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# IMPROVEMENT OF SLOPE STABILITY AS A RESULT OF COMBINING DIVERSE REINFORCEMENT METHODS

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**Abstract.** The paper presents several methods of slopes reinforcement using anthropogenic materials, geosynthetics and bio-engineering methods. The case study to be presented proves that complex combination of slope engineering techniques influences the factor of safety of slopes significantly. The reinforcing materials used consisted of tires mattresses, waste material from landfill site, composition of geotextiles, geogrids and vegetation cover. The assessment of applied solution efficiency was conducted using numerical modeling and long term observations of the reinforced structures. The computation of factor of safety was conducted including all the geotechnical parameters of materials used. Furthermore, the research revealed that application of plants with geotextile and compost underlying significantly improved the slope stability conditions. The results of numerical analysis and comprehensive observation confirmed the correctness of combination of the methods applied. The computed factor of safety for bare slopes has significantly increased, and basically, no signs of failures were noticed at the site.

**Key words:** landfill, slope failure, geotextile, vegetation cover, recycled material

## INTRODUCTION

A stability of slopes very often becomes one of main problems when considering embankment type landfills. The reclamation of such sites gives a lot of opportunities for the application of several reinforcement methods including i.e. bio-engineering techniques, utilization of reused materials or application of geotextiles. During the exploitation of a landfill and its reclamation quite commonly such anthropogenic materials as ballast waste and debris, used tiers mattresses, diluted leachate, fly ash and sewage sludge, all used for the slope stability improvement are utilized [Pisarczyk 2004, Drągowski 2010]. There are also many researches conducted on utilization of waste combustion and power plant by-products improving the stability of engineering structures [Katsumi et al. 2010, Koda 2012].

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The paper presents the slope stability improvement of Radiowo landfill located nearby Warsaw. Radiowo landfill is located in the north-western part of Warsaw. Since early 60's to 1991 it was the place, where municipal waste from all around Warsaw was disposed. Currently, it covers ca. 15 ha area, and exceeds the height of 55 m. Since 1992 only non-composted waste from Radiowo compostory plant have been disposed on the landfill. The non-composted waste consists mainly of: plastics, textiles, glass and debris. The organic matter content for this waste is ca. 4%. Central and southern parts of the landfill are filled with old municipal waste (15–40 years), while the upper layers in the north part are filled with fresh non-composted products.

The combination of above mentioned reinforcement techniques were used for the stability improvement of the Radiowo landfill site. The stability reinforcement methods on the landfill consist of berms (constructed with selected waste materials), geogrids and mattresses made of used tires, and the utilization of slag as a backfill material was also considered for this purpose. The compost produced from mixed waste in the compostory plant could be utilized for the capping layer creation on the landfill's surface, and also could be used as vital layer enhancing the establishment of plants [Gourc and Staub 2010].

## MATERIALS AND METHODS

### Determination of geotechnical parameters of Radiowo landfill

The subsoil of Radiowo landfill generally consists of cohesive soils. The groundwater level is at the depth of 0–1.0 m. On the basis of CPT and DMT tests, following shear strength parameters for stability analysis were proposed: $\varphi' = 27°$, $c' = 40$ kPa (cohesive soils) and $\varphi' = 33°$ (non-cohesive soils). The investigation of the field's capacity of waste, i.e. maximum water content without the leachate, was also carried out on Radiowo landfill. The test results were used in the analysis of the water balance for the waste body on the landfills. The *in situ* tests were conducted to determine the mechanical parameters of waste for stability analysis, settlement prediction and estimation of bearing capacity for road foundation. The shear strength parameters for stability analysis were determined on the basis of waste morphological tests, WST and CPT tests [Manassero et al. 1996] as well as slope failure tests on trial embankments and back analysis of landslides.

The main purpose of these tests was to explore the existing landfill entirely, i.e. to determine shear parameters in order to assure safe slope inclination. The investigations consisting of displacement measurements, WST and CPT soundings [Jessberger 1993, Brandl 2008], back analysis (including slope failure tests) were carried out. In the case of Radiowo landfill, morphological composition of waste creates an additional factor influencing mechanical parameters. Organic matter content for non-composted waste is ca. 4%, while for fresh municipal waste it is 40–50% [Koda 2011].

The WST sounding was generally performed in the vicinity of the main road constructed on the landfill. The tests have been repeated when 5 m thick layer of waste had been laid. The sounding results are used for the quality control of the road foundation compaction. The average amount of $N_{20}$ for fresh waste was approximately 10, but for old waste – locally of approximately 5. The amount of $N_{20}$ increases twice, when disposed waste was separated with sand layers. The results of *in situ* tests are presented in Figure 1.

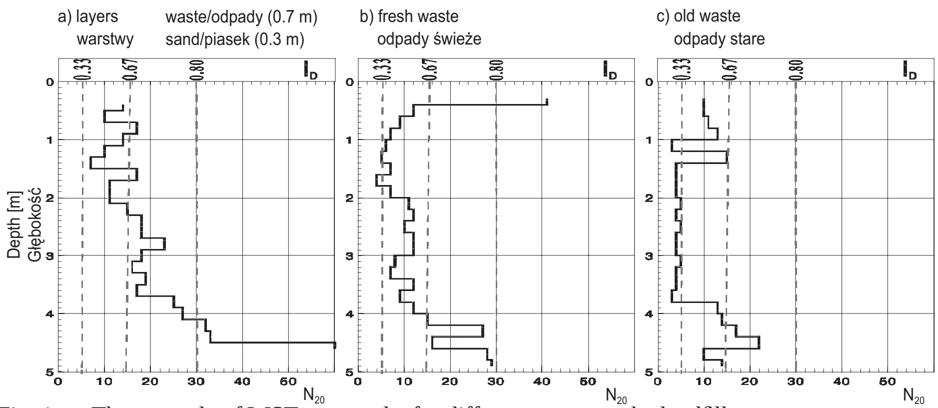


Fig. 1. The example of WST test results for different waste on the landfill
Rys. 1. Przykładowe wyniki sondowań WST dla różnych odpadów na składowisku

The CPT soundings in Radiowo were carried out in the northern part of the landfill, to the depth of approximately 25 m (Fig. 2). The CPT tests interpretation procedures, widely used for the evaluation of shear parameters for soils, were adopted for waste. The effective internal friction angle for waste was reached within the range of $\varphi' = 25–45°$, with local values $\varphi' = 20–25°$. These values were received after having considered waste as non-cohesive soils. Test results confirm the existence of waste cohesion. The CPT test interpretation for waste, analogically to cohesive soils, gave total shear strength of $\tau_{fu} = 80$ kPa for non-composted and $\tau_{fu} = 90$ kPa for municipal wastes.

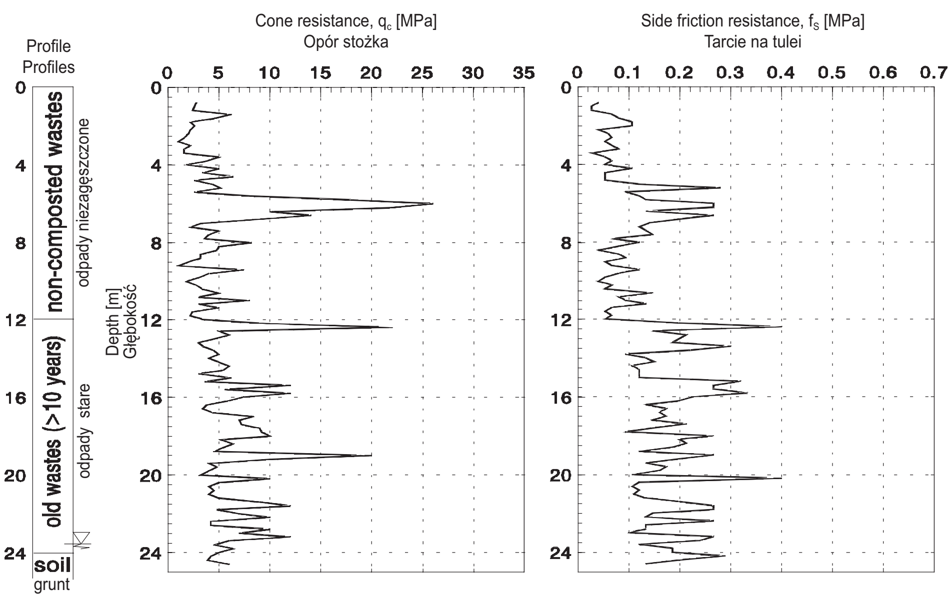


Fig. 2. The example of CPT test results for Radiowo landfill
Rys. 2. Przykład wyników sondowania CPT na składowisku Radiowo

The shear strength parameters of waste used in calculation were obtained from back analyses of previously occurred failures and from the trial loading of the experimental embankment (Fig. 3).

Fig. 3. Trial loading of the experimental embankment constructed on Radiowo landfill [Koda 2011]
Rys. 3. Obciążenia próbne nasypu doświadczalnego na składowisku Radiowo [Koda 2011]

**Numerical stability analyses of Radiowo landfill slopes**

The back-stability analysis by the Bishop (GEO-SLOPE program) and FEM (Z-SOIL program) methods were performed for three chosen cross-sections of Radiowo landfill and was applied for shear strength parameters verification (Fig. 4). The analysis for cross-section A-A, where the landslide occurred in 1991, is of particular importance. The failure surface was confirmed by the CPT tests. The results of calculation indicated that the surface of sliding was almost circle (Fig. 5). Slope inclination of the landfill just before the failure was 1:1.1, and its height was 46 m. Calculations with a classical method confirmed the results obtained by FEM Similar results achieved for stable slopes (Table 1).

Table 1. Stability factors from back-analysis of slopes on Radiowo landfill
Tabela 1. Współczynniki stateczności skarp składowiska Radiowo metodą analizy wstecznej

| Cross-section<br>Przekrój | F | Method<br>Metoda | Slope condition<br>Stan skarpy |
|---|---|---|---|
| A-A | 0.989<br>1.03 | Bishop<br>FEM | Landslide<br>Osuwisko<br>(in 1991) |
| B-B | 1.029<br>1.08 | Bishop<br>FEM | Slope with cracking<br>Spękania |
| C-C | 1.142<br>1.19 | Bishop<br>FEM | Stable slope<br>Skarpa stabilna |

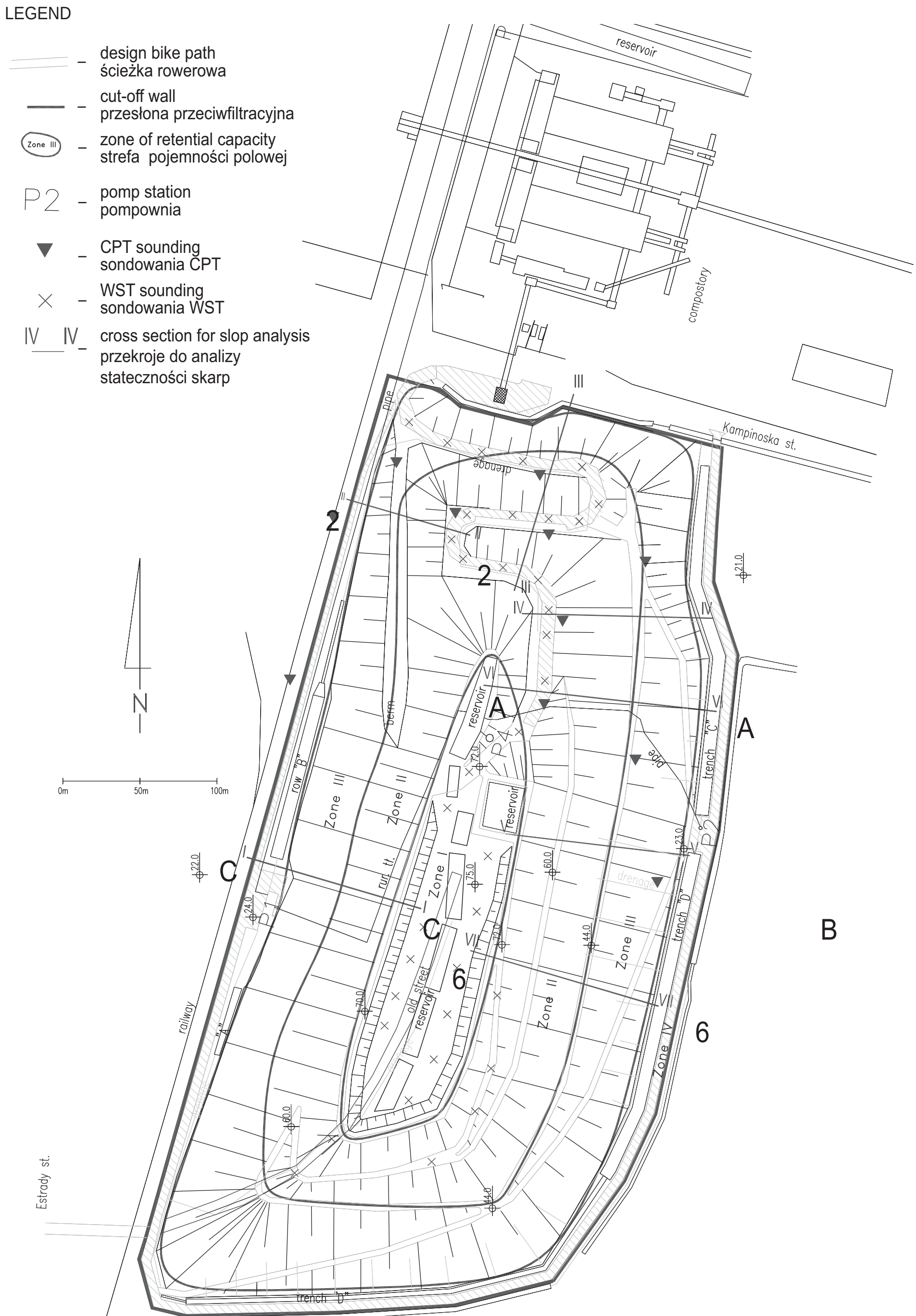


Fig. 4. Cross-sections for the back – and stability analysis on Radiowo landfill
Rys. 4. Przekroje wytypowane do analizy wstecznej skarp składowiska Radiowo

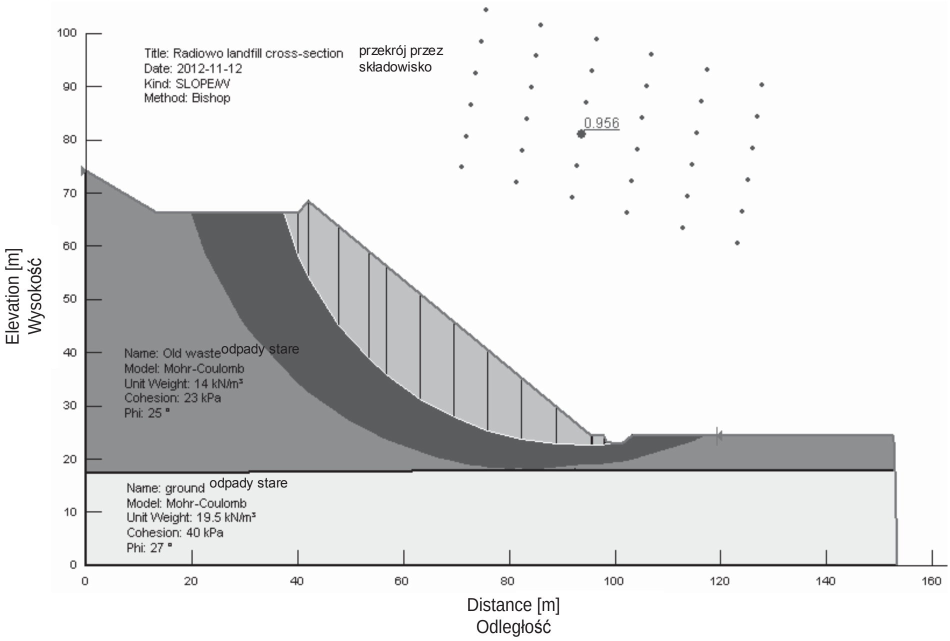


Fig. 5. Back-analysis of landslide in Radiowo landfill by Bishop method (Slope/W program)
Rys. 5. Analiza wsteczna osuwiska na składowisku Radiowo metodą Bishopa (program Slope/W)

In the case of Radiowo landfill, the morphological composition of waste creates an additional factor influencing mechanical parameters. The results of back-analysis confirmed the proper choice of shear waste parameters as well as the possibility of uses of both classical and FEM methods for stability landfill design. Next steps of calculation were carried out for the design of slope reinforcement and formation of the landfill surface.

## RESULTS

### Landfill slopes reinforcement with the use of anthropogenic materials and bio-engineering method

It is highly recommended that the inclination of the landfill slope should fall in the range of 1 : 3 – 1.2.5. Such conditions assure the stability of slopes and allow efficient implementation of the vegetation cover on the surface [Koda et al. 2012].

In cases when the slope failure is very likely to occur, it is recommended to undertake activities improving the stability [Fang 1993, Santos et al. 2010]. Most commonly applied solutions in such cases are:

- decrease of slope inclination (if there is enough space at the embankment toe),
- retaining wall, gabions or berms,
- reinforcement materials such as geosynthetics, horizontal reinforcement.

The example of utilisation of waste materials, as a reinforcement solution is presented for the Radiowo landfill site. The site boarders with a railway siding at west, and additionally in the close vicinity of the slope's toe there is also a gas pipeline installed. The initial inclination of 60 m high slope was 1 : 2.8, what made the slope potentially unstable. As the surrounding area was very limited, the reinforcement of the slope consisted of berm, and the higher part was reinforced with PE geogrid, and additionally three layers of used tires mattresses were build in, the scheme of construction is presented in Figures 6 and 7. The computations assuring the effectiveness of such solution are presented in Figure 8.

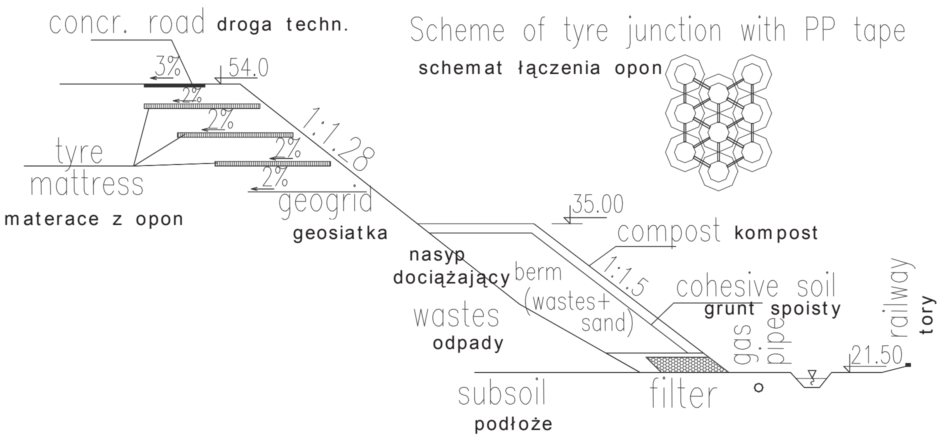


Fig. 6. Cross-section of the analysed reinforced slope at Radiowo landfill [Koda 2012]
Rys. 6. Przekrój przez wzmocnioną skarpę składowiska Radiowo [Koda 2012]


Fig. 7. Construction of the used tires mattresses layers on Radiowo landfill [Koda 2012]
Rys. 7. Konstrukcja warstwy materacy ze zużytych opon na składowisku Radiowo [Koda 2012]

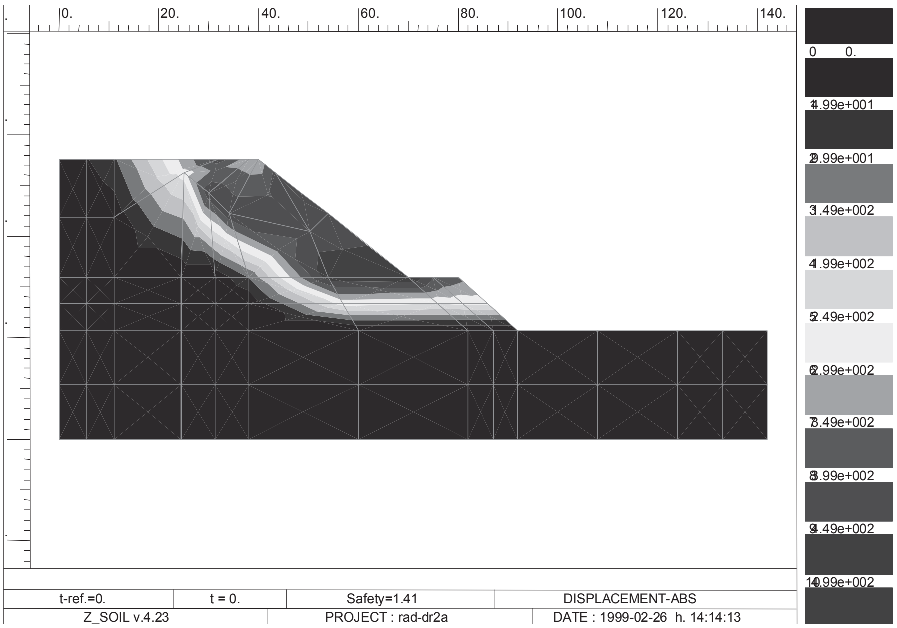


Fig. 8. Stability analysis of the western slope of Radiowo landfill with FEM [Koda 2011]
Rys. 8. Analiza stateczności zachodniej skarpy składowiska Radiowo metodą MES [Koda 2011]

The construction of berm (Fig. 9) allowed gaining additional space for the further waste disposal, which occurred to be a crucial advantage according to a huge problem of the waste management in Warsaw at the time. Within an actual construction plan of the landfill the amount of waste to be disposed at the site (ballast waste, slag, ash) is 450,000 Mg, and the waste to be reused (debris, ceramic waste, soil, compost, winning) is 300,000 Mg.

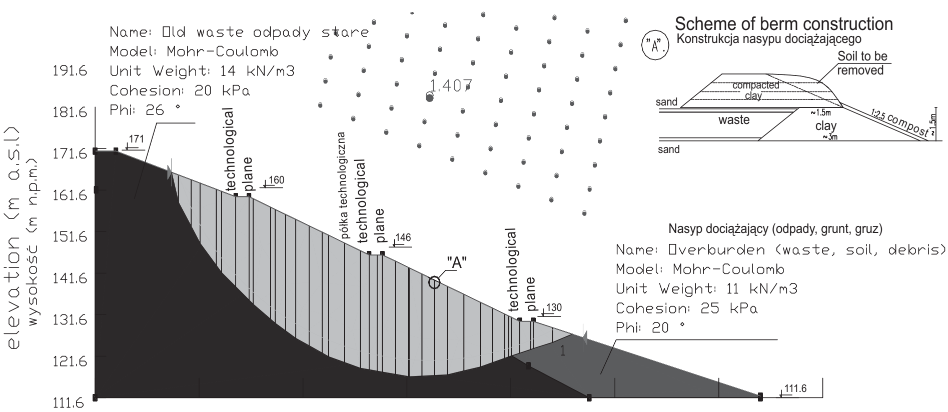


Fig. 9. The scheme of the berm construction with stability analysis
Rys. 9. Schemat konstrukcji nasypu dociążającego wraz z analizą stateczności

Beyond the technical activities for the slope stability improvement purpose on the Radiowo landfill, there were also bio-engineering techniques applied with additional use of geosythetics. By using the Slip4Ex spreadsheet [Greenwood 2006], it is possible to assess how the distribution and type of vegetation can influences the Factor of Safety. In the present study slopes, where the vegetation cover was applied, have been assessed to see whether implementation of plants affected the resulting stability significantly. In Slip4EX the Factor of Safety can be calculated by using several equations developed by Greenwood, however in this study the Greenwood General Method was used, as it presents similar characteristics to other methods used in this study. For the purpose of enhancing FOS, some parts of slopes where cover with trees, bushes, and grass. For those slopes additional computation have been conducted and the results presented in Table 2. The research proved that vegetation establishment has increased the factor of safety by as much as 20%. The overall scheme of FOS computation with the use of numerical modeling is presented in Figure 10.

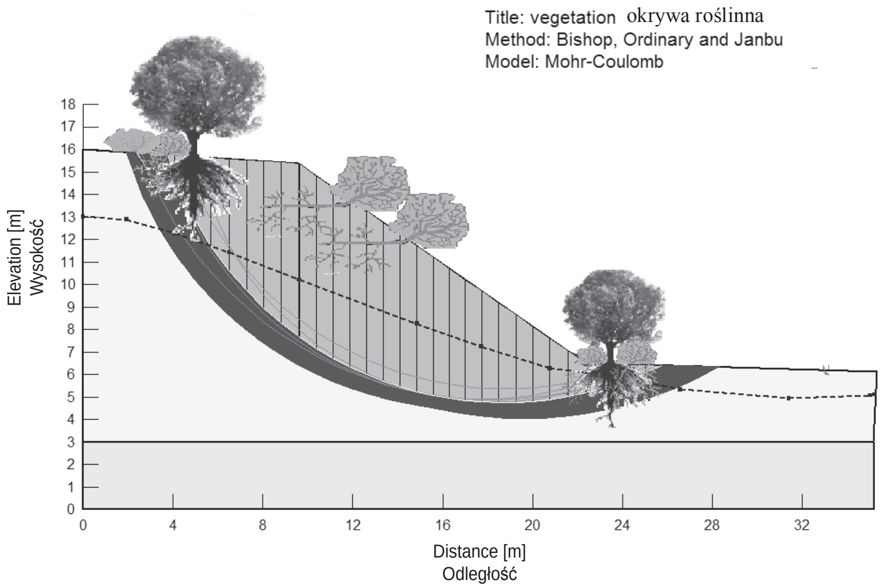


Fig. 10. The influence of the vegetation cover on slope stability [Osiński 2012]
Rys. 10. Wpływ okrywy roślinnej na stateczność skarpy [Osiński 2010]

For the confirmation of a reliability of the solutions presented in the paper Table 2 is provided, where the statement and comparison of factors of safety for landfill slopes before the introduction of reclamation activities and afterwards results are presented. Construction of berms seems to be the most effective method of the stability improvement of old landfills, however it needs the extension of the landfill in its close vicinity. The tire mattresses seem to be a cheap and effective method of the slope stability reinforcement in the landfill conditions. The stability factors of slope obtained from FEM method are a little higher than from classical methods. In the case of classical methods, it should be considered whether circle surface of sliding is suitable for a real failure mechanism.

Table 2. The results of the stability analysis for the Radiowo site acc. to Bishop, FEM and Greenwood methods
Tabela 2. Wyniki analizy stateczności Radiowa metodami Bishopa, MES, Greenwood

| Slope Cross-Section Przekrój skarpy | FOS without reinforcement Współczynnik stateczności bez wzmocnień | | Reinforcements Wzmocnienia | FOS with reinforcement Współczynnik stateczność z wzmocnieniami | | FOS with plants Współczynnik stateczność dla okrywy roślinnej |
|---|---|---|---|---|---|---|
| | Bishop | FEM | | Bishop | FEM | Greenwood |
| Western – I Zachodni | 1.04 | 1.13 | Berm (nasyp dociążający), tyre mattress (materac z opon), geogrid (geosiatka) | 1.40 | 1.42 | 1.52 |
| Northern – III Pólnocny | 1.03 | 1.11 | Inclination change (zmiana nachyleń), geogrid (geosiatka) | 1.68 | 1.75 | 1.84 |
| Ekstern – IV Wschodni | 1.18 | 1.23 | Berm (nasyp dociążający) | 1.57 | 1.62 | 1.78 |

## CONCLUSIONS

The reclamation of old sanitary landfills is a long term process, and it often requires complex and unusual technical and biological activities to be applied. The solutions presented in the paper show the variety of techniques and materials that could be used for the purpose of slope stability improvement, which is a crucial element in reclamation process of embankment type landfills.

The most appropriate slope stability improvement method for landfills is berms construction filled with ballast waste, debris and soil residues from a landfill. This kind of solution helps gaining additional space for the further waste storage and often becomes alternative for the waste management plan at the site. As the example showed utilisation of used tires mattresses could also be an effective method of the slope reinforcement. Furthermore, other waste material like compost could be a great substitute of humus for the surface reclamation layer establishment. It is also very useful material when considering The bio-engineering method which was successfully used for the natural reinforcement of slopes which positively influences also the erosion control on slopes, a factor directly driving to stability failures.

To sum up all the techniques combined together allowed achieving the required effect of the Radiowo landfill slopes stability improvement.

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## POPRAWA STATECZNOŚCI SKARP JAKO WYNIK ZASTOSOWANIA ZRÓŻNICOWANYCH METOD WZMOCNIENIA

**Streszczenie.** Artykuł przedstawia zastosowanie zróżnicowanych metod wzmocnienia skarp składowiska Radiowo przy użyciu materiałów antropogenicznych, geosyntetyków oraz metod bioinżynierii. Zaprezentowany w artykule przykład dowodzi, iż kombinacja zbrojenia oraz kształtowania skarp znacząco poprawia współczynnik stateczności ogólnej. Materiały zastosowane w celu wzmocnienia skarp składały się z materacy, zużytych opon, odpadów ze składowiska, materiałów geosyntetycznych, geosiatek oraz technik bioinżynierskich. Ocena efektywności zastosowanych rozwiązań została przeprowadzona na drodze modelowania numerycznego oraz długotrwałych obserwacji terenowych wzmocnionej konstrukcji. Obliczenia numeryczne przeprowadzono przy uwzględnieniu wymaganych parametrów geotechnicznych zastosowanych materiałów. Ponadto badanie dowiodło, iż zastosowanie okrywy roślinnej wyścielonej materiałem kompostowym znacząco poprawiło warunki stateczności skarp rozpatrywanego obiektu. Wyniki analiz numerycznych oraz obserwacje terenowe dowiodły poprawności zastosowanych rozwiązań, gdyż współczynnik stateczność ogólnej skarp wzmocnionych znacząco poprawił się w stosunku do warunków bez zbrojenia, a żadne oznaki utraty stateczności obiektu nie zostały do tej pory zaobserwowane.

**Słowa kluczowe:** składowisko, osuwisko, geosyntetyki, okrywa roślinna, materiały odpadowe

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