Stability analyses and design of a waste landfill enlargement in a seismic area

Analyses de stabilité et projet d'élargissement d'une installation de stockage en zone sismique.

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ABSTRACT: Static and seismic stability, taking into account the mechanical properties of subsoil, waste materials and lining systems, represent a major issue in the design of new landfill or enlargement of existing ones. The paper describes the geotechnical investigation, the stability analyses and the engineering solutions adopted for the enlargement of a non-hazardous waste landfill situated in a seismic area in Italy. The pseudo-static approach was adopted for seismic analyses. Stabilization measures including a soil-cement berm and passive pile rows were designed to ensure the stability of landfill and foundation soil during construction and service. The mix-design of the soil-cement berm was assessed by laboratory tests. The paper points out the main geotechnical issues posed by the safe and efficient design of modern landfills.

RÉSUMÉ: La stabilité statique et sismique, prenant en compte les propriétés mécaniques du sous-sol, des déchets et des systèmes d'étanchéité représente un aspect fondamentale des projet de nouvelles installations de stockage ou d' élargissement d'installations existantes. L'article décrit l'investigation géotechnique, les analyses de stabilité et les solutions adoptées pour l'élargissement d'une installation existante, située dans une région sismique en Italie. L'approche pseudo-statique a été adoptée pour les analyses sismiques. Des mesures de stabilisation incluant une berme en terre-ciment et des rangs de pieux ont été conçues pour garantir la stabilité en phase de construction et de service. La composition du mélange terre-ciment a été établie à l'aide d' essais de laboratoire. L'article met en évidence les problématiques géotechniques principales pour un projet en sécurité des installations de stockage modernes.

KEYWORDS: landfill, stability, composite liners, seismic, pseudo-static, soil-cement

1 INTRODUCTION

National regulations and international technical recommendations prescribe that the design of new landfills must be based on appropriate site characterization, description of construction phases, nature of waste materials and related environmental risks and issues. These indications must be respected also for the enlargement of existing facilities. In particular, stability plays an essential role in landfill design and operation.

One of the major issues related to the stability is the variability of waste, that can deeply affect their mechanical behavior. The unit weight of waste can vary from 5 to 15 kN/m^3 (Choudury and Savoikar 2008), due to their heterogeneous composition. The water content may also vary within a broad range (20-80%) (Beaven et al 2011). The shear strength of waste is influenced by age (Hossain 2009), composition and water content (Bray et al 2009). In the majority of cases, the shear strength at the interfaces of composite liners (e.g., between compacted clay and geomembrane) is the key factor that drives the safety estimation (Mitchell et al 1990). Shear strength at interfaces can be mobilized by small deformations and is mainly affected by temperature (Karademir et al 2011), type of contacted surfaces (Manassero et al 1996) and ageing in leachate (Pasqualini et al 2002).

Particular attention must be devoted to landfill constructed in seismic areas; their performance can be assessed by pseudo-static, simplified or deformational dynamic analysis (Seco e Pinto et al 1995, Castelli et al 2013). Shaking table tests (Yegian et al 1995) and centrifuge models (Kockel et al 1995) were used to understand the role of interfaces in seismic conditions and the interaction between waste and structures, respectively.

The paper describes the investigation and analyses carried out to design the enlargement of an existing non-hazardous waste landfill, situated in a seismic area in Italy. The definition of seismic actions is illustrated in the context of national regulations. The methods of stability analysis utilized and the assumptions adopted to model the different materials involved (soils, waste, lining systems) are described. Finally, the engineering solutions designed to ensure the stability during construction and operation of the landfill are presented. The paper points out the main geotechnical issues posed by the safe and efficient design of complex engineered systems such as modern landfills.

2 SITE AND PROJECT DESCRIPTION

2 .1 *Existing landfill and enlargement requirements*

The landfill is located in central Italy. The landfill area consists of an old closed plant and of a more recent plant, still partly operating but nearly exhausted; therefore, an enlargement has been planned. Fig.1 shows a plan view of the operating plant and the design contours of the enlargement, which should allow an increase in volume of landfilled waste of about 400,000 m^3.

In order to build the enlargement base, the design requires regularization and terracing of the ground surface in the steeper portion of the area (NW) and an excavation for a maximum depth of 20 m with respect to the current ground level in the flatter portion (SE). Fig.2 illustrates two representative cross-sections, showing the current profile of the ground, the design profile of the landfill base and the final profile of the waste body along the NW-SE, (section 5, Fig.2a) and NE-SW direction (section C, Fig.2b), respectively. The enlargement will partly rest on the existing waste body on the SW side. The bottom liner system will consist of (from the bottom upwards): 1 m compacted clay (CC), a rough HDPE geomembrane (GM), a nonwoven geoteoxtile protection layer (GTX), and 0.6 m coarse-grained drainage layer (DL).

On the NW side, the landfill site is bordered by steep slopes affected at the front by a local retrogressive instability, occasionally reactivated by heavy precipitations. Therefore, local stabilization measures were included in the design. Long-term monitoring with inclinometers allowed excluding deeper failures surfaces, potentially involving the upper portion of the slope.

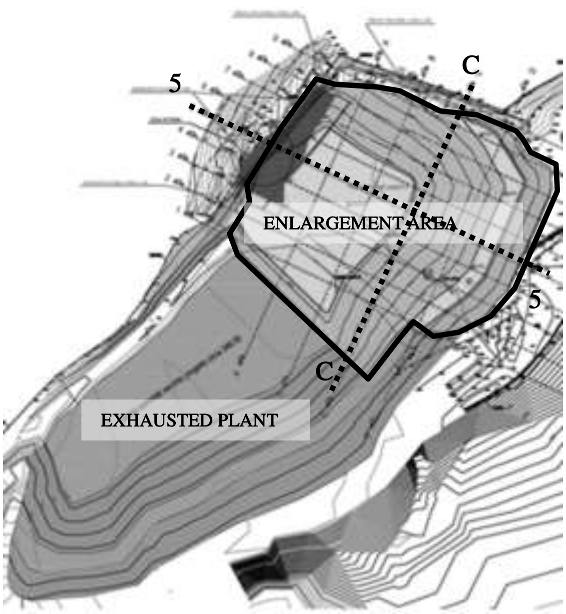


Figure 1. Plan view of the (nearly) full plant and planned enlargement

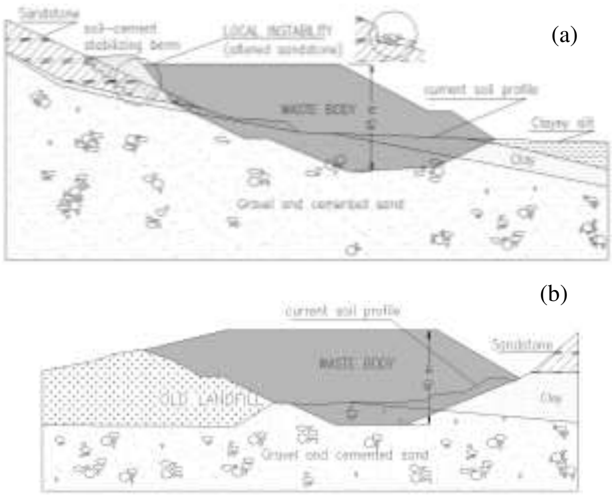


Figure 2. Cross sectional views of the landfill along the NW-SE direction –section 5 (a) and NE-SW direction –section C (b).

2.2 Geotechnical investigation

The geological setting of the site consists of plio-pleistocenic deposits of fluvio-lacustrine origin. The subsoil of the enlargement area was investigated by geotechnical and geophysical techniques. The subsoil along the NW-SE direction (Fig.2a) comprises of four stratigraphic units: (1) sandstone (alternating with silty sands and sandy silts) in the upper part of the slope only, with a maximum thickness of 13 m; (2) clay, of thickness varying from 2-3 m (upper part) to 8-9 m (lower part); (3) gravel and cemented sands, outcropping in the central part of the slope; (4) colluvial clayey silt, overlying the clay layer in the lower part of the slope, with a maximum thickness of 9 m. The local instability affects the exposed and altered front of the sandstone layer, resulting in scarps 3 to 10 m high and slide debris.

The soil along the NW-SE direction (Fig.2b) comprises of three stratigraphic units: (1) sandstone with sub-vertical faces; (2) clay with maximum thickness of 20 m; (3) base gravel and cemented sands, outcropping at the toe of the slope. The groundwater table was found at depth greater than 25 m below g.l. The mechanical and hydraulic characterization (by in-situ and laboratory tests) is summarized in Table 1.

2.1 Seismic actions

Stability analyses were carried out in static ad seismic conditions, as requested by Italian regulations (NTC 2008). A nominal life span of the structure of 50 y and the class of use typical of structures whose failure/collapse can cause high damage (Class III-NTC 2008) were assumed. This implies a reference period for the seismic action of 75 y. The expected peak acceleration on flat rigid ground (a_g) was determined from the seismic classification considering the Ultimate Limit State (ULS) of safeguarding of life (SLV), resulting in a_g=0.26g. In the absence of site specific analyses, Italian regulations allow introducing the site effects by identifying the subsoil category, on the basis of the parameter $V_{s,30}$, the equivalent shear wave velocity in the first 30 m of depth from g.l. The average $V_{s,30}$, determined by geophysical seismic refraction tests was about 700 m/s. The soil category was identified as B (soft rock/coarse-grained soils deposits of high density/fine grained soils of high consistency), and the corresponding stratigraphic amplification coefficient Ss equal to 1.15. As the landfill is located at about one half of the height of the slope, the topographic amplification coefficient S_t was assumed equal to 1.1. The peak ground acceleration a_{max} was thus 0.329g. The design pseudo-static seismic coefficient was calculated as $k_H=a_{max}\beta_s/g$, where the reduction factor β_s= 0.28 and the ratio k_V/k_H =±0.5. The same pseudo-static coefficients were assumed for soil deposits and waste body.

Table 1. Parameters for soils and artificial materials used in the analyses

LAYER	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	$E\cdot10^3$ (kN/m^2)	ν (-)	$k_x\cdot10^{-5}$ (m/day)	$k_y\cdot10^{-5}$ (m/day)	c'_k (kN/m^2)	ϕ'_k (°)	ψ_k (°)	R (-)
Soil parameters										
Altered sandstone	19.2	19.83	5	0.3	1.73	1.73	5	32	0	1
Clayey silt	19.2	19.83	5	0.3	1.73	1.73	5	32	0	1
Clay	20.3	20.86	50 (C) 10 (5)	0.3	6.05	6.05	8.2	26	0	1
Gravel/sand	18	20	20	0.3	10^5	10^5	2	38	0	1
Sandstone	25	25	4940	0.1	8.64	8.64	80	40	0	1
Parameters of artificial layers										
CC	19	19	4	0.25	0.864	0.864	0	30	0	0.6
Drainage layer	18	20	20	0.3	$4.32\cdot10^5$	$4.32\cdot10^5$	0	40	0	0.69
Waste	13	13	4	0.3	8.64	8.64	15	33	0	1
Soil-Cement (a)	19.5	19.5	45	0.12	0.864	0.864	16	37	0	0.49
Soil-Cement (b)	19.5	19.5	45	0.12	0.864	0.864	21	31	0	0.49

2.3 Soil-cement stabilizing berm

The enlargement works required, first of all, the solution of the local instability affecting the NW border of the site. In particular, a stabilizing berm was designed (Fig.2a). A compacted soil-cement mixture was selected to construct the berm, owing to the potential improvement of both the mechanical and hydraulic properties of soil offered by amendment with cement (Bellezza and Fratalocchi 2006). The most easily available materials to construct the berm are soils form two of the deposits found in the site. The two deposits (named S and C for simplicity) differ mainly in the fines content (63% for S, 81 % for C) whereas the clay fraction is approximately the same (18%). Both soils fully meet the suitability criteria defined by Daniel and Benson (1990) for soils to be compacted for landfill clay liner. The mix-design included the addition of 4% (by dry weight of soil) of Portland cement to the soils. To check the suitability for cement treatment, a laboratory study was conducted: soil-cement samples compacted by Standard Proctor procedure were tested for permeability and shear strength.

Fig.3 shows the Standard Proctor compaction curves and the *k* values of soils A and B as a function of the water content, *w*. Wet-of-optimum compacted samples (w > 17%) always ensure *k* values suitable for a bottom liner (*i.e.*, lower than 1×10^{-9} m/s). For these samples the shear strength parameters shown in Table 2 were determined at curing times of about 1-2 weeks. The obtained parameters were reduced to take into account that the in-situ mixing and compaction procedures are necessarily less controlled than the laboratory ones. To this purpose, according to previous experience documented in the literature (Pasqualini et al 1996) a partial safety factor of 2.4 was applied to c' and a factor of 1.2 to ϕ' (values in Table 2). Therefore, the stability analyses were carried out considering the following combinations of characteristic shear strength parameters (Table 1): (a) c' = 16 kPa, ϕ'=37°, (b) c' = 21 kPa, ϕ'=31°.

Further safety is ensured since all the samples were tested at short curing times. Indeed, reduction in hydraulic conductivity and increase in shear strength occur with increasing curing time (Bellezza and Fratalocchi 2006). Anyhow, the assumed design parameters will be verified by a test pad.

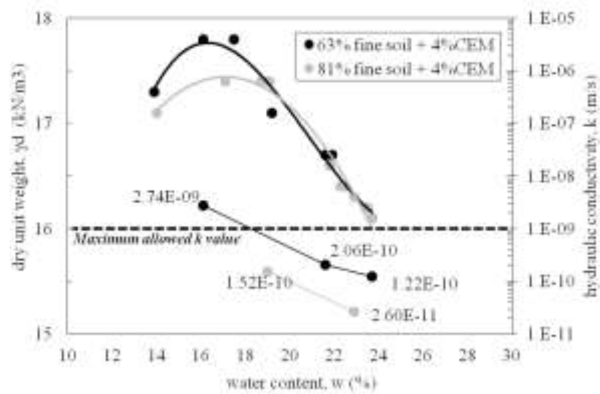


Figure 3. Compaction curves of soil A and B treated with 4% Portland cement (left axis) and hydraulic conductivity of the compacted specimens as a function of water content (right axis). Permeability tests were performed under an average effective stress of 25 kPa.

Table 2. Laboratory tests results on compacted soil-cement.

Spec.	Test	w (%)	γ_d (kN/m^3)	Curing time (days)	c' (kPa)	ϕ' (°)
S-4	DS	21.9	16.7	16	38	45
S-7	DS	19.2	17.1	7	52	41
C-H	DS	21.8	16.6	7	50	37
C-L	TX	22.8	16.3	7	62	36

3 STABILITY ANALYSES

3.1 Methods of analysis

The stability analyses were carried out using the limit equilibrium (LE) code STAP (v.11) and the finite element (FE) code PLAXIS (v.8.5). Although non circular slip surfaces can be analyzed with STAP, only circular surfaces (Bishop's method) were considered in the analyses with the LE method. STAP identifies the critical surface by assigning a grid of centers and a range of radii of the possible slip surfaces. The analysis requires the unit weights (γ_{sat} and γ_{unsat}) and the characteristic values of the shear strength parameters (c' and ϕ') of each layer. The waste was assigned ϕ'_k =33° c'_k=15 kPa (Bray et al 2009).

Stability analyses are carried out in PLAXIS by the *phi/c reduction* method (which implies a Mohr-Coulomb failure criterion). The additional parameters required by PLAXIS (elasticity modulus, E, Poisson coefficient, ν, vertical and horizontal permeability coefficients, k_y and k_x,, dilatancy angle, ψ) were deducted from the characterization or estimated from literature data (Table 1). The shear strength parameters of the interfaces were specified selecting conservative values from published data (Pasqualini et al 2002). The interface shear strength of composite liners was accounted for by the R parameter which reduces c' and the tangent of ϕ' (Table 1). For example, the shear angle of the CC-GM interface (19°) was assigned by specifying R=0.6 of the CC layer (30°).

The ULS of global instability was verified using the A2+M2+R2 combination of actions, soil parameters and resistances, as per NTC 2008. Therefore, the minimum safety factor, SF, for either LE or *phi/c reduction* method was 1.1. The analyses were conducted in 2-D, considering the construction phases and the final profile of the waste fill, in both longitudinal (Fig.2a) and transversal direction (Fig.2b).

3.2.Constuction phase

The excavation profile includes a soil-cement berm (see section 2.3) along the NW side of the enlargement, having the purpose of retaining the unstable front in the upper part of the slope (Fig.2a) and two parallel pile rows. Both static and seismic conditions in the presence of pile rows were considered, under the assumption that the complete filling of the waste to the highest elevation will take more than two years (therefore the excavation profile needs to be analyzed also in seismic conditions, as required by the regulations). Fig.4a shows the position of the piles and the critical slip surface (obtained by Bishop method – STAP) in the upper part of the slope, associated to a SF of 1.11.

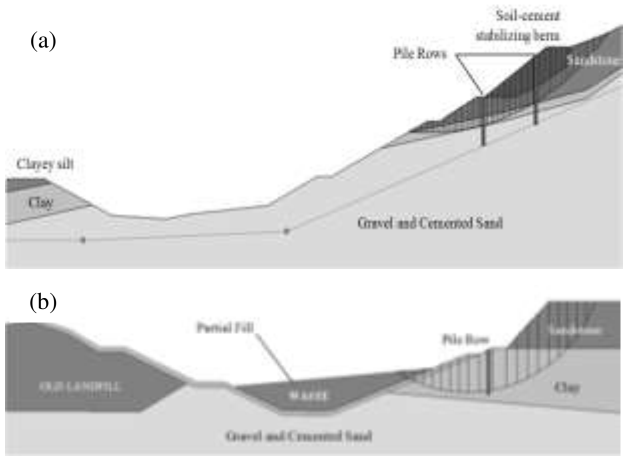


Figure 4. Critical slip surfaces in seismic conditions (a) along the NW-SE direction (STAP11); (b) along the NE-SW direction (STAP11)

The upper pile row (90 m in length) consists of 1 m diameter drilled piles, 20 m long and with 0.3 m clear spacing, partly intersecting the soil cement-berm; the lower row (85 m in length) consists of 1 m diameter drilled piles, 14 m long with 0.3 m clear spacing (Fig.4a).

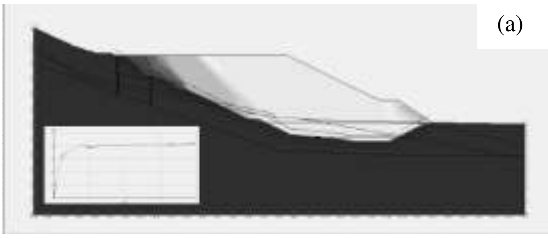
Along the transversal direction (Fig 4b), the results pointed out a potential instability of the excavation profile in seismic conditions, despite the introduction of an additional row of piles. However, as the disposal plan foresees filling of the first level of waste within less than two years, regulations allow limiting the analysis of the empty profile to static conditions only (end of excavation). With the partial filling, the stability is ensured also in seismic conditions (SF=1.12, critical slip surface in Fig. 4b). The pile row (85 m in length) consists of 0.8 m diameter drilled piles, 16 m long with 0.4 m clear spacing.

3.3 Final profile

The main advantage of the *phi/c reduction* method implemented in PLAXIS is that the most critical slippage surface is automatically identified. In this way, composite critical slip surfaces, partly intersecting the waste body, partly coinciding with interfaces in the liners can also be identified. Composite translational failure along the bottom liner systems and through the mass of waste mass is indeed a common failure mode in landfills (Koerner and Soong 2000; Blight 2008).

Fig.5 shows the an example of results obtained by PLAXIS in terms of total displacement increments in seismic conditions, for vertical inertial forces directed downwards (a) and upwards (b), respectively. The likely failure surface can be identified from the shadings, as the stable mass presents the uniform darkest shading. In Fig 5a, the failure surface associated with the minimum SF (1.165) is in fact a composite surface. In Fig.5b, the surface associated with the minimum SF (1.14) coincides with the bottom liner.

The stability was analyzed considering various situations, including a leachate mound of 2 m combined with seismic conditions, and a temporary interruption of the pumping system causing a leachate mound of 10 m (in static conditions). The SF was always found to be greater than 1.1. With reference to the transversal direction (section C), the stability conditions were ensured with or without leachate, both in static and seismic conditions. In particular, Fig.6 shows the critical slip surface (SF=1.244), entirely located in the waste body.



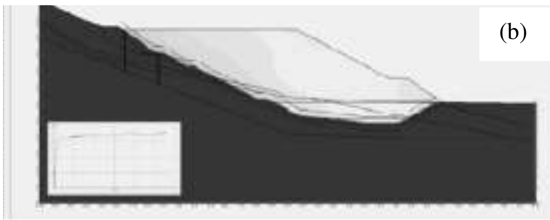


Figure 5. PLAXIS output of the *phi/c reduction* method under seismic conditions for section 5: (a) downward vertical inertial forces; (b) upward vertical inertial forces.

Figure 6. PLAXIS output of the *phi/c reduction* method under seismic conditions for section C: upward vertical inertial forces.

4 CONCLUSION

The paper illustrates a case history concerning the enlargement of a non-hazardous waste landfill, situated in a seismic area in Italy. This case pointed out that all relevant situations need to be considered in stability analysis since the most critical conditions can occur during construction (particularly in case of deep excavations). Calculations methods and tools able to take into account the presence and the mechanical behaviour of the interfaces in composite liners are essential for the stability assessment, as the interfaces can coincide with or represent part of the critical surface. The design of landfills should in general aim at optimizing the storage volume and fulfil the stability requirements. Stabilization techniques (e.g., stabilizing piles and retaining berms as in the reported case) can be successfully applied in order to ensure the global stability during construction and operation of the landfill.

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