CENTRIFUGE MODELLING OF SPOIL SLOPES WITHIN PIT-LAKE MINE RECLAMATIONS

MODELOWANIE WIRÓWKOWE ZBOCZY ZWAŁOWISK W RAMACH REKULTYWACJI KOPALNI ODKRYWKOWYCH W KIERUNKU WODNYM

Ge Cui, Thejesh Kumar Garala, Naman Kantesaria, Koushik Halder, Nhat-Phi Doan, Charles M. Heron, Alec M. Marshall
Faculty of Engineering, University of Nottingham, United Kingdom

Pit lakes are a common form of reclamation of areas where open pit mining activities have taken place. The development of these lakes often uses previous overburden materials, or "spoils", that are readily available. Depending on the local geology, these spoil materials can contain large proportions of high-plasticity clays, which poses challenges in terms of the analysis and design of the sloped banks constructed to form new lakes. This paper describes a study in which geotechnical centrifuge modelling was used to investigate the stability and performance, in terms of accumulated displacements over cycles of lowering and raising the lake water elevation, of slopes constructed with a high-plasticity clay. A "replica-spoil" material was used in the tests to replicate key characteristics of spoil materials from known spoil heaps in Europe. The paper describes the centrifuge models and testing procedure developed for the tests, as well as the challenges encountered with the use of the high-plasticity clay. Two slope angles were tested: a 15° slope to match the typical slopes at a known field site, and a steeper 24° slope. Pore pressures within the slope were measured over several cycles of lake water elevation change. Slope displacements were measured using local transducers placed at the slope crest and toe, as well as using a PIV image analysis technique. The slopes were shown to experience plastic deformations, with displacements accumulating over subsequent cycles of lake water level change. The 24° slope developed slightly larger accumulated displacements than the 15° slope, though neither slope showed signs of ultimate collapse. Results from the centrifuge tests provide invaluable data which can be used for the verification of numerical models considering similar stability scenarios.

Keywords: *slope stability, spoil, centrifuge, high-plasticity*

Zbiorniki wodne są powszechną formą rekultywacji terenów, na których prowadzono wydobycie metodą odkrywkową. Do ich budowy często wykorzystuje się wcześniejsze materiały nadkładowe, czyli materiał zwałowy, który jest łatwo dostępny. W zależności od lokalnej geologii, materiał ten może zawierać duże ilości iłów o wysokiej plastyczności, co stanowi wyzwanie w zakresie analizy i projektowania nachylonych brzegów budowanych w celu utworzenia nowych zbiorników. W niniejszej pracy opisano badania, w których wykorzystano modelowanie w wirówce geotechnicznej do zbadania stabilności i zachowania, pod względem skumulowanych przemieszczeń w cyklach obniżania i podwyższania poziomu wody w zbiorniku, zboczy zbudowanych z iłów o wysokiej plastyczności. Aby odtworzyć kluczowe cechy materiałów zwałowych ze znanych hałd w Europie, w badaniach użyto materiału równoważnego. W artykule opisano modele wirówkowe i procedurę badawczą opracowaną na potrzeby badań, jak również wyzwania napotkane przy stosowaniu iłów o wysokiej plastyczności. Testowano dwa kąty nachylenia zbocza: 15°, aby pasowało do typowych zboczy w znanym miejscu w terenie, oraz bardziej strome nachylenie 24°. Ciśnienia porowe w obrębie zboczy były mierzone przez kilka cykli zmian poziomu wody w zbiorniku. Przemieszczenia zbocza były mierzone przy użyciu lokalnych przetworników umieszczonych na szczycie i u podnóża zbocza, jak również przy użyciu techniki analizy obrazów PIV. Wykazano, że zbocza ulegają deformacjom plastycznym, a przemieszczenia kumulują się w kolejnych cyklach zmian poziomu wody w zbiorniku. Zbocze o nachyleniu 24° rozwinęło nieco większe skumulowane przemieszczenia niż to o nachyleniu 15°, jednak żadne ze nich nie wykazywało oznak ostatecznego zawalenia. Wyniki badań wirówkowych dostarczają bezcennych danych, które mogą być wykorzystane do weryfikacji modeli numerycznych uwzględniających podobne scenariusze stateczności.

Słowa kluczowe: *stateczność zboczy, zwałowisko, wirówka, wysoka plastyczność*

Introduction

According to the latest report on lignite utilization in the power sector (EU, 2020), European countries use more than 250 million tonnes of lignite per year as a fuel source in steam-electric power generation. Lignite is usually obtained by surface mining which creates an open pit. During extraction of lignite, overburden mine wastes, or "spoils", are excavated first and then dumped to a location near the mine site. Abandoned mine sites are often reclaimed by flooding, which creates pit lakes. The development of these lakes often uses "spoils", that are readily available, to create the side slopes.

Depending on the local geology, these spoil materials can contain large proportions of high-plasticity clays, which poses challenges in terms of the analysis and design of slopes created for the new lakes. Additionally, spoils are anisotropic materials with large spatial variation in properties (Masoudian et al. 2019, Zevgolis et al. 2021). To ensure safe utilization of the newly created pit lakes by the public, it is necessary to assess the risk of instability and seasonal ground movements of these pit lake slopes.

This paper describes a study in which geotechnical centrifuge modelling was used to study the stability and performance, in terms of accumulated displacements over cycles of lowering and raising the lake water elevation, of slopes constructed with a high-plasticity clay. An equivalent spoil material was used in the tests to replicate key characteristics of spoil materials from known spoil heaps in Europe. This equivalent spoil material was obtained through characterisation of real spoil materials through field and laboratory testing (details provided in the corresponding conference paper entitled "Characterizing spoil materials and developing an equivalent spoil material for physical model tests"). This paper describes the centrifuge models and testing procedures developed for the tests, as well as the results obtained from the centrifuge tests.

Experimental methodology

To achieve the above objectives, centrifuge tests were performed to investigate the stability and ground movements of slopes due to seasonal water level change. Centrifuge tests were conducted at a centrifuge scale of N=80 g (i.e. the nominal acceleration experienced by the model was 80 times gravity). The results presented below are at prototype scale, meaning that they have been factored by the appropriate scaling factor to be representative of a full-scale scenario (i.e. the full scale prototype). Model scale dimensions of length *(L)* and displacements are 80 times smaller than those presented below (e.g. $L_m=L_p/N$); while time *(t)* is scaled by N^2 (i.e. $t_m=t_p/N^2$), where subscripts *m* and *p* denote model and prototype, respectively.

Tab. 1. Geotechnical properties of equivalent spoil
Tab. 1. Właściwości geotechniczne materiału równoważnego

Geotechnical Property	Value
Specific gravity, G_s	2.52
Sand fraction (%)	0
Silt fraction (%)	50
Clay fraction (%)	50
Liquid limit, LL (%)	46
Plasticity index, PI (%)	25.6
Compression index, C_c	0.545
Recompression index, C_r	0.07
Effective friction angle, φ' (degrees)	28
Undrained shear strength, (kPa)	26
Air entry value, AEV (kPa)	280 (drying curve), 130 (wetting curve)

Spoil materials

The centrifuge models were prepared using an equivalent spoil material (50% silt + 30% bentonite + 20% kaolin mixture), which was developed to replicate the physical and mechanical characteristics of spoil materials obtained from spoil heap sites near Lake Most in the Czech Republic. More details regarding the characterization of real spoil material and the development of the equivalent spoil can be found in Garala et al. (2022). The geotechnical properties of the equivalent spoil are summarised in Table 1.

Centrifuge model layout

Based on the cross-section data of Lake Most in the Czech Republic, 15° and 24° slopes were modelled in the centrifuge experiments, which represent one gentle slope and one steeper slope. The slope heights are 6.2 m and 10.3 m for the 15° slope and 24° slope, respectively. To investigate the behaviour of the two slopes, two centrifuge models were prepared and tested. The model layouts are presented in Figure 1.

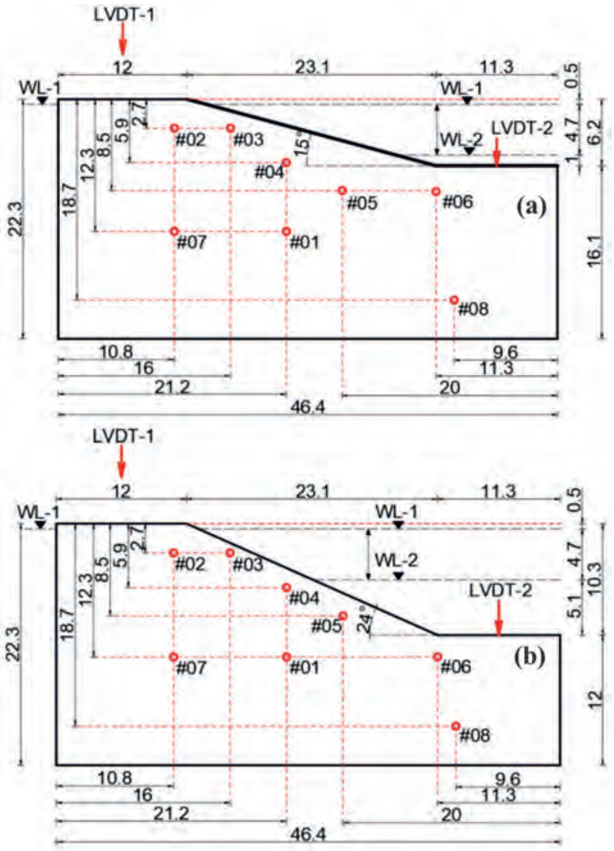

Fig. 1. Model layout in centrifuge testing (a) 15° slope (b) 24° slope (prototype scale; all in m)
Rys. 1. Układ modelu w badaniach wirówkowych (a) nachylenie 15° (b) nachylenie 24° (skala prototypowa; wszystkie wartości w m)

Eight pore pressure transducers (PPTs) were installed at the locations presented in Figure 1 to measure the pore pressure across the model. Two linear variable differential transformers (LVDTs) were used to measure the settlement of the slope at the crest and at the toe. As shown in Figure 2, to measure sub-surface soil displacements, the centrifuge strong box was designed with a transparent acrylic wall located at the front of the box to allow images to be captured using high resolution cameras throughout the duration of the tests. GeoPIV-RG (Stanier et al., 2015) was then used to process these images. The basic principle of the GeoPIV-RG is to first obtain the sub-surface soil displacements in pixel space, and then calibrate the pixel space displacements into objective space with the help of control points whose coordinates are already known, as shown in Figure 2.

Centrifuge testing procedure

The centrifuge soil model, comprised of a mixture of 50% silt (A50 silica flour), 30% bentonite, and 20% kaolin, was consolidated from slurry to obtain an initial soil model with constant height. PPTs were then installed at predetermined locations, see Figure 1, and LVDTs were used to monitor the model during a further consolidation phase in the centrifuge. After the initial soil model reached an equilibrium state, it was cut to one of the predefined geometries shown in Figure 1 to perform slope stability tests. These slope models, shown in Figure 2, were further stabilised in the centrifuge with a water level of 0.5 m below the slope crest.

Finally, the stability and ground movements of the slopes were assessed over typical cyclic water level fluctuations associated with changes in season. As shown in Figure 1, the water level for both slopes fluctuated between water level 1 (WL-1) and water level 2 (WL-2). The water level fluctuation procedure is detailed in Figure 3. The water level fluctuation cycle consists of two stages. In the first stage, the water level was reduced from WL-1 to WL-2 (4.7 meters drawdown) within approximately 44 days, and then the water level was maintained at WL-2 for 178 days (half a year). The water level was then increased from WL-2 to WL-1 (4.7 meters flooding) within 44 days and was then maintained at WL-1 for half a year. The water level on the left side of the slope was maintained at WL-1 throughout the fluctuation cycles. For the 15° slope, four water level fluctuation cycles were carried out while five water level fluctuation cycles were performed on the 24° slope. The water levels within the models were controlled with two standpipes and 7 solenoid valves. The PIV analysis was performed to capture the spoil movements at different stages of centrifuge testing.

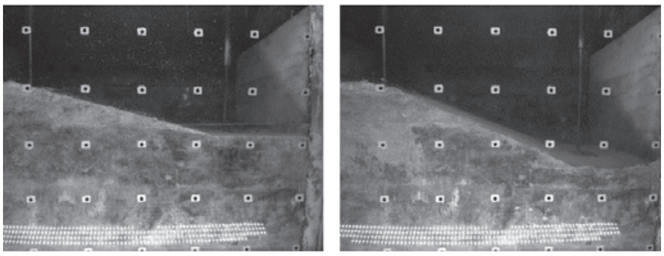

Fig. 2. Slope models in centrifuge testing prepared with an inclination of (a) 15° and (b) 24°

Rys. 2. Modele zboczy w badaniach wirówkowych z nachyleniem a) 15° i b) 24°

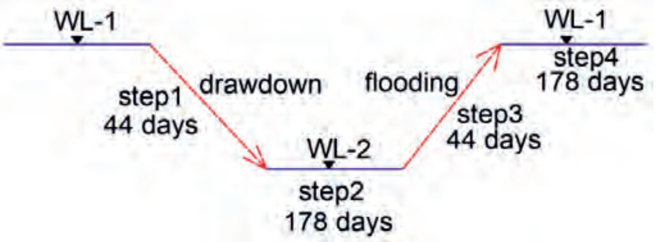

Fig. 3. Cyclic water level fluctuation cycle for both models

Rys. 3. Cykliczne wahania poziomu wody dla obu modeli

Centrifuge test results

This section presents results based on the measurements acquired from the PPTs, LVDTs and PIV imaging technique over the duration of the cyclic water level changes for both slopes.

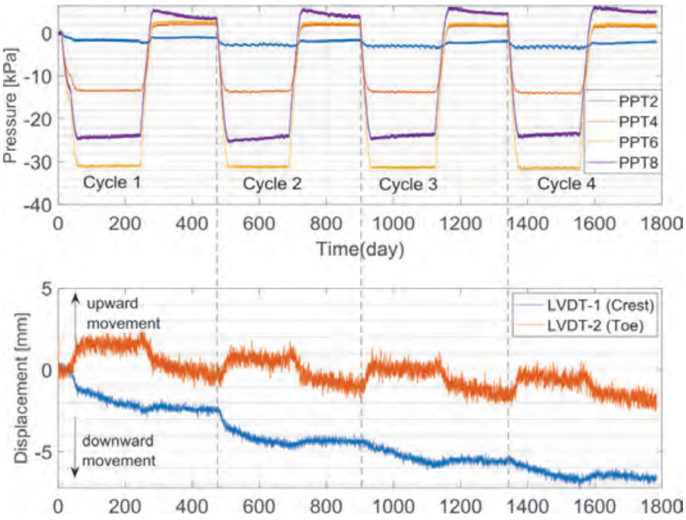

Fig. 4. Pore pressure and displacement of 15° slope

Rys. 4. Ciśnienie porowe i przemieszczenie w przypadku zbocza o nachyleniu 15°

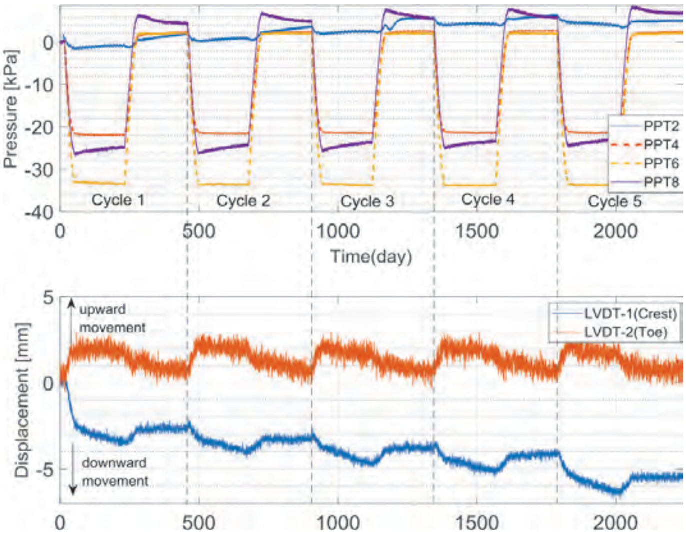

Fig. 5. Pore pressure and displacement of 24° slope

Rys. 5. Ciśnienie porowe i przemieszczenie w przypadku zbocza o nachyleniu 24°

Results from PPTs and LVDTs

Figures 4 and 5 present the change in pore pressure measured by the PPTs at four representative locations and the displacements measured by the two LVDTs for the 15° and 24° slopes, respectively. It can be seen from the PPT data that the change in pore pressure is consistent with the fluctuating water level as it decreases/increases with the decreasing/increasing water level. During each fluctuation cycle, the water level was maintained for half a year once the water table reached the target. It can be seen from Figure 4 that pore pressures are relatively constant over this period. Small fluctuations, see PPT8, are a result of the water level control system.

In terms of the displacement at the crest, it can be seen from Figures 4 and 5 that the crest settles with the reduced water level and moves back up slightly with the increasing water level. The settlement of the 15° slope over each cycle decreases with the water level fluctuation cycles: 2.5 mm for cycle 1, 2 mm for cycle 2, 1 mm for cycle 3 and 1 mm for cycle 4. The settlement accumulates with the water level fluctuation cycles and reaches 6.7 mm over 4 cycles. Similar levels of settlement over each cycle are also seen for the 24° slope.

On the contrary, the toes of both slopes move up with the decreasing water level and then settle with the increasing water level. The overall displacement of the 15° slope at the toe over each cycle is downward which indicates that the toe settles with the increasing number of fluctuation cycles. The settlement also accumulates with the fluctuation cycles and reaches about 2 mm over 4 cycles. However, the overall displacement of the 24° slope over each cycle is upward, and the displacement accumulates to approximately 1 mm over 5 cycles.

PIV results

The PIV imaging technique can provide the displacement field across the whole model, which can provide insights into the behaviour of the slopes under cyclic water level change. This section presents the tracked displacement field of both slopes over the water level fluctuation cycles.

First cycle behaviour

The displacement fields of the 15° slope and the 24° slope by the end of the first drawdown (step01 to step03) are shown in Figures 6 and 7, respectively. The top figure indicates the direction of the movement, and the bottom figure shows the amplitude of the displacement. It can be seen from Figures 6 and 7 that the whole slope moves towards the toe with the reduced water level. The largest displacement occurs near the middle of the slope: about 7 mm for the 15° slope and 10 mm for the 24° slope. It should be noted that some abnormal behaviour occurred just below the crest where a much larger displacement of 15 mm is observed. This is the result of a crack forming during the slope consolidation stage. As such, this cracked zone will not be considered from this point onwards.

Figures 8 and 9 present the displacement fields of the 15° slope and 24° slope from the end of the first drawdown to the end of the first flooding (step03 to step 05). It can be seen for both slope angles that the whole slope moves approximately 2 mm towards the crest when the water level is increased. This indicates both slopes experience a plastic deformation over the cyclic water level change, and that the PIV results are consistent with the LVDT measurements.

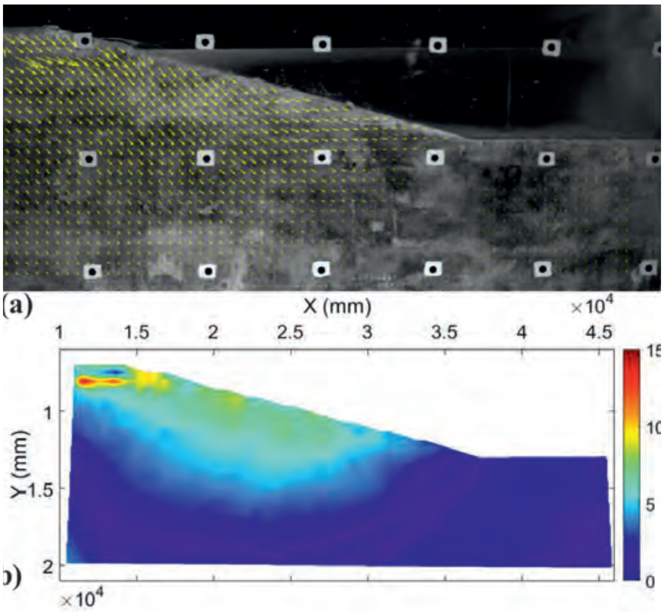

Fig. 6. First drawdown (step01-step03) of 15° slope (a) movement direction (b) displacement contours

Rys. 6. Pierwsze obniżenie poziomu wody (krok01-krok03) dla zbocza o nachyleniu 15° a) kierunek ruchu b) kontury przemieszczenia

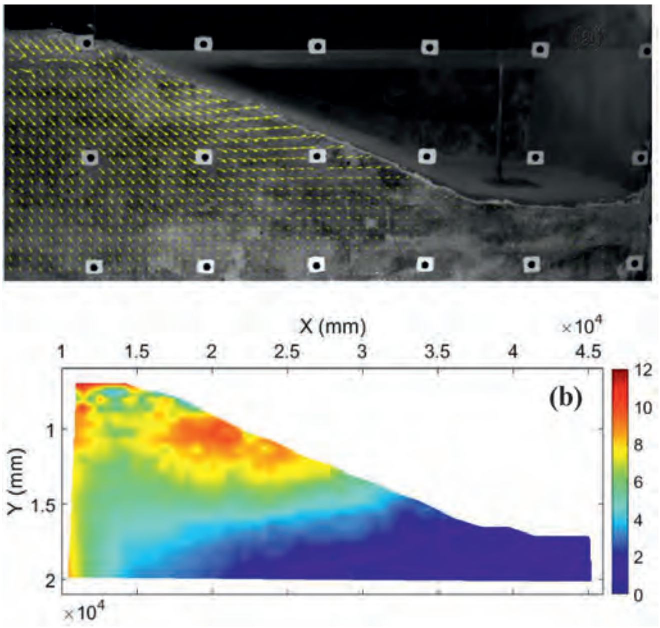

Fig. 7. First drawdown (step01-step03) of 24° slope (a) movement direction (b) displacement contours

Rys. 7. Pierwsze obniżenie poziomu wody (krok01-krok03) dla zbocza o nachyleniu 24° a) kierunek ruchu b) kontury przemieszczenia

Cyclic behaviour

Figures 10 and 11 present the displacement fields of the two slopes from the beginning to the end of each water level drawdown. It can be seen that slope displacements accumulate over the cyclic water level change. For the 15° slope, the largest deformation is approximately 7 mm for cycle 1, 11 mm for cycle 2, 12 mm for cycle 3, and 14 mm and for cycle 4. For the 24° slope, the largest deformation is approximately 10 mm for cycle 1, 12 mm for cycle 2, 13 mm for cycle 3, 15 mm for cycle 4, and 16 mm for cycle 5. Hence, the 24° slope developed slightly larger accumulated displacements than the 15° slope. The displacement of the toe area is approximately 2 mm over the duration of the fluctuation cycles for both slope angles.

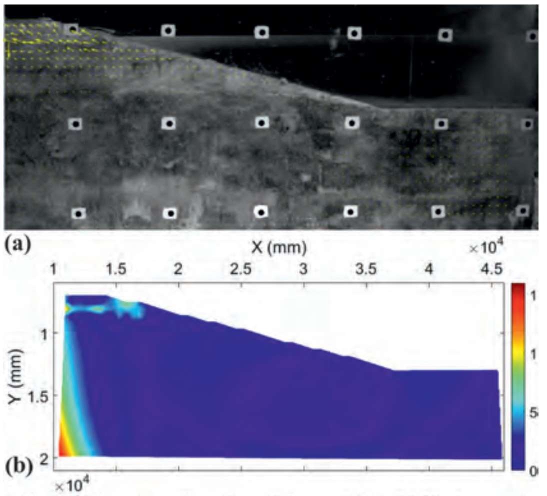

Fig. 8. First flooding (step03-step05) of 15° slope (a) movement direction (b) displacement contours

Rys. 8. Pierwsze zalewanie (krok03-krok05) dla zbocza o nachyleniu 15° a) kierunek ruchu b) kontury przemieszczenia

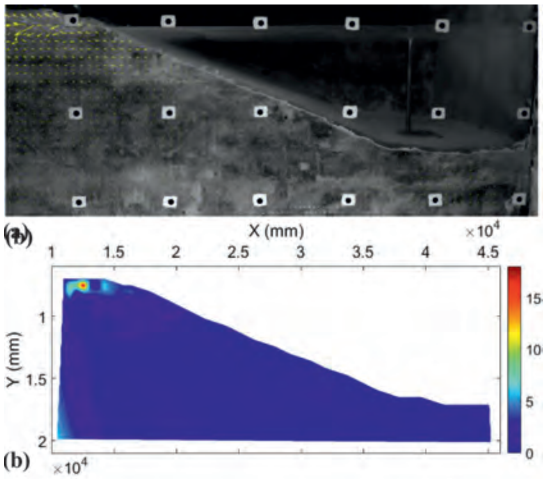

Fig. 9. First flooding (step03-step05) of 24° slope (a) movement direction (b) displacement contours

Rys. 9. Pierwsze zalewanie (krok03-krok05) dla zbocza o nachyleniu 24° a) kierunek ruchu b) kontury przemieszczenia

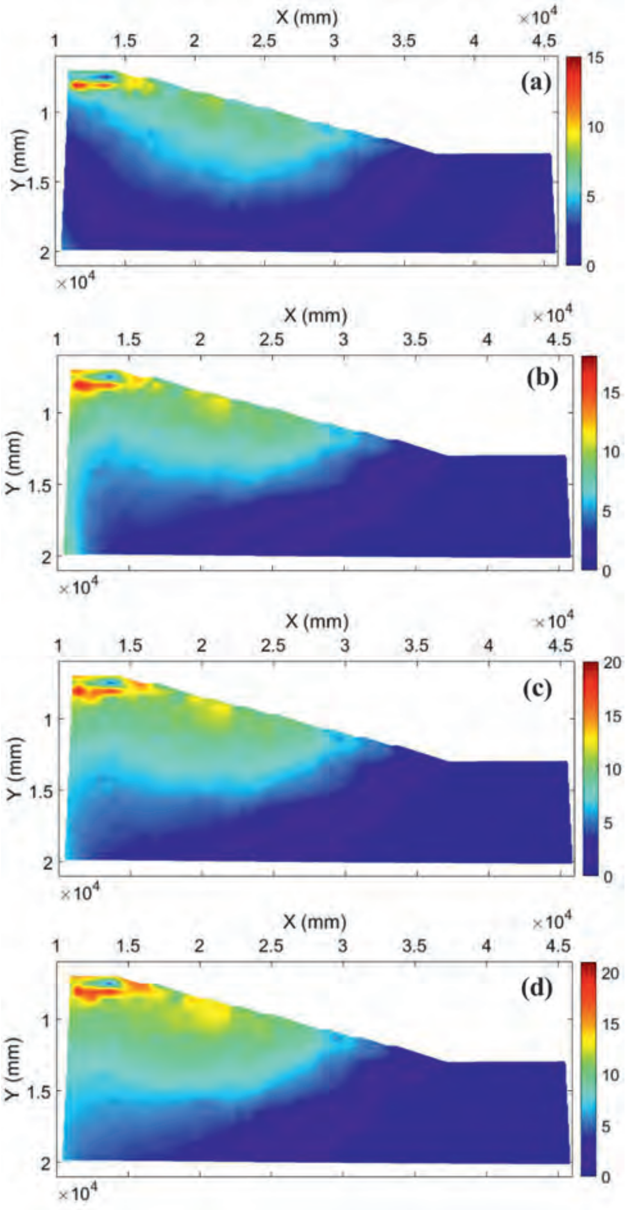

Fig. 10. Accumulated displacement (in mm) of 15° slope at 4 drawdown stages (a) drawdown 1 (b) drawdown 2 (c) drawdown 3 (d) drawdown 4

Rys. 10. Łączne przemieszczenie (w mm) zbocza o nachyleniu 15° w 4 etapach obniżania poziomu wody a) obniżenie 1 b) obniżenie 2 c) obniżenie 3 d) obniżenie 4

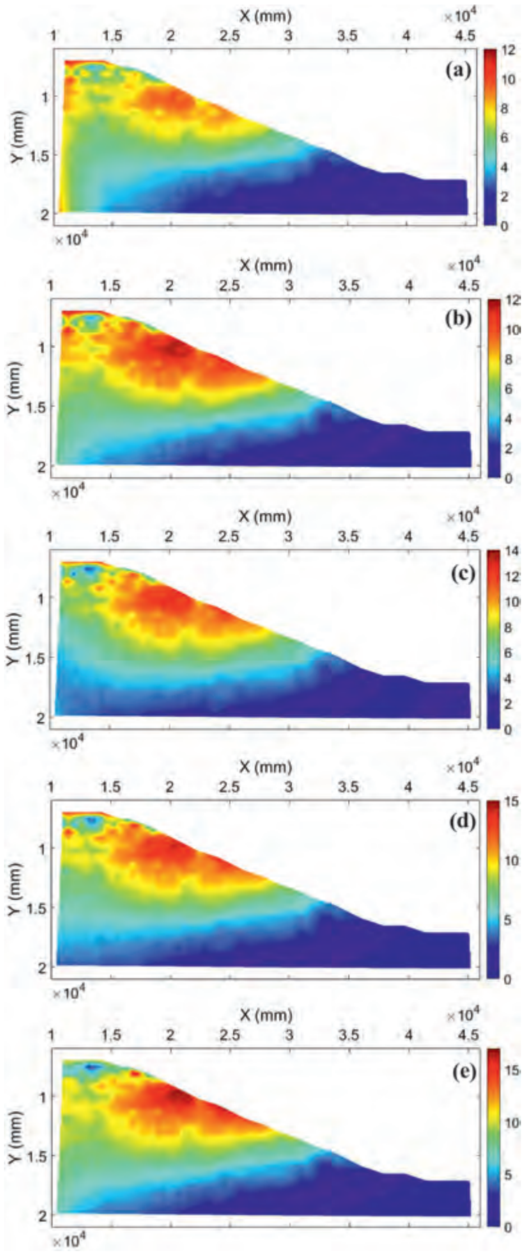

Fig. 11. Accumulated displacement (in mm) of 24° slope at 5 drawdown stages (a) drawdown 1 (b) drawdown 2 (c) drawdown 3 (d) drawdown 4 (e) drawdown 5

Rys. 11. Łączne przemieszczenie (w mm) zbocza o nachyleniu 24° w 5 etapach obniżania poziomu wody a) obniżenie 1 b) obniżenie 2 c) obniżenie 3 d) obniżenie 4 e) obniżenie 5

Conclusions

This study investigated the response of spoil made slopes under the action of reservoir drawdown. Centrifuge tests were carried out on two slopes: a 15° slope and a 24° slope. A water level change of 4.7 meters over about half a year was employed to model the seasonal water level fluctuation. The pore pressures and displacements were measured to evaluate the stability and performance of the two slopes during the cyclic water level fluctuation. It was found that the pore pressure decreases and increases with the decreasing and increasing water level and remains almost constant when the water level was maintained at a constant height. The displacement fields of the 15° slope and 24° slope over the first cycle indicate that the whole slope moves towards the toe when the water level decreases and then moves towards the crest when the water level increases with a much smaller amplitude.

This indicates that both slopes experience plastic deformation, and slope displacements accumulate, over the cyclic water level change where the largest displacements occur near the middle of the slope. For the 15° slope, the largest deformation is about 7 mm for cycle 1, 11 mm for cycle 2, 12 mm for cycle 3, and 14 mm for cycle 4. For the 24° slope, the largest deformation is about 10 mm for cycle 1, 12 mm for cycle 2, 13 mm for cycle 3, 15 mm for cycle 4, and 16 mm for cycle 5. The 24° slope developed slightly larger accumulated displacements than the 15° slope. Compared to the slope area near the crest, the displacement of the toe area remains almost constant, approximately 2 mm over the duration of the fluctuation cycles for both slopes.

Acknowledgements

This work received funding from the EU's Research Fund for Coal and Steel under the projects "RAFF – Risk Assessment of Final Pits during Flooding" Grant No. 847299.

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] Garala T. K., Cui G., Kantesaria N., Heron C., and Marshall A. (2022). *Uniform compacted models for centrifuge testing of plastic fine-grained soils.* 10th International Conference on Physical Modelling in Geotechnics, Daejeon, Korea, September 19-23, 2022.

[3] Masoudian, M. S., Zevgolis, I. E., Deliveris, A. V., Marshall, A. M., Heron, C. M., & Koukouzas, N. C. (2019). *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] Stanier, S. A., Blaber, J., Take, W. A., and White, D. (2015). *Improved image-based deformation measurement for geotechnical applications.* Canadian Geotechnical Journal, 53(5):727-739.

[5] 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.


Image courtesy of Lubelski Węgiel BOGDANKA S.A.

Heap of the Lubelski Węgiel Bogdanka coal mine, Poland