Geotechnical and Geoenvironmental Engineering, 147(7), 04021050.

Post-coal mining Lake Most, Czech Republic