# Numerical analysis of rainfall effects on the slope stability of open pit coal mines

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**Abstract.** As the world transitions away from coal, vast areas of closed coal mines and waste dumps must be appropriately reclaimed. One critical element for these areas' safety is slope stability, given the massive slopes of these mines and dumps. This work examines the effect of extreme rainfall on coal mines' slope stability by incorporating unsaturated soil mechanics principles in a practical way. Past extreme rainfall events recorded for a Greek lignite mining area were used, and climate projections concluded that this intensity is not expected to change. Then, rainfall infiltration was simulated using the Finite Element Method; a typical slope was employed concerning a lignite mining excavation of 200m height and 14° inclination on fine-grained soils. Finally, the stability was calculated using the Limit Equilibrium Method. Rainfall infiltration caused the Safety Factor to decrease, leading to failure. The groundwater rose at the slope's face from the slope's toe upwards and led to the development of a smaller and more local than the initial (before rainfall) sliding surface with a lower Safety Factor. Although this is a smaller surface than the initial one, it is still more than 50m high, proposing a significant hazard with severe consequences for the area.

## 1 Introduction

Environmental concerns and changes in the global energy mix lead the transition to the post-coal era and have resulted (or will soon result) to the closure of massive coal mining operations, particularly in Europe. However, coal regions should not be abandoned after mine closure while countries and societies reflect on the economic and social impact. The vast areas of closed mines and waste dumps must be appropriately reclaimed, or they will burden communities for decades. Safety is crucial for these areas in that framework, and technical issues must be faced. One such critical element is slope stability, given the massive slopes of these mines and dumps reaching 200m in height [1] . Their stability is even more jeopardized within the climate change framework as extreme rainfall events become more frequent and severe [2].

The influence of rainfall on the slope stability of open-pit coal mines has long been identified and considered for design purposes. The effect of rainfall on the slope stability of coal mines has been primarily based on observations and empirical correlations between precipitation rates and slope movements [3]. This type of analysis is practical but limited with respect to current knowledge and challenges related to post-mining hazards.

On the other hand, stability analysis of slopes in civil infrastructure has advanced, incorporating unsaturated soil mechanics and advanced hydrological concepts to evaluate precipitation's effect. Differences between the two types of slopes typically refer to the geometry and displacement tolerance. The height of the mines' excavations can often reach up to 200m or even more, versus typical heights up to 30m-40m for infrastructure slopes. Additionally, these large heights require smooth inclinations, usually less than 20°. Finally, mining slopes formed during mine operation have a large displacement tolerance (even in the order of magnitude of meters) [4], while infrastructure slopes have strict limitations.

This work examines the effect of extreme rainfall on massive coal mines' slope stability by incorporating unsaturated soil mechanics principles in a practical way based on geotechnical profiles from Greek lignite mines. A methodology that uses past rainfall events and projections to evaluate the rainfall intensity was used. Then, rainfall infiltration was simulated using the Finite Element Method (FEM). Finally, the stability was calculated using the Limit Equilibrium Method (LEM). The numerical model (geometry, properties) can be implemented similarly in many countries where similar conditions exist.

## 2 Framework of analysis, methods, and soil properties

Fig. 1 briefly presents the approach of this work. The rainfall intensity is initially estimated based on extreme past events and modified based on future projections. Moreover, the rainfall infiltration is calculated based on the rainfall intensity range and the unsaturated soil principles as implemented in numerical analysis by the

Finite Element Method (FEM). The most crucial assumptions are related to modeling the rainfall infiltration that determines the slope stability results. Finally, the slope stability is calculated by typical stability analysis methods. Both FEM with the shear strength reduction technique (RS [5]) and LEM (Slide2, [6]) were used for evaluating the Safety Factor; as both methods provided similar results in the present study, only the LEM ones are presented, being more direct for practical applications.

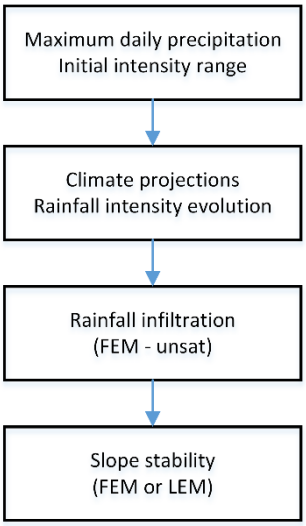


**Fig. 1.** Simplified flowchart presenting the methodology of this work

Opposite to works where rainfall was based on general estimations [7, 8] or was related to a particular rainfall time series [9], this work evaluated the rainfall intensity through past events and climate projections of the investigated area. A particular Greek mining area - the Megalopolis lignite basin - was employed for this area-specific range. Extreme events were targeted, ideally found in recordings of maximum daily rainfall that systematically existed for the area. The extremes of these recordings were translated into rainfall intensity.
Rainfall projections were based on regional climate projections conducted by an open-access platform, the Coordinated Regional Downscaling Experiment (CORDEX) [10]. The Earth System Grid Federation was used to access the CORDEX data [11]. Four scenarios were used for the Representative Concentration Pathways (RCP), the basic input parameter for climate projections. More details can be found in Theocharis et al. [12].

The lower flowchart part - rainfall infiltration and slope stability - is related to the specific slope (geometry, groundwater, soil, and unsaturated zone properties). The geometry of surface lignite mines differs from typical civil or natural slopes presenting large heights, smooth inclinations, and benches. A slope of 200m was employed with a smooth angle of 14° (Fig. 2.). For simplicity purposes, the role of benches in the stability was not investigated in the present work, given that simulating a planar slope is on the safe side (conservative assumption) ([13]). Moreover, the groundwater conditions, crucial for the stability, relate to the phase of the mine (operational, closed abandoned). A steady-state flow reaching the slope's toe was employed, being a conservative (but not extreme) assumption. The left boundary for groundwater analysis was defined as the groundwater depth ($H_w$) that relates to the depression cone around the excavation. A parametric analysis was considered for this depth from 10m to 30m.

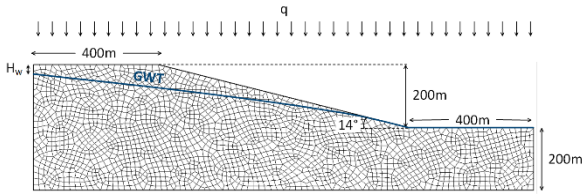


**Fig. 2.** Slope model geometry, groundwater table, and discretization for the FEM infiltration analysis

Finally, soil properties, including the unsaturated zone, are case- and site-specific. Fine-grained materials, especially silts (marls), are commonly observed in lignite mines, overlying and mixing with the lignite seams. Greek lignite mines were employed to obtain typical values [14], but the properties are similar in several other mines globally [13, 14]. A homogeneous slope was used for simplicity as the rainfall effect is emphasized rather than the stratigraphy. Notice that waste dumps can be simulated as a homogeneous material, at least on a preliminary analysis [15], and employing a weak zone stratigraphy typically appearing in lignite mine excavations (e.g., [13]) would propose similar trends. One special note is needed for the effect of the unsaturated zone (and suction) on the shear strength; this effect was not considered (as possible through an additional unsaturated shear strength) and only the Mohr-Coulomb shear strength existed. Soil properties are summarized in Table 1.

For the definition of the permeability in the unsaturated zone as a function of matric suction, the Van Genuchten [16] model was used. Generally measurements related to the unsaturated zone are not reported in the literature for areas such as those examined herein; thus, the parameters of the unsaturated zone were estimated based on the soil classification and experience mainly from Greek lignite mines [12-14]. A brief parametric analysis was conducted for the effect of the initial groundwater level and the model's saturated permeability. Future works must obtain real measurements of these parameters to obtain a complete overview of the effect of the unsaturated zone on the stability of these areas.

**Table 1.** Engineering parameters of the soil material

| Parameter | Value |
|---|---|
| Effective cohesion φ′ (°) | 40 |
| Effective friction angle c′ (kPa) | 22 |
| Soil unit weight γ (kN/m$^3$) | 17 |
| Saturated permeability $k_s$ (cm/s) | $5{\cdot}10^{-5}$ |
| Saturated water content (-) | 0.5 |
| Residual water content (-) | 0.2 |
| Van Genuchten parameter alpha (1/m) | 0.01 |
| Van Genuchten parameter n (-) | 1.3 |
| Van Genuchten parameter m (-) | 0.23 |

# 3 Results and discussion

## 3.1 Rainfall range: past events and projections

Fig. 3 presents the maximum daily rainfall recorded in the lignite region of Megalopolis. One extreme rainfall event stands out in 2016 when more than 200 mm of precipitation fell in one day. To be more exact, 213mm of precipitation within one day (24 hours) corresponds to 8.9mm/h, a heavy rain intensity. However, in practice, the rainfall fell in half that time; thus, the intensity approached 18mm/h. Due to its extreme intensity, this event was documented in the local press.

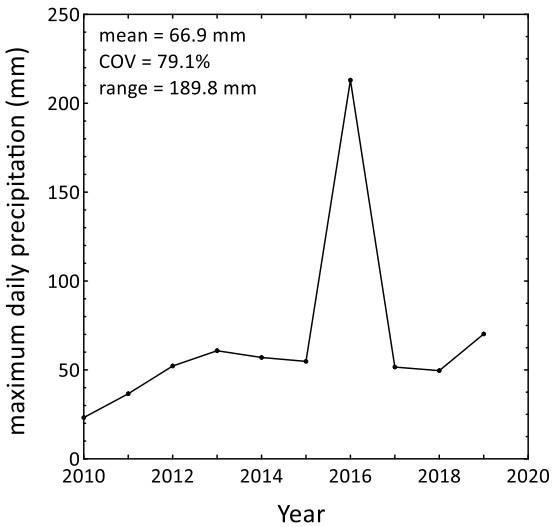


**Fig. 3.** Maximum daily precipitation for the last ten years for the Megalopolis lignite mining area

Eight regional climate models (named datasets) were used to evaluate the Megalopolis mine area's future climate conditions and to project the evolution of the rainfall intensity. Overall, from all models and projection results, it was concluded that the rainfall intensity range is not expected to vary much during the future decades in that area. As a result, the range obtained from measured rainfall in the area can be used as a representative for current and future design purposes. The extreme event recorded in 2016 is considered the maximum rainfall intensity (18mm/h), while for the analysis, two smaller intensities were also used for comparison. A maximum of seven days of rainfall was considered for the analysis. The intermediate days are also reported.

## 3.2 Rainfall infiltration and slope stability

Fig. 4. illustrates the groundwater pore pressures at the end of the steady-state analysis. The right boundary of the steady-state flow is defined at the slope's toe. The left boundary is a constant pressure head at the left edge of the model that, for the reference analysis, equals 20m ($H_w$=20m, see Fig. 2). A pink line in Fig. 4 defines the groundwater phreatic line (GWT) below where porewater pressures develop with depth. Above the phreatic line, suction develops based on the model and the parameters discussed above. Suction reaches 800kPa at the slope surface due to the combination of the depth of the groundwater table and the large slope height. At that largest suction the permeability based on the model parameters equals $2{\cdot}10^{-6}$ cm/s. This value is much smaller than the saturated permeability; notice that the rainfall infiltrates at that point with that permeability rather than the saturated one or the rainfall intensity. As a result, a significant percentage of runoff rainfall water is present.

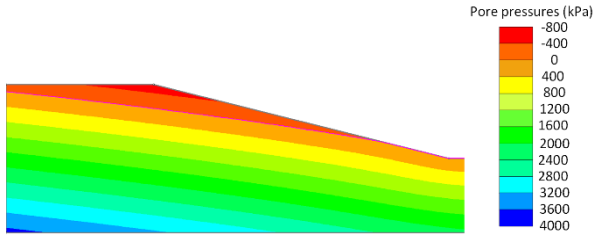


**Fig. 4.** Groundwater pore pressures developed at steady-state conditions

Based on the LEM stability analysis, the initial Safety Factor equals 1.14, including the additional "phenomenal" strength due to suction (Fig. 5). The spencer method with a non-circular sliding surface was used; the cuckoo search method was employed to define the sliding surface by a polyline based on a global optimization procedure. Notice that typically surface mining slopes are created with a Safety Factor of 1.1 to 1.2 if not specially treated for post-mining purposes. The sliding surface begins at approximately the middle height of the slope (108m), which is slightly above the edge of the groundwater phreatic line on the slope. Then with a non-circular shape, the sliding surface reaches the bottom of the excavation slightly to the right of the slope's toe.

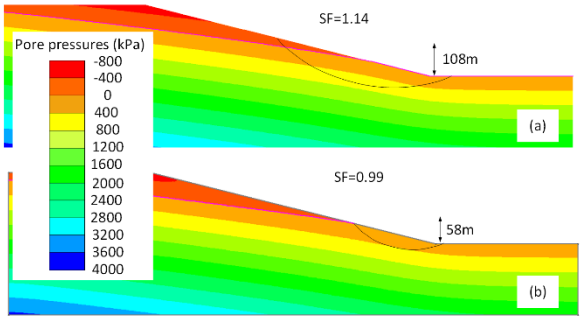


**Fig. 5.** Location of the sliding surface and distribution of pore pressures: (a) at the initial state and (b) at the end of the rainfall

At the end of the seven days of extreme rainfall, the final Safety Factor decreases to slightly less than 1. The sliding surface has almost half the initial surface's height, 58m versus 108m, and is also shallower. Nevertheless, even this sliding surface is significant in mass and could cause a major catastrophe in a reclaimed former mining area. The stability of the whole slope is then jeopardized if such a mass is unstable. The main mechanism related to the decrease in the Safety Factor is the rise of the groundwater phreatic line at the edge of the slope during the rainfall and the decrease of the suction stresses in that area. Notice that this happens as the phreatic line is not fixed and allowed to change during the rainfall. Overall, for the current analysis, an extreme rainfall intensity over a prolonged period can lead this massive slope (with a small initial Safety Factor) to failure.

Fig. 6 presents the evolution of the Safety Factor with the rainfall duration. With red line is the baseline scenario of extreme rainfall of 18mm/h, as reported for the area. As the rainfall continues, the Safety Factor decreases with time. Two smaller rainfall intensities were examined (Fig. 6), 9mm/h and 6mm/h, to evaluate their effect on stability and their differences from the extreme one. All three intensities affect the stability and might practically jeopardize the slope's safety. Nevertheless, if the rainfall intensity, the Safety Factor's decrease is smaller, as expected.

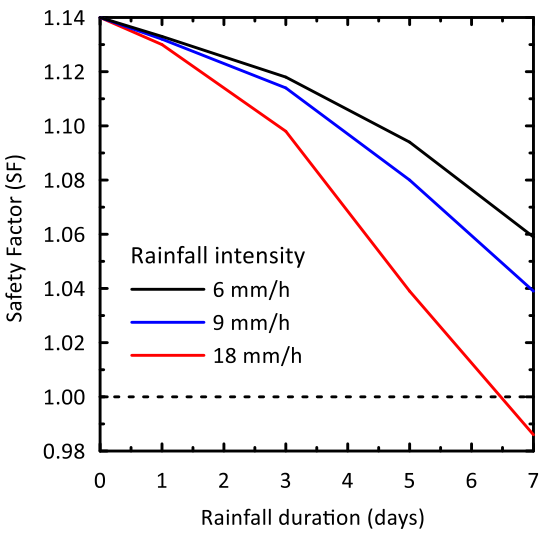


**Fig. 6.** Evolution of the Safety Factor (SF) with rainfall duration for three rainfall intensities

The effect of the initial groundwater table was evaluated, being crucial for the stability of the slope. As described above, the phreatic line was defined based on two limit conditions at the bottom of the excavation and the left boundary of the model that represents free field conditions. The left boundary was varied; the baseline depth was 20m, while two analyses for 10m and 30m were also investigated. Fig. 7 illustrates the evolution of the Safety Factor with time and for the three groundwater levels, for the extreme rainfall of 18mm/h. For the baseline analysis, the groundwater phreatic line was defined by an $H_w$ equal to 20m. The results present an almost identical effect of the rainfall on the rate of the decrease of the SF. However, if the initial groundwater level is higher, then the initial SF is lower, and the safety can be more probably affected by extreme rainfall.

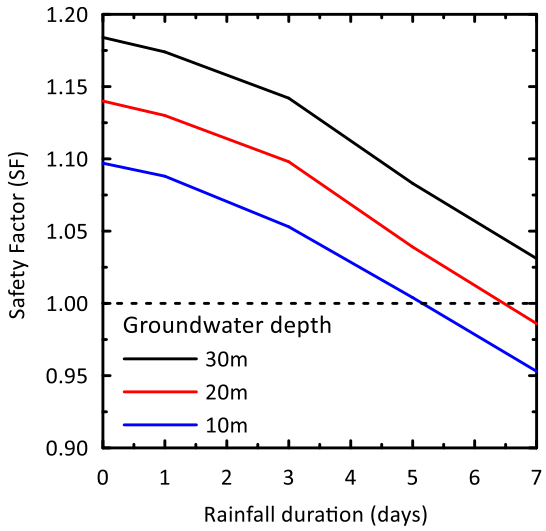


**Fig. 7.** Evolution of the Safety Factor (SF) with rainfall duration for three groundwater levels

Finally, the saturated permeability was varied, being a critical parameter for groundwater analysis. The other parameters defining the soil water characteristic curve should also be investigated in future works, with a specific need for further measurements regarding the unsaturated response of the soil materials under investigation. The baseline permeability was $5 \cdot 10^{-5}$m/s, and three smaller permeabilities related to fine-grained materials were examined. Fig. 8 presents the effect of the saturated permeability that is significant to the evolution of the Safety Factor. As the saturated permeability decreases, the soil becomes less permeable, and the rainfall effect is smaller.

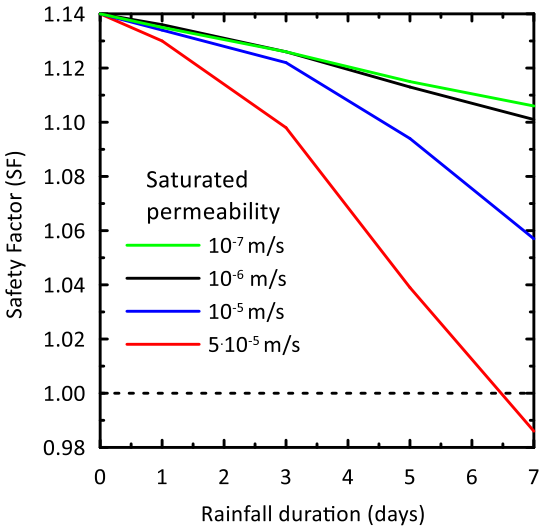


**Fig. 8.** Evolution of the Safety Factor (SF) with rainfall duration for various saturated soil permeabilities

## 4 Conclusions

Rainfall might affect the safety of deep excavations, in the present case of surface coal excavations of 200m deep, by causing slope stability issues. This issue has been investigated in open pit mining mainly indirectly by empirical observations and correlations. Nevertheless, toward the post-coal era and in view of climate change, these approaches are not enough to secure the post-mining areas. The present work numerically investigated the slope stability of deep coal mining excavations under rainfall infiltration. A typical slope was employed concerning a lignite mining excavation of 200m height and a smooth inclination of 14° on fine-grained soils.

An extreme rainfall intensity was used, as recorded for a Greek lignite mining area. Rainfall projections were employed that concluded that this extreme intensity is not expected to change drastically. Applying this extreme rainfall led to a decrease in the Safety Factor leading to failure for a prolonged period of seven days. The critical mechanism is the rise of the groundwater at the slope's face from the slope's toe upwards. This change leads to the development of a smaller and more local than the initial (before rainfall) sliding surface with a lower Safety Factor. Although this is a smaller surface than the initial one, it is still more than 50m high, proposing a significant hazard. This type of failure presents similarities with shallow failure surfaces presented in the literature after rainfall events. It is expected that the failure of such a significant soil mass will have severe consequences on the area, and it is a challenge for post-mining reclamation.

## 5 Acknowledgments

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