Assessment of bio-mechanical reinforcement materials influencing slope stability, based on numerical analyses

Évaluation des matériaux de renforcement bio-mécaniques qui influencent la stabilité des pentes par des analyses numériques

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ABSTRACT: The article is an answer proposal for the conclusion stated in European regulations regarding the environment friendly and more sustainable development, which among others includes utilising secondary and recycled material in order to obtain durable and stable cuttings and embankments. Bearing in mind that the slope stability and erosion control on embankments are the issues rising the nowadays geotechnics awareness through all around the world, the paper content provides the alternative engineering solutions to such problems. The techniques proposed in the paper mainly consist of the proper vegetation cover implementation on embankment slopes, the reinforcement of earth structures by utilising geotextiles and a combination of those two. Additionally, it is presented how secondary materials could be used as a vegetation development accelerating and enhancing material. In order to prove the reliability and efficiency of such activities the laboratory material tests and numerical modeling of slope failures were conducted.

RÉSUMÉ : L'article est une proposition de réponse à la conclusion énoncée dans les règlements européens concernant l'environnement de développement favorable et plus durable, ce qui comprend entre autres l'utilisation des matériaux de récupération et de recyclage afin d'obtenir des déblais et remblais stables et durables. Il est admis que la stabilité des pentes et le contrôle de l'érosion sur les remblais sont des problèmes qui apparaisse comme des priorités pour la géotechnique actuelle. Le papier propose des solutions d'ingénierie à ces problèmes. Les techniques proposées dans le document se composent principalement de la mise en œuvre de couverture végétale sur les talus, le renforcement des structures en terre en utilisant par géotextiles et une combinaison des deux. En outre, il est présenté comment les matériaux secondaires pourraient être utilisés comme un développement de la végétation accélérant et en améliorant le matériau. Afin de prouver la fiabilité et l'efficacité de telles activités, les essais de matériaux en laboratoire et la modélisation numérique des ruptures de pente ont été effectuées

KEYWORDS: slope stability, reinforcement, vegetation cover, recycled materials, landfill.

1 INTRODUCTION.

The most significant element of the embankment type landfill reclamation process is the reinforcement and biological stabilisation of slopes, which are very sensitive to several destabilisation processes like i.e surface erosion. The landfill stability improvement activities are divided into phase 1 - technical reclamation (implementation of civil engineering techniques), and phase 2 - biological restoration (establishment of the vegetation cover). For both of them it is highly recommended to use such recyclable materials as sewage sludge and fly ash as a landfill reinforcement filling (CEN/BT, 2009).

In 2012, in Poland the production of fly-ashes from the coal combustion was 18.5 mln tones. The amount of slag and ashes disposed on Polish landfills and usable for the road embankment construction and land reclamation is 261.8 mln tons. Furthermore, the annual production of sewage sludge in Poland is also significant - 500 000 tones, and could be successfully utilised in landfill reclamation process, as a rich in nutrients fertilizer (Koda et al 2012). The combination of carefully selected types of fly-ash, sewage sludge, soil and vegetation cover can be excellent alternative for the heavy engineering activities for the landfill slopes reinforcement. All the presented solutions are based on the analyses conducted at the Radiowo landfill site located near Warsaw.

2 SITE DESCRIPTION

The Radiowo landfill (embankment type) was established in 1962. It covers approximately 15 ha and the altitude is 60 m high. No protection system against the environmental pollution was introduced into the surrounding area at the start of the landfill operation.

The municipal solid waste was disposed there up to the early 90's. The local landslides treatment, changes in further exploitation, and the reinforcement treatment were required. Since 1993 only non-composted waste from the compostory plant has been disposed there (approximately 300 tons/day).
The remediation works on the landfill have been carried out since 1994. They include: slopes forming and planting, stability improvement solution, mineral capping, bentonite cut-off wall as a limitation of the groundwater pollution and a peripheral drainage.

The in situ and laboratory tests for Radiowo landfill has been performed since 1993. The field investigation consists of settlement measurements, geotechnical tests of waste, back analysis (as well as slope failure tests), quality tests of sealing (capping layer and vertical barrier) and filter materials. In the Radiowo landfill case, the morphological composition of waste creates an additional factor influencing the mechanical parameters. The organic matter content for non-composted waste is ca. 5 %. A location map involving cross sections selected for slope stability analyses is presented in Figure 1.

Nowadays, the landfill site is planning to be adopted as a winter sports activity complex. The construction plan has already been accomplished and accepted by a legal body, which is a requirement when considering new development plan for contaminated sites (for more detail please refer to Koda 2012).

3 UTILISATION OF ANTHROPOGENIC MATERIALS

One of the elements of the landfill reclamation process is the construction of capping system. It is a landfill surface cover protecting against the rainfall infiltration (limitation of leachate penetration). It provides good establishment conditions for the vegetation cover, and significantly enhances slopes stability.

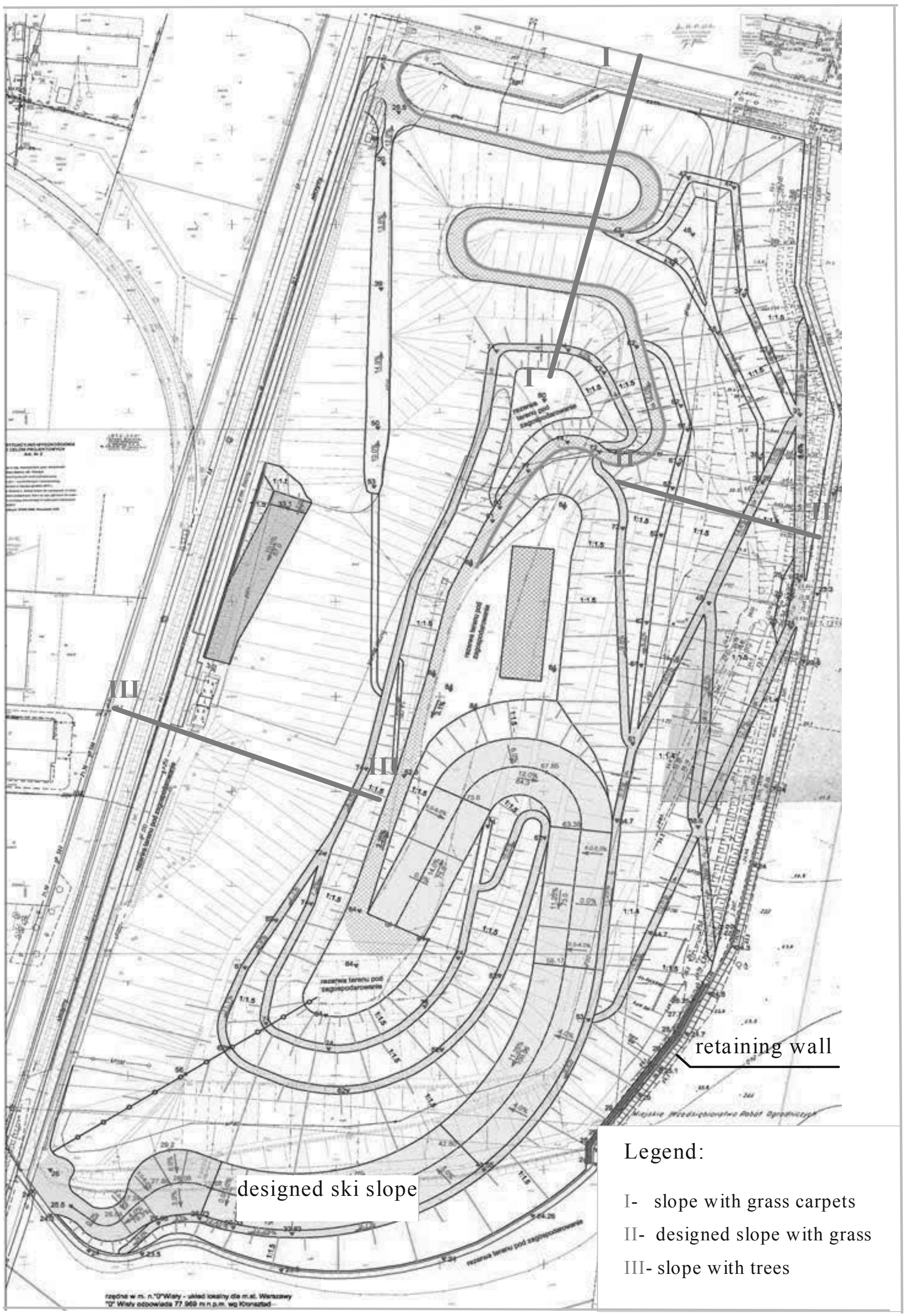

Figure 1. Current development plan of Radiowo landfill, and location of cross-section for slope stability analyses.

Because of its appropriate geotechnical properties like impermeability and good compaction conditions, flay-ashes mixed with cohesive soil are a great material for the capping system. Recently it was recommended to use geomembrane instead of mineral barriers to insulate the surface of the landfill, however there are lots of disadvantages like decreasing slope stability or slowing down the bio-chemical decomposition of waste. Applying mineral capping systems (made of ashes and sewage sludge), in many cases resulted in enhanced fermentation processes (Koda 2011).

The flay-ash is basically a by product of the coal combustion process in power plants. The mineral and chemical composition is determined by mineral elements present in coal. These minerals are: iron oxides, carbonates and clayey minerals. The properties of the flay-ash mainly depend on shape and size distribution of its particles. The bulk density of ashes contains in the range of 2000-2500 kg/m^3.

The reason for this is some of the particles are filled with gas. The chemical reactions proceeding during the coal combustion process produce mineral phases stated in Table 1.

Table 1. Mineral phases of the fly-ash (Koda and Osinski 2011).

Mineral phases	% content of total mass
Glass	60-83
Millite	4-25
Quartz	4-18
Hematite	0.5-2
Magnetite	1-7
Coke	0.5-5

The additional anthropogenic component which also presents high usability in terms of slope surface reinforcement is sewage sludge (Katsumi et al. 2010). The mineral elements of the sewage sludge are developing slowly and are not exposed to the erosion processes. This kind of material is hazardous when disposed but when treated by vegetation and additives it is safely absorbed and utilized by plants. Additionally it has to be mentioned that sewage sludge supply is free of charge. The mixture is applied by hydraulic seeders supplied with high pressure pumps, which enables spraying on different soil/material types. The advantage of using sewage sludge is that seeds are protected from the erosion and excessive drying. The viscosity of the sludge and its mixing ability with other components, assure even and smooth protection cover, and moreover, high adhesion to the sprayed surface. The most significant advantage of using the sewage sludge is the nutrition content, essential for the vegetation cover establishment. Especially the undrained sludge is rich in microelement, nitrogen, phosphorus, potassium and organic matter. Some of them are highly valuable for plants (Koda 2011), however cannot exceed normative values of dry mass. The usability of ashes and sewage sludge for the geotechnical purpose is determined by several physical and mechanical properties such as: capacity index in saturated conditions, grain-size distribution, maximum dry bulk density, swelling, internal friction angle, and passive capillarity.

4 VEGETATION COVER AS A RELIABLE METHOD OF SLOPE STABILITY IMPROVEMENT

Beyond described activities for the slope stability and erosion control improvement purpose on the Radiowo landfill, there were also bio-engineering techniques applied with additional use of geosythetics. Due to the usability assessment of the compost, from organic waste as an enhancing material for the grass carpets, an experimental plot was established within the compostory plant area (Koda, 2012). A composite (grass carpet) consisting of three elements was constructed: reinforcing material, substrate and grass seeds mixture was prepared. As a reinforcing material the geotextile (G) and geogrid (Gs) was used. A reinforcing material task was to connect particular elements of the carpet, improving the shear strength and hydraulics conditions, and also an increase of erosion control on landfill slopes. A porous structure of geotextile and geogrid enhances establishment of the root zone deeper into the surface.

During the selection of reinforcing material the mechanical properties and the stock was considered. The polypropylene materials guarantee long term durability and resistance to aggressive environmental conditions. A seeding suspension consisted of a mixture of three types of grass seeds: lawn type (MT), pasture type (MP) and “gazon” type grass seeds (G). A substrate consisted of sand and compost mixture in three different volumetric proportions: 1P/1K- 1:1 (1 measure of sand + 1 measure of compost), 1P/2K- 1:2 (1 measure of sand + 2 measures of compost), and K- pure substrate (100% compost). The scheme of experimental plot is presented in Figure 2.

Additionally an application of already described fly-ash and sewage sludge suspension on such slopes to accelerate the establishment of a green cover was also provided. The grass carpets were introduced in order to maintain the observation and to conduct further research on how does such solution influence conditions of slopes. The assessment of the effectiveness of bio-engineering activity on landfill slopes were undertaken after 1, 2, 6, and 10 years of the experiment duration. The result of the observation confirms the reinforcing purpose of the method, as even after 10 years of grass carpets establishment the slopes are evenly covered with plants, while on the slopes where only traditional method of planting was applied, the slope conditions are significantly worse. Additionally, the numerical analyses involving the influence of reinforcing layer also proved the correctness of applied method on slope of section I-I marked on Figure 1 where location map is provided. For the results please refer to Table 3.

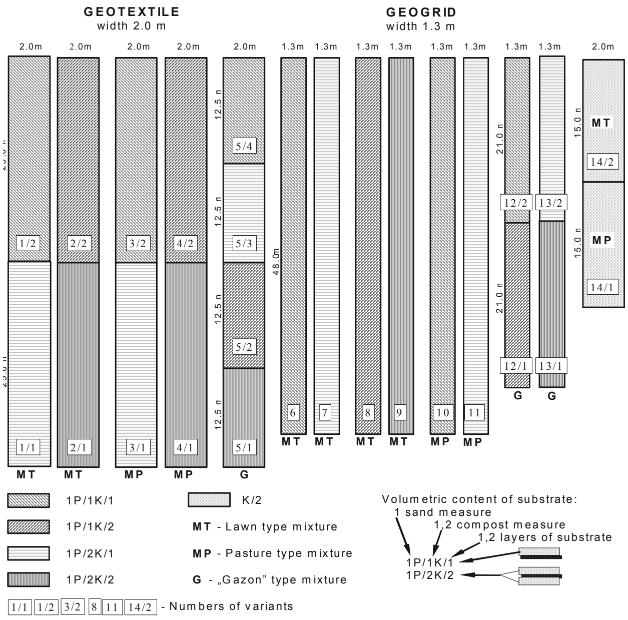

Figure 2. Scheme of the experimental plot established at Radiowo landfill slopes (Koda 2011).

The additional solution improving the slope stability is a proper establishment of high trees and shrubs on slopes (Coppin and Richards 1990, Norris and Greenwood 2003, Clark et al. 2003). Such activity was also conducted for Radiowo landfill site. Comprehensively analysed plant species were selected in terms of root system characteristics and assimilation ability in such specific ecosystem as contaminated land (Coppin and Richards 1990, Greenwood 2006).

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. Firstly, however the geotechnical parameters of waste had to be determined. For such purpose back analyses, CPT and WST tests were conducted on site. The back-stability analysis by the Bishops', Swedish (GEO-SLOPE program) and FEM (Z-SOIL numerical program) methods were performed for three chosen cross-sections of Radiowo landfill slopes and were applied for the shear strength parameters verification. The results are listed in Table 2.

Table 2. Shear strength parameters for municipal solid waste (Koda, 2011)

Material	γ [kN/m^3]	ϕ [°]	c [kPa]	Method
non-composted waste	11.0	20	25	failure tests, CPT, WST
non-composted waste + sand	12.0	25	23	failure tests, CPT, WST
old municipal waste	14.0	26	20	back-analysis CPT, WST

The computations of factor of safety including vegetation cover influencing slope stability were conducted with use of General Greenwood Method. Greenwood (2006) developed an equation, based on the limit equilibrium method, where parameters of plants existing on the slope are considered. These parameters are: root reinforcement forces, wind forces, or the mass of vegetation, or related to these, changes in the pore water pressure. In Slip4EX the Factor of Safety can be calculated by using several equations developed by Greenwood (2006), however in this study the Greenwood General Method was used, as it presents similar characteristics to other methods used in this study. A powerful equation of FOS concerning a vegetation influence, proposed by Greenwood is as follows:

$$F = \frac{\Sigma\left[(c' + c'_v)l + \left((W + W_v)\cos\alpha - (U + \Delta U_v)l - \left((U_2 - \Delta U_{2v}) - (U_1 + \Delta U_{1v})\right)\sin\alpha - D_w \sin\alpha(\alpha - \beta) + T\sin\Theta\right)\tan\varphi'\right]}{\Sigma\left[(W + W_v)\sin\alpha + D_w \cos(\alpha - \beta) - T\cos\Theta\right]} \quad (1)$$

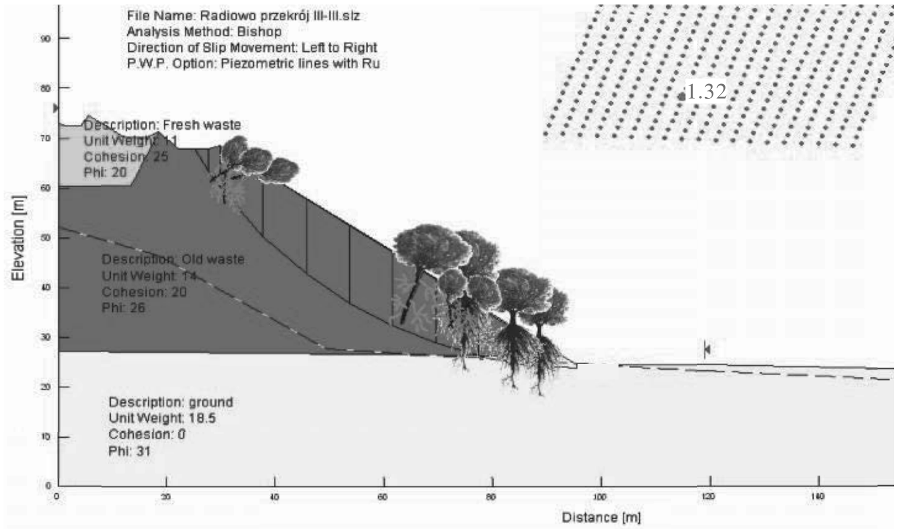

Figure 3. Numerical analysis of slope stability including the influence of vegetation cover (cross-section III-III please refer to Figure 1).

where all the parameters indexed with v mean changes according to vegetation influence. Additionally such parameters like D_w (wind force), T (tensile rooth strength) are also included in the equation. This method was basically developed to assess the stability of slope according to the soil reinforcement by anchors or geotextiles, or vegetation effects. 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. After full establishment and grow of proposed plants the numerical analyses of slope stability were conducted. A distribution of high vegetation cover on analysed slope (cross-section III-III) is presented in Figure 3.

Firstly the numerical analyses were conducted for bare slopes. The computations were based on Bishop method which was employed during analyses performed in GeoStudio2007 software. The second step was to determine factor of safety influenced by plants.

The results obtained proved that the factor of safety for the slopes covered with plant was improved as much as 20%. The initial results of numerical modeling for bare slopes has presented unstable condition, however long term monitoring proved that no sings of failure were noticed. The only reliable explanation for such state could be a presence of well developed vegetation on slopes. The example of results of numerical analyses for slope stability for bare and vegetated slopes is presented in Table 3.

Table 3. Comparison of numerical analyses of factor of safety for bare and vegetated slopes

Cross Section	Factor of safety	
	Bare slope Bishop method	Vegetated slope Greenwood method
I-I	1.30	1.38
II-II	1.35	1.42
III-III	1.15	1.32

5 CONCLUSIONS

The instability of slopes is one of the most significant problem concerning reclamation processes of landfill sites. The partial solution for this issue is presented in the paper. There are available methods, which are relatively simple, efficient, and cost effective. The use of fly ash and sewage sludge for the reclamation of the surface of landfill is an alternative.. It also solves the problem of the ash storage which, from the economical and environmental point of view, is very positive.

The reinforcement of slope does not require only heavy engineering methods, basic solution as a proper selection and implementation of plants is always worth consideration. It is definitely cost effective, environment friendly and reasonable technique accelerating landfill reclamation works. Furthermore, other waste material like compost could be a great substitute of humus for the surface reclamation layer establishment. The compost could be used for reinforced grass carpets production, which positively influences the erosion control on slopes, a factor which often determines processes of slope failure.

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