Investigation of Large Scale Slope Failure Mechanisms and Numerical Modeling for the Safe Design of Slopes in a Lignite Mine

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Abstract: With about 9.3 billion tons of reserve, lignite is a major source for energy production in Turkey. Turkish Coal Enterprises (TKI) produces about 60% of the yearly lignite production capacity. Can Surface Lignite Mine which is planned to produce approximately 2.5 million tons of 3000 kcal/kg coal, will be one of the main production areas of TKI. Possibility of large scale slope failures and their negative effects on mining operations in large Can Lignite Surface Mine on the northwestern Turkey were the major concerns in developing the proper excavation and lignite production directions, and plans for further expanding the mine in new production panels in order to meet the high lignite demand of the neighboring power plant. In order to understand mechanisms of slope failures first, a large scale landslide in an old production panel which occurred following the excavation of overburden in order to expose the thick lignite seam was studied in detail. This huge slide was modeled first by a slope stability analysis program using the method of slices for a rough estimation of parameters that controlled the slide. The detailed investigations of the sliding mass geometry, and associated displacements by using a finite difference program FLAC produced more information about the failure mechanism of the massive slide. The mechanism that controlled the landslide was explained by the presence of a weak layer right under the lignite seam everywhere in the lignite field. The peak friction angle activated along this layer during the slide was found to be around 8°, going down to 2 degrees in the residual state with excessive deformations for further excavation at the slope front. Considering that the lignite seam and the weak layer underneath were typically dipping with angles reaching up to 20 degrees from the edges towards the center in this basin, improvement alternatives had to be studied, and new excavation and production methodologies had to be developed with the aid of the numerical modeling.

Key-Words: Large scale failures, Lignite mine, Numerical modeling, Slope stability analysis

1. Introduction
Turkey has about 9.3 billion tons of lignite reserve, and with about 24 million tons of yearly production Turkish Coal Enterprises (TKI) produces about 60% of the yearly lignite production capacity. Providing coal for thermoelectric power plants, TKI is responsible for about 21% of Turkey’s electric power production. Projecting to produce approximately 2.5 million tons of 3000 kcal/kg coal yearly, Can Surface Lignite Mine is planned to be one of the main production areas of TKI. This mine had a serious large scale landslide during overburden removal operations.

Slope failures and the safety concerns regarding to the possible future failures may cause significant delays or breaks in the production of a mine. Especially when large scale landslides interrupt the operations in the parts of the mine, further production planning becomes difficult without slope stability analyses.

For slope stability analysis, slice methods which are based on the limit equilibrium theory had improvements in 1950’s and 1960’s with various methods developed with different assumptions on the shape of slip surfaces and the interslice forces [1, 7 and 10]. With the advancements in the computing and modeling techniques, numerical modeling of slope problems is becoming a more common practice, especially for solving complicated problems. Duncan [3] reviewed the advancements in finite element modeling for slope stability analysis and discussed the importance of the engineering aspects of approaching the problem, considering the advantages and limitations of finite element method. Hicks and Boughraroua [6] conducted finite element analysis to investigate the possible causes of slope failure for an underwater berm and identified the mechanism of the failure as the movements in a weak clay layer triggering liquefaction in the upper fill.

Chauliya et al. [2] applied numerical modeling using finite difference method to study the effects of biostabilization of the dump slope of an opencast coal mine, and found that maximum deformations occur
near the crest region during dump failure. Therefore, deformation monitoring suggested to be conducted near the crest of the dumps. Kourdey et al. [8] used a finite difference model to study the circular failure in an open pit cut, and concluded that for more complicated problems such as with discontinuities and water in the slopes it is more reliable to use a numerical method than sliced segments, since more accurate stress results and variation of safety factor along the sliding surface are achieved. Wang et al. [12] carried out reliability analysis of an open pit coal mine slope by obtaining the slip surface using engineering geological analysis, model experiment, and FLAC numerical analysis; they emphasized on the importance of the spatial variability of the rock mass strength on stability.

The work here describes investigations conducted for the safe and uninterrupted future production in Can B Panels of the Turkish Coal Enterprises’ lignite mine on the northwestern Turkey. Panel Can B is the only production panel in the district, and since the 2.5 million tons of lignite has been contracted, its stability is very critical and important. Slope analyses were conducted by SLIDE program which is a method of slices program based on the limit equilibrium techniques, and FLAC code which is a finite difference program capable of handling large deformations. A total of 65 sections have been studied for the stability analyses. With the models generated based on these programs, first a previous major slide in the region was investigated, and the mechanisms and slope parameters leading to this large scale slide were determined. Based on these results, the optimum slope geometries and the production directions were studied, alternative solutions for the improvement were developed, and suggestions were made for the safe excavation and mine advancement for future production.

2. Description of the Mine and Site Conditions

Can lignite basin is located on the northwestern part of Turkey, and is known as Biga Peninsula, (Fig.1). The lignite region extends 11.5 kilometers in east-west and 5 kilometers in north-south directions. The lignite mines in the region are owned and operated by Turkish Coal Enterprises. Lignite coal seam with thicknesses varying from 1 to 35 meters is extracted by surface mining with panels of approximately 1 by 1.5 km. The mine production is planned to satisfy 2.5 million tons per year of large coal demand of a neighboring power plant of 320 MW capacity.

2.1. Geology of the region and the rock mass description

In the lignite district, Mineral Research Institute (MTA) carried out geological, geophysical and geotechnical studies covering the periods of April 2001 to August 2002. In this content, 78 core drilling (66 for reserve estimation and 12 for geotechnical purposes) operations amounting to 12450 meters were completed. Based on the drilling operations 142 million tons of proved reserve have been determined [5].

In the lignite district, Kulaksız et al. [9] distinguished 8 different lithological levels from bottom to top based on the field observations and drilling results. Level 1 with gray-white kaolinitic tuff, andesite and agglomerate forms the bottom unit of the lignite series. Level 2 is represented by gray-brown and red colored laminated claystones; the thickness may change between 0-5 meters. Level 3 is called “lignite zone”. Inside the lignite zone, claystones in thin, and sometimes in thick layers exist. The thickness of the layers changes between 0-35 meters. Level 4 takes place above the “lignite zone” and is formed by fossiliferous laminated claystones and laminated claystone-marl-tuff intercalation units with the thickness changing 0-80 meters. Level 5 is called “lower agglomerate” and thickness changes between 20-100 meters. Main unit is the agglomerate-tuff intercalation. Agglomerate is composed of andesite-basalt spillage type volcanic gravels and blocks. Tuffs include red colored claystones and sandstones. Level 6 is represented by claystone, tuff and tuffaceous units, thin limestone layers, and marl; it is intensively folded. The thickness changes 20-100 meters. Level 7 is called “upper agglomerate level” and consists of andesite and basalt in form of gravels.
or in blocks and tuff intercalations. The maximum thickness is 200 meters. This level is rarely observed in the pit area. Level 8 consists of residual soil and alluviums which are discordantly located in a thickness between 0-15 meters.

Bedding inclination lies mostly between 3 -10°, however, following the coal seam this may go up to 20° in some regions, especially at the edges towards the center of the basin. The faults in the basin are reported to have E-W strikes with dips around 65° -85° in general.

In the content of a geotechnical study, MTA (Yoleri et al., [13]) core recoveries were generally high (more than 80%) for all drillings. RQD values were lower than 20% in claystones and changing 0 to 90% for agglomerate unit. SPT values were changing between 13-24, providing 40%-54% of relative density. Permeability of conglomerate and tuff rock masses was low to impermeable, based on Sharp et al. [12] classification. Unit weight of the agglomerate was 18.07 to 20.55 kN/m³, and for claystone it was 16.95 to 18.70 kN/m³. Rocks showed high plasticity. Uniaxial compressive strength values were 0.30 to 36.20 MPa for agglomerate, and 0.16 to 32.30 MPa for the claystone. All rock types had high to very high slake durability values based on Gamble [4] classification.

2.2. Laboratory shearing properties for the rock units

Accepting a Mohr-Coulomb type shear failure, results of previous laboratory investigations are presented in Table 1 as cohesion c and internal friction angle Φ of the several rock units around the coal seam. When available, the values in this table were presented as a range of values summarized from the reports of different investigations in the region. And when a range is available average values are also indicated in the table.

These are laboratory values and rock shear properties governing the previous slide are to be determined by back analyses. However, these values constituted a good start for the analyses, as the input values for the numerical models were kept within the ranges given in the table. On the other side, boreholes and field observations showed that kaolinitic tuff layer at the base of the lignite becomes very weak when it is wetted during rainy seasons by yielding very low shear parameters.

<table>
<thead>
<tr>
<th>Rock Types</th>
<th>Residual Friction Angle (°)</th>
<th>Cohesion, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altered agglomerate-tuff</td>
<td>15.12-27.04 (21.08)</td>
<td>1.19-24.86 (12.93)</td>
</tr>
<tr>
<td>Pliocene sediments</td>
<td>20.01-26.37 (23.19)</td>
<td>1.39-2.49 (1.94)</td>
</tr>
<tr>
<td>Laminated claystone</td>
<td>(20.64)</td>
<td>(9.30)</td>
</tr>
<tr>
<td>Altered andesite</td>
<td>(17.17)</td>
<td>(8.96)</td>
</tr>
<tr>
<td>Altered claystone</td>
<td>(29.24)</td>
<td>(12.49)</td>
</tr>
</tbody>
</table>

Table 1 Laboratory shearing parameters [13]

3. Circular Slope Failure Analyses

SLIDE program with Bishop Simplified Method was used for circular failure analyses. Program gives the minimum safety factor for a critical sliding surface of its own, or user can define circular or noncircular surfaces and find their safety factors.

A unit weight of 20 kN/m³ was used for all analyses. Observing the range of cohesion and friction angle values in Table 1 for the dominant rock units above the coal seam, friction angles varied between 15 - 27° and the cohesion was in the range of 1.10-24.86 kPa in the analyses. As seen in the table, the average cohesion was 12.93 for the most dominant weathered agglomerate-tuff unit above the coal seam. For back analyses and the determination of friction angle, no circular failures were observed to exist in the region. Although believed to be a conservative value, first choice for the friction angle was 17°, since the existing slope walls with this angle were stable against circular failure. Thus, by taking general slope angle as 17°, and c=12.93 kPa and Φ=17° to represent the rock units above the coal seam, first analyses were carried out for the slope walls dipping north on a number of north-south cross sections. Safety factors were determined for different cross sections, and the cross section identified as 502400 was found to be critical, having the lowest values of the safety factors. As seen in Fig.2, critical circles and corresponding minimum safety factors directly given by the slice methods are for the failures restricted to the small benched areas at the slope front. These small failures represented with a safety factor of 0.87 in Fig.2 were not expected to cause serious safety concerns and breaks in the mine.
operations. When circles reaching and intersecting the crest of the slope were introduced, safety factor reaches around one for such circles with this choice of slope parameters and geometry. On the other hand, considering that small bench failures of the type represented by a safety factor of 0.87 are not observed in the region, cohesion and friction angle in the models were increased till these failures disappear and safety factor becomes higher than one. This analysis resulted in a cohesion of $c=16$ kPa and $\Phi=20$ which were the values used in further analysis of circular failures for different excavation and production alternatives.

The two most possible advancement directions of the mine were from north to the south and from south to the north. Slope geometries for the overburden removal were normally introduced by benches of 15 m high and 23-25 m wide. Advancing from north to the south was preferred by the mine management, owing to the production requirements and groundwater problems around the small creek and lake in the southern end of the region.

Due to the surface water problems, time consuming drainage measures were to be taken for the excavation starting at the south and advancing to the north. However, as will be described later, this direction was favorable against possibility of massive sliding down towards the south along a weak layer. With this direction of advancement, weak layer was expected to dip opposite to the slope face, and thus yield no stability problems. Circular failure analyses for both advancement directions were carried out, considering that mine management may take drainage measures and start mining from the south in future.

In the analyses the slopes were assumed to be half-saturated to stay on the conservative side, since the area is rainy. The groundwater condition and other conditions are believed to be better than the ones assumed here. However, it was decided to continue with the shear parameters determined above, since there were no circular failures to be analyzed to obtain further information about the real slope parameters.
identify mechanism and conditions involved in the slide, and the parameters controlling the sliding.

**4.1 Simulation of sliding along a weak layer with SLIDE program**

First a noncircular sliding surface was introduced by using “Ordinary Method of Slices” in the SLIDE program. The geometry of the previous slide was defined by introducing a tension crack at a location as observed in the field; tension crack was connected to the weak layer at the bottom of the coal seam, then following the bottom of the coal layer, sliding surface intersected the working area of the mine at the south end of the panel. Based on the borehole and site investigations described above, 2-10 m thick weak layer at the bottom of the coal seam was kaolinitic tuff. The cohesion for this layer was kept at 9.87 kPa which is the lowest value for this layer in Table 1. Ground water was introduced both into the weak layer and tension crack. Sliding was simulated by keeping the cohesion constant and reducing the friction angle till the factor of safety fell below one as seen in Fig.5, resulting in a mobilized friction angle of 6.1° for this slide. This simulation with full water pressure in the weak layer and the tension crack represents the worst conditions. Actual ground water conditions during the slide are unknown. In fact, for the same sliding surface the safety factor is found as 1.51 for a dry tension crack. This means that, in order to model initiation of such a slide with a dry tension crack, friction angle must be lowered to around 4°. This is not realistic considering that the major shearing part of the weak layer, which extends about 1 km, is dipping towards the slope face at an inclination of about 7°, and with this geometry the slope is currently stable unless there is an excavation activity at the slope front. Seeing the difference in the safety factors of these two extreme cases and considering the large extent of the slide compared to the relatively small tension crack height, amount of the water in the tension crack was believed to play an exaggerated role in the stability analysis with slice methods. Therefore, it was decided to continue further analysis with a program using a different modeling technique.

**4.2 Investigation of mechanisms of sliding along a weak layer using FLAC program**

It is important to understand the mechanism of sliding along the weak layer properly, since this will effect the future production plans greatly. Slice methods are basically developed for circular surfaces and analyses were found to be too sensitive to the water level in the tension crack. Studying the sliding mechanism in detail was continued by using another program called FLAC which employs the finite difference method, and is capable of handling large deformations as a result of a massive landslide. With models generated using this program, it was possible to match model displacements and field displacements, as well as the observed cracking locations in the back of the massive landslide.

First a mesh of 1750 finite difference elements was generated. As in the previous analysis a weak layer of 10 m thick kaolinitic tuff was located under the coal seam, for which the cohesion was taken as above and the friction angle was to be varied. Ground water level was kept a little above this layer without fully filling the tension crack to prevent the excessive water pressure in the crack. Different material zones were to be identified in the model frame as seen in Fig.6. The region underneath the weak layer was not expected to contribute to the slide, and therefore it was kept elastic with high values of mechanical parameters. In order to prevent complications in the model due to small insignificant early bench failures at the slope front, a strengthened region with high cohesion and friction angle values was formed. For the agglomerate unit above the coal seam the shear input parameters used were $c=12.93$ kPa and $\Phi=17°$. In general, finite
difference models are continuum models, and it is not possible to introduce a crack or a discontinuity directly, therefore a relatively weak region in which cracking and separation of the sliding mass is expected was introduced in the back around the observed tension crack location. In this zone, mechanical properties were $c=9.87$ kPa and $\Phi_w=6$, which were kept lower than regular agglomerate-tuff unit forming most of the upper part of the slope. This way, a specific cracking location as in the SLIDE case was not forced into the model here; instead FLAC model was left free to form its own separation surface in a relatively wide zone.

In FLAC during the solution process in time steps, time histories of significant sliding parameters such as displacement, velocity, and stress and strain were followed and recorded at specified nodes. As the sliding proceeds the program can be paused and current condition of the sliding mass and related parameters can be checked. In order to study the sliding geometry and mechanism, monitoring points 1-2 at the slope front and points 3-10 on the slope crest at the back were defined as in Fig.8. In this figure, displacement vectors clearly show the movement of the sliding mass towards the working area at the slope front, and the separation of the mass in the back.

In the analyses friction angle $\Phi_w$ for the weak kaolinitic tuff layer was progressively reduced down from 14 to 2, and each time significant parameters such as displacements at the specified locations were recorded for the same number of time steps, that is 5800 steps. Friction angle-displacement behaviour was studied for the monitoring points with the highest displacement magnitude at the slope front and on the crest at the back. Fig.9 shows displacement values versus different friction angle values for model monitoring point 1 at the slope front. Displacements around 1 m initially show a linear behaviour with friction angle of the weak layer varying form 14 to 9. Displacement rate increases around a friction angle of 8, and around 6 a nonlinear behaviour with a rapidly increasing displacement rate is observed. When displacement reaches around 20 m, weak layer friction angle tends to a value around 2. The same trend is observed for the model monitoring points in the back. As found by Chaulya et al. [2] deformations were higher at crest of the slope. For the model monitoring point 8 displacement magnitudes reach around 30 m.
for the residual state and in this case vertical component of the displacement is much higher, leading to the rotational movement of the sliding mass. This point is very close to the observed tension crack locations in the field. These results show the success of the model in studying and identifying the mechanism of slope failures in the region. As a result, in further slope stability analyses for other sections and production alternatives, a peak friction angle of $\Phi_w=8$ was accepted as the input friction angle value for the weak layer whenever it is in a potentially sliding position.

![Graph showing displacement values for different friction angles at the slope front for monitoring point 1.](image)

**Fig.9 Displacement values for different friction angles at the slope front for monitoring point 1.**

### 5. Analyses for Other Sections and Improvements against Weak Layer Sliding

After identifying the sliding conditions and the mechanism, and determining the peak friction angle controlling the sliding along the weak layer, further stability analyses were carried out for other sections with different excavation directions and alternatives. For its simplicity, SLIDE program with the ordinary method of slices was preferred in the most of following studies. Effect of faults on the sliding surface and stability was investigated first. For the critical sections improvement alternatives were evaluated to increase stability.

#### 5.1 Effect of faults on the mechanism of sliding along the weak layer

The section used for the back analysis involved an uninterrupted continuous sliding surface which in the most of the section was inclined steadily around 7 towards the slope front. The current sections to be studied for further production of the mine, however involves a lignite seam intersected by local faults. Lignite seam and the kaolinitic tuff layer at its bottom are squeezed and thrown up between local faults in some sections, changing the steady profile of the sliding surface. When a part of the shearing surface is uplifted between the local faults, there are three possibilities to introduce the sliding surface into the models:

(i) uplifted sliding surface is not exactly followed; it is assumed that, following the general inclination of the shear surface, sliding mass shears through the soft layer about 20-30 m below the uplifted lignite seam;

(ii) shearing occurs through the weak layer, but this time fluctuations of the sliding surface due to the local faults in the section is exactly followed, (Fig.10),

(iii) shear surface follows the general trend of the overall sliding mass without fluctuating between the faults; but, since the thickness of the weak layer is limited to 10 m maximum and below this there is a strong layer, shearing in the uplifted zones between the faults occurs through the strong layer; this case is represented by the highest safety factor of 1.57 for the same 502400 section.

Safety factors for the cases above vary between 0.98-1.57, differing significantly according to the choice of noncircular sliding surface geometry disturbed by fault movements. Among these cases, the last one seems to be the most probable choice for layers showing fluctuations, considering that this is a large scale slide and inertia of the huge sliding mass is not supposed to have any difficulty in shearing some local strong pockets between the faults. In fact, slopes in this section and nearby sections with similar sliding surface position fluctuations are currently in a stable condition; therefore this choice is adopted for further stability analyses whenever there are fluctuating coal seam and weak layer positions in the other parts.

![Graph showing factor of safety in section 502400; shearing through a very thick weak layer following the seam position fluctuations.](image)

**Fig.10 Factor of safety in section 502400; shearing through a very thick weak layer following the seam position fluctuations.**
5.2 Improvements in the slope geometry against sliding along the weak layer

In front of the slope bottom leaving a sufficient amount of lignite without extracting it, forces shear surface following the weak layer shear through the relatively strong lignite. This increases the resistance to shearing compared to the case where all lignite is extracted in front and shear surface comes out following the weak layer. This is an effective improvement measure as found by comparing the safety factors of around 0.8 and 0.9 for the lignite extracted fully case to the some lignite left in front case (Fig.11) for which safety factors rise above 1.0. In the analyses, weak layer sliding surface with two separation alternatives around the tension crack positions in the back is considered; separating through an existing fault in front or forming a circular cracking type separation surface in the back. Safety factors increase to 1.14 and 1.39 in Fig.11 where a coal pillar is left in the front and shearing occurs through this. With more than 60% improvement in the safety factor, this measure proves to be very effective, especially for separation surfaces close to the slope front.

Another alternative for the improvement in safety factors is to use platform type relatively low depth and stepwise larger width slope fronts. Depth of the overburden here is reduced almost by a half with stripping a sufficiently thick layer at the slope front. The slope angle in front of this depth reduced section can now be kept higher than regular overall slope angle; this way the mass in the front acts like a resisting pillar against the large load of the sliding mass forcing from the back of the slope. Fig.12 shows the results of the improvement efforts in safety factors by using a lower 17° slope angle in the front platform section, where safety factors are 1.09 and 1.27 for the separation surfaces near slope front, and 1.21 for land separations very far away from the slope front. A platform type wide bench at the slope front with a higher front slope angle results in a better situation.

Increasing the slope angle at the front of the wide bench to 30 degrees makes an improvement of about 10% in the safety factors for the land separation cases close to the slope front. For huge slides with land separations extending too far back however, this improvement loses its effectiveness.

5.3 Investigation of safe advancement directions

When all sections showing the lignite seam in the basin are studied, it is observed that the seam and the kaolinitic tuff layer underneath are inclined towards the center of the basin in all directions. For safe slopes against potential landslides along the weak layer, it is suggested that mining activity should proceed from edges towards the center of the basin in all directions. For safe slopes against potential landslides along the weak layer, it is suggested that mining activity should proceed from edges towards the center of the basin in all sections. Urgent demand of the power plant and the immediate production requirements force the mine management to extract lignite advancing from the north to the south, until the drainage measures are undertaken and mining starts from the southern edge. Using the method of slices with noncircular sliding surfaces, safety factors for this advancement direction were studied, and found to remain in a safe range for most of the sections, provided that the improvement measures described above are taken. This is still a risky advancement direction as reflected by the weak layer connected to the surface with a circular failure surface yielding a factor of safety of 0.63 in Fig.13. However, these are relatively low volume local slides and are supposed to be managed without a serious interruption in the mining activities. Safety factors for large landslides extending way back are seen to be sufficiently high with the proposed slope front improvements.
6. Conclusion
Slope stability control is a major issue in planning the future mining activities in coal measure formations involving weak ground. Circular failure analysis with regular slice methods may not be sufficient to solve complicated slope stability problems with weak layers dipping towards the coal extraction areas. Finite difference models with capability of handling large deformations proved to be effective in the analysis to determine the mechanism and parameters leading to a massive landslide in a lignite mine. The geometry of the noncircular sliding surface, shear parameters, and the deformations were successfully identified from the back analysis of a landslide in the region. A kaolinitic tuff layer following the base of the lignite seam was found to be the cause of the massive slide. For future safe production planning of the mine, the problem was not solved by lowering the general slope angle, since the weak layer under the seam had very low shear strength parameters when it is wetted with mobilized friction angle going down to 8 degrees. It was suggested to advance the mining activities from the edges towards the center of the basin which would keep the weak formation dipping opposite to the slope face. Leaving a sufficient amount of relatively strong coal pillar in the extraction area at the slope front was also found to be effective in controlling stability of the slopes.

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References: