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Slope stability aspects for municipal waste landfills. Case studies and numerical modelling

Aspects concernant la stabilité des pentes des centres de stockage de déchets ménagers. Etudes de cas et modélisation numérique

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ABSTRACT: Instability phenomena in waste landfills are not rare, even if the level of knowledge and awareness increased in the last years. But insufficient knowledge about the characteristics of the waste and poor execution, associated to insufficient geotechnical investigation of the sites and the use of inappropriate sites lead to many cases of landfills instability. This can be seen for new landfills, as for old ones. Old waste dumps are often located in dried (or partially dried) valleys, natural gulches or ravines, therefore waste is often placed on sloped ground. Their mechanical characteristics are often very poor and, due to lack of drainage systems, are in saturated state. Therefore, instability can appear at every stage of the operation, during the closure or post-closing. When consolidation works are foreseen drainage measures are always considered, which will change the saturation state of waste to an unsaturated one. Paper presents general aspects about slope stability in landfills, some case studies from Romania and a 3D numerical modelling in saturated and unsaturated conditions for the closure of an old landfill.

RÉSUMÉ: Les phénomènes d'instabilité dans les centres de stockage de déchets ne sont pas rares, même si le niveau de conaissances et de conscience a augmenté ces derniers années, Mais, la conaissance insuffisante des caractéristiques du déchet et la mauvaise éxécution, associées à une investigation géotechnique insuffisante et l'utilisation des sites impropres engendre multiples cas d'instabilité des dépôts de déchets. Ceci peut être constaté aussi bien pour les nouveaux centres de stockage, que pour les anciens. Les anciens dépôts d'ordures ménageres sont souvent emplacés dans des vallées séchées our partiellement séchées, dans des ravines ou gorges ou canyons, donc les déchets sont placés souvent sur des pentes. Leurs caractéristiques mécaniques sont souvent très faibles et, dû au manque de systèmes de drainage, sont à l'état saturé. Donc, les instabilités peuvent apparaître àtoutes les phases d'opération, pendant la fermeture ou post-fermeture. Quand des ouvrages de consolidation sont envisagé les mesures de drainage sont toujours prises en compte, ce qui va changer l'état de saturation en non-saturé. L'article présente des aspects généraux sur la stabilité des pentes des centres de stockage de déchets, quelques études de cas de Roumanie et une modélisation numérique 3D en conditions saturées et non-saturées pour la fermeture d'un vieux dépôt de déchets.

Keywords: slope stability; landfill; municipal waste; numerical modelling; unsaturated conditions

1 INTRODUCTION

Waste landfills comprise generally many types of natural or man-made slopes for which the stability has to be considered: for dikes, landfilling cells, closing system or even those within waste mass during the operational phase. Prior to regulatory requirements for lining waste, landfills stability was considered as an operation problem of minor concern, the slipped waste being simply repositioned (Sharma, Lewis, 1994). Once such systems have been introduced, they could have been damaged by the waste movements and more attention was paid for the stability issues.

For new landfills, problems can arise starting with the site, as many sites are difficult ones, including prone to landslides. Sometimes the geotechnical investigation is not thorough and these aspects are not correctly identified. Once construction started, instability can appear as the stress conditions are modified. Specific for new landfills which include lining and drainage systems are the instability of such systems on slopes: slopes too steep, rupture within the drainage or lining system, slippage of the lining along the slope etc. During the operation of new landfills problems can appear on the form of internal rupture, within the waste mass, due to too high water content of waste, insufficient control and too steep slopes. This type of rupture can be associated to slippage along the lining systems, giving translational rupture, of large size. An interesting aspect that can be emphasized regarding new landfills, at least for Romania, is the following: the European legislation has been implemented through very detailed provisions of the national technical norm. After 20 years we saw that this was very inefficient, as it has been considered as a „recipe“ and a „recipe“ can be applied by everyone, even not experienced, without engineering judgement or adaptation to the site etc. As a result, we are confronted more and more often to lack of investigations, lack of calculation for the design, as the „recipe“ is unique for all sites and situations.

As other countries, Romania still have many old waste dumpsites which have to be closed and which are experiencing instability phenomena, either before closing or during the closure works or even post-closure. As they have no design or operation rules, the waste is in loose state, saturated with leachate, having very poor mechanical characteristics. The combination between a sloped-site and poor mechanical characteristics, together with presence of leachate (which is not drained) can often lead to instability phenomena. Besides the instability itself, this involves also environmental problems as leachate exfiltrations.

The paper presents some case studies of municipal landfill instability from Romania and for the closure of an old dumpsite a numerical modelling before and after consolidation, in saturated and unsaturated conditions.

2 EXAMPLES OF INSTABILITY PHENOMENA IN MUNICIPAL WASTE LANDFILLS IN ROMANIA

In this paragraph are presented some municipal landfills from Romania, which have been affected (in various stages) by instability phenomena due to poor investigation/design.

2.1 Examples – insufficient geotechnical site investigation

For new landfills often the chosen site is a very poor one (not useful for other purposes): instability problems, difficult soils, difficult morphology etc.

Figure 1 is showing a photo of a site for a new landfill, located on a hill, investigated by means of max. 9 m depth boreholes, no slope stability analyses, no hydrogeological study. During the works, which started at the slope toe, landslides occurred. The site had to be reinvestigated, with proper slope stability analyses and a consolidation work has been built, including drainage system (deep drainage) and a permeable pile retaining wall (alternating reinforced concrete piles and geotextile-encased gravel piles).

Figure 1. Example 1 – new landfill site – insufficient geotechnical and hydrogeological investigation

2.2 Examples – improper geotechnical design

The Romanian technical norm imposes maximum 1:3 (V:H) slope for the landfills, but only for the cover, this provision, of course, not exonerating the designer to check the slope stability for the site and work specific conditions, in various situations that can occur, especially from overcharges and groundwater (leachate) point of view. For new landfills it is important to consider different possible levels of the leachate, the circulation of the construction engins on the slope, but also, if the case, the seismic action.

Figure 2 (left) shows the case of a new landfill, under construction at the time the photo has been taken, with too steep slope for the cells, of 2:3 (V:H), for 28 m in height and 60 m slope length. A simple stability analysis for the drainage layer on this slope showed the following:

- for dry conditions the safety factor was F_s = 1.22,
- for horizontal seepage, F_s = 0.92, unstable
- for seismic conditions, F_s = 0.96, unstable
- for construction equipment up slope in dry conditions, F_s = 1.22,
- for equipment up slope + horizontal seepage, F_s = 0.95, unstable
- for equipment down the slope, F_s = 1.16.

Figure 2. Example 2 – new landfill – improper design of the side slopes without geotechnical calculations – before (left) and after remodelling (right)

Also, the geocomposite clay liner to be installed on this slope was tensioned with 85 kN/m, above its tensile strength. Therefore, the slope was remodelled to a less steep inclination (1:3 V:H) and by introducing a berm and a veneer reinforcement by geogrid in the drainage layer (Figure 2 - right).

Figure 3 shows another situation, where measures haven’t been taken and the result was the slippage of the lining and drainage system and tear of geosynthetic materials. The slope of the cover was 1:3 (V:H), thus following the technical prescription, but no geotechnical calculations have been carried out. The slope length varied between 50 m and 120 m, without berms.

Figure 3. Example 3 – closing of an old landfill – improper design of the side slopes without geotechnical calculations

Shear tests have been performed at the interface between the various materials in contact (shear box and inclined plane – Figure 4), the results showing that the friction angles varied between 14° and 19° (for 18° slope inclination). The tensile force to be overtaken by the drainage geocomposite (108 kN/m) was far beyond its strength, leading to the observed rupture. But also, it has been found that the geomembrane was textured on only one face and had very heterogeneous roughness and that the drainage geocomposite has a too low peel strength and non-homogeneous bonding between the components (Figure 5).

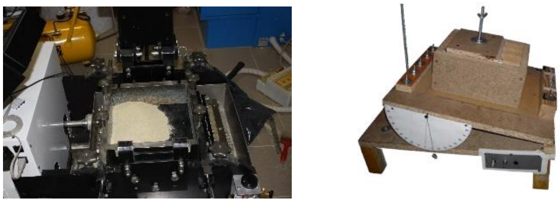


Figure 4. Example 3 – shear tests at interface (Batali et al, 2014)

Figure 5. Example 3 – peel test on the drainage geo-composite (Batali et al, 2014)

Figure 6 (left) shows another example of improper design, but also improper execution, this time for the dikes of a new landfill, which have been built using inadequate materials (local clays) and without proper compaction, which eventually led to failure of the dikes. The dikes had to be demolished and re-built using the local soil improved by mixing with hydraulic binders (fly ash and lime) (Figure 6 right).

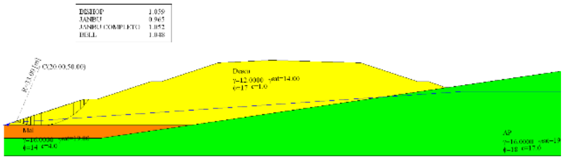
Figure 6. Example 4 – new landfill – improper design and execution of the dikes (left), after reconstruction (right)

Figure 7 shows the situation of a big existing landfill, in operation since 1974, which closure was in progress when a major landslide occurred within the waste mass. This accident led to a major pollution of the adjacent river and the national road passing nearby was threatened.

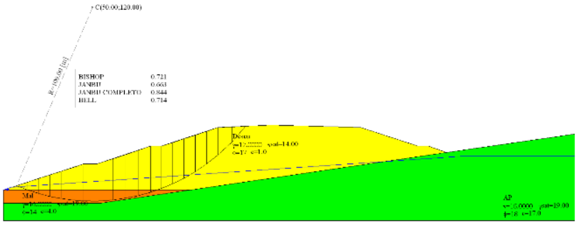
Figure 7. Example 5 – old landfill – major landslide - failure within waste mass

The forensic analysis carried out showed that the geotechnical investigation consisted of only a couple of boreholes of max. 6 m deep and disposed around the site, therefore no knowledge about the geotechnical characteristics of the site below the waste, no hydrogeological data and no slope stability analysis. Also, the landfill had no drainage system, thus the leachate accumulated within the waste mass, leading to the instability phenomenon. A new, proper, geotechnical investigation allow to carry out slope stability analysis. The waste geotechnical characteristics ($\phi = 17°$, $c = 0$ kPa) have been chosen based on litterature and by back – calculation such as obtaining a safety factor slightly less than 1 for the actual conditions. Figure 8 shows the LEM results for the actual situation in static and seismic conditions.

To be noted that the technical regulations recommend to check the stability also by superposing a high level of water and the seismic action. Also, to be noted that the failure surface in static conditions is in the waste mass, which corresponds to the observations on site after the landslide occurred, while for seismic conditions the critical failure surface is deeper caused by the presence of a muddy layer (deposited waste from waste water treatment plant) discovered during the final geotechnical investigation.



a - results for static conditions - characteristic values: $F_s = 0.97$



b - results for seismic conditions - characteristic values: $F_s = 0.67$

Figure 8. Example 5 – old landfill – results of LEM stability analyses with characteristic values

The stability analyses showed that the rise of the leachate level in absence of a drainage system, combined with an overcharge at the slope crest by an additional waste mass were the cause of this phenomenon. But, in fact, the lack of design and investigation can be considered to be the real cause. The landfill is now under consolidation works including pile retaining structure and a gabion retaining wall and drainage system.

3 CASE STUDY: STABILITY OF AN OLD LANDFILL, NUMERICAL MODELLING AND CONSOLIDATION MEASURES

3.1 General description

The studied municipal landfill was in operation since the ‘70s, being developed on a site with a general, relatively gentle slope, presenting a main valley and 2 – 3 tributary valleys, all with variable flow. The landfill had to be closed, due to lack of protection systems against pollution, using a classical capping system comprising (from bottom to top): a support layer, a drainage layer for gas collection, a geosynthetic clay liner (for waterproofing), followed by a water drainage layer and 1.0 m of local soil (from which the last 0.15 m were made of topsoil). During the closing process fissures appeared in the capping soil layer, showing that mass movements were occuring (figure 9).

Figure 9. Case study – old landfill – fissures appeared during the capping works – slope

3.2 Geotechnical conditions

No geotechnical investigation has been carried out before the design of the closure, while the design was a typical one, according to the “recipe”, with no stability analysis. Geotechnical and hydro-geological investigations performed after the events on site showed that the waste layer was thicker than expected (up to 19.60 m) and an old man-made excavation filled with waste, having a maximum thickness of 19.6 m, was emphasized. The ground beneath the waste was a clay, sometimes silty, in saturated state, soft to stiff consistency. Figure 10 is showing a cross-section.

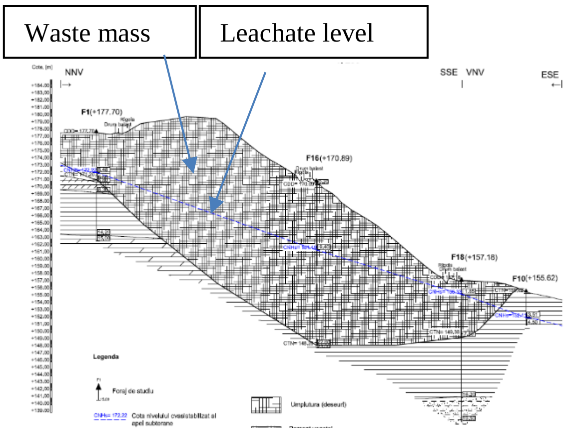


Figure 10. Case study – old landfill – cross-section

The leachate level was particularly high, varying between +0.24 m (above ground level) and -10.04 m (below ground level). It was supposed that the natural valleys existing on site were blocked by the waste, obstructing the natural water flow and producing accumulation of leachate. The permeability of the waste has been determined by 10 in situ tests.

3.3 Stability analysis using LEM, consolidation measures

Conventional stability analyses using limit equilibrium methods (LEM) have been conducted and the conclusions were the following (all given values of the safety factor were obtained using characteristic values of the geotechnical parameters):

- the landfill in its final stage was not stable in static conditions and for the high leachate level found on site (F_s = 0.97 – Figure 11). The shear strength parameters for the waste have been calibrated based on litterature and by back-calculation for this case (ϕ = 24°, c= 0).

- the critical slip surfaces were found mainly within the waste mass and the main instability factor is the high leachate level.

Figure 11. Case study – old landfill – LEM stability analyses static conditions, characteristic values F_s = 0.97

- if leachate level is lowered to a max. level of +1.50 m above the natural ground level the landfill becomes stable in static conditions (F_s = 1.82), but still unstable in seismic conditions (F_s = 1.16, but when using EN 1997-1 an EN 1998-5 + RO National Annex F_s = 0.93).

Thus, it was proposed to consolidate the landfill in 2 main stages:

1. a drainage system - 6 vertical wells and 3 lines of drainage trenches - for lowering the leachate level to approx. +1.50 m above the ground level, level to be maintained min. 270 days, while monitoring the landfill settlements.
2. a mechanical consolidation for ensuring the required safety margin against failure in seismic conditions – a geosynthetic - reinforced soil bench disposed at slope toe (Figure 12).

The conventional LEM stability analyses showed that the bench increases the stability of the landfill in seismic conditions to a safety factor slightly above the limit (F_{smin} = 1.04). Calculations have been carried out according to EN 1997-1 (Eurocode 7).

3.4 3D numerical analysis

A 3D numerical model of the landfill was developed, having 60 m height, 250 m width and 265 m length. For the landfill layers the general Mohr-Coulomb model was used and the following parameters (Table 1):

The analysis has been performed in the following situations (Batali et al, 2017):

- actual state of the landfill, high leachate levels, static conditions;
- drainage system in function, leachate level at approx. +1.50m above the natural ground level, in static and seismic conditions;
- post-drainage with the reinforced bench, in static and seismic conditions, considering saturated state for all layers;
- same as previous, but using unsaturated soil properties for the desaturated waste layer;

All analyses were performed using Midas GTSNX. The stability analysis, both for saturated and unsaturated state, was conducted using the Strength Reduction Method (SRM). For the unsaturated analysis was used the van Genuchten model. For the seismic analysis a nonlinear time - history analysis was performed, in combination with SRM.

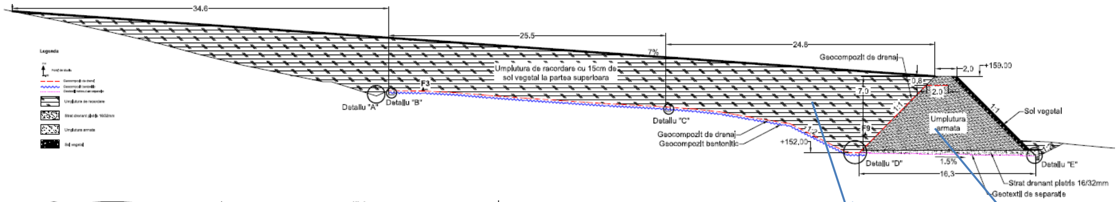


Figure 12. Case study – old landfill – proposed consolidation

Table 1. Geotechnical parameters

No.	Description	Unit weight γ_k (kN/m^3)	Young's modulus E_k (kPa)		Shear strength parameters			Permea-bility co-efficient k (cm/s)
			natural	satu-rated	ϕ_k (°)	c_k (kPa)	c_{uk} (kPa)	
1	Clay, silty clay, medium soft to stiff	19.50	9574	8740	16	32	90	1.5 x 10^{-8}
2	Municipal waste (mixed with clay)	12.00	2500	-	24	0	-	1.4 x 10^{-4}

For the actual state of the landfill, with high leachate level and for static conditions, the obtained safety factor value is F_s = 0.80 (Figure 13), therefore the slope is not stable (as observed on site). The conventional LEM analysis using Janbu method (see Figure 11) returned a factor of safety F_s = 0.97.

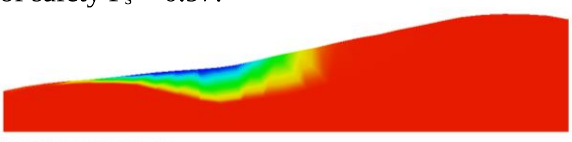


Figure 13. Case study – old landfill – Stability analysis with SRM– static conditions, actual state – F_s=0.8

Figure 14 presents the results for the landfill in post-drainage conditions in static conditions (F_s=1.81). For seismic conditions F_s=0.98 using SRM. The corresponding values for LEM are F_s=1.82 and 1.1, respectively.

After introducing the reinforced-soil bench SRM results are the following: static – F_s=1.86 (Figure 15), seismic – F_s=1.07 (Figure 16). Similar results were found with LEM, but more optimistic than those with SRM: static – F_s=2.1, seismic – F_s=1.3.

The last performed analysis was the one using the unsaturated function of the software (Figure 17). This was activated only for the waste layer (to be drained), the natural clay soil will not be desaturated by the drainage system.

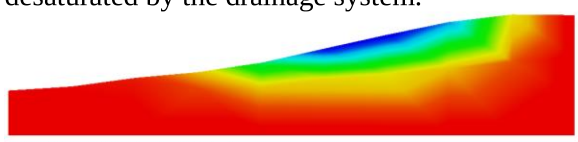


Figure 14. Case study – old landfill – Stability analysis with SRM – post-drainage – static – F_s = 1.81

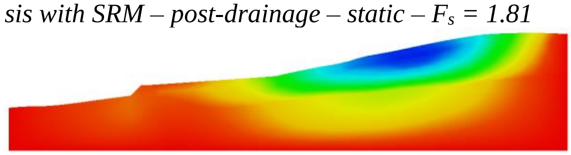


Figure 15. Case study – old landfill – Stability analysis with SRM – post-drainage+bench – static – F_s = 1.86

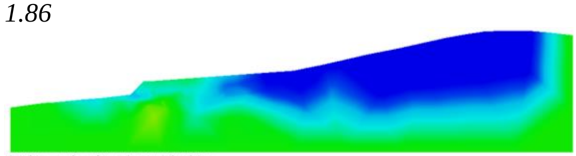


Figure 16. Case study – old landfill – Stability analysis with SRM – post-drainage+bench – seismic – F_s = 1.07

The unsaturated parameters of the waste were estimated based on its composition (having quite large clay fraction) and the UNSODA database (Leij et al., 1996). The dewatering was modelled during the estimated period of 270 days of drainage operation. One can note on Figure 17 that the shape of resulted displacements is correlated to the dewatered level. Only the seismic analysis has been performed for this situation (the most severe case for the design).

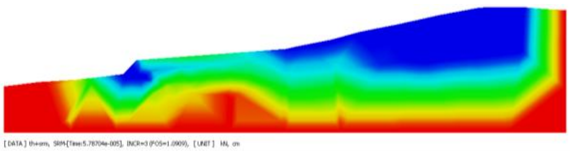


Figure 17. Case study – old landfill – Stability analysis with SRM + unsaturated function – post-drainage+bench – seismic – F_s = 1.09

The minimum factor of safety in this case was only slightly higher than for saturated conditions: 1.09 instead of 1.07. Analyses performed in the past showed higher differences (in some cases up to 40%), but for natural ground, not waste and LEM (Batali, Carastoian, 2016), not SRM. The possible explanations are: uncertain waste parameters deduced by back-calculation; improvement of shear strength characteristics due to unsaturation not accurately estimated.

4 CONCLUSIONS

Both new and old landfills can experience slope instability as they involve many slopes, from natural, site-belonging ones, to dikes, cells etc. The specific landslides occuring in landfills are related to the presence of lining and drainage system and are involving both the waste mass and natural ground.

The paper presented in its first paper some examples of instability phenomena in landfills from Romania, both new landfills and old dumpsites, together with the causes of the phenomena.

In it second part the paper presents a case study of an old dumpsite which experienced instability phenomena during its closure. For this case stability analyses have been performed both using LEM and 3D-FEM methods, in various stages. The consolidation measures included drainage and mechanical consolidations and the stability analyses considered the state before and after each consolidation stage. For simulating the dewatering, an unsaturated 3D-FEM analysis has been carried out. Also, the seismic action has been considiered by means of a time-history analysis. The comparison of results showed in general good correlation, but differences were lower than those expected, this being probably due to incertitude regarding waste parameters. SRM in conjunction with FEM and unsaturated numerical modelling allow a more realistic stability analysis, especially for heavy drainage situations, as the presented case.

5 REFERENCES

Batali, L., Carastoian, A., 2016, Slope Stability Analysis Using the Unsaturated Stress Analysis. Case Study, *Procedia Engineering* **143**, 284 - 291

Batali, L., Carastoian, A., Popa, H., Pantel, G., 2017 Instability phenomena in municipal waste landfill. Numerical modeling in saturated and unsaturated conditions, *Energy Procedia* **112** (2017), 481 – 488

Batali, L., Popa, H., Pantel, G., Butnarciuc, N., Olinic, E., Manea, S., 2014 Associations geosynthetics –mineral materials used for civil engineering works, *Romanian Journal of Materials* **44** (3) 272 – 282

Leij, F.J., Alves, W.J., van Genuchten, M.Th., Williams, J.R. The UNSODA unsaturated hydraulic database EPA/600/R-96/095, U.S. Environmental Protection Agency, Cincinnati, OH. 1996

Sharma, H.D., Lewis, S.P., 1994 Waste containment systems, waste stabilization and landfills: design and evaluation. New York, John Wiley and Sons