Landfill slopes reinforcements for adapting the structure into a new development plan: Radiowo landfill case study

Renfort de talus d'une décharge dans le but d'adapter la structure dans un nouveau plan de développement: étude de cas de la décharge de Radiowo

Eugeniusz Koda, Tomasz Pasik, Piotr Osinski, Anna Miszkowska, Bartłomiej Bursa.
Department of Geotechnical Engineering, WULS-SGGW, Poland, eugeniusz_koda@sggw.pl

ABSTRACT: Radiowo landfill is an embankment type structure located in Warsaw, Poland. For the purpose of adapting the old municipal landfill into a winter sport complex, the slopes of the structure required major reinforcements. Due to lack of space for overburdens and berms construction, the retaining walls and sophisticated geosynthetics reinforcement constructions were applied at the site. The investigation of mechanical properties of the waste material is still a challenging task. Thus, in the study the geotechnical parameters used for analyses were based on CPT investigation results as well as back analyses of landslides on the landfill and test embankments. The computations involved static and displacement analyses for the structure filled with reinforced soil and for masonry structure. To determine the most reliable and accurate critical slip surfaces both standard methods i.e. LEM and FEM were used. Additionally a new approach applying Genethic Algorithms for locating the slip surface was presented. The modeling was performed using numerical methods applying the approaches specified in Eurocode 7 standards.

RÉSUMÉ: La décharge de Radiowo est une structure de type remblai située à Varsovie, Pologne. Dans le but d'adapter l'ancienne décharge municipale en un complexe de sports d'hiver, les talus de la structure nécessitent de grands renforcements. En raison du manque d'espace pour la mise en place de remblais et de risbermes, des murs de soutènement et des géosynthétiques de renforcement sophistiqués ont été installés sur le site. L'étude des propriétés mécaniques des déchets est encore une tâche difficile. Dans cette étude, les paramètres géotechniques utilisés pour les analyses ont été basées sur les résultats de CPT ainsi que sur l'analyse de glissements de terrain sur les décharges et sur des remblais de test.. D'autres calculs ont impliqué l'analyse statique et de déplacement pour la structure remplie de sol renforcé et pour la structure en maçonnerie. Pour déterminer les surfaces de glissement critique les plus fiables et les plus précises, on a utilisé des procédés classiques, à savoir Méthode d'équilibre limite (MEL) et Méthode des éléments finis (MEF). De plus, une nouvelle approche appliquante les Algorithmes Genethiques pour localiser le plan de cisaillement a été présentée. Les analyses ont été effectuées en utilisant les méthodes numériques et en appliquant les méthodes spécifiées dans la norme Eurocode 7.

KEYWORDS: Landfill, reclamation works, slope stability, geotechnical investigation, reinforcements, numerical analyses.

1 INTRODUCTION

In the paper the solutions and analyses for landfill slopes stability improvements were presented and discussed. The reinforcements introduced at the landfill were applied due to complex reclamation works, for the future ski slope construction at the site. The reclamation works on landfills are usually a long term process (Koda and Osinski 2015). They often require application of sophisticated engineering techniques, and using filling material of specific characteristics. Most of old municipal landfills in Poland were usually exploited with no concern regarding appropriately planned earth works, even for very steep landfill slopes. That was the main cause for number of severe slope failures, expanding the actual landfills areas and contaminating surrounding sites. As an example Radiowo landfill case study was described.

Due to changing conditions on exploited landfills it has been recently recommend using so called observational method, mainly to verify applied reinforcements and stability improving solutions (EN 1997-1 :2004, Brandl 2008). Based on this method the whole plan of reclamation works on Radiowo landfill were performed. To increase geotechnical safety of the entire landfill body there were several approaches proposed. They mainly concerned slope stability improvements by filling the slopes with reinforced soils (geogrids), waste material (ballast waste mixed with soil, used tires, debris, fly ash sewage sludge mixtures). Also heavy construction works like retaining walls (steel sheets, concrete blocks) took place and additional loading embankments were proposed. The materials used and improvement locations are presented in Table 1. All works had to be performed before introducing winter sport facilities. 3D view of new shape of the landfill body is presented in Fig. 1.

Table 1. Improvements used at Radiowo landfill slopes (Koda and Osinski 2015).

construction material	application	location
composting plant waste	slope improvements, landfill body shaping	load embankments
steel profiles, concrete blocks	slope toes	retaining walls
used tires, geogrid, geotextiles	vertical mattresses	landfill slopes
debris ,ballast waste	access roads beddings	access roads

2 RADIOWO LANDFILL SITE DESCRIPTION AND FUTURE DEVELOPMENT PLAN

Since early 1962 to 1991 the municipal waste from Warsaw has been disposed at Radiowo landfill. Since 1992 only ballast wastes from the composting plant have been deposited on the landfill and later, since 2012 only waste from the treatment plant have been stored there. Actually, it covers ca. 16 ha area, and its height is about 60 m. Initially there was no protection system against environmental contamination. Since 1994, the remedial works concerning stability reinforcement, forming and planting the slopes, mineral capping, drainage construction, recirculation system and bentonite cut-off wall have been constructed on the landfill. The cut-off wall barrier was designed mainly to minimize the spread of contaminants into the surrounding soil-water environment as well as to provide favorable hydraulic conditions.

In the near future the landfill site is planned to be adopted to be used as a ski slope with all winter complex facilities included

(Figure 1). It is planned that at the new designed level (84 m above "0" level), at the crest of the landfill the viewing points, snowboard half pipe, upper ski station and the starting point of the ski slope will be introduced. During the whole season it is planned to launch the ski lift on the south-west part of the landfill and on the west side the sled slope will be open. However,, the main part of the new development plan is to construct the ski slope of 30 m width, of 56 m altitude difference, inclination up to 14% and the total length of 650 m.

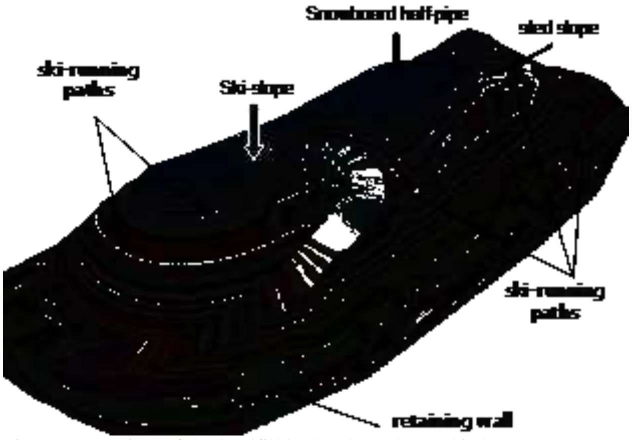

Figure 1. 3D view of the landfill body adapted to a ski slope.

3 LANDFILL SLOPES REINFORCEMENTS AND SLOPE STABILITY ANALYSIS USING DIFFERENT COMPUTATIONAL APPROACHES

3.1 *Slope reinforcements and material parameters*

One of the main challenges of reclamation works of Radiowo landfill was to improve the stability conditions of slopes so it could be safely use as a ski slope. Due to the ownership issues of an area attached to the landfill site the engineering works on slopes mainly consisted of retaining walls construction. To reinforce the north part there were steel sheets used, with layers of HDPE geogrid above it. Additionally a masonry retaining wall of 6.2 m height, with backfill reinforced by geogrids and geotextiles has been constructed in the south-east (Miszkowska et al. 2015, Kiersnowska et al. 2017). A location and structural design of the masonry retaining wall is presented in Figures 1 and 2.

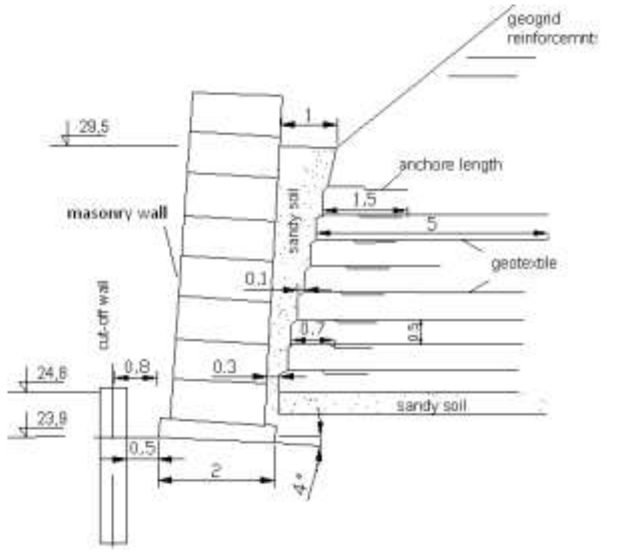

Figure 2. Cross section of retaining wall (Miszkowska et al. 2015).

Due to new development plan of the landfill site it will be also necessary to construct an earth embankment in the south part. The new inclinations of slopes is planned to be from 1:1.5 to 1:2. In other parts of the landfill also loading embankments, anthropogenic material mixtures, and mattresses of used tires were used. In the case of Radiowo landfill the main challenge was to precisely determine the geotechnical parameters of waste built into the slope, so the stability analyses could be reliable. For this purpose mechanical parameters of waste were investigated by using three main groups of tests. These were back analyses, trial loading and geotechnical in situ tests (CPT, WST). Based on those results the parameters could be established and adopted to further calculations. The geotechnical parameters of material are presented in Table 2. In both cross sections there are three main geotechnical layers distinguished (from the top: ballast waste, old waste, subsoil).

Table 2. Geotechnical parameters of landfill slopes filling material (Koda and Osinski 2015).

filling material	γ [kN/m^3]	ϕ [°]	c [kPa]	E [MPa]
old waste	14.0	26.0	20.0	15.0
ballast waste	11.0	22.0	25.0	10.0
subsoil	18.5	31.0	0.0	70.0

Reliable landfill slope stability analyses were crucial for determining the safety of planned geometry of the landfill body (Koda and Osinski 2015). Due to diversity of the landfill slopes filling material the comparative stability analyses using different computational methods were required. The most common methods are limit equilibrium (LEM) and finite element method (FEM) (Griffiths and Lane 1999). On Figure 3 a 3D view of actual geometry for the landfill body is presented. On this figure also a location of the cross sections that were used for further computation is shown. There is A-A cross section for which an additional loading embankment was constructed, and B-B (south-east slope) where such reinforcements as retaining wall and geosynthetics were applied.

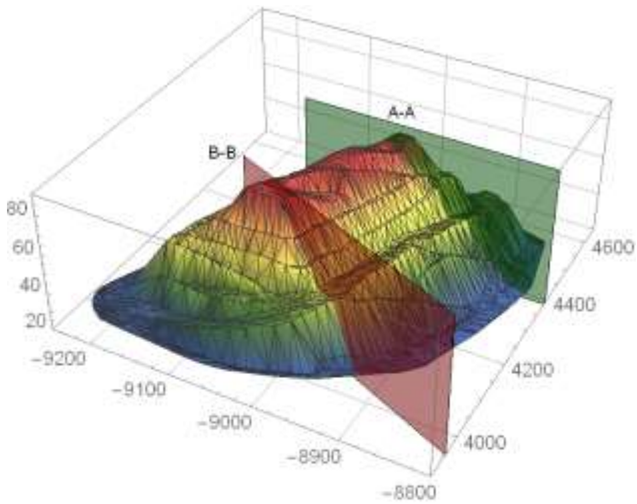

Figure 3. 3D visualization of Radiowo sanitary landfill and A-A cross-section.

3.2 *Spencer's Method with Genetic Algorithm procedure location of critical unconstrained failure surface*

Nowadays, commonly used methods for evaluation of factor of safety (FOS) are so called slice methods i.e. Bishop, Spencer, Morgenstern-Price (Bishop 1955, Spencer 1967). The Spencer method is one of the most popular in engineering practice (Osinski et al. 2014). Its principal assumption is including all interslice forces when determining FOS. There is a number of commercial software easily available where slice methods are used. However, only few of them offer effective way of determining the most unfavorable shear plane. Presently, most popular procedure for the slip surface determination is a grid point method. It is based on computing the entire combination of circle centre location and the length of radius, plotting the shear plane for which the FOS is the lowest. This method applies only when circular shear plane is considered. It seams that wiser solution for shear plane location is to use Genetic Algorithm (Goldberg 1989). This approach is a lot less time consuming and allows determining any shape of the failure slip surface. An application of Genetic Algorithm to locate the critical shear plane has already been describe by number of researchers (Li et al. 2010). However, lack of the access to source codes when trying to repeat the solutions raises an issue.

Pasik and Van der Meij (2016) proposed the source code in Mathematica language, where Genetic Algorithm was defined and adapted to locate any geometry of the failure shear plane. The evaluation of generated failure shapes was conducted in D-Geo Stability (Deltares Systems 2016). To obtain the solutions the algorithm considers a lower number of surfaces (up to 3000) when in cases proposed by other authors this number can reach up to 15000 (for hybrid algorithms) (Zhu and Chen 2014).

The analyses of stability in section A-A (Figs. 3 and 4.) were performed by using D-Geo Stability. Every shear plane is defined as a table of any number of components $\{l_1,..,l_n\}$, where every single one is defined by actual number from 0 to 1 (Fig. 5). Every searching section of 1 has finite length and defined end coordinates.

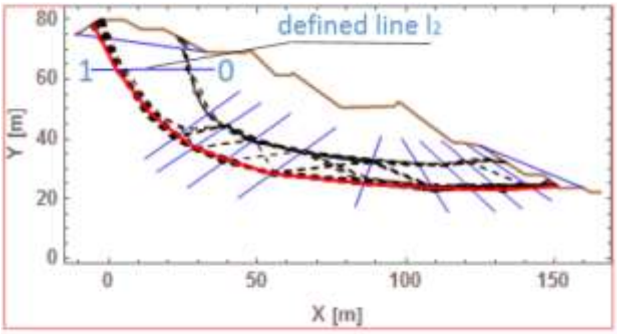

Figure 5. Definition of searching lines and last population of slip surfaces.

After defining searching section the algorithm generates the initial population consisting of 40 elements, which in the next stage were subjected to genetic operators i.e. selection, crossing, mutation. In result new population is better fitted to a purpose function which in this case is the lowest FOS. The procedure was repeated 40 times. The population fitting result in each generation, what is presented on Figure 6. The most significant from the entire population is an element of best fitting, and it defines searched failure plane. For the analyzed section A-A the FOS= 1.25 (red line in Fig. 5).

3.3 *Finite Element Method*

For the cross- section A-A there were also preformed FOS analyses using FEM, by applying method of shear strength reduction (Griffiths and Lane 1999). For the final computation an 8-node quadrilateral elements were assumed. To present the shear planes the accumulated plastic strain contour graphs were plotted on Figure 7. Additionally the failure planes computed by using Bishop and Spencer combined with Genetic Algorithm methods were also plotted on the same figure. For all the methods the FOS was very much similar: 1.26 for Bishop and, 1.256 for Spencer and FEM. The critical shear surfaces for the cross section A-A were of very much similar geometry.

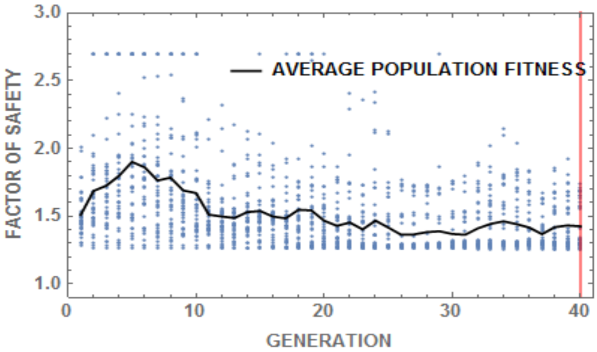

Figure 6. Population fitting versus number of generations.

However, it needs to be emphasized that the shape of failures for FEM and Spencer combined with Genetic Algorithm are nearly overlapping each other.

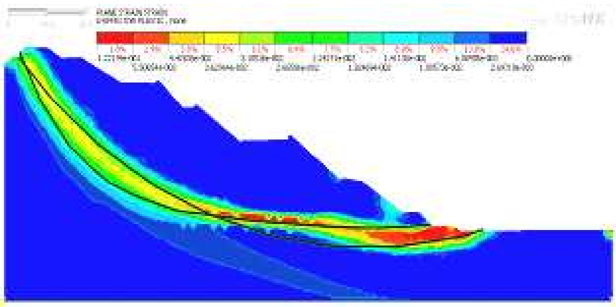

Figure 7. FEM results of accumulated plastic strain (Midas GTS NX) and LEM critical slip surfaces (D-Geo Stability).

3.4 *Limit equilibrium method and finite element method for reinforced slope*

For the purpose of investigating the geotechnical safety of the landfill adapted to new development plan there were also preformed calculations of FOS for the reinforced slope in section B-B, using LEM and FEM. This is the section where retaining masonry wall (Fig. 2) was constructed (south-east part of the landfill). Due to planned ski slope that will overcome this part in a future, beside the wall there were also proposed geogrids to be built into the filling above the masonry. The geogrids of reduced tensile strength 10 kN, were introduced in 5 layers, each of 7 m length. The location of cross section B-B is presented on Figure 3. The initial calculations for bare slope revealed that the safety was not met. However, for the computations of reinforces slope (i.e. retaining wall and geogrids) a global FOS increased up to 1.49. The calculation also involved determining the weakest local slip surfaces. The results are presented in Figure 8. For the down slope local FOS was 1.22, and for the middle part local FOS was 2.45.

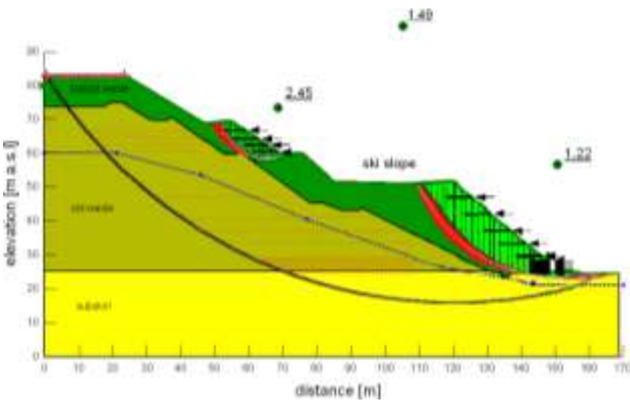

Figure 8. Slope stability analyses for reinforced slope using Bishop method, computations for three slip surfaces (cross section B-B).

The calculations for LEM were based on Bishop method by using Slope/W software. It applies the method of slices, but in contrast to Spencer and LEM, it assumes only cylindrical critical shear plane. For this reason for the section B-B there were also performed analyses using FEM (Fig. 9). Comparing those two approaches (LEM and FEM), it can be noted that the locations and shapes for plotted slip surfaces, are very much similar (bearing in mind that Bishop's method considers only cylindrical slip surface). Also the results for FOSs (global and local) revealed insignificant differences. The results for FEM computations are presented in Fig. 9.

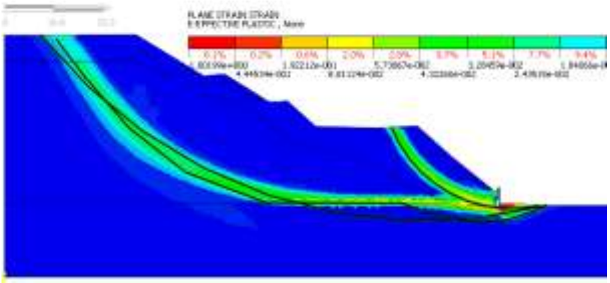

Figure 9. Slope stability analyses for reinforced slope using finite element method (cross section B-B).

The modeling gave very promising answers on the landfill body safety, and appropriates of used stability improving solutions. It is worth mentioning that such reinforcements as geogrid (HDPE) layers were also used in the north slope of the landfill in 1993. Recently the geosynthetic samples have been excavated and examined in the laboratory to determine mechanical condition of the material after 20 years of service (Koda et al. 2016). Based on obtain results the reduction factors for tensile strength could have been verified and applied in present computations.

4 CONCLUSIONS

In the paper the solutions for landfill slopes reinforcement were presented. All the works were aimed at meeting the safety requirements stated in new development plan for restored site. The landfill is planned to be adopted as a ski slope with number of winter sports facilities included. This makes the entire investment quite complex and demanding from geotechnical safety point of view. To meet strict requirements the landfill body needs to be engineered, and the slopes in some parts had to be reinforced by using geotechnical structures or anthropogenic filling materials.

One of the most efficient ways of reinforcing the slope is construction of loading embankments. However, this solution applies only when the space at the toe of the slope is accessible. In other cases when access is limited or the land ownership issues comes up, the retaining structure could be of great alternative. In this case however, a slope required additional protection like: geosynthetic reinforcements, using anthropogenic filling materials or waste to stabilize the slope. To investigate the appropriateness of proposed solutions slope stability analyses were presented. The computations reveal that the geotechnical safety of analysed slopes was met.

In the first case for cross section A-A the FOS obtained by using three different methods Bishop, Spencer combined with Genetic Algorithm and FEM gave very good agreements. The analyses revealed that Spencer method, employing Genetic Algorithm procedure for determining the location of critical unconstrained failure surface, is very good approximation of FEM (SRM). It refers to the shape of a shear plane and also to FOS computations. The approach applies in cases when effective assessment of reinforced landfill slope is required.

In the other case the stability analyses was performed for cross section B-B, where retaining masonry wall and layers of HDPE geogrid were implemented. The computations revealed that the proposed solution remain safe value of factor of safety for the analysed section. The factors of safety were computed for local and global slip surfaces. To avoid obtaining uncertain and unreliable geometry of critical slip surfaces the calculations involved both LEM and FEM. The comparison gave a clear answer that the results are reliable, and the reinforcements perform very well.

5 REFERENCES

Bishop A.W. 1955. The use of the slip circle in the stability analysis of slopes. *Géotechnique* 5, No. 1, 7–17.

Brandl H. 2008. Environmental geotechnical engineering of landfills and contaminated land. *Proc. of the 11th Baltic Sea Geotechnical. Conference on Geotechnics in Miritime Engineering*, Gdańsk, 803-826.

Cheng Y.M. and Lau C.K. 2008. *Slope Stability Analysis and Stabilization. New methods and insight.* London and New York, Routledge.

Deltares Systems. 2016. *D-Geo Stability. Slope stability so ware for so soil engineering.* Deltares, Netherlands.

EN 1997-1: 2004. Eurocode 7. Geotechnical design. Part 1. General rules.

Goldberg D. E. 1989. *Genetic Algorithms in Search, Optimization and Machine Learning, 1st Edition.* Addison Westley Longman Publishing Co., Inc., Boston, MA, USA.

Griffiths D.V. and Lane P. A. 1999. Slope stability by finite elements. *Géotechnique* 49 (3), 387-403.

Kiersnowska A., Koda E., Fabianowski W. and Kawalec J. 2017. Effect of the impact of chemical and environmental factors on the durability of HDPE geogrid in a sanitary landfill. *Applied Sciences* 7(1), No. 22; doi:10.3390/app7010022

Koda E. and Osinski P. 2015. Application of alternative methods of slope stability improvement on landfills. *Proc. of the 16th European Conference of Soil Mechanics and Geotechnical Engineering*, Edinburgh, 2717-2722.; doi:10.1680/ecsmge.60678

Koda E., Osinski P., Kiersnowska A. and Kawalec J. 2016. Stabilizacja georusztem heksagonalnym podłoża pod trasę narciarską na składowisku *Acta Scientiarum Polonorum – Architectura* 15(4) [in Polish].

Li Y.-C., Chen Y.-M., Zhan T. L., Ling D.-S. and Cleall P. J. 2010. An efficient approach for locating the critical slip surface in slope stability analyses using a real-coded genetic algorithm. *Canadian Geotechnical Journal* 47 (7), 806-820.

Miszkowska A., Stępień S., Jasko A. and Koda E. 2015. Wpływ temperatury na parametry wytrzymałościowe geotkaniny wykorzystanej do budowy konstrukcji oporowej na składowisku. *Acta Scientiarum Polonorum – Architectura* 14(1), 43-53. [in Polish].

Osinski P., Rickson R.J., Hann M.J. and Koda E. 2014. Assessment of slope stability influenced by vegetation cover and additional loads applied *Annals of Warsaw University of Life Sciences – SGGW Land Reclamation* 46 (2), 81-91.

Pasik T. and Van der Meij R. 2016. Locating critical circular an unconstrained failure surface in slope stability analysis with tailored Genetic Algorithm - Mathematica code. [draft].

Spencer E. 1967. A method of analysis of the stability of embankments assuming parallel interslice forces. *Géotechnique* 17, No. 1, 11–26.

Zhu J. and Chen C. 2014. Search for circular and noncircular critical slip surfaces in slope stability analysis by hybrid genetic algorithm. *Journal of Central South University* 21 (1), 387-397.