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PARAMETRIC SIMULATIONS ON THE STABILITY CONDITIONS OF THE MINING SLOPES OF OPEN PIT COAL MINES BY APPLYING THE FINITE ELEMENT METHOD

Master of Science Thesis

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Abstract

This study embarks on a parametric investigation into the stability of open-pit slopes in the Choremi field of the Megalopolis lignite center, emphasizing the critical interplay between geological characteristics and engineering practices. Utilizing the Plaxis 2D program for numerical finite element analyses, the influence of the mechanical properties of clay layers located between the lignite layers and Quaternary red clay deposits—specifically cohesion, internal friction angle, and Young's modulus—impact slope stability. A pivotal part of the research explores the influence of groundwater dynamics by simulating variations in the water table level and assessing its effects on slope stability in conjunction with mechanical properties. A noteworthy aspect of this methodology includes sets of scenarios where the groundwater level is systematically lowered to evaluate potential mitigation strategies against slope instability. Furthermore, the role of excavation geometry modification is examined, particularly through the adoption of less steep slope designs, as a proactive measure to enhance stability. The conclusions underscore the significance of integrating effective groundwater management and thoughtful excavation design in bolstering the stability of open-pit mines, offering invaluable insights into the optimization of excavation strategies in similar geological settings.

Introduction

Mining has historically been regarded as one of the world's oldest industries (Jiang et al., 2017), and as a high-risk industry (Patterson and Shappell, 2010). Accidents, hazards and disasters demonstrate many similarities in terms of their significant impact on their victims (Lyra, 2019), mine owners (Li et al, 2019), mine employees (Aliabadi et al., 2018; Li et al., 2019), governments (Lyra, 2019), policy makers (Kong et al., 2018; Dozgon & Leveson, 2018), the economy (Gui et al., 2019; Xiao et al., 2019), local communities (Lyra, 2019), as well as the environment and human health (Shao, 2019; Cordeiro et al., 2019). Mine employees face relatively hazardous working conditions compared to employees in other sectors (Lenné et al., 2012). Hazards and accidents that occur in mines and quarries significantly affect the sustainable development of mining production, as well as the entire economy and society (Lu and Li, 2011). Mining hazards encompass a broad range of catastrophic incidents that arise from or are provoked by mining operations. These incidents can happen at both operational and non-operational mine sites (Loupasakis, 2020).

In this case study, the importance of mitigation strategies against slope stability issues in the Megalopolis Open pit is examined, as well as the influence of the mechanical properties of clay layers located between the lignite layers and Quaternary red clay deposits.

The study area

The Megalopolis lignite center is in the central part of the Peloponnese and belongs administratively to the regional unit of Arcadia. Megalopolis constitutes one of the most important energy centers in Greece and the systematic exploitation of the region's lignite deposits began in the 1970s. Megalopolis has been the object of study of various researchers in the past, who have focused on the geomorphological, lithological, and stratigraphic interpretation of the area (Lüttig and Marinos 1962; Gold 1963; Lönhert and Nowak 1965; Vinken 1965; Hiltermann and Lüttig 1969).

The plateau of Megalopolis is located at an average altitude of 300 m to 500 m and is surrounded by Mount Taygetos to the south, by Mount Mainalo to the north, by the Lykaion and Tenadio mountains to the west. The altitude of the basin ranges between 200m and 400 m, while the total area of the Megalopolis basin is estimated at 180 km^2 to 200 km^2, and its maximum axis at 18 km in a north-east-south-west direction. The drainage of the basin is achieved naturally through the hydrological system of the river Alpheus and its tributaries.

Numerical analyses and FEM method

Since the 1970s, significant advancements in the assessment of stability and displacements have been achieved, propelled by technological progress (Duncan, 1996). The widespread adoption of numerical analyses has been facilitated by the enhancement of software design alongside the expansion of computer capabilities (Hammouri et al., 2008). Nowadays, numerical analyses represent the most prevalent and dependable approach for addressing geotechnical problems, offering high levels of reliability and the advantage of rapid execution (Brinkgreve & Galavi, 2014). This progress demonstrates a pivotal shift towards more precise and efficient analytical methods in geotechnical engineering, marking a significant leap forward in our ability to predict and mitigate potential geotechnical failures.

The finite element method (FEM) is used to predict the stability of the slope, in addition to the calculation of deformations and displacements. At the same time, finite element method (FEM) can be used to simulate the heterogeneous behaviour between formations, as well as the behaviour of discontinuities through their properties (Sloan, 2013b).

When examining slope stability, compared to other methods such as Limit Equilibrium Analysis (LEM), which does not offer the possibility of easily determining the block where it slips and the slip surface (Zheng et al., 2005a), the FEM method is an important tool for identifying the failure mechanism (Potts et al., 1990; Matsui & San, 1992c; Oblozinsky et al., 2001; Cai & Ugai, 2003). Secondly, the gradual process of slope failure, which is brought about by the reduction of certain rock mass parameters, can be monitored (Griffiths & Lane, 2001; Faheem et al., 2003). Therefore, the necessary decisions and placement of support measures can be made in the stages prior to failure (Griffiths & Lane, 2001). Finally, factors that are related to the stability of the slope in addition to the mechanical properties of the rock mass, such as rainfall and water influence, can be considered in the calculations (Zheng et al., 2005a).

Geological, geotechnical, and hydrogeological setting

In the Choremi field of the Megalopolis lignite center, two main zones of exploitable lignite are identified. The upper lignite zone is located between +330 m and +360 m above sea level and is characterised by intermediate clay layers. The lower lignite zone, on the other hand, is located between +285 m and +315 m above sea level, and within this zone there are also layers of clay and marl. The lignite beds have been deposited with an incline of 3% to 8% from east to west. Consequently, the inclination of the strata is unfavorable since the advance of exploitation in the lignite basin takes place towards the western edges of the basin.

Regarding the geological formations included in the numerical analyses, in order of depth where they are found are:

- the Quaternary deposits with high percentages of red clay,
- the lignite layers, and
- clay layers.

When conducting the numerical analyses, it was considered that the clay layers between the lignite layers play an important role in the stability of the open excavation. At the same time, to simplify the experimental procedure, the assumption was made that the mechanical characteristics of the clay layers are similar along the entire cross-section where it was examined. The parametric analyses performed in this study were conducted using PLAXIS 2D.

Parametric Analyses

In the 1st set of parametric analyses, the influence of the mechanical characteristics of the clay layers between the lignite layers and the Quaternary red clay deposits, in the absence of an aquifer were examined regarding the stability of the open excavation. In the 2nd set of parametric analyses, the groundwater level is inserted in the simulation, which is located at -6 m below the bed of the Alpheus River, and its level follows a lowering up to the foot of the slope at position: x: +1050 m.

In the 3rd set of parametric analyses, the effect of the gradual exploitation of the groundwater to the permeable-permeable contact at a depth of -30 m from the initial level for mechanical characteristics of clay layers c=80 kPa and φ=24°, and c=43 kPa and φ=30° respectively for the red clay layer is examined. This series aims to evaluate the influence of the groundwater on the slope stability under varying piezometric conditions. Finally, the 4th set of parametric analyses examines how the geometry of the open excavation affects the overall slope stability, by removing a part of the upper lignite layer and making the slopes less steep. Each series of analyses was designed to build in part on the findings of the previous set, progressively examining the interaction of the mechanical characteristics of the geological formations with the geometry of the excavation and groundwater management. Finally, the 3rd and 4th series of analyses aim to examine practical strategies for mitigating the stability issues of open excavation slopes.

The combinations of the mechanical properties examined are summarized in the following table:

Table 1. A summary of the combinations of the mechanical properties of the two formations examined.

	A/A	Cohesion (kPa)	Internal Friction Angle (°)	Young's Modulus E (kPa)
Clay Layers	1	100	20	40.000
	2	80	24	30.000
	3	70	28	50.000
Quaternary Deposits	1	50	25	40.000
	2	43	30	30.000
	3	30	35	50.000

Commentary on results

The comparison of the results of the first two sets of analyses indicates distinct differences in excavation stability due to the different geotechnical conditions where they occur (Figures 1& 2).

In the 1st set of analyses where no aquifer was introduced in the model, the values of the safety factor ranged between 1.5 and 2. In contrast, in the 2nd set of analyses, the addition of a groundwater level demonstrates a significant reduction in the safety factor to the extent that critical stability conditions prevailed, and this highlights the urgent need for decisions to mitigate stability issues. Moreover, adding a high groundwater level forms a realistic, yet unfavorable scenario where multiple failure slip-surfaces are created both in the upper and lower-level benches, indicating a gradual failure of the open excavation.

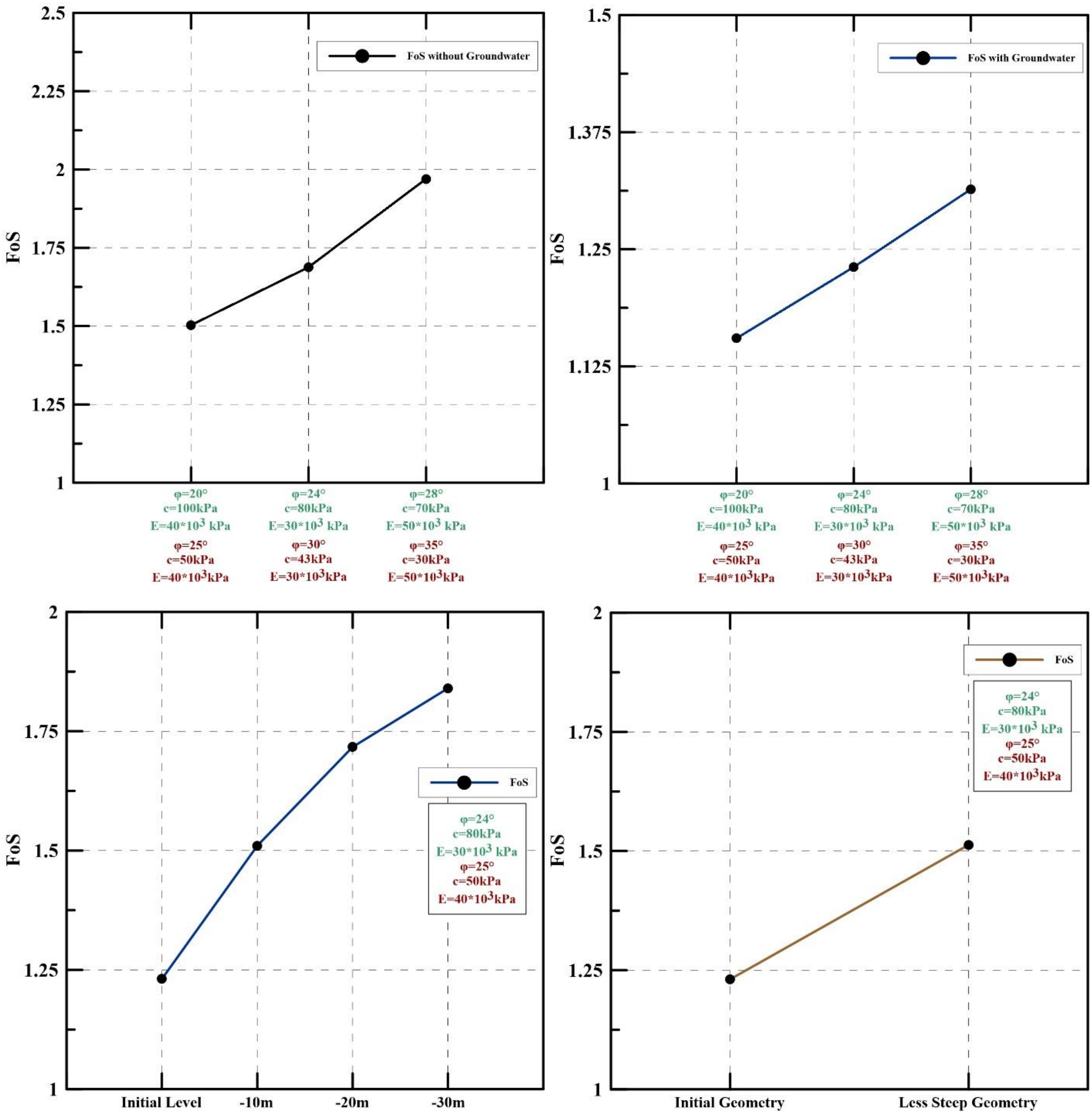

Figure 1. Summary of the Factors of Safety (FS) for each series of parametric analyses.

On the other hand, it is observed that lowering the groundwater level by 20 m, the final displacements are reduced just as significantly compared to the previous case (reduction by 10m). This is because lowering the water table level, in addition to reducing the pore water pressure, contributes to an increase in the shear strength of the material, especially for formations such as clay layers. Also, the reduction of groundwater level has reduced pore water pressures from critical slip surfaces. The failure surfaces are of smaller extent, however, there is also a gradual collapse of the excavation. Finally, by further lowering Finally, as the groundwater level from -20m to -30m, the extent of failure surfaces is smaller and limited to bench scale failures.

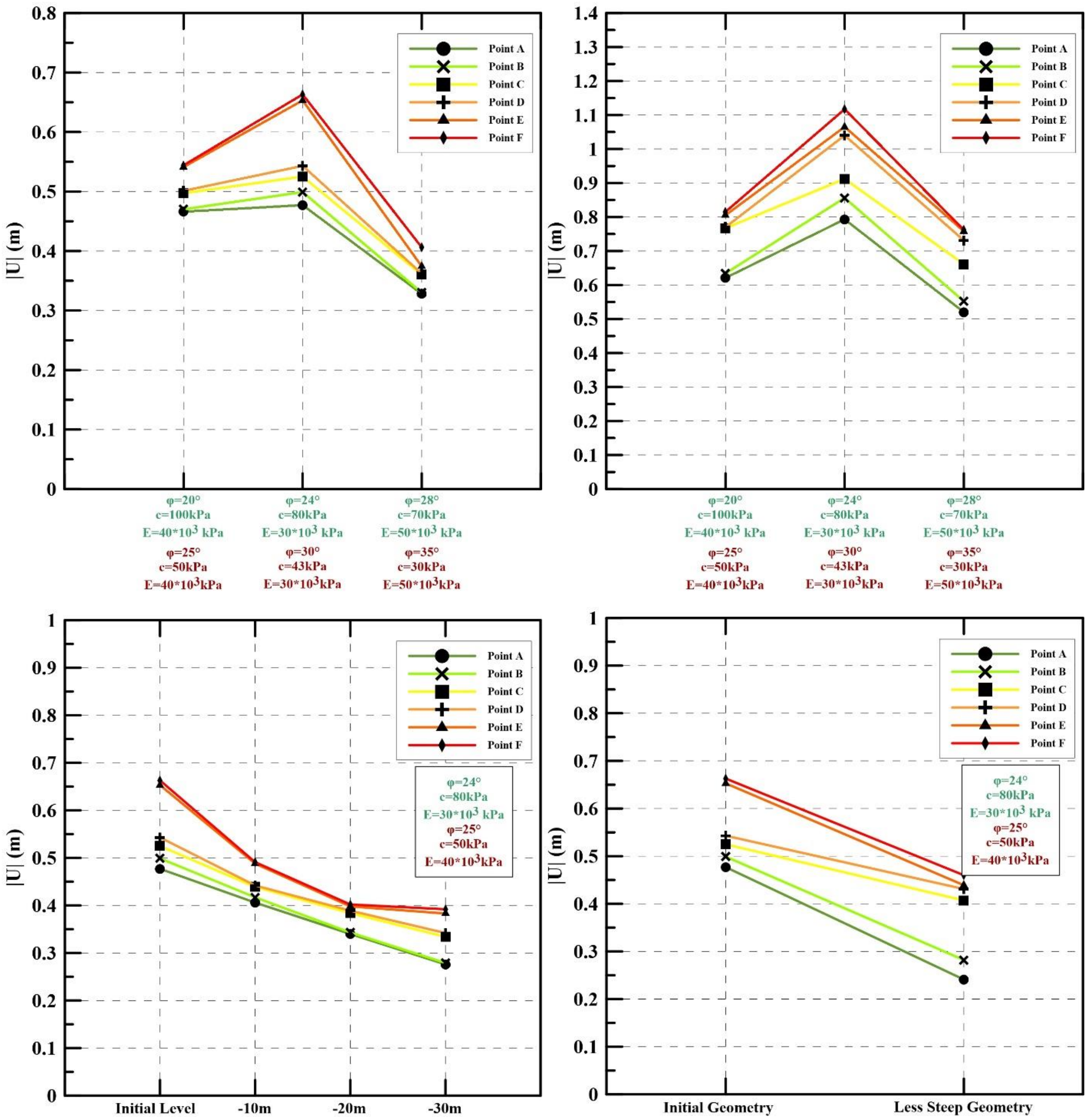

Figure 2. Comparison of Total Displacements for each series of parametric analyses.

In the 4th set of parametric analyses, the value of the safety factor is observed to increase significantly, and the marginal acceptable value of the stability factor (1.231) increases to 1.52. This FS value indicates that despite the adverse hydrostatic stresses where groundwater is exerted, the stability conditions can be mitigated by reducing the slope angle and removing material from the upper benches.

Conclusions

The growth of technology and the development of numerical simulation methods have made a significant contribution to reducing accidents and improving safety conditions in the mining industry. In contrast to the past, numerical analyses are the most widespread and reliable way of solving geotechnical issues.

The finite element method (FEM) is proved to be capable of providing reliable solutions to geotechnical issues, such as the calculation of the stability of open-pit excavations in two-dimensional models. In addition to the prediction of slope stability, the calculation of deformations and movements of the excavation can also be calculated. Finally, parametric analyses can be performed, allowing the user to test different mechanical properties values and solutions, to select the safest and most economical decision.

In relation to the study area and the numerical analyses carried out using Plaxis 2D, conclusions are drawn on the factors affecting the stability of the open pit excavation in the Choremi Field of the Megalopolis Lignite Centre. These analyses indicate the influence of the mechanical properties of the clay layers and Quaternary red clay deposits. High values of internal friction angle and cohesion lead to increased values of the safety factor. In contrast, Young's Modulus E appears to have an increased effect on the observed displacements, where increased values of Young's Modulus E led to lower total displacements in the simulation. From the first two sets of analyses, subtle differences in excavation stability are identified due to the different geotechnical conditions prevailing, where in the absence of an aquifer, the values of the safety factor ranged between 1.5 and 2. In contrast, with the introduction of an aquifer in the simulation, extensive slope stability issues are observed.

Furthermore, the geometry of the working slopes, as well as the management of groundwater, are highlighted as key aspects in maintaining stability. By operating surface pumping stations and drilling drainage wells around the perimeter of the excavation, the water table level is humbled and pore water pressures from critical slip surfaces are reduced. When groundwater management is accompanied by less steep slopes, stability conditions are significantly improved. Therefore, the appropriate combination of these two solutions has a positive effect on stability issues where they are identified within the study area.

With the corresponding decisions regarding changing the geometry of the working slopes in the open pit, and the draining of the groundwater, it is evident that the factor of safety is increased, and the total displacements are significantly reduced. The excavation of gentler slopes and the removal of material from the upper and intermediate benches have a positive effect on stability, as the slopes are unloaded, and this aims to a less extended zone of potential slip surfaces.

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