Reanalysis of the Kettleman Hills Landfill Slope Stability Failure

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Abstract— The paper presents results of the Kettleman Hills landfill slope stability failure reanalysis in two – dimensional and three - dimensional models. The analysis was performed using the computer codes FLAC (v.5.0) and FLAC3D (v.4.0), respectively, which are Finite Difference Method codes. The investigation was based on Shear Strength Reduction Technique (SSR). The approach taken considered the problem as one of statics. The failure was caused by waste mass movement along the slip surface located in the geosynthetic layer, which was characterised by relatively low strength properties as compared with values of these parameters for the waste layer as well as for the subgrade. Obtained values for the factor of safety differ from each other and depend on the kind of analysis conducted. These results are caused by the possibility of performing the real geometry of the landfill in 3D modelling issues.

I. INTRODUCTION

One of the most important aspects of mining waste management is its safe disposal. One of the tasks of the Min-Novation project has been to promote good practice in this area. The analysis of landfill failures allows one to better understand the processes which can occur during their exploitation. The knowledge gained in this way can be used to design new solutions, which improve the safety of these facilities.

The Kettleman Hills landfill is a hazardous waste disposal facility located on an area of 14.5 ha near Kettleman City (California, USA). The Kettleman Hills landfill was situated in flat basin surrounded by side slopes with an average slope gradient of 23 - 24˚. The Phase I-A, with an area of about 6 ha and located in northern part of the basin, had been filling up since 1987. The waste layer was underlined by a protective compacted liner system. On March 19th, 1988, the maximum height of the object reached 27 m and the slope stability failure occurred. The waste layer rapidly slid in – a southeast direction. Landslide dimensions included 10.7 m depth and 4.3 m height. Figure 1 shows the topography of the Kettleman Hills landfill after the failure occurred. The dashed lines indicate the location of the landslide. The size of the cracks created was between 2.5 cm to 120 cm. The largest of these occurred in the southern part of the landfill. The landslide also caused disruptions and tears in the liner system on the landfill side slope.

The Kettleman Hills landfill failure was caused by the movement of a waste layer, which ran along the slip surface, located in the protective compacted liner system (double liner system which had isolated the subgrade) at the interface between geomembrane – compacted clay (on the base liner system) and geosynthetics layers (on the side liner system).

The paper presents the Kettleman Hills landfill failure reanalysis in two – dimensional and three - dimensional models. The analysis was performed using the computer codes FLAC (v.5.0) and FLAC3D (v.4.0), respectively, which based on the Finite Difference Method. The investigation was based on the Shear Strength Reduction Technique (SSR). The approach taken considered the problem as one of statics. The results of the studies were compared to values obtained in previous analysis.
Based on the geometry defined in figures 3 and 4, the three-dimensional model was constructed. Firstly, the geometry of particular layers was drawn in AutoCAD, then the surfaces of each layer were created in the Surfer 9.0 code, afterwards the data were implemented in the FLAC3D code through a program written in C++. The next step was setting up a mesh in each model. The generated numerical models are shown in figures 5 and 6.

The boundary conditions for the bottom and sides of the models were fixed against horizontal and vertical displacement, respectively. In both cases, the single interface between the waste layer and the subgrade was modeled as the protective compact liner system. The calculations were made using a Coulomb-Mohr plasticity model.

For the purpose of the analysis three representative layers were used (waste, interface, subgrade). Table 1 contains values for geotechnical parameters for each layer which were implemented for analysis.

### III. LANDFILL SLOPE STABILITY ANALYSIS (SSR)

The most likely explanation is that the damage occurred in the liner system, which underlined the waste layer. This assumption is confirmed by observations, which were made after the failure had happened as well as the results of the previous stability analysis.

The Kettleman Hills landfill slope stability failure analysis was conducted using the reduction of the friction angle value for the interface.

In the two-dimensional slope stability analysis of the Kettleman Hills landfill, the instability occurred for the factor of safety $FS = 0.99$ (for the friction angle $\phi = 4.3^\circ$). Figure 7 illustrates the distribution of the shear strain in the layer of waste and its relationship to the factor of safety value. It can be seen that shear strains are growing to a decreasing value of $FS$. Damage of the waste layer appeared

**Fig. 3.** The Kettleman Hills landfill basin geometry (top view).

**Fig. 4.** The Kettleman Hills landfill basin geometry (cross-sections).

**Fig. 5.** The Kettleman Hills landfill 2D model.
Source: Own study.

**Fig. 6.** The Kettleman Hills landfill 3D model.
Source: Own study.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Parameters</th>
<th>Source</th>
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<tr>
<td>Subgrade</td>
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<tr>
<td>$\gamma$</td>
<td>1730 kg/m$^3$</td>
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<tr>
<td>$c$</td>
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</tr>
<tr>
<td>$\phi$</td>
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<tr>
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<td>$8 \times 10^7$ Pa</td>
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</tr>
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<tr>
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<tr>
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<tr>
<td>$K$</td>
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<td>$K_0$</td>
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<td>Normal stiffness</td>
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<tr>
<td>Shear stiffness</td>
<td>$50 \times 10^6$ Pa/m</td>
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</table>

first in its lower part in close proximity of the interface. Afterwards the failure embraced the middle part of the layer. At the moment of instability the damage was present throughout the layer.

The value of the friction angle received for instability in this analysis is comparable with the results obtained in other studies for the facility. M. Chang in his research for a 2D model analysis gained a minimum value of $\phi = 5.0^\circ$.

The value for the friction angle for which there was the instability of the slope landfill in 2D analysis ($\phi = 4.3^\circ$) was the starting point for the continuation of a three-dimensional model calculation.

$FS=1.31$

$FS=1.17$

$FS=0.99$

![Fig. 6. Factor of Safety and Shear Strain distribution in 2D analysis. Source: Own study.](image)

Three dimensional analysis showed that for the value of the friction angle $\phi = 4.3^\circ$ the factor of safety is much lower than in 2D results, and it is set to $FS = 0.76$ (Figure 7). This indicates that landfill slope stability was lost at a higher value of the friction angle than the one received in 2D analysis.

The stress strain distribution obtained from analysis which are shown in figure 7 corresponds to disruptions and cracks observed on the landfill after the failure occurred.

$$FS = 0.76$$

$$\phi = 4.3^\circ$$

![Fig. 7. Shear stress increase - 3D analysis. Source: Own study.](image)

Table 2 shows the successive changes in the value for the friction angle, which were applied to the 3D model in order to determine the strength parameters for interface at the time of failure.

<table>
<thead>
<tr>
<th>$\phi$ [°]</th>
<th>4.3</th>
<th>6.0</th>
<th>8.0</th>
<th>9.0</th>
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<tr>
<td>FS</td>
<td>0.76</td>
<td>0.9</td>
<td>0.99</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Source: Own study

Further calculations carried out for the 3D model showed that the loss of stability was obtained for a friction angle of $\phi > 8.0^\circ$. Figure 8 shows the increase of the deformation connected with decreasing of the friction angle value. The figure includes also the comparison between shear strain and displacement distribution which arise for the given value of the friction angle. It can be seen that displacements propagation is compatible with shear strain distribution. It is visible particularly, when the factor of safety value dropped under unity.

![Fig. 8. Shear strain distribution (a); Displacement distribution (b). Source: Own study.](image)

By comparing 2D and 3D analyses, it was observed in both cases that shear strain appeared first at the bottom of the waste layer (in the close neighborhood of the interface). In
other words, the slippage in the 3D model occurred at first along the back part of waste layer (FS values from 1.05 to 0.99) - just like in 2D analysis results. Afterwards, when shear strain zone is increasing to the top of the waste layer, the value of the factor of safety is falling to FS = 0.99. At the point of instability occurred the shear strain zone, which included all cross-sectional thickness of waste layer. Using low-strength parameters for the interface, for which the factor of safety is lower than unity, one is able to determine the progress of the slip surface. For the value of friction angle $\varphi = 6.0^\circ$ the failure continued to develop by crossing again the entire waste layer up to the upper corner, which connects the waste layer with interface (FS=0.9). Continued damage progress (for $\varphi = 4.3^\circ$) caused the sliding surface at the back side of interface. The shape obtained for FS = 0.76 recalls a characteristic wedge figure.

Further comparison between 2D and 3D analysis results indicates that for the same value of friction angle $\varphi= 9.0^\circ$ we received a different value for the factor of safety - FS = 1.31 for 2D, FS = 1.05 for 3D (figure 9). The lower value of the FS for 3D analysis is caused by the possibility of reproducing the real geometry conditions of the object.

The next indicator for the coming landslide is a large increase of displacement velocities. Table 3 compares displacement velocity for different factor of safety values. It can be seen that when the FS value is falls, the movement of the velocity vector becomes much more orderly.

<table>
<thead>
<tr>
<th>FS</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.31</td>
<td>8.376e-5</td>
</tr>
<tr>
<td>0.99</td>
<td>2.354e-4</td>
</tr>
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</table>

Table 3: Velocity displacements – 2D analysis

The abnormal displacement increase is related to the values of the velocity and it is also the indicator for impending landslide. Figure 10 shows increasing displacement obtained in 2D analysis which are connected with decreasing values of factor of safety.

As in the case of the velocity displacement vector, there is a direct connection between the falling value of factor of safety and spreading displacements.

Landslide development can be seen also in plasticity index distribution. Figure 11 presents the failure zone spreading as the result of shearing, which is due to the reduction of the mechanical property values. This destruction process starts in the lower part of the waste layer, afterwards cuts the layer and finally reaches the entire cross section of the layer and passes to the damage zone due to tensile stress.

The progressive failure effects were more significant in interface plasticity analysis. Figure 11 shows the relation between slip surface development and decreasing factor of safety values. For the factor of safety is FS = 1.05, the slope is stable because the interface is not yet fully plasticized. The figure shows the place in the basin of the landfill, on the interface surface, which has not yet reached the peak shear strength. The same location was received by Filz et al. (2001) in the analysis of landfill slope stability (the analysis was carried out using the finite element method).
Figure 12 shows a progressive slip surface plastification and its relation to a decreasing factor of safety value. For the friction angle $\phi = 9.0^\circ$, the slip surface area is not yet fully plasticized. It can be seen that in the middle of the basin there is a place, which has not reached the peak shear strength value. The location of this place is in agreement with that received by Filz et al. (2001).

Fig. 12. Plasticity distribution on the interface - 3D analysis. Source: Own study.

IV. CONCLUSIONS

The stability of the Kettleman Hills slope failure was reanalyzed using 2D and 3D models implemented in FLAC v. 5.0 and FLAC 3D v. 4.0, respectively. The calculations relied on the Finite Difference Method. The analysis was conducted using the Shear Strength Reduction Technique. In the present study, the parameter value which decreased was that of the friction angle.

The 3D model successfully reflected the landslide geometry. The trend of damage in the 3D model was located in the same places as real cracks which were observed after failure occurred.

The slip surface was located in a geosynthetic layer which was characterized by relatively poor strength values in comparison with the waste layer and subgrade parameters.

It was found that the failure occurred when the value of the friction angle amounts to 4.3 (for 2D analysis) and 8.0 (for 3D analysis). Similar results for the stability analysis were received by Chang.

The analysis also made it possible to obtain information about the progress of the landslide, including its direction, range and slip surface shape.

The considerations above lead to the following conclusions:

1. The key point for the Kettleman Hills landfill slope stability failure was insufficient strength of the geosynthetic layer (complete interface plasticity was equivalent to the slide surface occurrence).

2. Comparison of the results of the planar and the spatial analysis shows that there are notable differences between the values of the friction angle for which the landfill slope instability occurred.

3. The reason that the spatial analysis registers instability for greater values of the friction angle is connected with the ability to reproduce real conditions of the landfill geometry as well as to perform propagation of the shear strain deformations.

4. Three-dimensional stability analysis confirms the major benefits of using spatial analysis. The continuation of this type of calculation allows one to determine the appropriate size of the strength parameters for materials used for protective and isolate barriers in compacted liner systems used in landfill construction.

ACKNOWLEDGMENT

Financial support for this work was given by organisations named below:

Part-financed by the European Union (European Regional Development Fund and European Neighbourhood and Partnership Instrument)

Scientific work financed from science funds in 2011-2013 allocated for co-financing implement international project
REFERENCES


