The December 29th 2010 Xerolakka Municipal Solid Waste landfill failure

29 décembre 2010 : l'échec d'enfouissement Xerolakka

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ABSTRACT: On December 29th 2010, a 30 m high slope failed at the Xerolakka Municipal Solid Waste landfill in Greece. The failure resulted in temporary interruption of the landfill disposal activities and closure of the landfill access road; it also received significant media attention. A reconnaissance of the landfill slope instability was performed a few hours after the failure. Subsequent data collection, field investigations and numerical analyses were performed to better characterize the causes of the instability. Data collection included review of available data regarding the landfill design and the waste material at the Xerolakka landfill. Field investigations included Lidar surveying to closely map the post-failure geometry, as well as shear wave velocity measurements that were used as a basis for characterization of the MSW material and comparison with data available in the literature. Numerical analyses included limit equilibrium as well as finite element analyses. The results of the investigation indicate that the failure was caused by a combination of factors, including, inappropriate waste disposal practices, inadequate compaction, leachate and gas pressure generation and increased steepening of the landfill slopes.

RÉSUMÉ: Le 29 décembre 2010, une pente de 30 m de haut a échoué à la mise en décharge des déchets Xerolakka solides municipaux en Grèce. L'échec a entraîné une interruption temporaire des activités de mise en décharge et la fermeture de la route d'accès à la zone d'enfouissement et d'élimination ont reçu une attention médiatique importante. Une reconnaissance de l'instabilité de la pente d'enfouissement a été réalisée quelques heures après l'échec. Après la collecte des données, enquêtes sur le terrain et des analyses numériques ont été réalisées afin de mieux caractériser les causes de l'instabilité. La collecte des données comprenait un examen des données disponibles concernant la conception de la décharge et les déchets à la décharge Xerolakka. Les enquêtes de terrain inclus Lidar arpentage de près cartographier la géométrie post-rupture, ainsi que les mesures de vitesse de cisaillement d'ondes qui ont été utilisées comme base pour la caractérisation de la matière MSW et comparaison avec les données disponibles dans la littérature. Des analyses numériques incluent équilibre limite ainsi que des analyses par éléments finis. Les résultats de l'enquête indiquent que la panne a été causée par une combinaison de facteurs, y compris, les mauvaises pratiques d'élimination des déchets, le compactage insuffisant, le lixiviat et la génération de la pression du gaz et l'augmentation accentuation des pistes d'enfouissement.

KEYWORDS: Municipal solid waste, landfill, slope failure, shear wave velocity

1 INTRODUCTION

To protect public health and the environment, Municipal Solid Waste (MSW) landfill slopes need to be stable. Unfortunately, numerous landfill slope failures have been documented in the literature (e.g. Eid et al. 2000, Hendron et al. 1999, Kavazanjian and Merry 2005, Huvaj-Sarihan and Stark 2008) and many more remain undocumented. Although such failures are undesirable, it is important to learn from them so that similar occurrences are avoided in the future.

This paper presents the field observations from a reconnaissance study performed within hours after the December 29th 2010 Xerolakka landfill slope failure, as well as subsequent field measurements and stability analyses that were executed to better understand the causes of the failure.

2 THE XEROLAKKA LANDFILL

The Xerolakka landfill is one of the nine MSW landfills in the Region of Western Greece, located 5 km east of the City of Patras. It is a canyon landfill at the foothills of the Panachaikon Mountain. It started receiving waste in September 1993 and presently receives 300 tn of waste daily (Sufalnet, 2006).

The site is located on a geologic sequence of Pleistocene and Pliocene claystone, marls and siltstones with lenses of sandstones that are generally considered intact. The groundwater table fluctuates seasonally significantly.

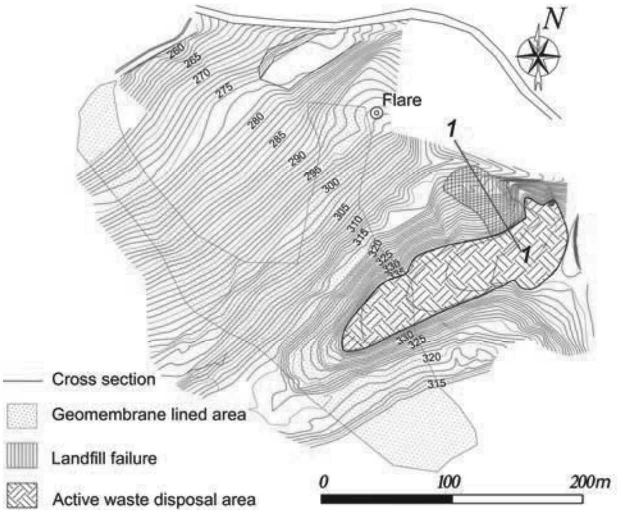

Figure 1. February 2011 topographic map of the Xerolakka canyon landfill.

A topographic map of the landfill is shown in Fig. 1. The first cell of the landfill was geomembrane-lined. Subsequently the use of geosynthetics was discontinued because of the presence of impermeable geologic formations (Seisakis and Roussos, 1994). Due to strong public opposition, new cells were not constructed, as anticipated in design. In the absence of an alternative waste management solution, the landfill continued to receive waste. Thus, a waste mound with increasing height and slope inclination was formed (shown in the southeast side of Fig. 1) which partially failed on December 29th 2010.

3 FIELD OBSERVATIONS

On December 29th 2010, early in the morning (around 08:00 am), a failure of one of the landfill slopes occurred in the active waste disposal area. The authors performed on-site reconnaissance at 14:00. The waste slide had plan dimensions of 50 m by 30 m and its crest was located at the top of the landfill (absolute elevation of +340 m) whereas its toe reached the access bench 27 m below. The volume of the slided waste mass is estimated to be equal to 12,000 m^3. The waste slide debris covered one of the landfill benches that was used as access road to the active waste disposal area, thus disrupting landfill disposal operations. During the reconnaissance visit, the waste that covered the access road was already partially removed and pushed downhill. A view of the slide from the West is shown in Fig. 2 and a view of the slide from its toe after removal of the waste from the landfill access bench is shown in Fig. 3.

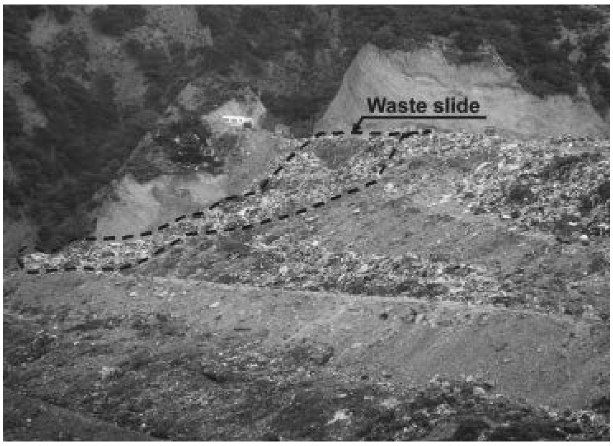

Figure 2. Waste slide view from the western side of the MSW landfill.

Figure 3. Waste slide view from the access bench located at the toe of the slide.

The waste slide is located adjacent to the graded canyon slopes with the Northeast portion of the slide exposing the native rock mass (also shown on the left side of Fig. 3). Precipitation on the steep canyon slopes in the vicinity of the waste slide drains towards the waste mass due to the absence of surface water cutoff drainage ditches and percolates in the waste.

The uppermost layer of MSW in the active waste disposal area (i.e., the landfill crest) was not compacted and did not include any daily soil cover. The compaction of waste had reportedly ceased for at least a year prior to the failure and daily soil cover was not used for many months, possibly years. The absence of daily soil cover on the top waste layers can be seen at the right side of Fig. 2. In addition, the gas collection system was not operational.

The crest of the landfill was not graded properly to manage surface water runoff due to precipitation and in the vicinity of the failure slide mass, rainfall water was found to be ponding. Leachate was observed to pour from the toe of the waste slide whereas an interceptor trench that was built next to the landfill bench was also found to contain leachate. Media photos from earlier in the morning of the 29th of December indicate a large wet area in the vicinity of the failure, apparently from liquids that came out of the waste mass.

The December 29th 2010 failure occurred four days after a rainfall event. A weather station located in the Port of Patras at a distance of 4.5 km away from the landfill and at an absolute elevation of +6 m, recorded approximately 11 mm of precipitation for that event and a total of 16.5 mm in the five days prior to the failure. Ten days earlier, another event with a precipitation of 20 mm occurred. This amount of precipitation is lower than the corresponding amount of rainfall in the past two years; however, the geometry (height and inclination) of the landfill slopes had changed in the last year, adversely affecting its stability. The complete absence of surface water management system and daily soil cover, would have allowed for the rainfall water to easily percolate in the waste mass.

4 FIELD MEASUREMENTS

A high-resolution 3-D topographic map of the landfill area was generated by performing terrestrial LIDAR (Light Detection and Ranging) measurements, in addition to conventional geodetic survey. The measurements utilized land-based laser scanning technology and allowed a reliable definition of the failed waste mass. Field measurements of the in situ shear wave velocity (V_{S0}) were also performed. Shear wave velocity is a critical parameter that has been used to characterize the MSW (Zekkos, 2011). In this project, V_{S0} was used to characterize the MSW and assist in the selection of values for MSW material properties. Shear wave velocity profiles were also explicitly used for the performance of seismic stability analyses that are not described herein.

The small strain shear wave velocity of waste material was evaluated as a function of depth by applying the Spectral Analysis of Surface Waves (SASW) and Refraction Microtremor (ReMi) techniques. The application of these techniques is preferred in the case of landfills due to their non-intrusive nature (Matasovic et al., 2011). The V_{S0} vs. depth profile is shown in Fig. 4.

Fig. 4 compares the V_{S0} vs depth profiles measured at Xerolakka landfill with the data available in the literature. The mean and mean±sigma V_{S0} curves are shown for MSW in three geographic regions, specifically southern California (Kavazanjian et al. 1996), northern California (Lin et al. 2004) and Michigan (Sahadewa et al. 2011). It is observed that the in situ data from Xerolakka are in the lower range of the literature V_{S0} data. This difference may be attributed to a number of factors including waste composition, but more importantly the absence of waste compaction and daily soil cover. It should be mentioned that, following the waste slide, the placement of waste (from Dec. 2011 to May 2012) was carried out in a single thick lift (~8 m), overlain by a soil cover ranging from 1 to 3 m.

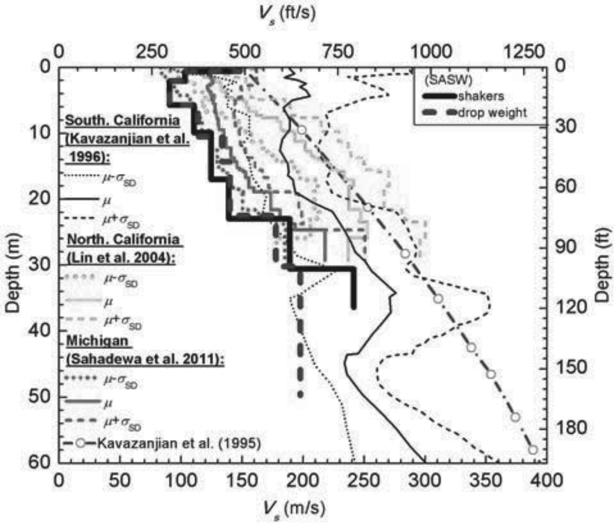

Figure 4. Comparison of V_{S0} vs depth profile at Xerolakka landfill with other published cases of landfills.

5 PROPERTIES OF MUNICIPAL SOLID WASTE

No site specific data was available on the MSW that was disposed of at the Xerolakka landfill. Thus, for the performance of the limit equilibrium and finite element stability analyses, the measured V_{S0} was used to guide the selection of MSW properties. For the performance of the analyses the unit weight, shear strength, deformation modulus (for the finite element analyses) and Poisson's ratio of MSW are required and were selected as follows:

Unit Weight: The selection of the MSW unit weight has an impact on the stability of the waste mass. On the basis of the available landfill information and the Zekkos et al. (2006) recommendations, for the 30 m thick waste mass, an average unit weight value of 12 kN/m^3 was used. This value is also consistent with the unit weight value used for the design of the landfill facility (Koronis 1995).

Shear Strength: The selection of appropriate shear strength parameters is critical in evaluating the stability of the waste mass. Bray et al. (2009) recommended a generic MSW shear strength envelope. The recommended strength envelope was the mean fit to a large dataset, however, various factors such as waste composition and unit weight may result in variations from this envelope. For example, the unit weight has an important impact on the shear resistance of MSW. As reported by Zekkos et al. (2010), for waste with the same waste composition, a reduction in unit weight by 2kN/m^3 results in an approximate reduction in shear strength by 20%. Considering the absence of compaction and daily soil cover as well as the particularly low measured shear wave velocity of the MSW, the shear strength of the Xerolakka landfill MSW was reduced by 20% from the shear strength envelope recommended by Bray et al. (2009).

MSW elastic modulus and Poisson's ratio: The large-strain elastic modulus E_{ref} is an explicit input parameter in finite element analysis. The value of E_{ref} impacts the calculated displacements, but does not influence significantly the calculated factor of safety. In the present study, it was assumed that the modulus is equal to 1/10 of the small-strain elastic modulus E_o, which was calculated from the measured small strain shear modulus G_o, whereas the Poisson's ratio value was assumed to be equal to 0.1, based on data available in the literature (Zekkos, 2005).

6 STABILITY ANALYSES

Stability analyses of the Xerolakka landfill slope failure were performed using both limit equilibrium (Geo-Slope 2007 – SLOPE/W) and finite element (PLAXIS, 2004) analyses and the material properties described earlier. Each analysis methodology has its strengths and limitations. In finite element analyses, there is no requirement to predefine candidate failure surfaces; instead, the failure surface with the lowest factor of safety is identified using the phi-c reduction methodology (PLAXIS, 2004). Another known advantage of the FEM is its ability to calculate displacements in every prescribed stage of calculation as well as its ability to model progressive failure. In limit equilibrium methodology, the factor of safety for a large number of failure surfaces is calculated and the one with the lowest factor of safety is the critical one. For the calculation of the factor of safety, the Spencer method (Spencer, 1967) is used. Limit equilibrium methods do not account for the presence of strain softening materials, since no consideration of strains or displacements is made.

It is important to note that, in the case of Xerolakka landfill, it is very difficult to evaluate the actual pore pressure regime within the waste mass due to the unavailability of field data. Thus, stability analyses were performed for two cases: complete absence of leachate table (provided a leachate and gas collection system was operating properly) and for the case of a high leachate table resulting from the absence/non operative leachate and gas collection system. The leachate table used in the analyses was estimated on the basis of field observations, namely: 1) the presence of ponding water at the crest of the landfill (near the waste slide) and 2) observed seepage at the toe of the waste slide. The high leachate table is intended to account in a conventional manner for the presence, and possibly flow, of leachate and more importantly the generation of gas due to biodegradation. The amount of gas generated can be significant and for that reason, modern landfill facilities are equipped with a gas collection system that collects the gas and either combusts it using a flame or uses it to generate energy. There was no gas collection system in the active waste disposal area. Gas and leachate pressures would result in a reduction of the effective stress in the waste and a subsequent reduction in the factor of safety.

7 RESULTS OF ANALYSES AND DISCUSSION

Analyses were performed for the selected properties and the cross-section geometry at the location of the failure. The inclination of the slopes in the upper part of the landfill is as high as 1.2:1 (horizontal to vertical). In the case of absence of leachate table and gas pressure ("dry tomb" landfills), the results of analyses indicate a stable condition with a calculated factor of safety equal to 1.60, i.e., higher than the 1.50 typically required. Additional analyses were performed with the assumed leachate table, as shown in Fig. 5.

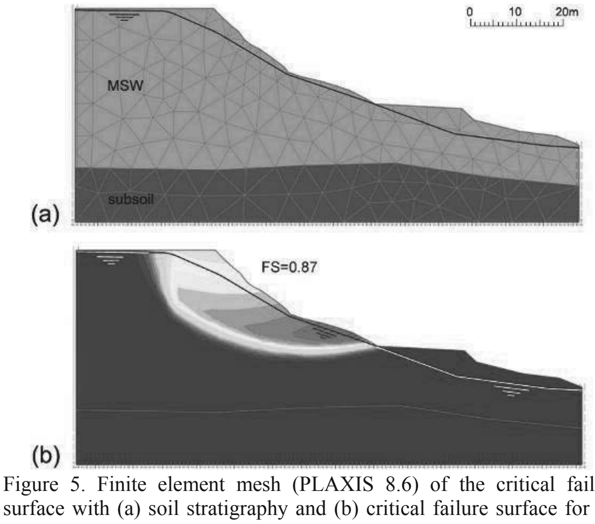

Figure 5. Finite element mesh (PLAXIS 8.6) of the critical failure surface with (a) soil stratigraphy and (b) critical failure surface for the estimated leachate table.

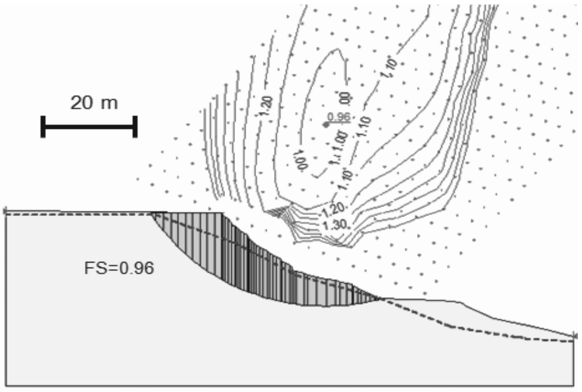

Figure 6. Limit equilibrium model (GeoStudio 2007 – SLOPE/W) with critical failure surface for the estimated leachate table.

For these conditions, the factor of safety based on finite element analyses is calculated equal to 0.87, indicative of unstable conditions.

Analyses using the limit equilibrium method (Geo-Slope 2007 – SLOPE/W) resulted in similar critical failure surfaces for dry conditions and for the assumed leachate table (shown in Fig. 6). The factor of safety is equal to 1.60 for dry conditions and 0.96 for the assumed water table.

The results of the above and additional analyses indicate that the reduction in the factor of safety due to the presence of leachate is significant and much greater than the impact of other uncertainties, such as the unit weight of waste material.

8 CONCLUSIONS

The waste slide that occurred on December 29th 2010 has height of 27 m and width of 30 m and involved a waste mass of 12,000 m^3. The waste slide engaged MSW material only. On the basis of the reconnaissance studies, the field measurements and the stability analyses, the waste failure is attributed to poor landfill practices (absence of compaction and daily soil cover), the steep inclination of the waste mass and the increased percolation of rainfall water in the waste mass (and associated gas pressure generation) due to the absence of daily soil cover and surface water management system. The analyses also indicated that failure would not be incipient under dry conditions.

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