INVESTIGATION OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND

DOAN CONG BIEN

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil, Transportation and Geo-resources Engineering

Suranaree University of Technology

Academic Year 2023

การสืบค้นเรื่องความล้มเหลวขนาดใหญ่ของดั้มประกอบขยะที่เหมืองแม่เมาะ ในประเทศไทย

นายดวน กง เบียน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมโยธา ขนส่ง และทรัพยากรธรณี
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2566

INVESTIGATION OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis Examining Committee

....

(Prof. Dr. Panich Voottipruex)

Chairperson

....

(Assoc. Prof. Dr. Menglim Hoy)

Member (Thesis Advisor)

....

(Prof. Suksun Horpibulsuk)

Member (Thesis Co-Advisor)

....

(Prof. Dr. Avirut Chinkulkijniwat)

Member

....

(Dr. Apichat Suddeepong)

Member

....

(Assoc. Prof. Dr. Yupaporn Ruksakulpiwat)

Vice Rector for Academic Affairs

and Quality Assurance

....

(Assoc. Prof. Dr. Pornsiri Jongkol)

Dean of Institute of Engineering

ดวน กง เบียน : การสืบค้นเรื่องความล้มเหลวขนาดใหญ่ของดั้มประกอบขยะที่เหมืองแม่เมาะในประเทศไทย (INVESTIGATION OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND)
อาจารย์ที่ปรึกษา : รองศาสตราจารย์ ดร. MENGLIM HOY, 92 PP.

คำสำคัญ: ความล้มเหลวของดั้มประกอบ/ดินถล่ม/อิเล็กทริคอลเรซิสทีที/วิธีไฟไนต์เอลิเมนต์/เหมืองถ่านหินแบบพับเปิด/ระดับน้ำที่สูง

วิทยานิพนธ์นี้ได้ทำการศึกษาการเกิดขึ้นของปัจจัยที่เป็นไปได้และสาเหตุที่ทำให้เกิดความล้มเหลวของดั้มประกอบขยะในเหมืองถ่านหินแบบพับเปิดที่ใหญ่ที่สุดในประเทศไทยความล้มเหลวของดั้มประกอบในขนาดใหญ่นี้ได้ครอบคลุมพื้นที่ประมาณ 1.56 ตร.กม. เมื่อวัสดุทิ้งสูงถึง 135 เมตร เหนือระดับพื้นดินเดิม เหตุการณ์นี้เกี่ยวข้องกับการเคลื่อนย้ายมวลขยะ 70 ล้านลูกบาศก์เมตรในพื้นดิน ยาว 1.2 กม. กว้าง 1.3 กม. สาเหตุของความล้มเหลวนี้ได้ถูกสืบค้นในงานวิจัยนี้โดยใช้วิธีการสืบค้นทางวิทยาศาสตร์เพื่อการดำเนินการแก้ไขปัญหาการสืบค้นทางภูมิศาสตร์และภูมิเทคนิคถูกทำเพื่อละลายลักษณะของวัสดุดั้มและเงื่อนไขน้ำที่สูงการวิเคราะห์ทางทำลายด้วยตัวเลขของอิเล็กทริคอลเรซิสทีทีและการจับคู่ผลการวิเคราะห์กับท่อบอร์โฮลและการตีความเพื่อแสดงภาพรวมของเงื่อนไขภูมิศาสตร์ของวัสดุดั้ม ในท้ายที่สุด ความมั่นคงของดั้มประกอบได้ถูกสืบค้นโดยใช้วิธี finite element (โปรแกรม Plaxis 2D) โดยการวิเคราะห์อย่างละเอียดของข้อมูลที่ได้รับการศึกษาสาเหตุของความล้มเหลวของดั้มประกอบขยะสามารถจำแนกเป็นสองปัจจัยหลัก ได้แก่ การมีระดับน้ำที่สูงที่เชื่อมโยงกับความดันน้ำในช่องโพลและการมีชั้นฐานที่อ่อนแรงที่ตั้งอยู่ระหว่างฐานแข็งและวัสดุดั้มชั้นฐานที่อ่อนแรงนี้ คือ คลายสโตนที่ถูกฝังอยู่ในพื้นที่ที่มีน้ำเค็มเพิ่มขึ้นตามเวลา กับปริมาณขยะที่เพิ่มขึ้นเมื่อมีการทิ้งขยะในพื้นที่แม่น้ำและบ่อธรรมชาติ และการซึมอากาศฝนตกลงมา ทำให้เกิดการมีที่เฝออยู่ในพื้นที่ดั้มประกอบความล้มเหลวของ ดั้มนี้สามารถจัดอยู่ใน รูปแบบของ การล้มเหลวแบบเหวี่ยงซึ่งเป็นการเคลื่อนที่ โดยมีการแปลงทางแนวนอนของแนวเส้นเหวี่ยงและการแกว่งลงของแนวเส้นเหวี่ยงที่เป็นส่วนที่ทำนายได้ ผลลัพธ์จากงานวิจัยนี้จะช่วยให้ทีมวิศวกรทางภูมิศาสตร์ และเหมืองแร่ในการค้นหาทางออกทั้งระยะสั้นและระยะยาวเพื่อปรับปรุงความมั่นคงของดั้ม

สาขาวิชา วิศวกรรมโยธา
ปีการศึกษา 2566

ลายมือชื่อนักศึกษา ....
ลายมือชื่ออาจารย์ที่ปรึกษา ....
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ....

DOAN CONG BIEN : INVESTIGATION OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND. THESIS ADVISOR : ASSOC. PROF. MENGLIM HOY, Ph.D., 92 PP.

Keywords: Waste Dump Failure/Landslide/Electrical Resistivity Tomography/Finite Element Method/Open-Pit Coal Mine/Perched Water Table

This thesis investigates the mechanisms and causes behind a significant failure in the waste dump at the Mae Moh Lignite Mine, Thailand, which affected an area of 1.56 km2 and involved the displacement of a 70-Mm3 mass of dump material. Geophysical and geotechnical investigations, including electrical resistivity tomography and finite element analysis, were conducted to understand the waste dump materials and perched water conditions.

The research identified two primary factors contributing to the failure: a perched water table leading to high pore-water pressure and a weak basal layer at the interface between the hard foundation and the waste dump materials. The weak layer, composed of claystone, deteriorated due to increased waste deposition over natural river and pond areas, coupled with rainwater infiltration. The failure was categorized as a wedge mode, involving the horizontal translation of a passive wedge and the vertical subsidence of an active wedge.

The findings will enable geotechnical and mining engineering teams to identify short-term and long-term solutions to improve waste dump stability and facilitate ongoing material deposition to reach the intended target height. This research contributes to the broader field of geotechnical engineering and the management of waste dumps in mining operations.

School of Civil Engineering

Academic Year 2023

Student's Signature ....

Advisor's Signature ....

Co-Advisor's Signature ....

ACKNOWLEDGMENTS

First and foremost, I would like to express my profound gratitude to my thesis advisor, Asst. Prof. Dr. Menglim Hoy whose unwavering support, expertise, and encouragement have been indispensable throughout this research journey. Their guidance, thoughtful feedback, and commitment to academic excellence have played a pivotal role in shaping the trajectory of this thesis.

Heartfelt appreciation is extended to my co-advisor, Prof. Dr. Suksun Horpibulsuk for generously sharing their knowledge, providing valuable insights, and fostering a conducive learning environment during my time at Suranaree University of Technology. Their mentorship and dedication to fostering intellectual curiosity have been instrumental in my academic growth.

I am indebted to the distinguished faculty members of the School of Civil Engineering, particularly Professor Avirut Chinkulkijniwat, Associate Professor Pornpot Tangseng, and Dr. Nattaporn Charoentham. Their engaging lectures, scholarly guidance, and commitment to academic excellence have been a source of inspiration and enlightenment.

In addition, special thanks are due to my thesis committee Dr. Apichat for their rigorous examination, challenging questions, and invaluable suggestions that significantly enriched the quality of this thesis.

I wish to acknowledge the financial support from the Suranaree University of Technology under SUT Scholarships for Graduate International Students (Vithedbundit) during my Master’s degree. This research was financially supported by the Electricity Generating Authority of Thailand under contract no 64-G201000-11-IO. SS03G3008566 and Suranaree University of Technology. I also wish to thank all the staff and faculty members as well as friends at the School of Civil Engineering, Suranaree University of Technology for the academic, administrative, and technical support.

Last but certainly not least, I want to acknowledge the immeasurable support and love from my family. Their encouragement, understanding, and belief in my abilities have been a constant source of motivation.

To my darling, Huyen Thi Vu, her unconditional love, patience, and unwavering support have been the driving force behind this thesis. This achievement is as much theirs as it is mine.

Thank you to everyone who has been a part of this academic journey. Your contributions have made a lasting impact, and I am truly grateful for the privilege of learning and growing in this enriching academic environment

Doan Cong Bien

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF FIGURES (Continued)

SYMBOLS AND ABBREVIATIONS

EGAT	=	Electricity Generating Authority of Thailand
ERT	=	Electrical Resistivity Tomography
FEM	=	Finite Element Method
FS	=	Factor of Safety
LEM	=	Limit Equilibrium Method
OMS	=	Ordinary Method of Slices
PF	=	Probability of Failure
PP	=	Passive Wedge
SFM	=	South Field Mine
UAV	=	Unmanned Aerial Vehicles
USCS	=	Unified Soil Classification System
USRMS	=	US Symposium On Rock Mechanics
HK	=	Huai King
HL	=	Huai Luang
LEM	=	Limit Equilibrium Method
NK	=	Na Khaem
γ	=	Unit weight of soil
γ_{sat}	=	Total unit weight
γ_{unsat}	=	Dry unit weight
S_u	=	Undrained shear Strength
c’	=	Cohesive of soil
φ'	=	Friction angle
τ	=	Shear strength of soil
σ'	=	Effective stress
E’	=	Effective modulus of elasticity
k_x	=	Permeability of soil in the direction of x
k_y	=	Permeability of soil in the direction of y

CHAPTER I

INTRODUCTION

1.1 Problem Statement

The Mae Moh Mine, located in Lampang Province, Thailand, stands as the largest open-pit coal mine in Southeast Asia. Encompassing the entire surface lignite mine and external dumping areas spanning approximately 38 km^2 and 42 km^2, respectively, its scale is indeed noteworthy. Currently, the mine extracts about 16 million tons of coal annually, a quantity that accounts for a substantial 70% of Thailand's total lignite production. This vast coal reserve plays a pivotal role in generating electricity for the Mae Moh power plant (Udomchai et al., 2017). The Mae Moh Mine, initiated in 1955, has been under the operation of the Electricity Generating Authority of Thailand (EGAT). In recent years, the associated Mae Moh power plant has been a substantial contributor to the national power grid, generating an impressive 2,220 megawatts of electricity. This electricity output is strategically distributed, with 50% serving the North, 30% directed to the Central region, and the remaining 20% allocated to the northeast of Thailand.

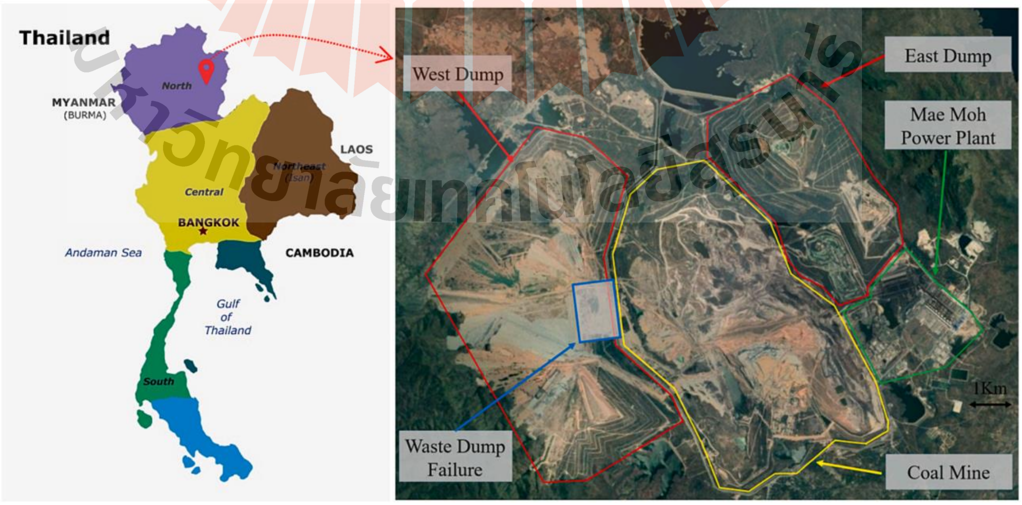


Figure 1.1 Location and the layout perspective of the Mae Moh Mine

Figure 1.1 illustrates the positioning of the Mae Moh power plant, the coal mine region, and the disposal sites, encompassing the west dump and east dump. The excess material extracted during mining operations was subsequently conveyed to the disposal areas using a conveyor system, as depicted in Figure 1.2.

Figure 1.2 Transporting the waste dump materials to the disposal area using a conveyor system.

According to EGAT's strategic plan, the Mae Moh Mine is projected to be excavated to a depth of around 500 meters from the original ground surface over the next four decades, making it the deepest open-pit lignite mine globally. Consequently, a substantial amount of overburden material, reaching approximately 260 meters from the original ground level, is anticipated to be deposited in the west dumpsite. However, a significant incident occurred on March 18, 2018, when a large-scale failure affected the west dumpsite, encompassing an area of approximately 1.56 km^2. This occurred as the dumped materials reached a height of 135 meters from the original ground, at an elevation of 330 meters above mean sea level (MSL).

The occurrence of the failure involved the displacement of a massive 70-Mm3 volume of dumped material, with dimensions extending to a length of 1.2 km and a width of 1.3 km. Consequently, the precarious stability of the waste dumpsite presents a considerable challenge for EGAT. To address this, comprehensive geotechnical examinations and the application of remedial strategies are imperative to facilitate the continuous disposal of waste materials generated during mining operations.

The exact cause of the failure at the west dumpsite in the Mae Moh Mine has not been completely documented due to the constraints of the experimental program in the laboratory and on-site investigation immediately following the incident. In response, the Center of Excellence in Innovation for Sustainable Infrastructure Development at Suranaree University of Technology was enlisted to identify the causes of the west dumpsite failure and recommend a practical approach to prevent similar failures in the future.

This research is primarily dedicated to investigating the failure mechanisms and causes associated with the waste dump site. It relies on historical and geotechnical test data, drawing parallels with global case studies for comparative analysis. To assess the resistivity of subsurface waste dump materials, the study employs electrical resistivity tomography (ERT) as a geophysical imaging technique. The ERT profiles, coupled with data from boring logs, facilitate the interpretation of soil profiles within the area of failure. After this investigation, the potential failure mechanism and slope stability of the waste dumpsite are scrutinized through finite element analysis using the Plaxis 2D software, leveraging geographical and material properties obtained during the study.

This paper thoroughly discusses various issues pertaining to notable movements or collapses observed in waste dumpsites of lignite mines worldwide (Kasmer et al., 2006; Steiakakis et al., 2009; Wang & Griffiths, 2019; Zevgolis et al., 2019). B. G. Richards et al. (1981) undertook an extensive slope stability analysis of the Goonyella mine in Queensland, Australia. Their study identified a direct association between the collapse phenomenon and the presence of water at the basal layer of the spoil foundation, leading to a consequential reduction in the shear strength of the soil. Furthermore, the manifestation of tension cracks in the overburdened materials at the crest, induced by significant settlement, notably contributed to the failure movement characterized by a bilinear wedge. An examination of a large-scale failure in the waste dumpsite of open-pit iron mines in China revealed that the predominant failure mode of the waste dump slope was a two-wedge failure (Wang & Chen, 2017). The observed movement was reported to initiate at the toe of the slope, progressing along the clay basement. This movement was characterized by the division into an active upper wedge and a lower passive wedge, with separation facilitated by the presence of tension cracks. Wang and Griffiths (2019) provided evidence that the failure of the dump slope at Muara Enim Mine in Indonesia was induced by heightened water pressures, emanating from an undisclosed weak clay layer in the foundation, exacerbated by the rapid loading associated with dumping. Concurrently, a comprehensive examination was conducted on a substantial waste dump slope failure covering an expanse of 0.3 km2 within the dumping site of a strip coal mine in Turkey (Kasmer et al., 2006). Following an extensive field and laboratory investigation, along with a back-analysis utilizing finite element analysis, the root causes of the failure were identified as the gradual softening (degradation) of the fill materials at the base of the dumpsite over time. The surfaces involved in the sliding failure encompassed a combination of circular pathways through the waste dump materials and a transitional surface located between the softened fill material and the waste dump material. In a related context, Steiakakis et al. (2009) documented a comparable stability issue in the South Field Lignite Mine in Northern Greece in 2004, where the failure mass of the deposit amounted to 40 Mm^3. The failure was attributed to the inherent low shear strength of the clay layer at the base of the slope and the elevated pore-water pressure within the overburdened materials.

The failure mechanism of the waste dump slope exhibited various modes of failure, with the causes attributed to the geological and hydrological characteristics of the waste dump area, the drainage system, and the dumping rate. Building upon insights from previous case studies, potential factors contributing to the failure included the softening of the soil layer and the accumulation of excessive pore-water pressure under undrained loading conditions. Consequently, the formation of the sliding failure surface occurred through active and passive wedges along a vulnerable zone at the interface between the weak soil layer at the base and the waste dump material.

The findings of this study are anticipated to empower the geotechnical and mining engineering teams, enabling them to efficiently devise both short-term and long-term solutions to enhance the stability of waste dumps. This will facilitate the ongoing dumping operations, allowing them to reach the targeted height.

1.2 Objective of study

To investigate the failure mechanism of the waste dump at the Mae Moh Mine, a comprehensive study involving geophysical and geotechnical investigations, as well as numerical analysis, was undertaken. The primary objectives of this research are outlined as follows:

1) To analyze and identify the potential causes leading to the failure of the waste dump at the Mae Moh open-pit lignite mine in Thailand.
2) Conduct finite element analysis, utilizing data obtained from geophysical and geotechnical investigations, to comprehensively study the behavior of large-scale instability within the deposit.

1.3 Organization of the dissertation

This thesis is structured into four chapters, following the outlined framework:

Chapter I the introductory section articulates the problem statement and highlights the primary objective of the study.

Chapter II presents the theoretical background and the literature review of the recent search papers that relate to the failure of waste dumps at lignite mines in the world.

Chapter III focuses on the 2018 landslide incident in a construction waste dump at Mae Moh mine in Thailand. This chapter encompasses the historical context of the construction waste dump, a detailed dump description, the presentation of sub-surface structure imaging results using Electricity Resistivity Tomography (ERT), and a numerical analysis simulation to evaluate potential factors contributing to the deposit failure.

Chapter IV summarizes the main research findings and offers recommendations for future studies.

1.4 References

Anagnostopoulos, A. (1979). The Mechanical Behaviour of the Megalopolis Lignites. Thesis presented to the National Technical University of Athens for the ...,

Bar, N., & Baczynski, N. (2017). Understanding and modeling a highly ductile 25+ years old active-passive landslide at Ok Tedi Mine in Papua New Guinea. Paper presented at the Workshop on World Landslide Forum.

Dassanayake, A., Phien-Wej, N., & Giao, P. (2016). Groundwater flow modeling and slope stability analysis for the deepening of Mae Moh open pit lignite min. *Geotechnical Engineering Journal of the SEAGS and AGSSEA, 47*(3), 101-115.

Igwe, O., & Chukwu, C. (2019). Slope stability analysis of mine waste dumps at a mine site in Southeastern Nigeria. *Bulletin of Engineering Geology and the Environment, 78*(4), 2503-2517.

Kainthola, A., Verma, D., Gupte, S., & Singh, T. (2011). A coal mine dump stability analysis—a case study. *Geomaterials, 1*(01), 1.

Kasmer, O., Ulusay, R., & Gokceoglu, C. (2006). Spoil pile instabilities with reference to a strip coal mine in Turkey: mechanisms and assessment of deformations. *Environmental geology, 49*(4), 570-585.

Kavvadas, M., Roumpos, C., & Schilizzi, P. (2020). Stability of Deep Excavation Slopes in Continuous Surface Lignite Mining Systems. *Geotechnical and Geological Engineering, 38*(1), 791-812.

Koner, R., & Chakravarty, D. (2016). Numerical analysis of rainfall effects in external overburden dump. *International Journal of Mining Science and Technology, 26*(5), 825-831.

Leonardos, M., & Terezopoulos, N. (2003). Rim slope failure mechanism in the Greek deep lignite mines–a case study. *Mining Technology, 112*(3), 197-204.

Monopolis, D., Stiakakis, E., Agioutantis, E., & Kavouridis, C. (1999). Geotechnical investigation at lignite mines. *Mineral Resources Engineering, 8*(04), 405-418.

Ngo, D. H., Horpibulsuk, S., Suddeepong, A., Hoy, M., Udomchai, A., Doncommul, P., . Arulrajah, A. (2020). Consolidation behavior of dredged ultra-soft soil improved with prefabricated vertical drain at the Mae Moh mine, Thailand. *Geotextiles and Geomembranes, 48*(4), 561-571.

Poulsen, B., Khanal, M., Rao, A. M., Adhikary, D., & Balusu, R. (2014). Mine overburden dump failure: a case study. *Geotechnical and Geological Engineering, 32*(2), 297-309.

Prountzopoulos, G., Fortsakis, P., Marinos, V., & Marinos, P. (2017). A large scale landslide in a coal mine in marly formations: Evaluation, analysis and rehabilitation. *ISSMGE International Journal of Geoengineering Case Histories, 4*(1), 29-45.

Punyawadee, V., Pothisuwan, R., Winichaikule, N., & Satienperakul, K. (2008). Costs and benefits of flue gas desulfurization for pollution control at the Mae Moh power plant, Thailand. *ASEAN Economic Bulletin*, 99-112.

Rajak, T. K., Yadu, L., Chouksey, S. K., & Dewangan, P. K. (2018). Stability analysis of mine overburden dump stabilized with fly ash. *International Journal of Geotechnical Engineering*, 1-11.

Richards, B., Coulthard, M., & Toh, C. (1981). Analysis of slope stability at Goonyella Mine. *Canadian Geotechnical Journal, 18*(2), 179-194.

Steiakakis, E., Kavouridis, K., & Monopolis, D. (2009). Large-scale failure of the external waste dump at the "South Field" lignite mine, Northern Greece. *Engineering Geology, 104*(3-4), 269-279.

Tzampoglou, P., & Loupasakis, C. (2018). Evaluating geological and geotechnical data for the study of land subsidence phenomena at the perimeter of the Amyntaio coalmine, Greece. *International Journal of Mining Science and Technology, 28*(4), 601-612.

Udomchai, A., Horpibulsuk, S., Suksiripattanapong, C., Mavong, N., Rachan, R., & Arulrajah, A. (2017). Performance of the bearing reinforcement earth wall as a retaining structure in the Mae Moh mine, Thailand. *Geotextiles and Geomembranes, 45*(4), 350-360.

Vassilis, M., Theodoros, T., Spyridon, P., Panagiotis, T., Alexandros, C., & Konstantinos, V. (2015). Large Induced Displacements and Slides Around an Open Pit Lignite Mine, Ptolemais Basin, Northern Greece. In *Engineering Geology for Society and Territory-Volume 2* (pp. 311-315): Springer.

Wang, Y.-k., Sun, S.-w., & Liu, L. (2019). Mechanism, Stability and Remediation of a Large Scale External Waste Dump in China. *Geotechnical and Geological Engineering, 37*(6), 5147-5166.

Zarlin, N., Sasaoka, T., Shimada, H., & Matsui, K. (2012). Numerical study on an applicable underground mining method for soft extra-thick coal seams in Thailand.

Zhan, L.-t., Zhang, Z., Chen, Y.-m., Chen, R., Zhang, S., Liu, J., & Li, A.-g. (2018). The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. *Engineering Geology, 238*, 15-26.

CHAPTER II

LITERATURE REVIEW

2.1 Slope stability Analysis

2.1.1 Limit Equilibrium Method (LEM)

The Limit Equilibrium Method (LEM) is the most typical approach for studying slope stability in both two and three dimensions in terms of total-stress analysis or effective-stress analysis. This method identifies possible failure mechanisms and produces factors of safety for specific geotechnical problems. It is a suitable option for evaluating the stability of earth-fill embankments, earth dams, retaining walls, foundations, open-pit mines, and landslides. The factor of safety (FS) plays an important role in the rotational design of slopes using force or moment equilibrium as shown in Figure 2.1. It can be used to define the stability of the slope by entering some parameters into the analysis, such as strength parameters, stiffness parameters, and strata. The factor of safety is assumed to be the same at all points along the failure slip surface. Thus, the mean values represent the assumed critical failure slip surface. Moment equilibrium is mostly used to judge rotational landslides, the other force equilibrium is mostly utilized to assess both rotational and translational landslides (Cheng & Lau, 2014).

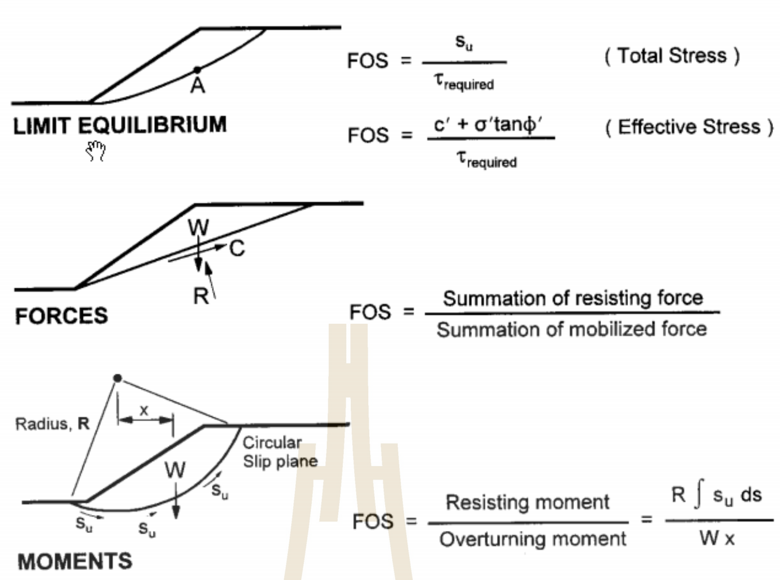


Figure 2.1 Derivation of safety factor (Abramson et al., 2001)

The factor of safety can be drawn as follows:

$$FS = \frac{\text{The available shear strength of soil}}{\text{The equilibrium shear stress}} \tag{2.1}$$

The Eq. (2.1) can be written as

$$FS = \frac{S_u}{\tau_{\text{required}}} \quad \text{in terms of total stress analysis} \tag{2.2}$$

Or $$FS = \frac{c' + \sigma' \tan\varphi'}{\tau_{\text{required}}} \quad \text{in terms of effective stress analysis} \tag{2.3}$$

In which: S_u = Undrained shear strength of soil

c' and ϕ' = The effective cohesion and effective friction angle, respectively

$\tau_{required}$ = the required shear stress for the equilibrium state

Generally, soil mass can be considered stable when the factor of safety is higher than 1.25 and slope failure can occur frequently as FS is less than 1.07 (Bowles, 1979). However, it was reported from some previous studies that numerous landslide problems are stable due to neglect and extra enhancement of vegetation or soil suction (Cheng & Lau, 2014). In some cases, an increase in the factor of safety needs to be required due to the high risk of loss of life or unpredictability.

An array of stability analyses, leveraging the limit equilibrium method, has been systematically applied to prognosticate the mode of slide failure. This methodological spectrum encompasses but is not restricted to, infinite slope analysis, planar surface analysis, circular surface analysis, slice analysis, and block analysis.

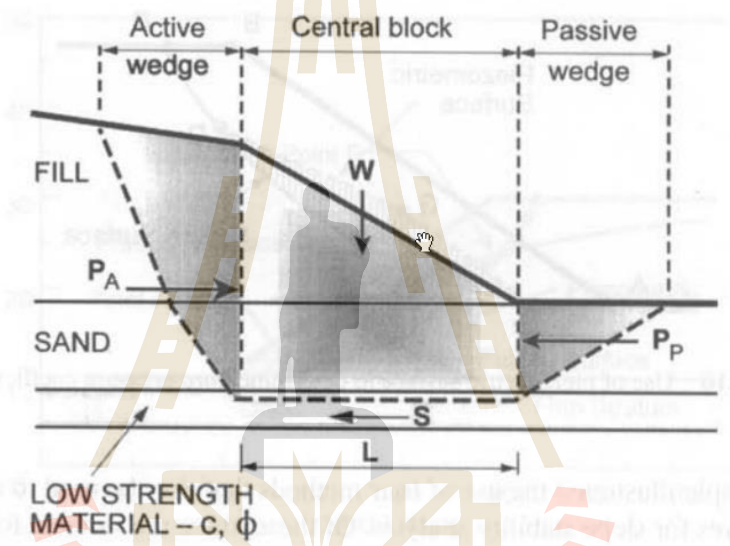


Figure 2.2 Scheme of block analysis (Abramson et al., 2001)

The safety factor might be computed in this situation where the embankment fill has a shear strength greater than that of a basal layer as well as a low shearing strength of a thin layer below (Figure 2.2). A block or wedge analysis supposes that soil is compacted as layers or blocks, such as an earth-fill dam, rock-fill dam, or waste dump. This analysis is relatively simple, uncomplicated, and can be carried out rapidly by hand calculation. The block consists of three parts, namely active wedge (P_A) at the head of the slope, Passive wedge (P_P) at the toe of the slope, and central block (W). The FS is defined as the horizontal resistance forces to the horizontal driving forces.

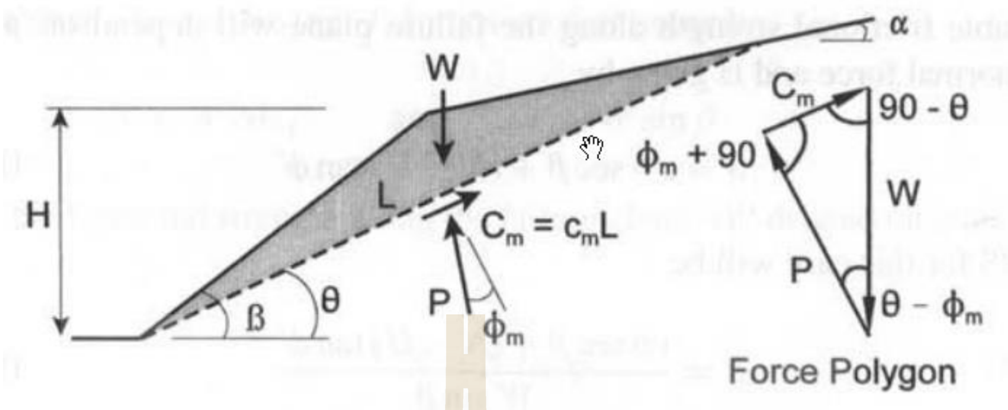


Figure 2.3 Scheme of planar surface analysis (Abramson et al., 2001)

The planar surface analysis might be utilized to evaluate a slope with a low shearing strength of the soil and the variety of soil strata of different soil components. The soil failure is considered as a block down to the sliding surface that all points are on the verge. A closed-form solution can be applied on planar surface analysis that relies on the geometry of a slope, and shear strength parameter of soil along slip failure.

Figure 2.3 illustrates the scheme of planar surface analysis. It should be pointed out that the influence of the inclination of the back slope is neglected. It means that it does not affect the safety factor value.

In the case of homogeneous soil, the inspection of man-made embankment might use circular surface analysis which is the simplest method to find the most critical slip in slopes. Two kinds of methods, namely the circular arc method (Figure 2.4) and the friction circle method (Figure 2.5).

The straightforward circular analysis is subjected to an expectation that the rigid, block failure will collapse in its central by rotational behavior. The method is derived from total stress analysis which the shear strength of soil throughout the length of the failure slip surface is considered as undrained shear strength. It means that the internal friction angle is assigned as zero. On the other hand, the probability of tension cracks is neglected.

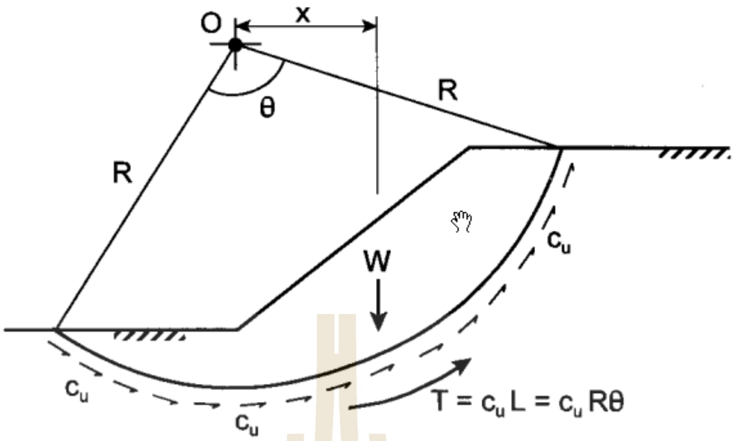


Figure 2.4 Scheme of circular arc method (Abramson et al., 2001)

The implementation of the friction circle method in geotechnical engineering was introduced by Glennon Gilboy and Arthur Casagrande (Taylor, 1937). It is supposed that the Mohr-Coulomb failure criterion is available and that the failure surface is cylindrical. This method is suitable for homogeneous slopes with soil frictional angles greater than zero. Cohesive and frictional angle components are used to perform the calculation.

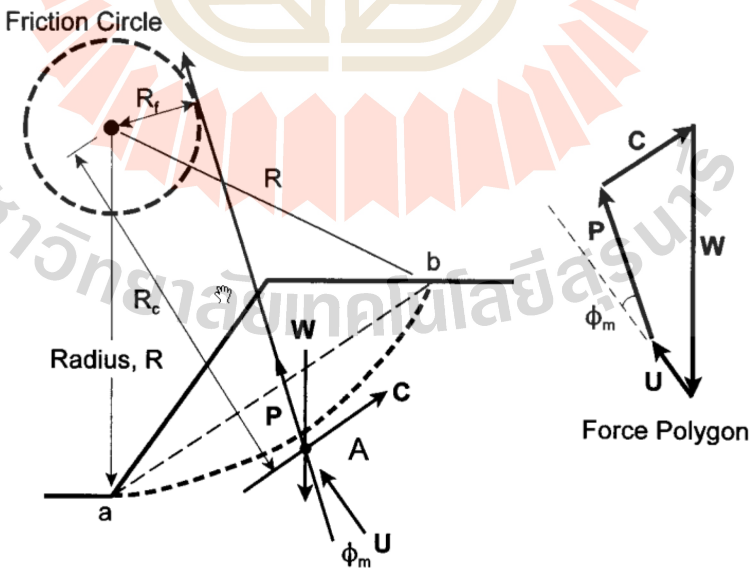


Figure 2.5 Scheme of friction circle method (Abramson et al., 2001)

The method of slices is the most ordinary technique for assessing the stability of geotechnical problems with intricate conditions, predominantly for slope stability **(Figure 2.6).** It can be performed either satisfying overall moment equilibrium or horizontal force equilibrium.

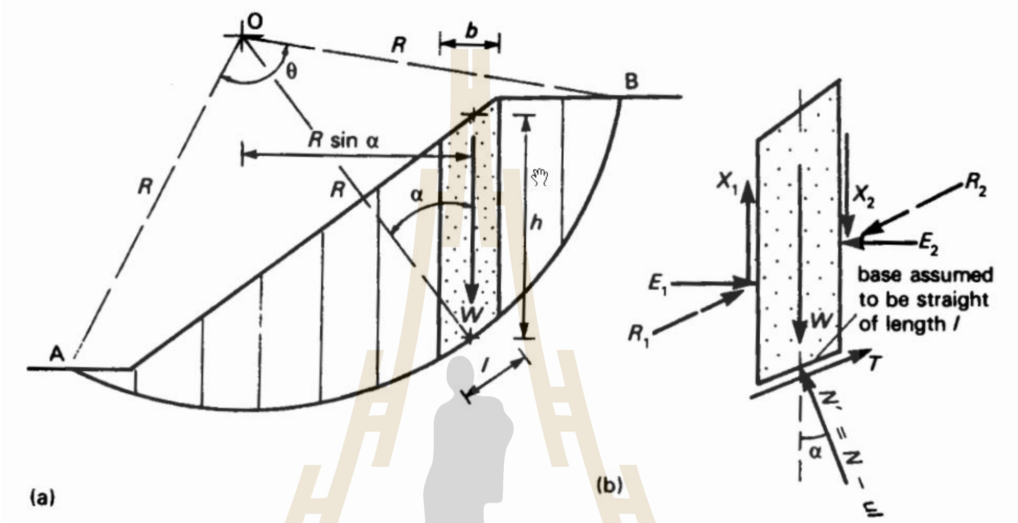


Figure 2.6 Scheme of the method of slices (Whitlow, 1990)
(a) Division of slip mass (b) Forces acting on slices

The slope stability analysis divides soil mass into a great deal of small slices as illustrated in Fig. 2.6 a. The small slices are influenced by the general system of force (Figure 2.6 b). The effective stress normal reacting force at the base of the slice (N') plays a major role in the computation of the safety factor. Many researchers have proposed methods of obtaining the N'-value, some are perfectly straightforward, and others are entirely complex.

For example, in the Ordinary Method of Slices (OMS), it is assumed that the inter-slice forces are neglected (E_1=E_2 and X_1=X_2) (Fellenius, 1936). The imperfection of this method is that the assumption of inter-slice force does not meet the requirement of inter-slice equilibrium due to a variety of base inclinations. For Bishop's Simplified Method, all of the shear forces are assumed zero(Bishop, 1955). It means that the tangential inter-slice forces are equal and opposite (X_1=X_2 and $E_1 \neq E_2$). The factor of safety estimated from this method is slightly underestimated

(Whitlow, 1990). In the Simplified Janbu Method, the inter-slice shear force is the absence of slope stability calculations. This method meets the requirement of vertical forces equilibrium for individual slices and general horizontal force equilibrium for all slices. In conclusion, The Ordinary method, Bishop’s simplified, and Janbu’s simplified neglect inter-slice forces in the slope stability analysis. It is believed that the moment equilibrium is not influenced by effective normal and pore pressure forces. From that, the factor of safety estimated from the three methods should not done for non-circular slip surfaces (Abramson et al., 2001). To overcome these issues, the Spencer method and Morgestern-price method are introduced. The two methods are similar due to both vertical and horizontal inter-slice forces being considered.

Table 2.1 Comparison of slope stability analysis (Fredlund & Krahn, 1977)

Method	Safety Factor (FS) Force Equilibrium	Safety Factor (FS) Moment Equilibrium	Inter-slice Force Assumption (H=horizontal, V=vertical)
Ordinary (Swedish or USBR) (Fellennius 1936)	No	Yes	Neglect H & V
Bishop's Simplified (Bishop 1955)	No	Yes	Neglect H & V
Janbu's Simplified (Janbu 1954; 1957; 1973)	Yes	No	Neglect V, Consider H
Janbu's Generalized (Janbu 1954; 1957; 1973)	Yes	No	Consider H &V
Spencer (Spencer 1967; 1973)	Yes	Yes	Consider H &V
Morgenstern-Price (Morgenstern and Price 1965)	Yes	Yes	Consider H &V
Lowe-Karafiath (Lowe and Karafiath 1960)	Yes	No	Consider H &V
Corps of Engineers (Corps of Engineers 1982)	Yes	No	Consider H &V

Table 2.2 Characteristics of Equilibrium Methods (Duncan & Wright, 1980)

Method	Characteristics
Slope Stability Charts (Duncan et al., 1987; Janbu, 1968)	Suitable for many geotechnical problems Applied for circular slip surfaces only Time-saving
Ordinary Method of Slices (Fellenius, 1927; Fellenius, 1936)	Meet a requirement of moment equilibrium Unsatisfied horizontal or vertical force equilibrium
Bishop's Modified Method (Bishop, 1955)	Applied for circular slip surfaces Meet a requirement of moment equilibrium Meet a requirement of vertical force equilibrium Unsatisfied horizontal force equilibrium
Force Equilibrium Methods (Engineers, 1970; Lowe, 1960)	Suitable for any kinds of slip surfaces Unsatisfied moment equilibrium Meet a requirement of both horizontal and vertical force equilibrium
Janbu's Generalized Procedure of Slices (Janbu, 1968)	Suitable for any kinds of failure slip surfaces Meet a requirement of equilibriums Permits side force locations to be varied More frequent numerical problems than other methods
Morgenstern and Price's Method (Morgenstern & Price, 1965)	Suitable for any kinds of failure slip surfaces Meet a requirement of equilibriums Allows side force locations to be varied
Spencer's Method (Spencer, 1967)	Any shape of slip surfaces Meet a requirement of equilibriums Allows side force locations to be varied

2.1.2 Finite Element Method (FEM)

The finite element method (FEM) is a particular numerical technique for solving differential equations. The FEM has broad-spectrum engineering applications. It was the first proposed to geotechnical engineering by (Clough & Woodward III, 1967). The Finite Element Method can be used to find the solution to numerous geotechnical problems that involve the interaction between structures and soil. The ability of FEM can generate many desirable characteristics of soil mass, such as stresses, displacements, and pore water pressure. It can be used to simulate the stage of construction such as backfill, consolidation, swelling, and dissipation of excess-pore water pressure. Seepage analysis and slope stability are also verified by FEM.

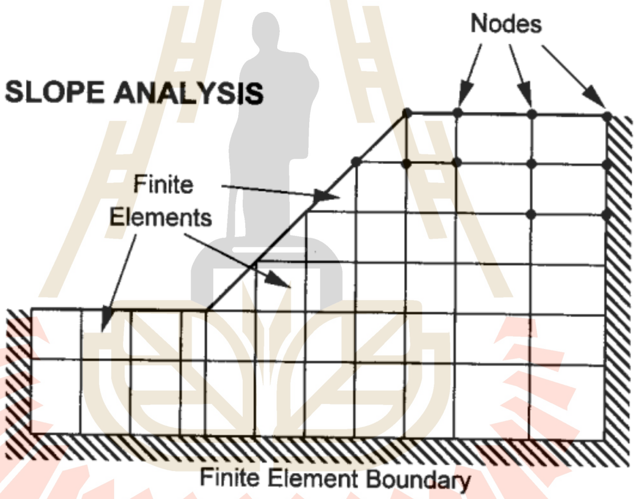


Figure 2.7 Scheme of Finite Element Method (Abramson et al., 2001)

The discrete units, isolated from the soil block, are denoted as finite elements (Figure 2.7). These elements are interconnected at their nodes and predefined boundaries of the continuum (Abramson et al., 2001).

Although FEM shows a great deal of advantages, it has its limitations. The results from finite-element analysis show calculated displacement greater than the measured displacement (Duncan, 1996). This is because the stiff of soils on site tends to be higher than soils in the lab due to aging effects. Besides, the samples suffered from disturbance during sampling and the process of transportation.

2.2 Previous studies and failure mechanisms of waste dumpsites

An increase in the dimension of the open-pit mine results in the amount of overburden removal. The mine by-products are excavated and transferred by trucks or conveyor belts to spread on end-dumped fills. The management of waste dump areas plays a leading role in the stability of a slope. There are many failures of mine waste dump have reported in the last two decades (Dawson et al., 1998; Omraci et al., 2003; Zevgolis et al., 2019; Zhan et al., 2018). It was documented from previous studies that the most failure mechanisms of deposits came from many factors contributing to the instability of the waste dump, such as high pore-water pressure with a thin layer of soft clay beneath the waste dump (Poulsen et al., 2014; Steiakakis et al., 2009; Su & Miller, 1995), wetting and seepage process (Lavigne et al., 2014; Vassilis et al., 2015; Yin et al., 2016), high moisture sensitive excavated soil caused reduction in shear strength of soils (Kasmer et al., 2006; B. Richards et al., 1981), the inclination of original slope surface (Kavvadas et al., 2020).

The spoil pile at Goonyella Mine in central Queensland, Australia was recorded as the failure of the basal layer and horizontal movement, forming a passive wedge and active wedge (Figure 2.8). The inclination of the basal layer was indicated to be worthy of attention in slope stability.

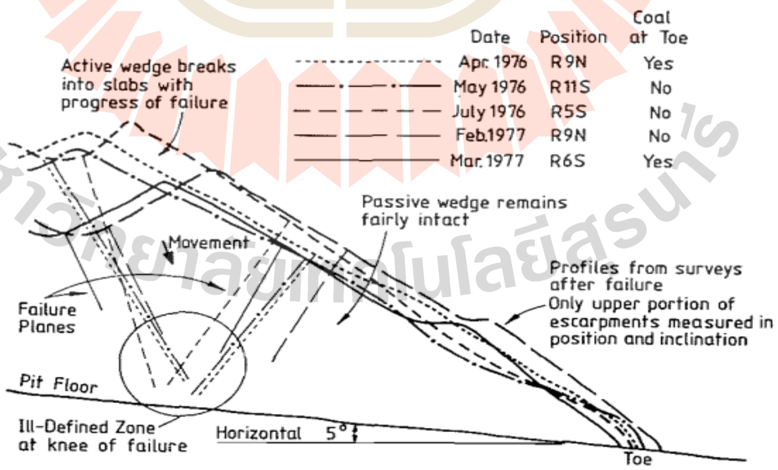


Figure 2.8 Monitoring results of a large overburden dump failure at Goonyella Mine, Australia (B. Richards et al., 1981)

Similarly, the collapse of the overburden dump in India caused the killing of 14 people in 2009 (Figure 2.9). The failure initiated settle at the crest of a slope and mobilization of a layer of high plasticity back cotton soil, establishing active wedge and passive wedge. The toe soil moved approximately 70 m from the original position. From laboratory test results, the internal friction angle of overburdened soil is typically from 35 to 40 degrees. However, it was reduced to around 15 degrees due to the saturation process.

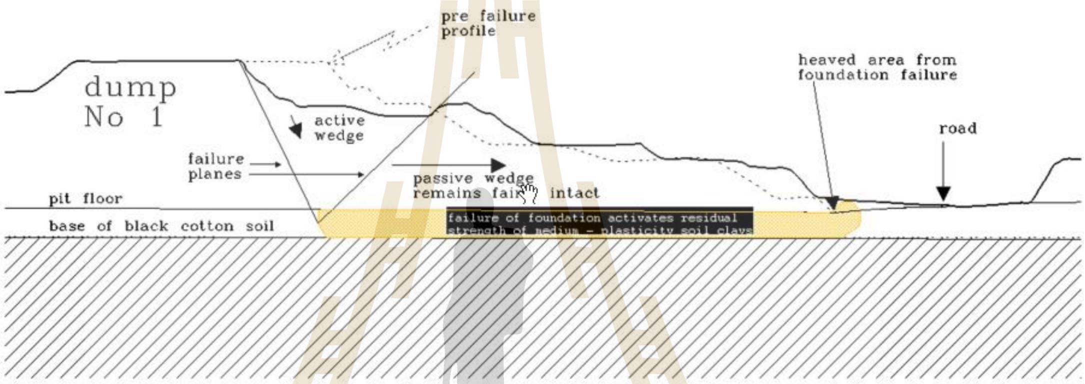


Figure 2.9 Failure mechanics of mine overburden dump in India (Poulsen et al., 2014)

Another case, the South Field Mine (SFM) in Northern Greece was claimed to fail in 2004 (Steiakakis et al., 2009). An enormous failure took action in the center of the waste dump (Figure 2.10 and Figure 2.11). A volume of 40,000,000 m^3 of soil was involved in mobilization as well as 2,500,000 m^3 of soil flowed to a distance of 300 m from the toe of the deposit (Kavouridis, 2004). From geotechnical investigation, high excess pore water pressure of the waste material was generated, together with a soft clayed layer beneath the dump. As a consequence, the low shearing strength of dump soil settled vertically and translational progressive landslide along with a lower layer, showing the slip surface failure at the base.

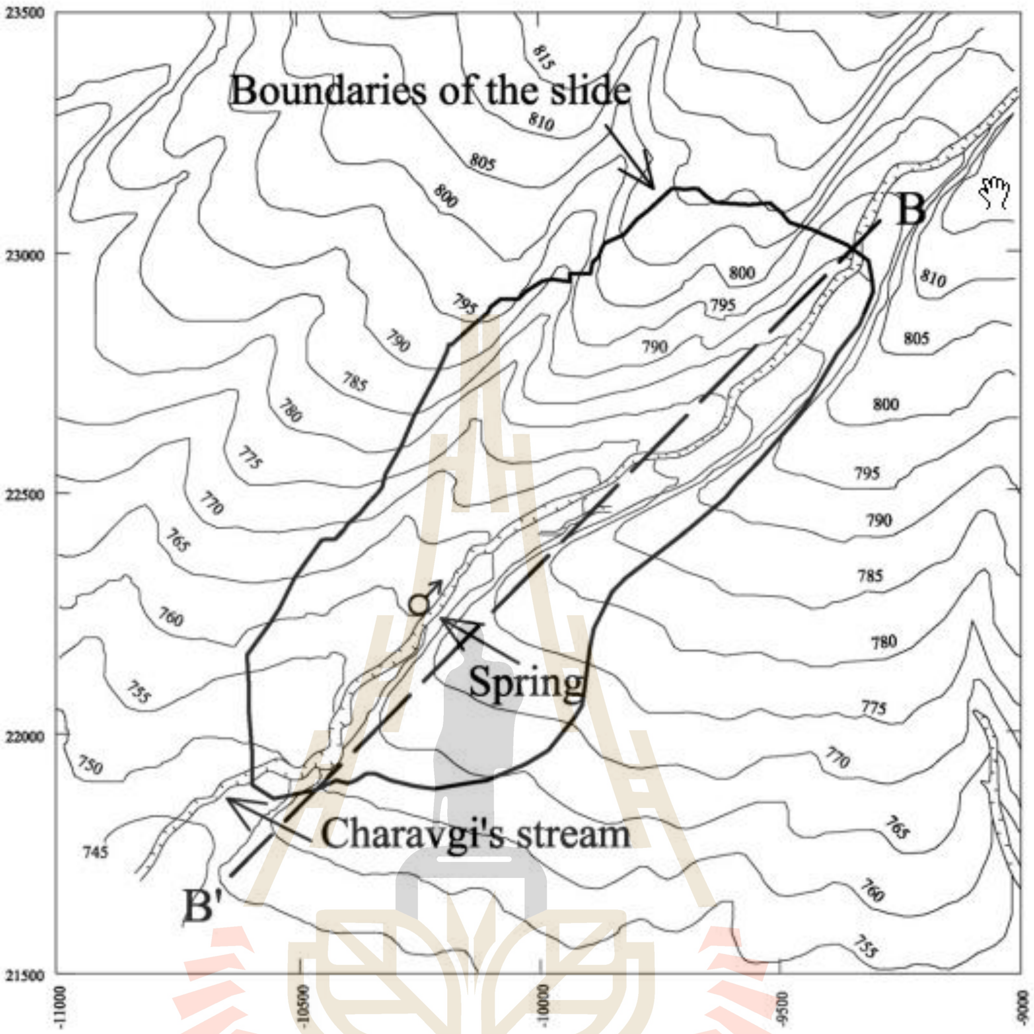


Figure 2.10 Schematic representation of South Field Mine (Steiakakis et al., 2009)

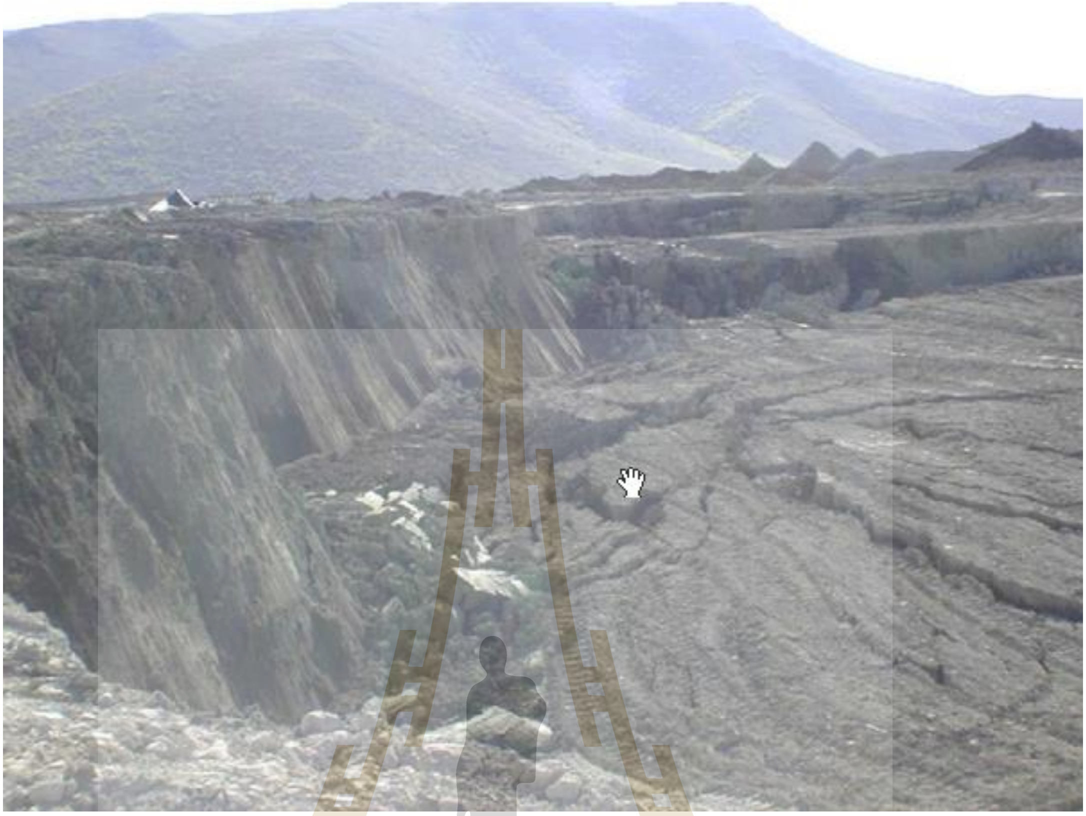


Figure 2.11 Main scarp of the dump failure (Steiakakis et al., 2009)

The Central Pit coal mine in Turkey, a large-scale spoil pile failure was published by (Kasmer et al., 2006). The overall area of 0.3 km^2 took place in 2001 (Figure 2.12). Observing from field investigation, several cracks occurred at the crest before the failure event, and the toe of a slope moved horizontally. It was concluded that the destruction was initiated as a result of the lowering shear strength of soil at the base of the dump and settlement at the crest of spoil due wetting process.

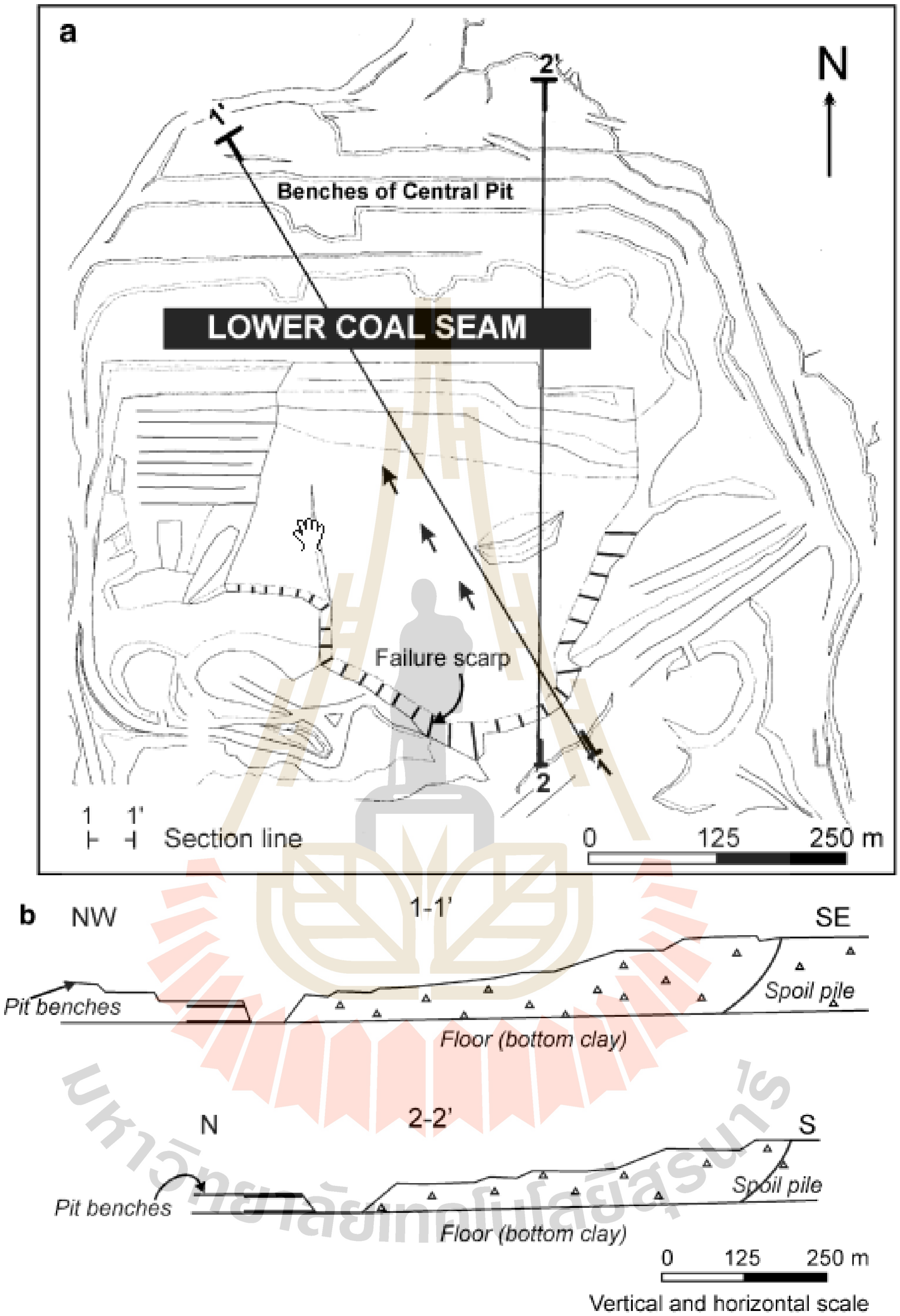


Figure 2.12 Schematic representation of Central Pit coal mine, Turkey

(a) A plan view of Central Pit and

(b) Typical cross-section of dump (Kasmer et al., 2006)

A comprehensive in-situ work was carried out to investigate the catastrophic landslide of a waste dump in 2015, in Shenzhen, China (Figure 2.13 and Figure 2.14).

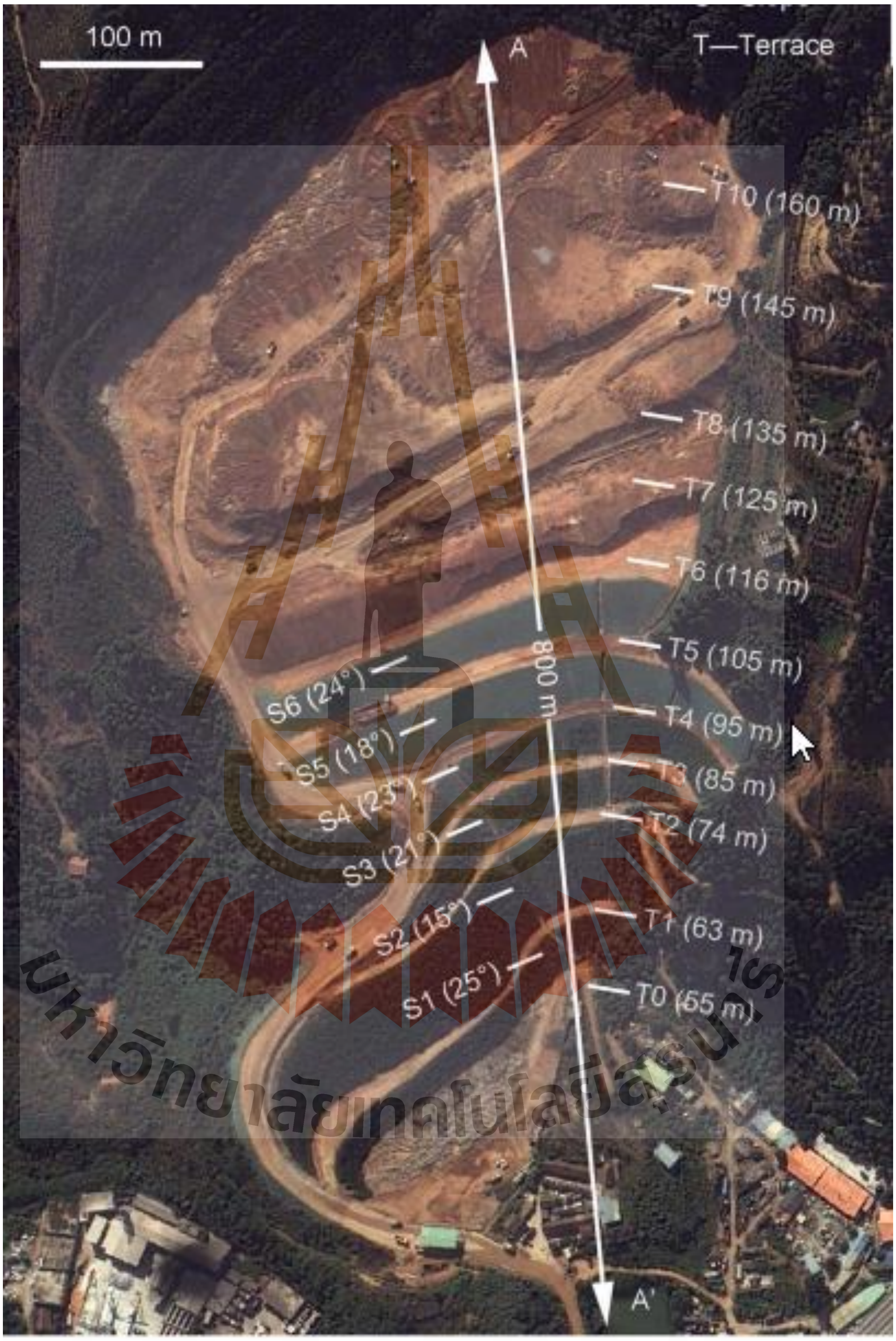


Figure 2.13 Aerial view of the 2015 Shenzhen landslide (Zhan et al., 2018)

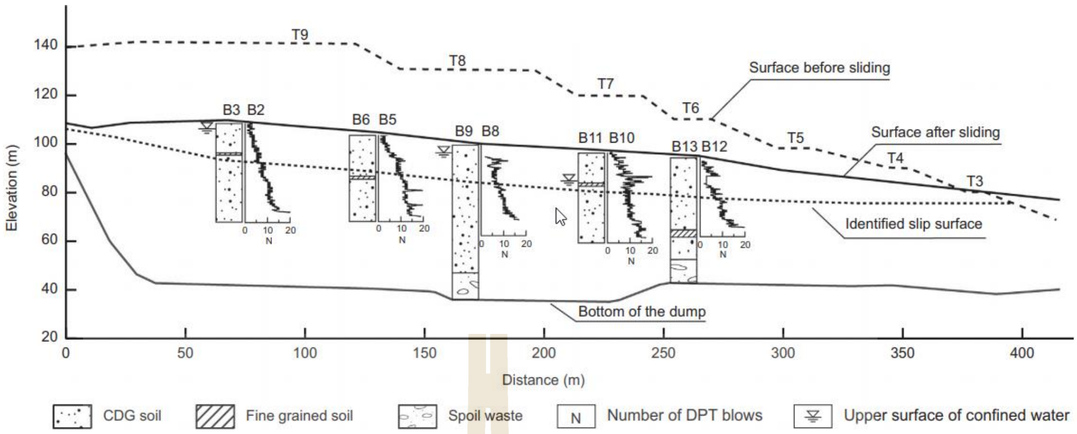


Figure 2.14 Cross-section of the 2015 Shenzhen landslide (Zhan et al., 2018)

The deep-seat translational failure of the 2015 Shenzhen landslide is an overall mass of 2,500,000 m^3, resulting in the loss of 77 lives and the demolishing of 33 blocks. It was a quarry mine before changing to a construction waste dump. The construction high of 110 m was completely finished in 22 months, with around 58,000,000 m^3 of loose-fill material. With high-speed deposited rate caused the development of excess pore water pressure in low-permeability material. A poor drainage system induced a higher groundwater table due to rainfall infiltration—low shear strength of waste material due to inadequate compaction.

2.3 References

Abramson, L. W., Lee, T. S., Sharma, S., & Boyce, G. M. (2001). Slope stability and stabilization methods: John Wiley & Sons.

Anagnostopoulos, A. (1979). The Mechanical Behaviour of the Megalopolis Lignites. Thesis presented to the National Technical University of Athens for the ...,

Bar, N., & Baczynski, N. (2017). Understanding and modelling a highly ductile 25+ years old active-passive landslide at Ok Tedi Mine in Papua New Guinea. Paper presented at the Workshop on World Landslide Forum.

Bishop, A. W. (1955). The use of the slip circle in the stability analysis of slopes. *Geotechnique, 5*(1), 7-17.

Bowles, J. E. (1979). Physical and geotechnical properties of soils.

Cheng, Y. M., & Lau, C. (2014). Slope stability analysis and stabilization: new methods and insight: CRC Press.

Clough, R. W., & Woodward III, R. J. (1967). Analysis of embankment stresses and deformations. *Journal of the Soil Mechanics and Foundations Division, 93*(4), 529-549.

Dassanayake, A., Phien-Wej, N., & Giao, P. (2016). Groundwater flow modeling and slope stability analysis for deepening of Mae Moh open pit lignite min. *Geotechnical Engineering Journal of the SEAGS and AGSSEA, 47*(3), 101-115.

Dawson, R., Morgenstern, N., & Stokes, A. (1998). Liquefaction flowslides in Rocky Mountain coal mine waste dumps. *Canadian Geotechnical Journal, 35*(2), 328-343.

Duncan, J., Buchignani, A., & DeWet, M. (1987). An engineering manual for slope stability studies. Department of Civil Engineering. *Geotechnical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA*.

Duncan, J., & Wright, S. (1980). The accuracy of equilibrium methods of slope stability analysis. *Engineering Geology, 16*(1-2), 5-17.

Duncan, J. M. (1996). State of the art: limit equilibrium and finite-element analysis of slopes. *Journal of Geotechnical engineering, 122*(7), 577-596.

Engineers, U. A. C. o. (1970). Engineering and design: Stability of earth and rock-fill dams. In: Dept. of the Army, Corps of Engineers Washington, DC.

Fellenius, W. (1927). Erdstatische Berechnungen. revised edition. *W. Ernst u. Sons, Berlin*.

Fellenius, W. (1936). Calculation of stability of earth dam. Paper presented at the Transactions. 2nd Congress Large Dams, Washington, DC, 1936.

Fredlund, D., & Krahn, J. (1977). Comparison of slope stability methods of analysis. *Canadian Geotechnical Journal, 14*(3), 429-439.

Igwe, O., & Chukwu, C. (2019). Slope stability analysis of mine waste dumps at a mine site in Southeastern Nigeria. *Bulletin of Engineering Geology and the Environment, 78*(4), 2503-2517.

Janbu, N. (1968). Slope stability computations, soil mechanics and foundation engineering report. *Technical University of Norway, Trondheim*.

Kainthola, A., Verma, D., Gupte, S., & Singh, T. (2011). A coal mine dump stability analysis—a case study. *Geomaterials, 1*(01), 1.

Kasmer, O., Ulusay, R., & Gokceoglu, C. (2006). Spoil pile instabilities with reference to a strip coal mine in Turkey: mechanisms and assessment of deformations. *Environmental geology, 49*(4), 570-585.

Kavouridis, K. (2004). Report of the General Management of Mines (PPC), on the interception and stabilization of the failure in the South Field Mine. *Unpublished technical report, in Greek*.

Kavvadas, M., Roumpos, C., & Schilizzi, P. (2020). Stability of Deep Excavation Slopes in Continuous Surface Lignite Mining Systems. *Geotechnical and Geological Engineering, 38*(1), 791-812.

Koner, R., & Chakravarty, D. (2016). Numerical analysis of rainfall effects in external overburden dump. *International Journal of Mining Science and Technology, 26*(5), 825-831.

Lavigne, F., Wassmer, P., Gomez, C., Davies, T. A., Hadmoko, D. S., Iskandarsyah, T. Y. W., . . . Heng, M. B. (2014). The 21 February 2005, catastrophic waste avalanche at Leuwigajah dumpsite, Bandung, Indonesia. *Geoenvironmental Disasters, 1*(1), 1-12.

Leonardos, M., & Terezopoulos, N. (2003). Rim slope failure mechanism in the Greek deep lignite mines–a case study. *Mining Technology, 112*(3), 197-204.

Lowe, J. (1960). Stability of earth dams upon drawdown. Paper presented at the Proc. 1st Pan American Conference on Soil Mechanics and Foundation Engineering, Mexico City, 1960.

Monopolis, D., Stiakakis, E., Agioutantis, E., & Kavouridis, C. (1999). Geotechnical investigation at lignite mines. *Mineral Resources Engineering, 8*(04), 405-418.

Morgenstern, N. u., & Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Geotechnique, 15*(1), 79-93.

Ngo, D. H., Horpibulsuk, S., Suddeepong, A., Hoy, M., Udomchai, A., Doncommul, P., . . . Arulrajah, A. (2020). Consolidation behavior of dredged ultra-soft soil improved with prefabricated vertical drain at the Mae Moh mine, Thailand. *Geotextiles and Geomembranes, 48*(4), 561-571.

Omraci, K., Merrien-Soukatchoff, V., Tisot, J.-P., Piguet, J.-P., & Nickel-SLN, L. (2003). Stability analysis of lateritic waste deposits. *Engineering Geology, 68*(3-4), 189-199.

Poulsen, B., Khanal, M., Rao, A. M., Adhikary, D., & Balusu, R. (2014). Mine overburden dump failure: a case study. *Geotechnical and Geological Engineering, 32*(2), 297-309.

Prountzopoulos, G., Fortsakis, P., Marinos, V., & Marinos, P. (2017). A large scale landslide in a coal mine in marly formations: Evaluation, analysis and rehabilitation. *ISSMGE International Journal of Geoengineering Case Histories, 4*(1), 29-45.

Punyawadee, V., Pothisuwan, R., Winichaikule, N., & Satienperakul, K. (2008). Costs and benefits of flue gas desulfurization for pollution control at the Mae Moh power plant, Thailand. *ASEAN Economic Bulletin*, 99-112.

Rajak, T. K., Yadu, L., Chouksey, S. K., & Dewangan, P. K. (2018). Stability analysis of mine overburden dump stabilized with fly ash. *International Journal of Geotechnical Engineering*, 1-11.

Richards, B., Coulthard, M., & Toh, C. (1981). Analysis of slope stability at Goonyella Mine. *Canadian Geotechnical Journal, 18*(2), 179-194.

Spencer, E. (1967). A method of analysis of the stability of embankments assuming parallel inter-slice forces. *Geotechnique, 17*(1), 11-26.

Steiakakis, E., Kavouridis, K., & Monopolis, D. (2009). Large scale failure of the external waste dump at the “South Field” lignite mine, Northern Greece. *Engineering Geology, 104*(3-4), 269-279.

Su, W., & Miller, H. (1995). Waste pile stability and debris flow formation. Paper presented at the The 35th US Symposium on Rock Mechanics (USRMS).

Taylor, D. W. (1937). Stability of earth slopes. *J. Boston Soc. Civil Engineers, 24*(3), 197-247.

Tzampoglou, P., & Loupasakis, C. (2018). Evaluating geological and geotechnical data for the study of land subsidence phenomena at the perimeter of the Amyntaio coalmine, Greece. *International Journal of Mining Science and Technology, 28*(4), 601-612.

Udomchai, A., Horpibulsuk, S., Suksiripattanapong, C., Mavong, N., Rachan, R., & Arulrajah, A. (2017). Performance of the bearing reinforcement earth wall as a retaining structure in the Mae Moh mine, Thailand. *Geotextiles and Geomembranes, 45*(4), 350-360.

Vassilis, M., Theodoros, T., Spyridon, P., Panagiotis, T., Alexandros, C., & Konstantinos, V. (2015). Large Induced Displacements and Slides Around an Open Pit Lignite Mine, Ptolemais Basin, Northern Greece. In *Engineering Geology for Society and Territory-Volume 2* (pp. 311-315): Springer.

Wang, Y.-k., Sun, S.-w., & Liu, L. (2019). Mechanism, Stability and Remediation of a Large Scale External Waste Dump in China. *Geotechnical and Geological Engineering, 37*(6), 5147-5166.

Whitlow, R. (1990). *Basic soil mechanics*.

Yin, Y., Li, B., Wang, W., Zhan, L., Xue, Q., Gao, Y., . . . Li, A. (2016). Mechanism of the December 2015 catastrophic landslide at the Shenzhen landfill and controlling geotechnical risks of urbanization. *Engineering, 2*(2), 230-249.

Zarlin, N., Sasaoka, T., Shimada, H., & Matsui, K. (2012). Numerical study on an applicable underground mining method for soft extra-thick coal seams in Thailand.

Zevgolis, I. E., Deliveris, A. V., & Koukouzas, N. C. (2019). Slope failure incidents and other stability concerns in surface lignite mines in Greece. *Journal of Sustainable Mining, 18*(4), 182-197.

Zhan, L.-t., Zhang, Z., Chen, Y.-m., Chen, R., Zhang, S., Liu, J., & Li, A.-g. (2018). The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. *Engineering Geology, 238*, 15-26.

CHAPTER III

INVESTIGATION OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND

3.1 Description of the waste dump slope failure

The Mae Moh Mine is situated in the Mae Moh district of Lampang province, Thailand, as illustrated in Figure 1.1, within the Mae Moh tertiary basin characterized by a thickness exceeding one thousand meters. Geological investigations in the Mae Moh basin have identified three primary categories of formations—Na Kheam, Huai King, and Huai Luang, as detailed by (Songtham et al., 2005; Touch et al., 2015; Zarlin et al., 2012). The Na Kheam formation, distinguished as the principal lignite-bearing formation, exhibits a thickness ranging from 250 to 400 meters, predominantly comprised of lignite seams, and interposed with gray to greenish-gray claystone and mudstone. The Huai King formation encompasses a fluvial sequence, comprising semi-consolidated fine to coarse sandstone, claystone, mudstone, and conglomerate, presenting various colors (green, yellow, blue, and purple) and variable thicknesses ranging from 15 to 150 meters. The Huai Luang formation, the youngest tertiary formation, includes red to brownish-red semi-consolidated and unconsolidated claystone, siltstone, and sandstone, with thicknesses spanning from 5 to 350 meters, as depicted in Figure 3.1. The materials extracted from the mine surface were subsequently conveyed to the west dumpsite through the use of a belt conveyor, facilitating the creation of the initial terrace on a slope, as depicted in Figure 3.2.

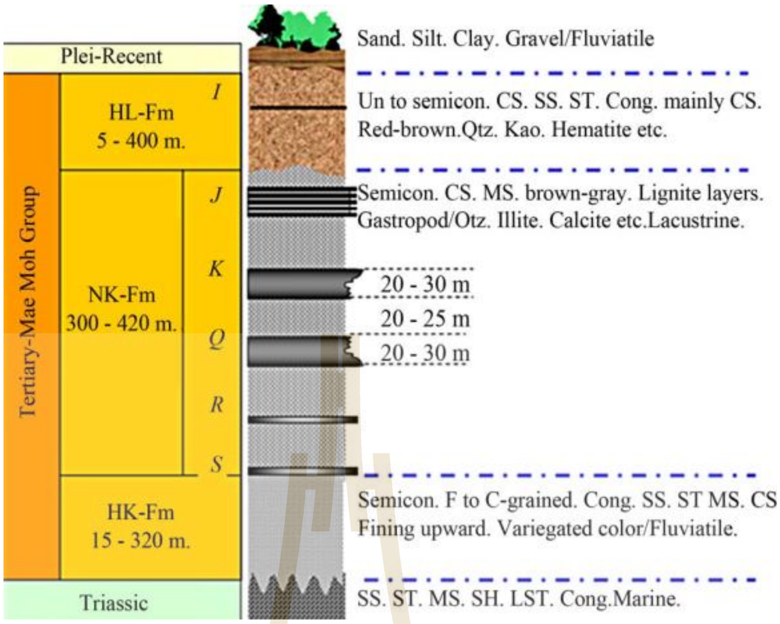


Figure 3.1 Generalized stratigraphic column

Figure 3.2 Log of surface soil borehole

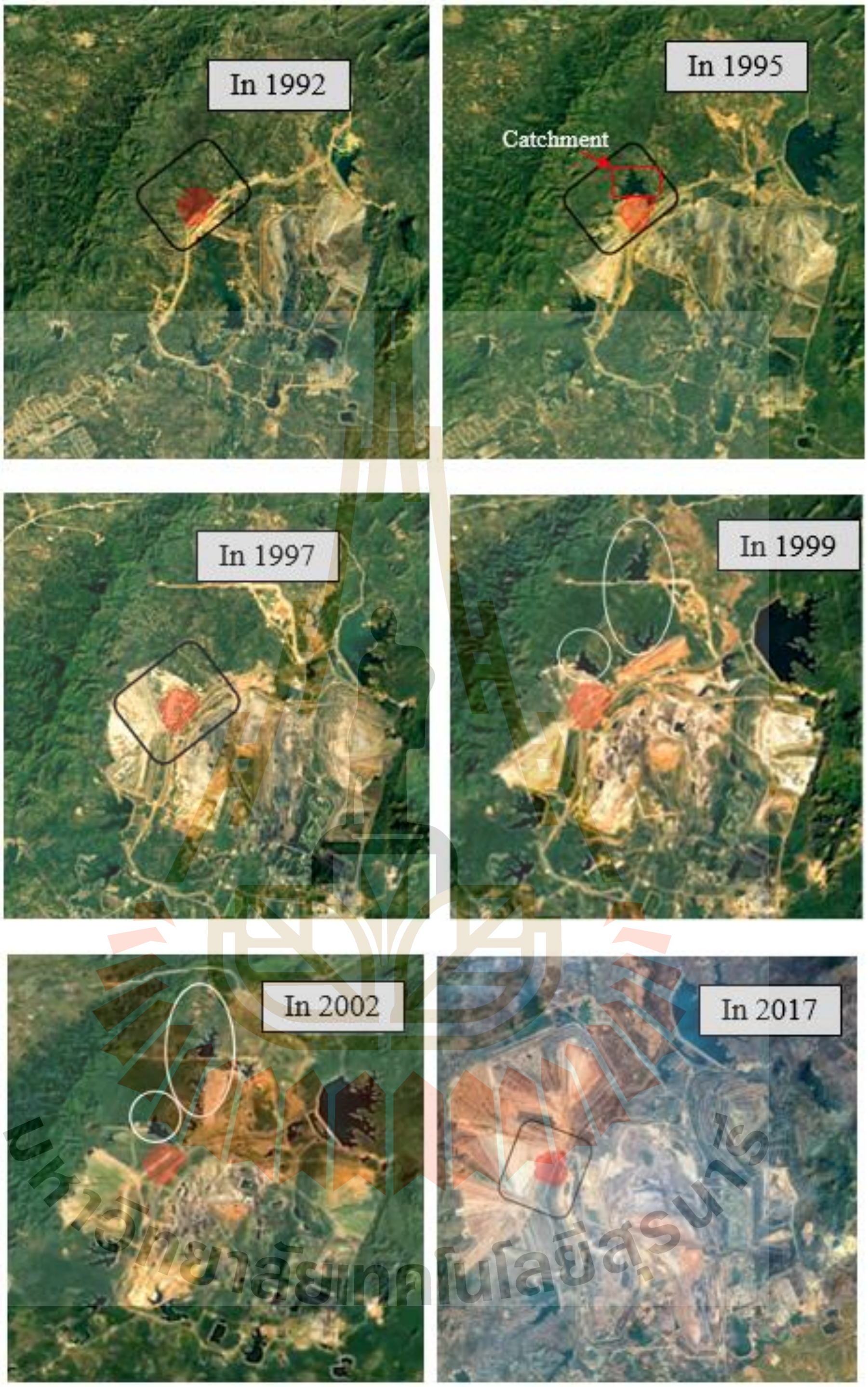
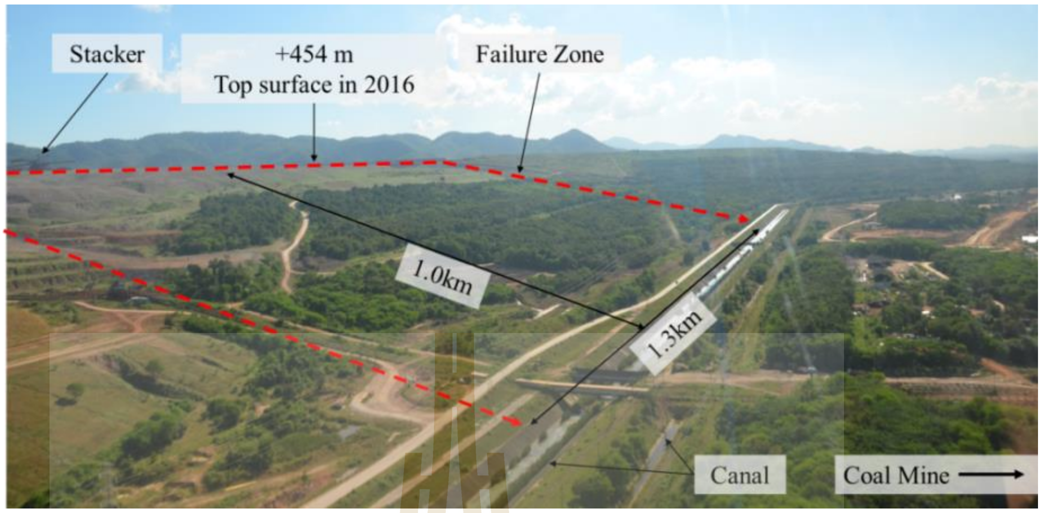


Figure 3.3 Changes in the topography of the study areas from 1992 to 2017

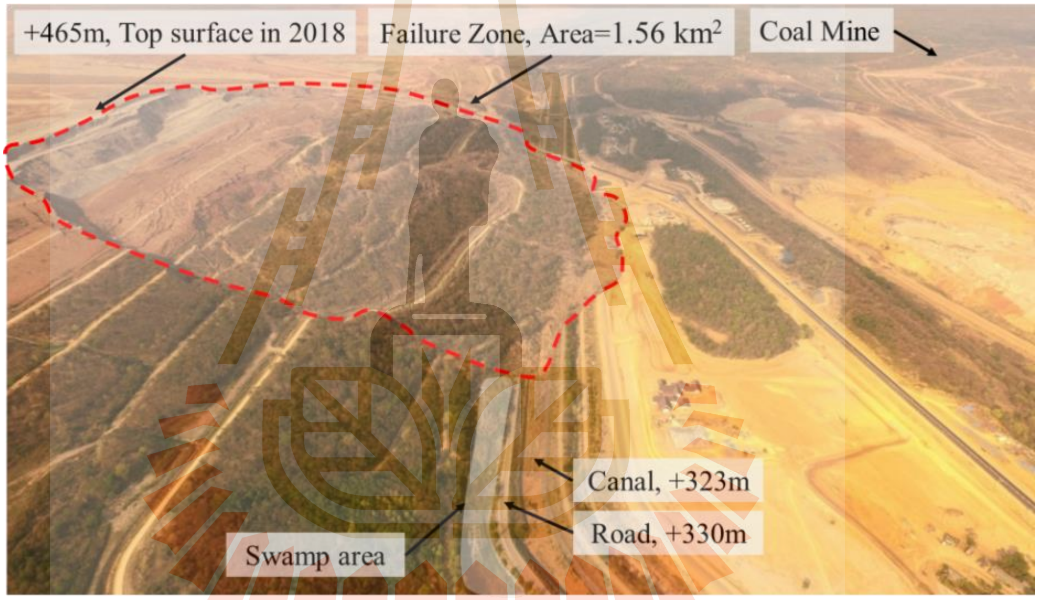
Figure 3.3 delineates the progression of surface topography at the waste dumpsite between 1992 and 2017. A substantial disposal of coal mining wastes, originating from mineral resource extraction and processing, was extensively directed to the West Dumpsite. The initially planned elevation for the waste dump materials ranged from 330 m MSL to 590 m MSL, with a designed height of 260 m. Vegetation, in the form of trees and shrubs, was intentionally introduced on the slope of the terrace surface.

The disposal procedure commenced with the initial deposition of coal waste materials into the swamp area at the dump site. Subsequent continuous dumping into existing rivers and natural ponds resulted in the elevation of the catchment from +326m MSL to approximately +340m MSL by 1995. Over the years, the spatial extent of waste material deposition expanded, ultimately encompassing the catchments until the conclusion of the observation period in 2017.

Initially characterized by a granular composition exhibiting a relatively high effective friction angle, the waste dump materials underwent substantial degradation during wetting and drying cycles associated with seasonal variations. This deterioration rendered the material easily breakable by hand and prone to slaking, transforming into fine clay particles with relatively high voids. Consequently, the overall waste dump material transitioned into a loosely compacted clay, devoid of a distinct peak strength, after several years of deposition. The initial dump materials in the swamp were anticipated to undergo significant slaking, resulting in the formation of a weak clay layer above a hard foundation.



(a)



(b)

Figure 3.4 The Unmanned Aerial Vehicles (UAVs) images of the waste dump area:

(a) captured before the failure in November 2016 and

(b) captured after the failure in March 2018.

On March 18, 2018, the waste dumpsite experienced a collapse characterized by rotational slumping at the crest and the translation of a mass at its toe in a spreading manner. This failure of the waste dump slope covered an area of approximately 1.56 km2, occurring when the waste dumping reached an elevation of +465 m MSL, representing a height of approximately 135 m measured from the initial dump elevation of +330 m MSL. Figure 3.4(a-b) presents aerial views of the waste dump area before and after the catastrophic waste dump slope failure, captured using the Unmanned Aerial Vehicles (UAV) technique.

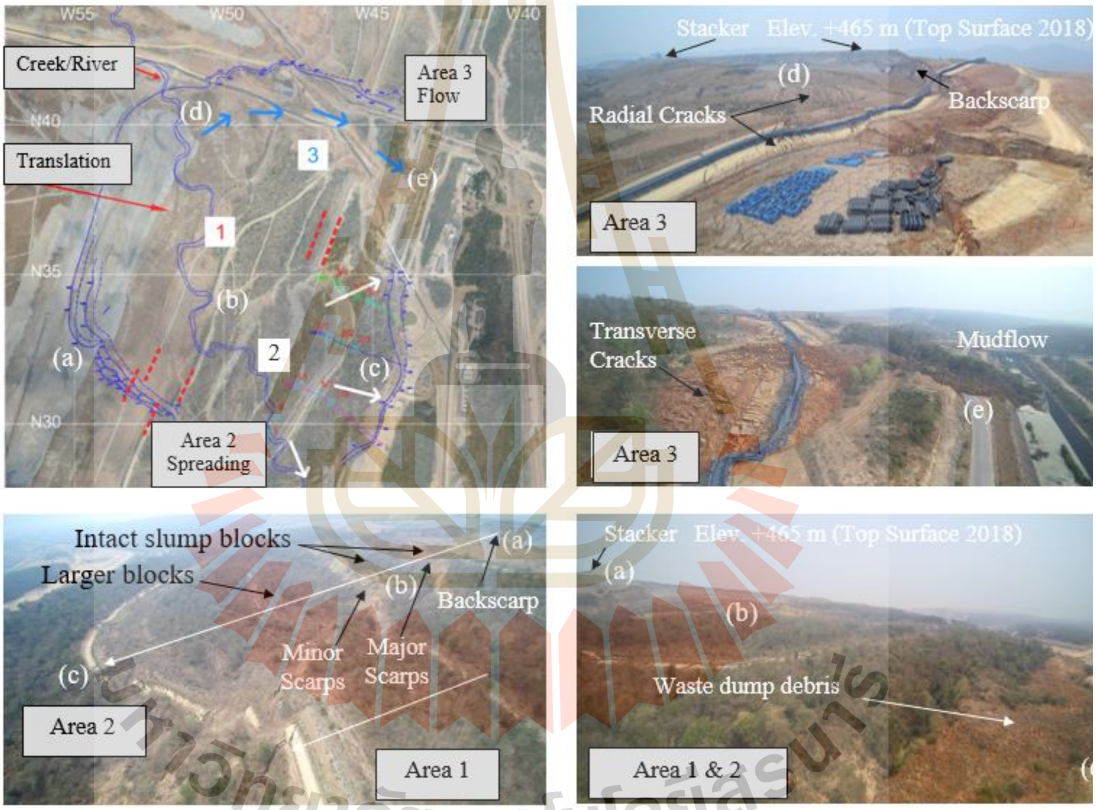


Figure 3.5 Development of the West waste dump collapsed in the failure

Figure 3.5 delineates the failure zone, partitioned into three distinct areas denoted as Areas 1, 2, and 3. Areas 1 and 2 represent the principal bodies of failure. In Area 1, the failure exhibited cohesiveness and underwent lateral translation sliding, slipping approximately 50 to 70 m. Conversely, Area 2 experienced rotational sliding and spreading over a distance of roughly 200 to 300 m, displaying indications of mudflow at the deposit's toe. The major and minor scarps, measuring approximately 45 m and 25 m in height at the top and central region of the failure zone, respectively, were observed. The crest of the slope demonstrated vertical slumping between the back scarp and prominent scarp (active wedge), while the larger spreading blocks constituted the passive wedge. The observed phenomenon was classified as a deep-seated multi-wedge failure mechanism, as documented by (Poulsen et al., 2014; Simmons & McManus, 2004). In Area 3, the initial failure occurred at the top, characterized by an immediate movement collapse following the landslide's body, subsequently flowing toward the toe of the slope. Numerous transverse and radial cracks were identified at the first and second benches.

3.2 Geophysical and geotechnical investigation

Thorough geophysical and geotechnical investigations were undertaken to delineate the characteristics of the waste dump. The utilization of electrical resistivity tomography, an advanced geophysical technique, involved the systematic arrangement of electrodes to measure changes in electrical resistivity properties. The recorded variations consistently correlated with alterations in lithology, water saturation, fluid conductivity, porosity, and permeability. This dataset facilitated the mapping of stratigraphic units, geotechnical structures, fractures, and groundwater within the waste dump.

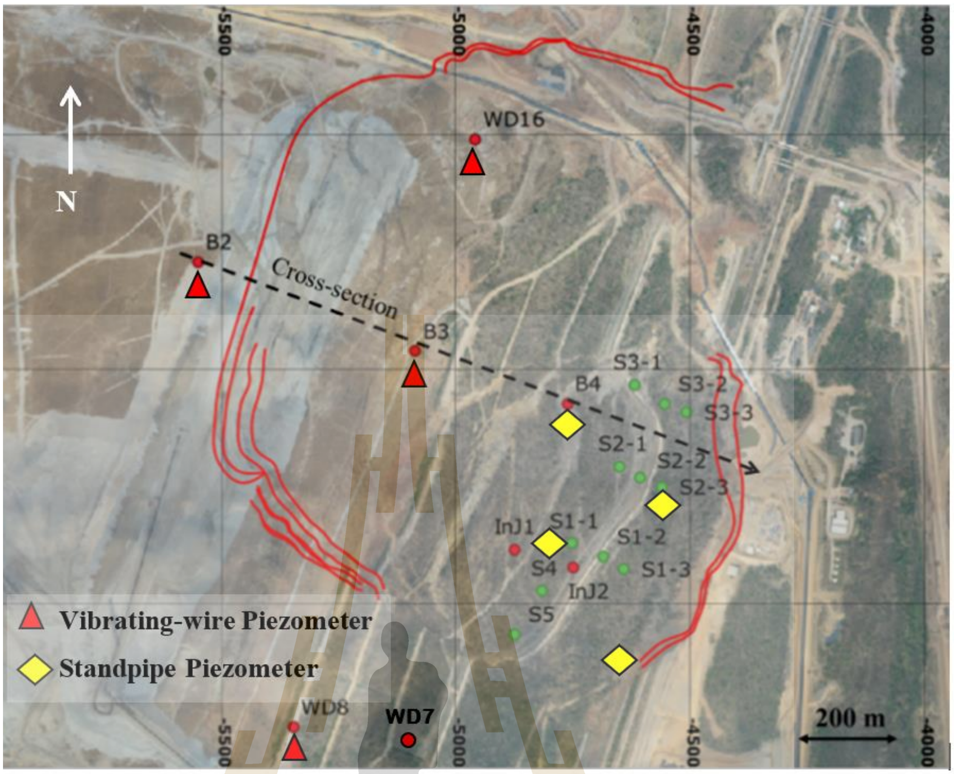


Figure 3.6 The locations of boring logs and piezometers monitoring

Within the landslide zone, a comprehensive geotechnical investigation was conducted, incorporating remote sensing applications, field monitoring, boring logs, and geotechnical laboratory tests. The primary objective was to characterize water table conditions within the waste mass and ascertain key materials engineering parameters. Following the waste dump failure incident, a total of 19 borehole tests were executed within the failure zone, as illustrated in Figure 3.6. Approximately one month after the waste dumpsite failure, 11 borehole tests (designated as S1 to S5) were carried out at the toe of the slope. In March 2019, two additional boreholes (InJ1 and InJ2) were specifically drilled to investigate the failure plane between the waste dump materials and the existing original ground. Further borehole tests were conducted in January 2020, including two boreholes (WD7 and WD8) located next to the south boundary of the failure zone, and one borehole (B2) near the top elevation of the waste dump. Additionally, Boreholes B3 and B4 were positioned in the middle of the failure zone, and Borehole WD16 (next to the north boundary of the failure zone) was tested in June and August of 2020.

In addition to borehole tests, vibrating-wire, and standpipe piezometers were strategically installed and monitored at locations depicted in Figure 3.6 to observe water table fluctuations and pore-water pressure. Utilizing a cement-bentonite grout mixture proved to be a reliable method for measuring pore-water pressure, given its capability to provide readings with a notable time lag. This approach, well-documented in projects of a similar nature, exemplifies our commitment to precision and reliability in gathering essential data for a thorough understanding of the site conditions (Mikkelsen & Green, 2003; Wan & Standing, 2014).

Figure 3.7 provides a cross-sectional view (a-a) of the slope profile of the waste dumpsite, as indicated in Figure 3.6. The dashed black line and the solid red line delineate the pre-failure and post-failure slope profiles of the waste dumpsite, respectively, with the original ground approximately at an elevation of +330 m MSL. The dashed blue lines represent the water levels obtained from piezometer monitoring. Upon scrutiny of the slope profiles before and after the failure, it becomes evident that the principal slumping block underwent vertical movement at the highest elevation (+465 m MSL in 2018), acting as an active wedge. This vertical movement was succeeded by horizontal translation, functioning as a passive wedge, with the resulting debris spreading toward the toe of the waste dump area.

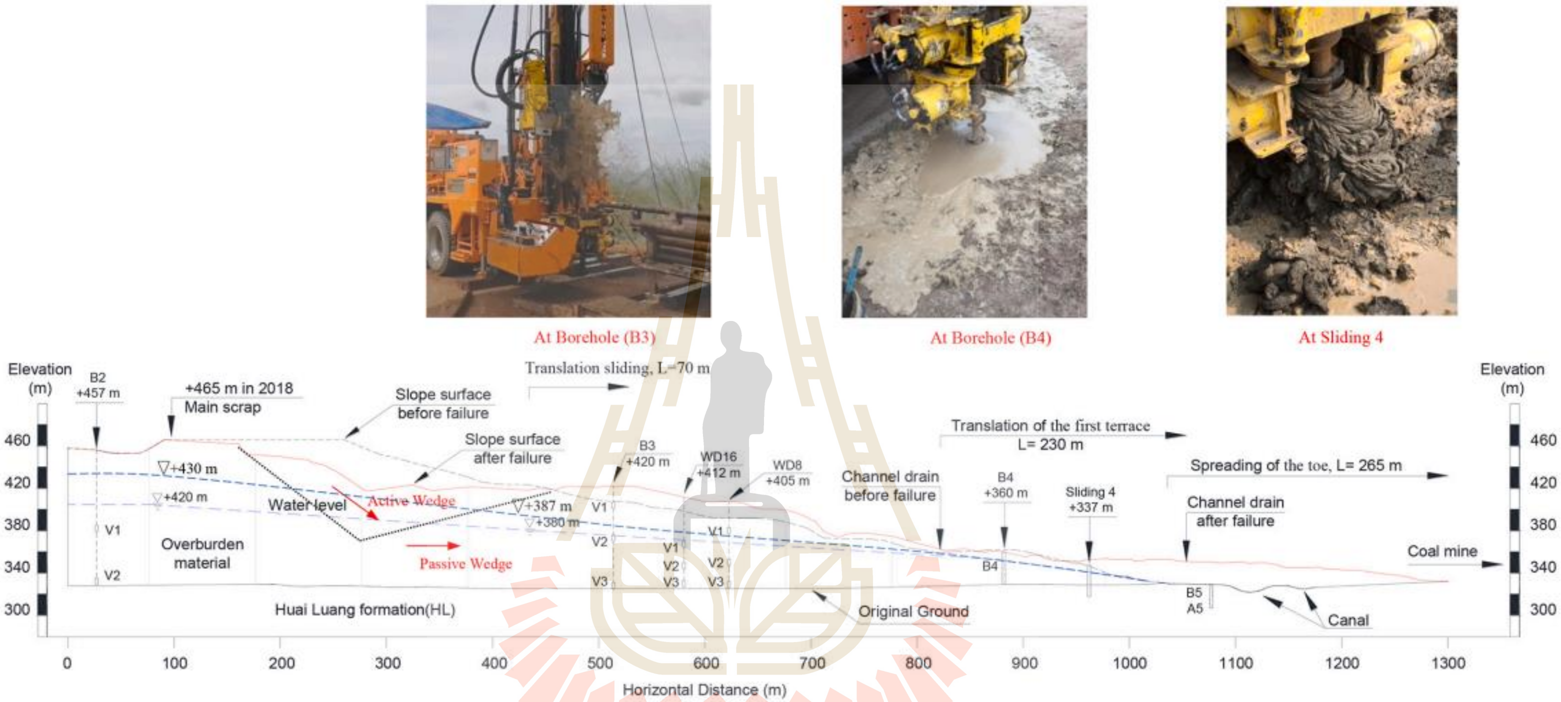


Figure 3.7 The topographic configuration of the waste dump's slope

The waste dump materials encountered at Borehole B2 primarily comprised fragments of claystone, classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Additionally, a weak clay layer, with a depth of approximately 3 m, was identified above the existing original ground level at an elevation of +331 m MSL. In the case of Borehole B3, a significant outflow of water within the deposit was observed during the drilling process. This water discharge persisted for approximately 3 hours, starting at a depth of 82 m from the top evaluation at +420 m MSL, and roughly 10 m above the existing ground level (elevation of +331 m MSL).

This phenomenon may be attributed to elevated excess pore water pressure, recognized as a primary factor instigating landslide failures (Ouyang et al., 2017; Wang & Sassa, 2003). The topsoil profile at Borehole B4, characterized by a top elevation of +360 m MSL and a thickness of about 5 m, is predominantly comprised of claystone. Below this topsoil, during the drilling process, medium clay was encountered at a depth of approximately 10 to 15 m. Additionally, about 2 m of weak clay was identified above the existing ground level.

Significantly, the medium clay and weak clay were situated within an existing swamp area, as depicted in the topography evolution of the waste dumpsite (Figure 3.3). A typical soil profile at the toe of the waste dumpsite, derived from a series of boring logs (Borehole S2-1, S2-2, and S2-3), revealed that the overburdened materials, approximately 10 m in thickness, consisted of relatively moist claystone. The underlying layer comprised clayey soils, spanning approximately 10 to 12 m in thickness. Additionally, layers of weak material (swamp clay), measuring about 3 to 5 m, were identified above the original ground foundation at elevations ranging from approximately +325 m to +327 m MSL.

The vibrating-wire piezometer boreholes (B2, B3, WD16, and WD8) were meticulously backfilled with cement-bentonite grout. The strategic placement of piezometers at various locations and depths is depicted in Figure 3.7, where the nomenclature for vibrating-wire piezometers adheres to the format B-V. Here, B denotes the borehole name, and V signifies the position of the vibrating-wire piezoelectric sensor, exemplified by designations such as B2-V2, B3-V3, WD16-V3, and

WD8-V3. Figure 3.8 provides an illustration of the observed pore water pressure from the piezometers at different locations. Over a year of observation, water levels exhibited negligible fluctuations. Pore-water pressure monitoring at B2-V2, B3-V3, WD16-V3, and WD8-V3, positioned proximately to the original ground level, revealed that the pressures within the failure zone (B3-V3 and WD16-V3) exceeded those outside the failure zone (WD8-V3).

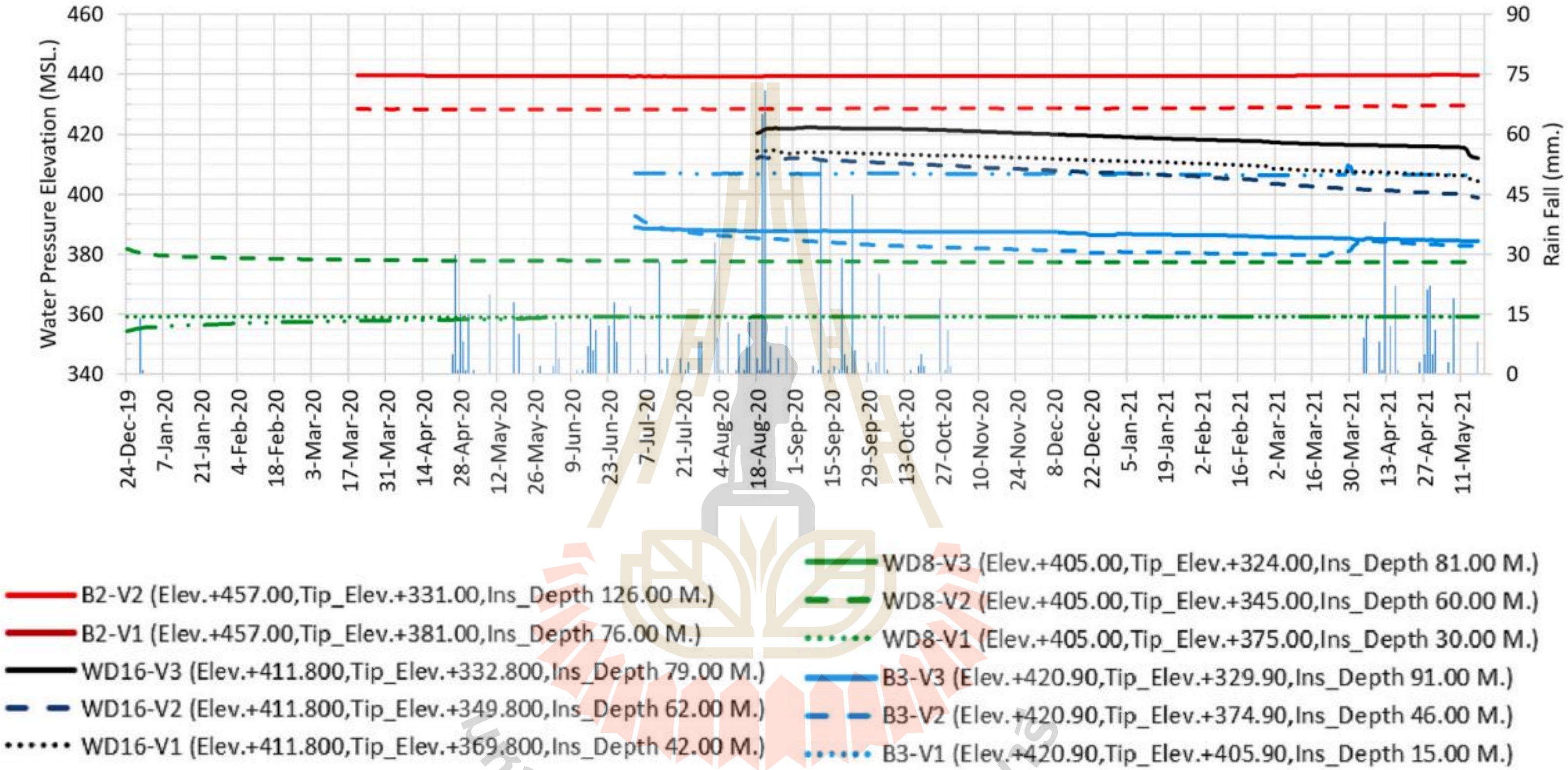


Figure 3.8 The measured water pressure elevation monitored from piezometers

3.3 Electrical resistivity tomography (ERT) method

In pursuit of a comprehensive understanding of subsurface conditions within the waste dumpsite, the electrical resistivity tomography (ERT) technique was systematically employed alongside geophysical and geotechnical investigations. ERT serves as a geophysical imaging method designed to assess the electrical resistivity of subsurface materials. Leveraging the principle that different materials exhibit unique electrical resistivities, this technique provides valuable insights into the subsurface condition. Its versatile applications extend to mineral exploration, groundwater monitoring, and geotechnical engineering, as evidenced by studies (Al-Fares & Al-Hilal, 2018; Suzuki et al., 2000; Thompson et al., 2012).

The ERT technique involves the controlled injection of an electrical current into the ground via a specific pair of electrodes, while simultaneously measuring the resulting voltage across another designated pair of electrodes. Systematic variations in electrode positions and current direction are implemented to capture multiple measurements at various points and depths beneath the surface. Adhering to Ohm's law, the measured voltage values are then converted into apparent resistivity values for the ground segment situated between the two electrodes. Utilizing input current, measured voltage, and array geometry, a resistivity model of the subsurface (pseudo-section) is meticulously generated (Edwards, 1977). The resultant image depicting subsurface ground resistivity is subject to interpretation to discern variations in soil or rock properties.

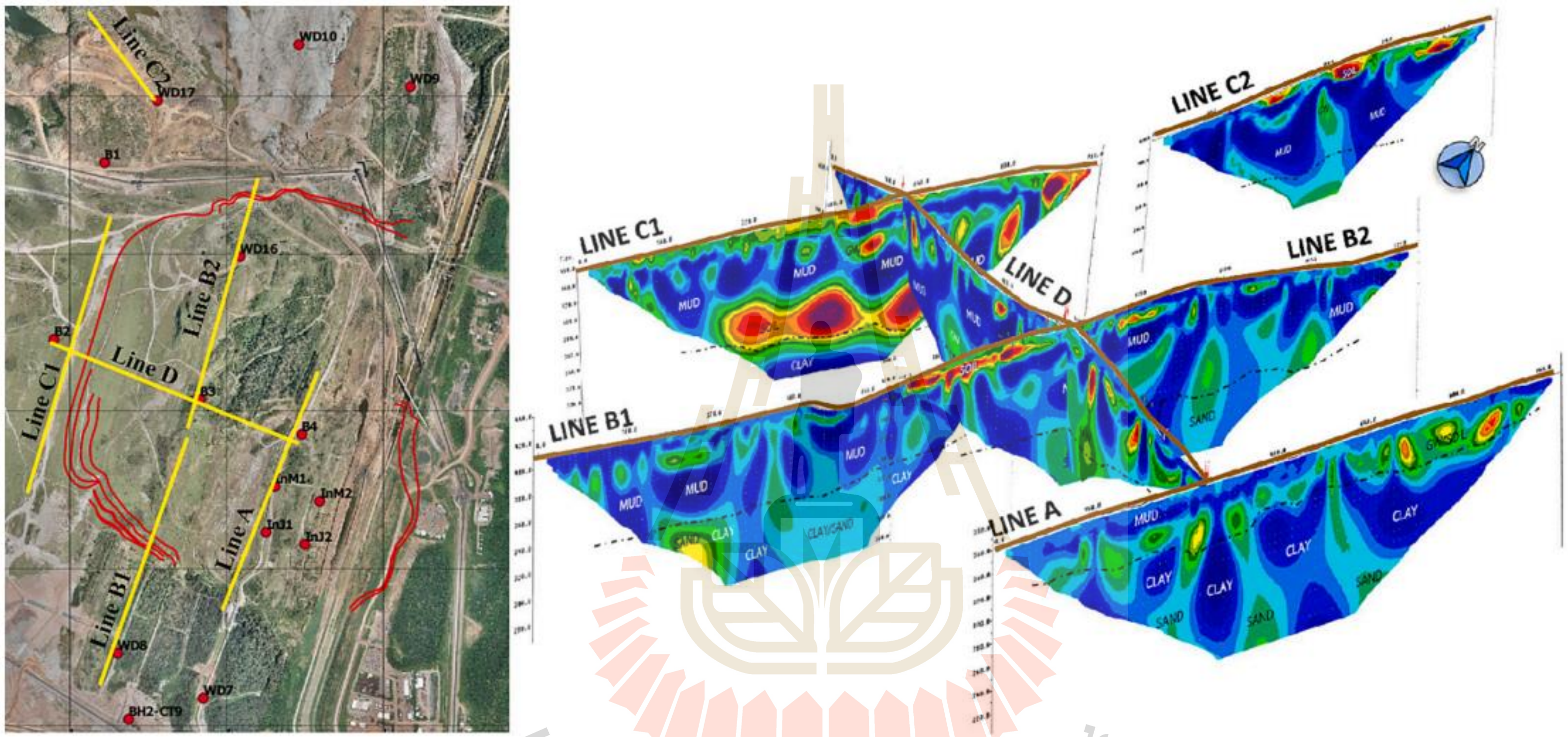


Figure 3.9 The positions of the electrical resistivity tomography (ERT) profiles within this investigation

Within the scope of this study, four Electrical Resistivity Tomography (ERT) profiles (LINE A, LINE B1, LINE B2, and LINE D) situated within the collapsed zone and two additional ERT profiles (LINE C1 and LINE C2) in proximity to the failure zone were systematically examined, as illustrated in Figure 3.9. These ERT profiles were strategically positioned to intersect the specified boring logs outlined in Figure 3.6, offering a comprehensive understanding of the soil profiles. The recorded resistivity values spanned from 2 to 40 Ohm.m (Ωm). Based on these resistivity values, the subsurface materials were systematically classified into three distinct groups: clay and silt materials (2 – 8 Ωm), clayey-sand materials (12.5 – 17.5 Ωm), and sandstone or lignite materials (23 – 40 Ωm). (Al-Fares & Al-Hilal, 2018; Pasierb et al., 2019; Porras et al., 2022).

Figure 3.10 specifically illustrates the ERT profile for cross-section Line C1, providing insights into the inhomogeneous nature of the waste dump materials. The resistivity values, calibrated with soil properties at boring log B2, offered a comprehensive understanding of the subsurface properties and groundwater level within the elevation range of +342.02 m MSL to the existing ground elevation of +330 m MSL. In this segment, resistivity values spanning from 12.5 to 17.5 Ωm indicated clayey-sand materials, while the detected water table at approximately elevation +440 m MSL, in alignment with piezometer analysis, was identified as a perched water table, situated within the waste material and surpassing the ground surface.

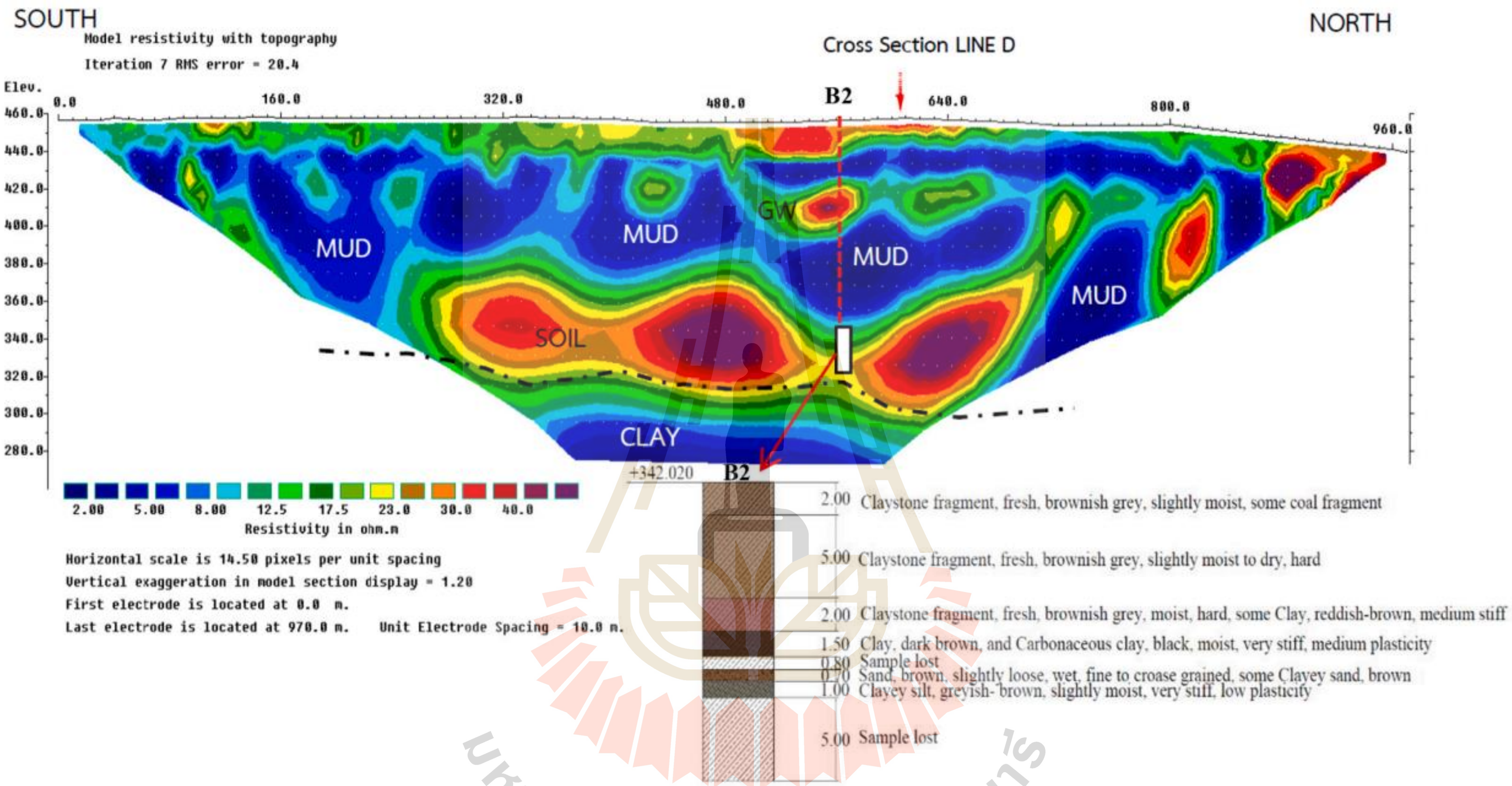


Figure 3.10 Cross-sectional Line C1 ERT profile

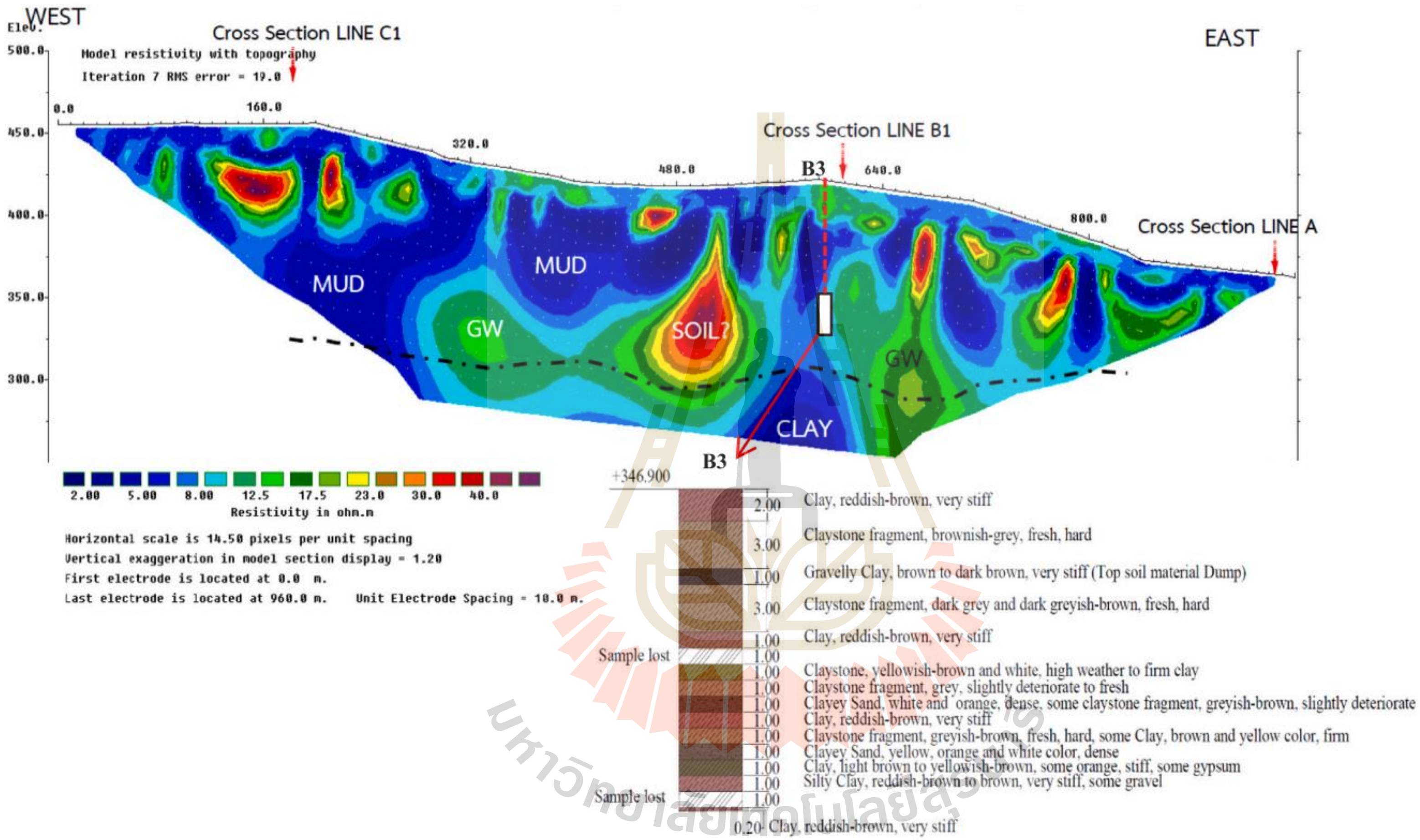


Figure 3.11 Cross-sectional Line D ERT profile

The resistivity values along the longitudinal cross-section of the failure zone, depicted in Figure 11 (Line D), illustrate the gradual descent of the perched water table from the highest elevation (WEST) to the lowest elevation (EAST). Examining the resistivity values within the elevation range of +346.9 m MSL to the existing ground elevation +330 m MSL, corresponding to the soil profile from boring log B3, revealed a range of 5 to 10 Ωm. This range indicated the presence of clay materials with high moisture content, aligning with the soil properties identified in the boring log. The consistency between resistivity values and soil properties reinforces the characterization of clay materials with elevated moisture content.

Figure 3.12 portrays the ERT profile of the transverse cross-section Line A, situated at the lower part of the slope within the failure zone. The resistivity values in this profile were compared with soil profiles from boring logs B4, In J1, and In M1. The results exhibit agreement, confirming the presence of silty clay materials with high moisture content, as identified through both ERT and boring log analyses. Despite the inhomogeneous nature of waste dump materials with varying moisture contents, to simplify the analysis of the failure caused using the finite element method, the materials were assumed to be homogeneous, as illustrated in Figure 3.6.

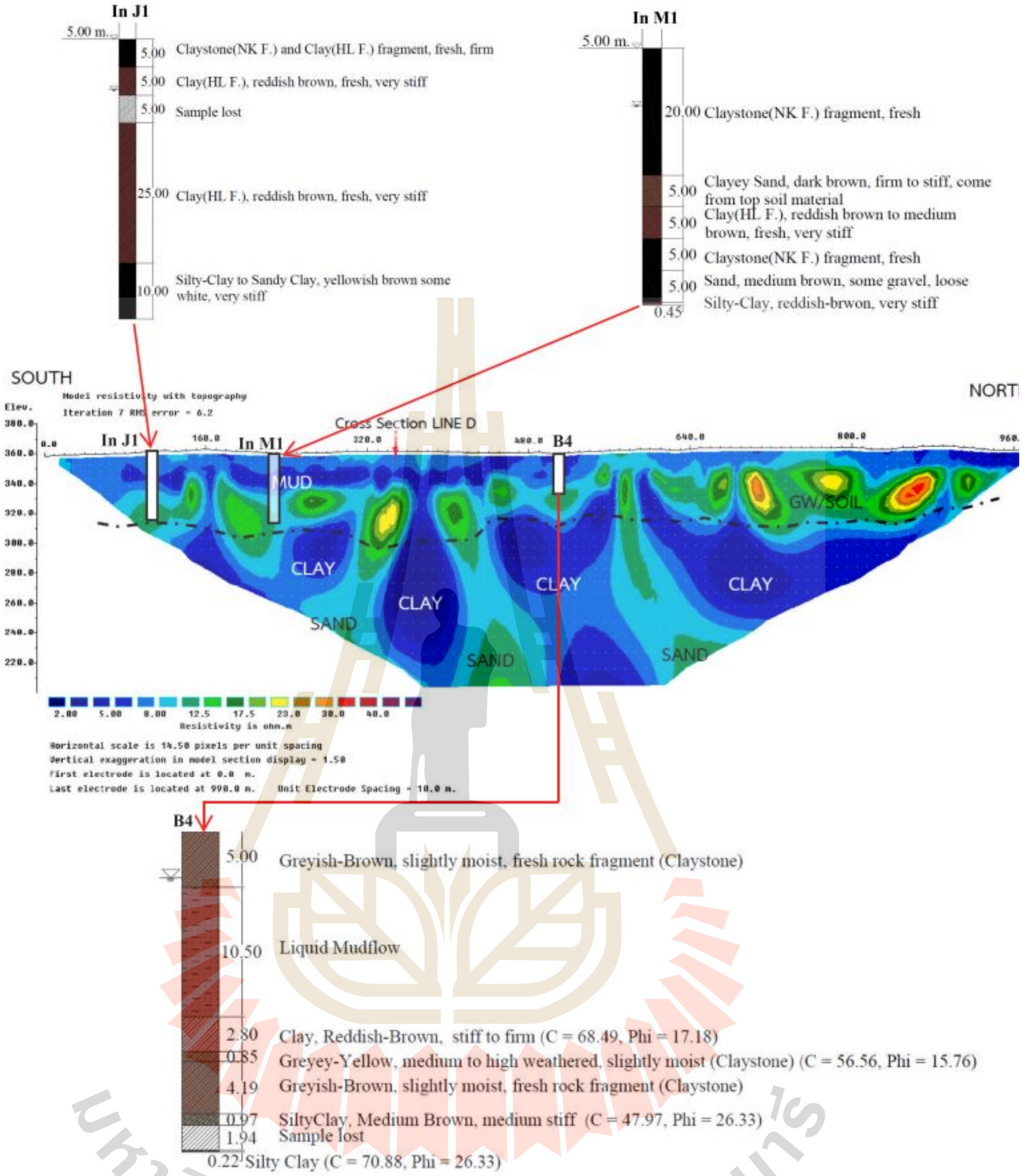


Figure 3.12 Cross-sectional Line A ERT profile

3.4 Reference

Abramson, L. W., Lee, T. S., Sharma, S., & Boyce, G. M. (2001). Slope stability and stabilization methods. John Wiley & Sons.

Al-Fares, W., & Al-Hilal, M. (2018). Integration of electrical resistivity tomography with electromagnetic and soil radon measurements for characterizing the leakage problem in Afamia B dam, Syria. Geofísica internacional, 57(4), 275-287.

Bowles, J. E. (1979). Physical and geotechnical properties of soils.

Cheng, Y. M., & Lau, C. (2014). Slope stability analysis and stabilization: new methods and insight. CRC Press.

Clough, R. W., & Woodward III, R. J. (1967). Analysis of embankment stresses and deformations. Journal of the Soil Mechanics and Foundations Division, 93(4), 529-549.

Dawson, R., Morgenstern, N., & Stokes, A. (1998). Liquefaction flowslides in Rocky Mountain coal mine waste dumps. Canadian Geotechnical Journal, 35(2), 328-343.

Duncan, J., Buchignani, A., & DeWet, M. (1987). An engineering manual for slope stability studies. Department of Civil Engineering. Geotechnical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Duncan, J. M. (1996). State of the art: limit equilibrium and finite-element analysis of slopes. Journal of Geotechnical engineering, 122(7), 577-596.

Edwards, L. (1977). A modified pseudosection for resistivity and IP. Geophysics, 42(5), 1020-1036.

Engineers, U. A. C. o. (1970). Engineering and design: Stability of earth and rock-fill dams. In: Dept. of the Army, Corps of Engineers Washington, DC.

Fellenius, W. (1927). Erdstatische Berechnungen. revised edition. W. Ernst u. Sons, Berlin.

Fellenius, W. (1936). Calculation of stability of earth dam. Transactions. 2nd Congress Large Dams, Washington, DC, 1936,

Fredlund, D., & Krahn, J. (1977). Comparison of slope stability methods of analysis. Canadian Geotechnical Journal, 14(3), 429-439.

Janbu, N. (1968). Slope stability computations, soil mechanics and foundation engineering report. Technical University of Norway, Trondheim.

Kavouridis, K. (2004). Report of the General Management of Mines (PPC), on the interception and stabilization of the failure in the South Field Mine. Unpublished technical report, in Greek.

Kavvadas, M., Roumpos, C., & Schilizzi, P. (2020). Stability of Deep Excavation Slopes in Continuous Surface Lignite Mining Systems. Geotechnical and Geological Engineering, 38(1), 791-812.

Lavigne, F., Wassmer, P., Gomez, C., Davies, T. A., Hadmoko, D. S., Iskandarsyah, T. Y. W., Gaillard, J. C., Fort, M., Texier, P., & Heng, M. B. (2014). The 21 February 2005, catastrophic waste avalanche at Leuwigajah dumpsite, Bandung, Indonesia. Geoenvironmental Disasters, 1(1), 1-12.

Lowe, J. (1960). Stability of earth dams upon drawdown. Proc. 1st Pan American Conference on Soil Mechanics and Foundation Engineering, Mexico City, 1960,

Mikkelsen, P., & Green, G. E. (2003). Piezometers in fully grouted boreholes. FMGM-field measurements in geomechanics, Oslo, Norway.

Omraci, K., Merrien-Soukatchoff, V., Tisot, J.-P., Piguet, J.-P., & Nickel-SLN, L. (2003). Stability analysis of lateritic waste deposits. Engineering Geology, 68(3-4), 189-199.

Ouyang, C., Zhou, K., Xu, Q., Yin, J., Peng, D., Wang, D., & Li, W. (2017). Dynamic analysis and numerical modeling of the 2015 catastrophic landslide of the construction waste landfill at Guangming, Shenzhen, China. Landslides, 14(2), 705-718.

Pasierb, B., Grodecki, M., & GwóŹdŹ, R. (2019). Geophysical and geotechnical approach to a landslide stability assessment: a case study. Acta Geophysica, 67(6), 1823-1834.

Richards, B., Coulthard, M., & Toh, C. (1981). Analysis of slope stability at Goonyella Mine. Canadian Geotechnical Journal, 18(2), 179-194.

Simmons, J. V., & McManus, D. A. (2004). Shear Strength Framework for Design of Dumped Spoil Slopes for Open Pit Coal Mines. In Advances in geotechnical engineering: The Skempton conference (pp. 981-991). Thomas Telford Publishing. https://doi.org/doi:10.1680/aigev2.32644.002610.1680/aigev2.32644.0026

Songtham, W., Ratanasthien, B., Watanasak, M., Mildenhall, D. C., Singharajwarapan, S., & Kandharosa, W. (2005). Tertiary basin evolution in northern Thailand: A palynological point of view. Natural History Bulletin of the Siam Society, 53(1), 17-32.

Spencer, E. (1967). A method of analysis of the stability of embankments assuming parallel inter-slice forces. Geotechnique, 17(1), 11-26.

Su, W., & Miller, H. (1995). Waste pile stability and debris flow formation. The 35th US Symposium on Rock Mechanics (USRMS),

Suzuki, K., Toda, S., Kusunoki, K., Fujimitsu, Y., Mogi, T., & Jomori, A. (2000). Case studies of electrical and electromagnetic methods applied to mapping active faults beneath the thick quaternary. In Y. Kanaori, K. Tanaka, & M. Chigira (Eds.), Developments in Geotechnical Engineering (Vol. 84, pp. 29-45). Elsevier. https://doi.org/https://doi.org/10.1016/S0165-1250(00)80005-X

Taylor, D. W. (1937). Stability of earth slopes. J. Boston Soc. Civil Engineers, 24(3), 197-247.

Thompson, S., Kulessa, B., & Luckman, A. (2012). Integrated electrical resistivity tomography (ERT) and self-potential (SP) techniques for assessing hydrological processes within glacial lake moraine dams. Journal of Glaciology, 58(211), 849-858.

Touch, S., Pongpanlarp, P., Pipatpongsa, T., & Takemura, J. (2015). Underground water in open pit mining at Mae Moh mine of Thailand. ASEAN Engineering Journal, 4(1), 126-143.

Vassilis, M., Theodoros, T., Spyridon, P., Panagiotis, T., Alexandros, C., & Konstantinos, V. (2015). Large Induced Displacements and Slides Around an Open Pit Lignite Mine, Ptolemais Basin, Northern Greece. In Engineering Geology for Society and Territory-Volume 2 (pp. 311-315). Springer.

Wan, M. S., & Standing, J. R. (2014). Lessons learnt from installation of field instrumentation. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 167(5), 491-506.

Wang, G., & Sassa, K. (2003). Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content. Engineering Geology, 69(1), 109-125. https://doi.org/https://doi.org/10.1016/S0013-7952(02)00268-5

Wang, J., & Chen, C. (2017). Stability analysis of slope at a disused waste dump by two-wedge model. International Journal of Mining, Reclamation and Environment, 31(8), 575-588. https://doi.org/10.1080/17480930.2016.1270498

Whitlow, R. (1990). Basic soil mechanics.

Yin, Y., Li, B., Wang, W., Zhan, L., Xue, Q., Gao, Y., Zhang, N., Chen, H., Liu, T., & Li, A. (2016). Mechanism of the December 2015 catastrophic landslide at the Shenzhen landfill and controlling geotechnical risks of urbanization. Engineering, 2(2), 230-249.

Zarlin, N., Sasaoka, T., Shimada, H., & Matsui, K. (2012). Numerical Study on an Applicable Underground Mining Method for Soft Extra-Thick Coal Seams in Thailand. Engineering, 04(11), 739-745. https://doi.org/10.4236/eng.2012.411095

CHAPTER IV

STABILITY ANALYSIS OF A LARGE-SCALE WASTE DUMP FAILURE AT THE MAE MOH MINE IN THAILAND

4.1 Stability Analysis by the Finite Element Method

In this chapter, the primary objective of this investigation is to identify the cause of the waste dump slope failure by analyzing the stability of a waste dumpsite, considering its geometry and construction sequence. The analysis results are then compared against established minimum stability criteria explicitly formulated for mine waste dumpsites, as documented in prominent research and practical literature.

Various analytical techniques were employed to assess waste dumpsite stability, broadly categorized into two main groups: deterministic and probabilistic. The deterministic method aims to determine a specific index value representing stability, such as the factor of safety (FS) or strength reduction factor (Goh et al., 2019; Zhang & Goh, 2012). This approach is frequently intertwined with numerical modeling techniques, including finite element and distinct element methods.

The probabilistic techniques are geared towards establishing a probability of failure (PF), denoting the likelihood of a failure of a given magnitude based on the variability of input parameters(Giasi et al., 2003; Xu & Low, 2006). The correlation between the factor of safety and probability of failure for overall static stability is outlined as follows: FS < 1.1, PF > 20%, FS = 1.1 – 1.2, PF = 10 – 20%, FS = 1.2 – 1.3, PF = 5 – 10%, FS = 1.3 – 1.5, PF = 1 – 5%, and FS > 1.5, FS <1% (Jefferies et al., 2008; Read & Stacey, 2009; Tapia et al., 2007).

In the field of geotechnical engineering, the assessment of stability for both natural and man-made earthworks often involves a parametric study. Traditional methods rely on the factor of safety, as determined through the limit equilibrium method. Pioneered by Janbu (1954), Bishop (1955), and Morgenstern and Price (1965) based on the method of slices, this approach has a lengthy history. However, it is not exempt from limitations, including assumptions about the failure plane's shape, forces acting between slices, and a lack of consideration for strain and displacement compatibility (Krahn, 2003). Consequently, despite its widespread use, the method's high reliability continues to be a subject of ongoing investigation. In contrast, the finite element method, particularly when utilizing a strength reduction technique, has gained increasing favor in recent decades. The strength reduction technique, introduced by Zienkiewicz et al. (1975) entails estimating the safety factor through a simultaneous reduction in the effective friction angle and effective cohesion of the soil material. Therefore, this research employed the finite element method through the utilization of the Plaxis 2D computer software to examine the failure of the waste dump slope. Plaxis 2D is a widely adopted software for addressing intricate geotechnical and mining challenges, renowned for its capacity to model soil behavior with high precision (Afiri & Gabi, 2018; Albataineh, 2006; Udomchai et al., 2017).

In general, the stability of a mine waste dumpsite is governed by a range of factors. Based on the site investigation and electrical resistivity tomography (ERT) profiles, this study categorizes these factors into three primary considerations: the foundation geometry and condition, the waste dumpsite geometry, material properties, and construction sequence, and the presence of perched water conditions.

To analyze the potential causes of waste dump failure, this study conducted a comprehensive examination through three distinct cases. The first case focused on dry waste dump materials and their consequences. The second case simulated an increase in the perched water table. A comparative analysis between these two cases was undertaken to discern the impact of the perched water table on waste dump failure.

Within the waste dump mining area, a perched water table can form due to impermeable materials, like clay or waste rock, creating a barrier that impedes downward water movement. The recorded annual rainfall in the Mae Moh Mine, as depicted in Figure 3.8, is representative of typical tropical region precipitation. Rainfall prompts water infiltration through the waste dump, and impermeable layers trap the water above, resulting in the development of perched saturated zones. Over prolonged periods, with cycles of wet and dry seasons, these perched zones may expand or merge, culminating in the formation of a large interconnected perched water table.

The third simulation case (Case 3) incorporates the inclusion of a thin and weak basal layer above the hard foundation and beneath the waste dump materials. This layer accounts for the degradation of the waste dump material (claystone) discovered in the swamp area during geophysical and ERT investigations. The incorporation of this layer aims to model the potential sliding failure of the dumpsite resulting from the gradual weakening of the basal layer over time.

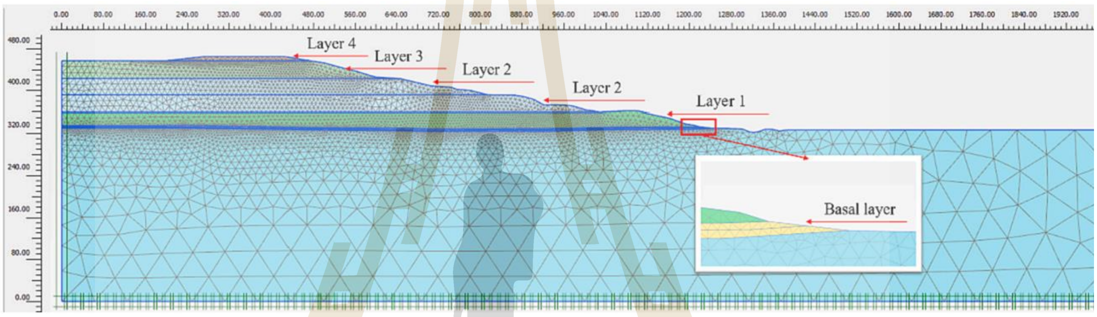


Figure 4.1 Finite element modeling of the waste dump slope

The finite element modeling incorporated geological and perched water conditions, as depicted in Figure 4.1. The waste dump, with a maximum height of 135 m and an average slope inclination of 10% (horizontal to vertical ratio of 1:6), was situated above the original ground, represented as a horizontal line. The waste dump materials were stratified into four sub-layers to account for the history of the waste dumping process. A 4-meter basal layer was assumed to be a weak clay layer based on field and geotechnical investigations. The foundation layer beneath the waste dump was considered a hard stratum. The waste dump material itself was modeled as normally consolidated material, indicating no prior stress history or compaction. This modeling approach aimed to capture essential geological and structural features influencing the waste dump slope stability.

The finite element analysis was conducted using the Mohr-Coulomb constitutive model, selected for its appropriateness in representing the soil characteristics and stage construction at Mae Moh Mine. This model, widely utilized in analogous mining studies, is known for its simplicity and effective approximation of soil behavior (Afiri & Gabi, 2018; Albataineh, 2006; Udomchai et al., 2017). The Mohr-Coulomb model relies on five soil parameters: friction angle, cohesion, Young's modulus, Poisson's ratio, and dilatancy angle. For clay soils, the dilatancy angle was set to zero. When the friction angle was less than 30 degrees, the dilatancy angle was also set to zero. In cases where the friction angle exceeded 30 degrees, the dilatancy angle equaled the friction angle minus 30 degrees (Brinkgreve, 2005).

There were totally six stages of the construction process, including (1) the generation of initial stresses and installation of the first terrace, (2) the installation of the second terrace, (3) the installation of the third terrace, (4) the installation of the fourth terrace, (5) the installation of the fifth terrace, and (6) the determination of the factor of safety (FS). The soil parameters of the waste dump materials obtained from the laboratory testing required for finite element analysis are presented in Table 4.1. Undisturbed samples of the basal soil were collected using thin wall tube samplers according to ASTM D6519. It was found that the samples were clayey sand with high organic content. Hence, it was impossible to obtain the undisturbed sample for laboratory triaxial tests.

Table 4.1 Soil Parameters for Finite Element Analysis of Waste Dump Materials

Soil parameters	Dump soil (Layer 4)	Dump soil (Layer 3)	Dump soil (Layer 2)	Dump soil (Layer 1)	Basal Soil*	Foundation soil	Ui
Material model	M-C	M-C	M-C	M-C	M-C	M-C	-
Drainge type	Drained	Undrained (A)	Undrained (A)	Undrained (A)	Undrained (A)	Undrained (A)	
Unsaturated unit weight, γ_{unsat}	18	18	18	18	16		kN
Saturated unit weight, γ_{sat}	20	20	20	20	18		kN
Young's modulus, E'	20	40	45	60	60		M
Poission's ratio, ν'	0.25	0.3	0.3	0.3	0.3		-
Initial void ratio, e_{init}	1	1	0.8	0.8	0.8		-
Cohesion, c'	1	35	50	70	1-20		kI
Friction angle, φ'	25	15	17	20	12-20		De
Permeability, k	-	6.0E-04	6.0E-04	5.5E-04	5.5E-04		m

* Note: the shear strength parameters (c' and ϕ') of the basal soil layer were varied for case III finite element analysis.

The meticulous calibration of the constitutive model played a pivotal role in ensuring the precision of simulation outcomes. This intricate process involved the careful adjustment of model parameters to closely align with the observed behavior, emphasizing the accurate replication of failure mechanisms and deformation patterns.

The successful calibration affirmed the appropriateness of the chosen constitutive model and its parameters for capturing the specific conditions that culminated in the waste dump failure. Subsequently, armed with a validated model, a comprehensive parametric study was conducted to delve further into the underlying causes of the failure.

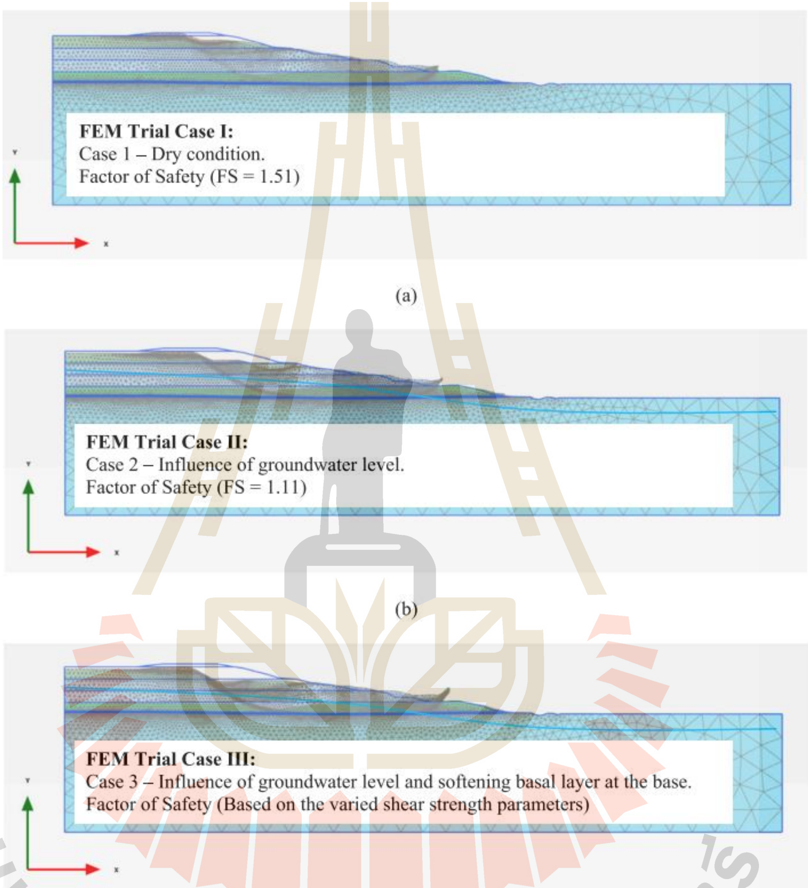


Figure 4.2 Finite element analysis results of the waste dump slope: (a) case 1 – dry condition, (b) case 2 – influence of groundwater level, and (c) case 3 – influence of groundwater level and softening basal layer at the base.

Figure 4.2 displays the results of the finite element analysis for the three cases. In Case 1 (Figure 4.2a), a minor slope sliding mechanism is observed with a factor of safety of 1.51, indicating the stability of the waste dump slope under dry conditions. Transitioning to Case 2 (Figure 4.3b), where the influence of the perched water table is considered, a major sliding failure mechanism is evident with a factor of safety of 1.11. This observation aligns with field assessments of soil movement at the toe and along the base of the dump. Moreover, the soil mass movement at the top of the model corresponds to the formation of active and passive wedges, consistent with descriptions in prior studies (B. G. Richards et al., 1981; Zhan et al., 2018). This substantiates the significant impact of the perched water table on the waste dumpsite's stability, positioning it as a primary contributing factor to the waste dump failure.

In light of the comprehensive field and geotechnical laboratory investigations, it was recognized that the characteristics of the weak soil in the basal layer above the original ground level played a pivotal role in the failure of the waste dump. Consequently, a meticulous parametric study was undertaken, involving the variation of shear parameters—specifically, the effective friction angle and effective cohesion values—to meticulously evaluate their impact. In this particular instance, the effective cohesion was fixed at 1 kPa, and the effective friction angle values were systematically adjusted to identify the minimum value resulting in a factor of safety greater than 1. Subsequently, variations in effective cohesion values were explored to discern their influence on the stability of the waste dump slope.

As depicted in Figure 4.2c, the waste dump slope experienced failure when the effective friction angle of the weak clay layer dipped below 12 degrees. The observed failure mechanism mirrored that of Case 2, with the factor of safety registering below 1.0 in this particular scenario.

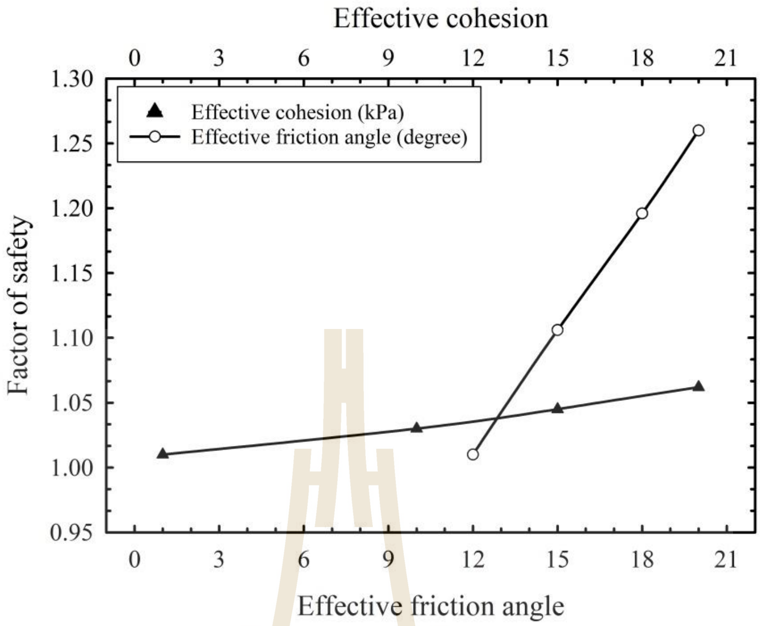


Figure 4.3 Influence of effective cohesion and friction angle of weak clay layer on the factor of safety of waste dump.

Figure 4.3 delineates the correlation between the shear strength parameters, specifically the effective friction angle and effective cohesion, and the factor of safety of the waste dump slope. The graphical representation underscores that the stability of the waste dumpsite is notably more influenced by variations in the effective friction angle compared to changes in effective cohesion. This observation aligns with prior research on high waste dump slope failures (Poulsen et al., 2014). This reinforces the notion that the waste dump failure stemmed from the presence of a thin, degraded soil layer above the hard foundation, exhibiting weaker characteristics than the waste dump materials and susceptible to sliding failures involving the formation of active and passive wedges. This phenomenon closely resembles findings from previous investigations into waste dump failures, as documented by various researchers (Kasmer et al., 2006; Poulsen et al., 2014; Steiakakis et al., 2009; Wang & Griffiths, 2019; Zevgolis et al., 2019). The formation of the basal layer can be attributed to the gradual degradation of claystone waste in the swamp area, eventually transforming it into clayey soil over an extended period.

Upon careful consideration of both the site investigation data and the results derived from finite element analysis, the identified factors contributing to the waste dump failure predominantly involve the presence of a perched water table inducing heightened pore-water pressure and the potential degradation of waste dump materials interfacing with the foundation. The failure within the dump's basal zone aligns with a wedge failure mode, characterized by kinematics encompassing the horizontal translation of a passive wedge and the vertical subsidence of an active wedge.

In response to the outcomes of this investigation, it is recommended to employ advanced soil improvement techniques, such as the installation of vertical or horizontal drains, to effectively mitigate water pressure within the waste dump material. This strategic approach is intended to bolster stability as dumping operations progress toward the targeted height. Additionally, a systematic regimen of monitoring pore-water pressures and deformations through inclinometers during the dumping process is strongly advocated, providing a proactive means to detect and address potential stability challenges.

This research significantly advances the understanding of the contributing factors leading to the catastrophic waste dump slope failure at the Mae Moh Mine. While previous case studies have underscored factors like excess pore water pressure, weak foundation layers, and wedge failure mechanisms, this study provides a comprehensive examination of the unique combination of causal elements specific to the Mae Moh dump failure. The utilization of an integrated methodology, combining electrical resistivity tomography imaging with geotechnical field data, enables a detailed characterization of the complex stratification of waste layers and hydrogeological conditions. The application of 2D finite element stability analyses, driven by empirical data, quantifies the respective impacts of elevated perched groundwater and strength reduction within a thin degraded clay layer above the rigid foundation. These nuanced insights will serve as a basis for informed and targeted remediation strategies, optimizing stability considerations as dumping activities progress toward the ultimate height.

4.2 Conclusions

The investigation into the catastrophic waste dump failure at the Mae Moh Mine was prompted by data obtained from the Electricity Generating Authority of Thailand (EGAT). According to EGAT, the excavation at Mae Moh Mine, located in the northeast region of Thailand, is planned to extend to a larger and deeper scale, reaching depths of up to 500 m. Consequently, the waste material was initially intended to be dumped to a height of 260 m. However, a significant failure occurred, covering an area of approximately 1.56 km2 when the dump had reached a height of only 135 m from the original ground level. This research aimed to ascertain the cause of this catastrophic waste dump failure through a meticulous examination of slope stability at the dump site. The investigation incorporated a comprehensive geophysical approach, employing electrical resistivity tomography, coupled with geotechnical methods such as field observation, borehole exploration, remote-sensing techniques, geotechnical laboratory tests, and finite element analysis.

The results of the geophysical and geotechnical investigations revealed that the subsoil profile of the waste dump was characterized by heterogeneity and varying moisture contents. The deposition of different types of mine waste materials over time contributed to this variability in the subsoil profile. Notably, the presence of a weak and degraded claystone layer above the hard foundation, particularly in swamp areas, was identified during the investigation. The formation of a perched water table, caused by impermeable materials obstructing downward water movement, was observed in the waste dump mining area. The inadequate drainage system at the dumpsite was also noted, suggesting that the seepage force or the influence of the perched water might be significant contributors to slope failure.

Another potential cause of the slope failure was identified in the reduced shear strength of the degraded clay layer situated between the original foundation and the waste dump body. The primary failure mode of the waste dump slope was identified as an active/passive wedge failure, initiated at the toe of the slope and propagating along the clay basement. Tension cracks formed at the rear part of the slope, leading to the destabilization of the mass. The subsequent movement of the mass resulted in the formation of upper active and lower passive wedges, exhibiting a two-wedge failure mode.

This study is expected to provide valuable guidance to the geotechnical and mining engineering teams in efficiently devising short-term and long-term remediation solutions. Moreover, it aims to assess the long-term implications for waste dumps, especially those intended to reach the target height.

4.3 References

Afiri, R., & Gabi, S. (2018). Finite element slope stability analysis of Souk Tleta dam by shear strength reduction technique. *Innovative Infrastructure Solutions*, *3*(1), 1-10.

Albataineh, N. (2006). *Slope stability analysis using 2D and 3D methods* University of Akron].

Bishop, A. W. (1955). The use of the slip circle in the stability analysis of slopes. *Geotechnique*, *5*(1), 7-17.

Brinkgreve, R. B. (2005). Selection of soil models and parameters for geotechnical engineering application. In *Soil constitutive models: Evaluation, selection, and calibration* (pp. 69-98).

Giasi, C., Masi, P., & Cherubini, C. (2003). Probabilistic and fuzzy reliability analysis of a sample slope near Aliano. *Engineering Geology*, *67*(3-4), 391-402.

Goh, A. T., Zhang, W., & Wong, K. (2019). Deterministic and reliability analysis of basal heave stability for excavation in spatial variable soils. *Computers and Geotechnics*, *108*, 152-160.

Janbu, N. (1954). Application of composite slip surface for stability analysis. Proceedings of European Conference on Stability of Earth Slopes, Sweden, 1954,

Jefferies, M., Lorig, L., & Alvarez, C. (2008). Influence of rock-strength spatial variability on slope stability. Continuum and Distinct Element Numerical Modeling in Geo-Engineering. Proceedings First International FLAC/DEM Symposium on Numerical Modeling, R. Hart, C. Detournay and P. Cundall (editors), Kasmer, O., Ulusay, R., & Gokceoglu, C. (2006). Spoil pile instabilities with reference to a strip coal mine in Turkey: mechanisms and assessment of deformations. *Environmental Geology*, *49*(4), 570-585. https://doi.org/10.1007/s00254-005-0092-1

Krahn, J. (2003). The 2001 RM Hardy Lecture: The limits of limit equilibrium analyses. *Canadian Geotechnical Journal*, *40*(3), 643-660.

Morgenstern, N. u., & Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Geotechnique*, *15*(1), 79-93.

Porras, D., Carrasco, J., Carrasco, P., & González, P. J. (2022). Imaging extensional fault systems using deep electrical resistivity tomography: A case study of the Baza fault, Betic Cordillera, Spain. *Journal of Applied Geophysics*, *202*, 104673. https://doi.org/https://doi.org/10.1016/j.jappgeo.2022.104673

Poulsen, B., Khanal, M., Rao, A. M., Adhikary, D., & Balusu, R. (2014). Mine overburden dump failure: a case study. *Geotechnical and Geological Engineering*, *32*(2), 297-309.

Read, J., & Stacey, P. (2009). Guidelines for open pit slope design.

Richards, B. G., Coulthard, M. A., & Toh, C. T. (1981). Analysis of slope stability at Goonyella Mine. *Canadian Geotechnical Journal*, *18*(2), 179-194. https://doi.org/10.1139/t81-023

Steiakakis, E., Kavouridis, K., & Monopolis, D. (2009). Large scale failure of the external waste dump at the "South Field" lignite mine, Northern Greece. *Engineering Geology*, *104*(3-4), 269-279.

Tapia, A., Contreras, L., Jefferies, M., & Steffen, O. (2007). Risk evaluation of slope failure at the Chuquicamata Mine. Slope Stability 2007: Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering,

Udomchai, A., Horpibulsuk, S., Suksiripattanapong, C., Mavong, N., Rachan, R., & Arulrajah, A. (2017). Performance of the bearing reinforcement earth wall as a retaining structure in the Mae Moh mine, Thailand. *Geotextiles and Geomembranes*, *45*(4), 350-360. https://doi.org/https://doi.org/10.1016/j.geotexmem.2017.04.007

Wang, W., & Griffiths, D. V. (2019). Case study of slope failure during construction of an open pit mine in Indonesia. *Canadian Geotechnical Journal*, *56*(5), 636-648. https://doi.org/10.1139/cgj-2017-0662

Xu, B., & Low, B. (2006). Probabilistic stability analyses of embankments based on finite-element method. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(11), 1444-1454.

Zevgolis, I. E., Deliveris, A. V., & Koukouzas, N. C. (2019). Slope failure incidents and other stability concerns in surface lignite mines in Greece. *Journal of Sustainable Mining*, *18*(4), 182-197.

Zhan, L.-t., Zhang, Z., Chen, Y.-m., Chen, R., Zhang, S., Liu, J., & Li, A.-g. (2018). The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. *Engineering Geology*, *238*, 15-26.

Zhang, W., & Goh, A. T. (2012). Reliability assessment on ultimate and serviceability limit states and determination of critical factor of safety for underground rock caverns. *Tunnelling and Underground Space Technology*, *32*, 221-230.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

5.1 General summary

The main objective of this study was to investigate the potential mechanisms and possible causes of the West Waste Dump in the Mae Moh mine. A piece of detailed information and a discussion of the failure were represented in Chapter 1. The literature review of the slope stability analysis including the Limit Equilibrium Method and Finite Element Method was provided. Additionally, the number of waste dump failures around the world is illustrated in Chapter 2. Chapter 3 presented the potential mechanisms and possible causes of a large-scale waste dump failure in the Mae Moh Lignite Mine. The following conclusions can be summarized from this study:

1) The slope stability of the waste dumpsite was conducted based on a comprehensive geophysical investigation using electrical resistivity tomography and geotechnical investigation, including field observation, borehole exploration, remote sensing technique, geotechnical laboratory tests, and finite element analysis.

2) The geophysical and geotechnical investigation results indicated that the waste dump subsoil profile was inhomogeneous and had various moisture contents.

3) The inadequate drainage system of the dumpsite was found during the investigation. Hence, the seepage force or the effect of the perched water might be the cause of the slope failure.

4) The reduced shear strength of the degraded clay layer, which existed between the original foundation and the waste dump body, might be the other potential cause of slope failure.

5) The collapsed waste dump can be categorized as a two-wedge model in which the moving mass was divided into upper active and lower passive wedges and the active wedge pushed a passive wedge horizontal movement.

5.2 Recommendation for future works

In this study, building on the findings and conclusions drawn from the current study, there are several areas where future research can contribute to a more comprehensive understanding of waste dump failures and aid in the development of effective mitigation strategies. The following recommendations are proposed for future works:

1) Improved drainage system analysis: Conduct a detailed investigation focusing on the drainage system of waste dumpsites. Evaluate the effectiveness of drainage systems in preventing the accumulation of perched water and seepage forces. Develop improved drainage strategies to enhance slope stability and reduce the risk of failure.

2) Advanced Geophysical Techniques: Explore advanced geophysical techniques for a more accurate characterization of subsoil profiles. Consider the integration of innovative methods to assess moisture content and heterogeneity in the waste dump. This could include the use of advanced imaging technologies and real-time monitoring systems.

3) Three-Dimensional Slope Stability Analysis: Expand the slope stability analysis to a three-dimensional framework. This could involve more sophisticated numerical modeling techniques, such as advanced Finite Element Analysis or other advanced numerical methods. A 3D analysis would provide a more realistic representation of the waste dump's stability under varying conditions.

4) Risk Assessment and Management: Develop a comprehensive risk assessment framework for waste dump failures. Consider factors beyond geophysical and geotechnical aspects, such as climate change, socio-economic factors, and land-use planning. Formulate effective risk management strategies to mitigate the impact of potential failures.

APPENXDIX

PUBLICATIONS

List of Publications

Hoy, M., Doan, C. B., Horpibulsuk, S., Suddeepong, A., Udomchai, A., Buritatum, A.,.& Arulrajah, A. (2024). Investigation of a large-scale waste dump failure at the Mae Moh mine in Thailand. *Engineering Geology*, 107400.

Cong Bien Doan, Suksun Horpibulsuk and Menglim Hoy. Large-scale failure of waste dump at the Mae Moh open-pit lignite mine, Thailand. *KKU International Engineering Conference 2021*.

Engineering Geology 329 (2024) 107400

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Investigation of a large-scale waste dump failure at the Mae Moh mine in Thailand

Menglim Hoy[a,b,d,*], Cong Bien Doan[a], Suksun Horpibulsuk[a,b,c,d,*], Apichat Suddeepong[b,d], Artit Udomchai[b,d], Apinun Buritatum[b,d], Apipat Chaiwan[e], Prajueb Doncommul[f], Arul Arulrajah[g]

[a] School of Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[b] Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[c] Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand
[d] Program in Civil and Infrastructure Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
[e] Geotechnical Engineering Department, Mae Moh Mine, Electricity Generating Authority of Thailand, Lampang, Thailand
[f] Mae Moh Mine Planning and Management Division, Electricity Generating Authority of Thailand, Thailand
[g] Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

A R T I C L E I N F O

Keywords:
Waste dump failure
Landslide
Electrical resistivity tomography
Finite element method
Open-pit coal mine
Perched water table

A B S T R A C T

This research investigates the potential mechanisms and possible causes of a large-scale waste dump failure in the Mae Moh Lignite Mine, which is Thailand's largest open-pit coal mine. The large-scale failure of the waste dumpsite covered an area of approximately 1.56 km^2 when the dump materials reached a height of 135 m from the original ground. The failure event involved the mobilization of a 70-Mm^3 mass of the dump material with 1.2 km in length and 1.3 km in width. The causes of this failure were investigated in this research based on a scientific investigation approach for the remedial action. The geophysical and geotechnical investigation was first performed to characterize the waste dump materials and the perched water condition. The electrical resistivity tomography analysis was also performed within the failure zone and its results were calibrated with the boreholes and interpreted to depict the overview of the geotechnical conditions of waste dump materials. Finally, the stability of the waste dumpsite was investigated using the finite element method (Plaxis 2D program). Based on the critical analysis of the studied data, the causes of waste dump slope failure could be attributed to two main factors, which are the presence of a perched water table associated with the high porewater pressure and the presence of a weak basal layer at the interface between the hard foundation and the waste dump materials. This weak basal layer was the claystone deposited in the swamp area above the hard foundation and deteriorated over time with the increasing amount of waste dumped. The dumping of waste materials over the natural river and pond and the rainwater infiltration over time caused the presence of a perched zone in the waste dumpsite. Failure of the dump slope can be classified as due to a wedge mode of failure, which causes the kinematics with the horizontal translation of a passive wedge and vertical subsidence of an active wedge.

1. Introduction

The Mae Moh Mine, Lampang Province, Thailand, is the largest open-pit coal mine in Southeast Asia, and consists of the lignite mine and external dumping areas of approximately 38 km^2 and 42 km^2, respectively. The mine contributes to 70% of Thailand's lignite production, with a current extraction rate of approximately 16 million tons of coal annually to generate electricity in the Mae Moh power plant (Udomchai et al., 2017; Ngo et al., 2020). The Mae Moh Mine commenced operations in 1955 and is operated by the Electricity Generating Authority of Thailand (EGAT). In recent years, the Mae Moh power plant has been producing 2220 MW of electricity, of which is distributed 50% to the North, 30% to the Central, and 20% to the northeast of Thailand.

Fig. 1 shows the location of the Mae Moh power plant, the coal mine

* Corresponding authors at: School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand.

E-mail addresses: menglim@g.sut.ac.th (M. Hoy), suksun@g.sut.ac.th (S. Horpibulsuk), suddeepong@g.sut.ac.th (A. Suddeepong), artit.u@g.sut.ac.th (A. Udomchai), apipat.c@egat.co.th (A. Chaiwan), prajuab.d@egat.co.th (P. Doncommul).

https://doi.org/10.1016/j.enggeo.2023.107400
Received 23 June 2023; Received in revised form 14 December 2023; Accepted 27 December 2023
Available online 1 January 2024

Fig. 2. Spreading the waste dump materials to the dumping area via a conveyor system.

and hydrological features of the waste dump area, drainage system, and dumping rate. Based on the previous case studies, the softening of soil layer and the build-up of excess porewater pressure under undrained loading conditions were found to be the potential causes of the failure. Consequently, the sliding failure surface occurred in the formation of active and passive wedges along a weak zone at the interface between the weak soil layer at the base and the waste dump material.

3. Site investigation of failed west waste dumpsite at the Mae Moh Mine

3.1. *Description of the waste dump slope failure*

The Mae Moh Mine is located in Mae Moh district, Lampang province, Thailand (Fig. 1) in the Mae Moh tertiary basin with a thickness of more than a thousand meters and three main categories of geological formations, including Na Kheam, Huai King, Huai Luang (Songtham et al., 2005; Touch et al., 2015; Zarlin et al., 2012). The Na Khaem formation is the most significant lignite-bearing formation with a thickness of 250 to 400 m and is primarily composed of lignite seams and gray to greenish gray claystone and mudstone. The Huai King formation is a fluvial sequence consisting of semi-consolidated fine to coarse sandstone, claystone, mudstone, and conglomerate, with different colors (green, yellow, blue, and purple) and thickness (15 to 150 m). The Huai Laung formation, including red to brownish-red semi-consolidated and unconsolidated claystone, siltstone, and sandstone, is the youngest tertiary formation with a thickness ranging from 5 to 350 m. The excavated materials from the mine surface were then transferred to the west dumpsite by utilizing a belt conveyor to establish the first terrace of a slope.

Fig. 3 shows the surface topography evolution of the waste dumpsite from 1992 to 2017. The enormous disposal of the coal mining wastes from extracting and processing mineral resources was widely dumped into the West Dumpsite. The preliminary designed height for the waste dump materials was 260 m, deposited from +330 m MSL to +590 MSL. The trees and shrubs were planted on the slope of the terra surface. The disposal of coal waste materials was first dumped i swamp area at the dumpsite. The waste materials were then conti ously dumped into the existing rivers and natural ponds, which caus the elevation of the catchment from +326 m MSL to approximat +340 m MSL in 1995. The spread of the waste materials was in a lar area and finally covered the catchments until 2017. The characteristic the waste dump materials was initially granular in nature with a re tively high effective friction angle. However, the waste dump materi were significantly broken down by the wetting and drying cycles due seasonal changes. This material slakes into fine clay particles w relatively high voids. As a result, the waste dump material, in gene became a loose compacted clay with no pronounced peak strength af a few years of dumping. The first dump materials in the swamp w expected to be seriously slaked and became weak clay layer above ha foundation.

On March 18, 2018, the waste dumpsite collapsed with the rotatio slumping at the crest and translation of a mass at its toe in a spreadi manner. This waste dump slope failure covered an area of approximat 1.56 km^2 when the waste dumping reached an elevation of +465 m M which was about 135 m in height measured from the first dump ele tion of +330 m MSL. Fig. 4**(a-b)** shows the aerial views of the wa dump area before and after the catastrophic waste dump slope failu using an Unmanned Aerial Vehicles (UAV) technique.

Fig. 5 demonstrates the failure zone, divided into three main ar (Areas 1, 2, and 3). Area 1 and Area 2 were the main failure bodies. Area 1, the failure stayed intact and slipped about 50 to 70 m by late translation sliding. Area 2 failed by rotational sliding and spreading approximately 200 to 300 m, where a sign of mudflow was visible at toe of the deposit. The major and minor scarps were about 45 m and m in height at the top and the central region of the failure zo respectively. It was indicated that the crest of the slope was slumped i vertical movement between the backscarp and prominent scarp (act

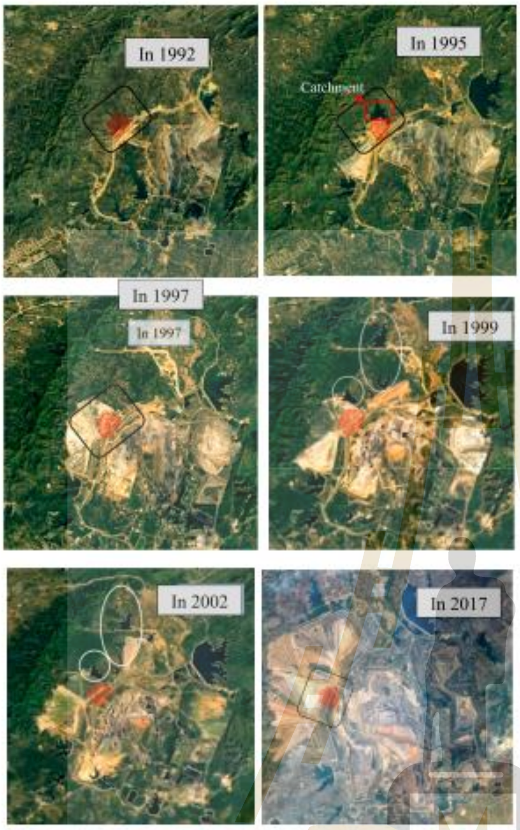


Fig. 3. Topography evolution of the study areas between 1992 and 2017.

wedge), while the spreading larger blocks were the passive wedge. This phenomenon was categorized as a deep-seated multi-wedge failure mechanism (Poulsen et al., 2014; Simmons and McManus, 2004). Area 3 indicated the initial failure in the top (initial movement collapse) immediately after the landslide's body and then flowed to the toe of the slope. A number of transverse and radial cracks were found at the first and second benches.

3.2. Geophysical and geotechnical investigation

Geophysical and geotechnical investigations were performed to identify the characteristics of the waste dump. Electrical resistivity tomography, an advanced geophysics technique for characterizing subsurface materials, was employed to determine the changes in the electrical resistivity properties achieved by the organization of electrodes. The changes were consistently collected and were found to correspond with variations in lithology, water saturation, fluid conductivity, porosity, and permeability which might be used to map stratigraphic units, geotechnical structure, fracture, and groundwater.

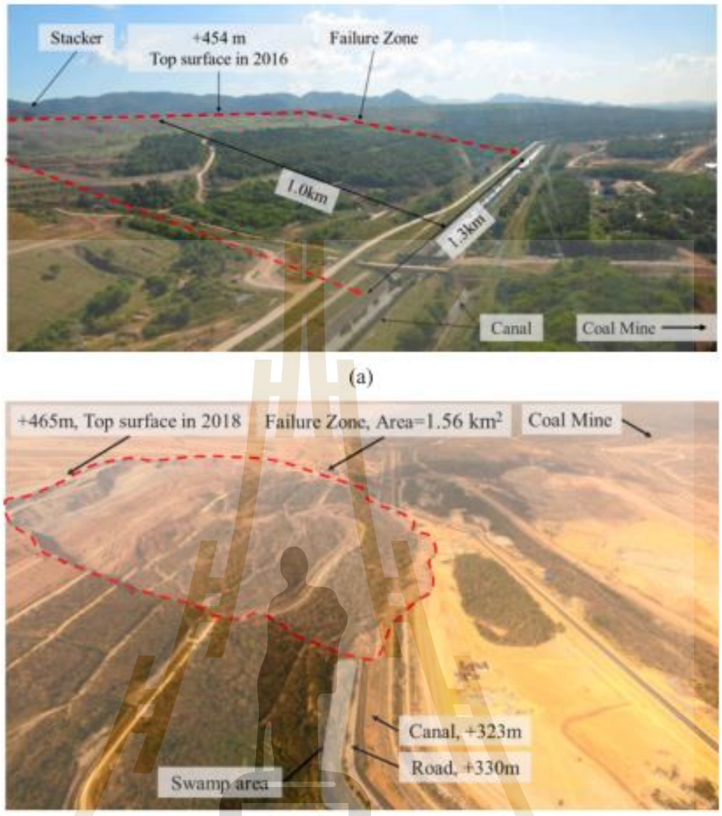
In the landslide zone, the geotechnical investigation, including remote sensing application, field monitoring, boring logs, and geotechnical laboratory tests, were carried out to characterize water table conditions in the waste mass and the materials engineering parameters. After the waste dump failure incident, 19 borehole tests were carried out within the failure zone, as shown in Fig. 6. 11 borehole (designated as S1 to S5) tests were carried out at the toe of the sl about 1 month after the waste dumpsite failure. In March 2019, t boreholes (InJ1 and InJ2) tests were conducted to investigate the fail plane between the waste dump materials and the existing origi ground. In January 2020, two boreholes WD7 and WD8 (next to south boundary of the failure zone) and one borehole B2 (close to the elevation of the waste dump) test were carried out. Boreholes B3 and were located in the middle of the failure zone, and borehole WD16 (n to the north boundary of the failure zone) test was conducted in Ju and August of 2020, respectively. In addition, vibrating-wire a standpipe piezometers were installed and recorded at the locati shown in Fig. 6 to observe the water table and porewater pressure cement-bentonite grout mixture has been one of the most dependa methods to measure porewater pressure as a reading of a piezoelec sensor with notable time-lag and was also utilized in this project (M kelsen and Green, 2003; Wan and Standing, 2014).

Fig. 7 demonstrates the slope profile of the waste dumpsite at a cro section (a-a), as shown in Fig. 6. The dashed black line and the solid line indicated the waste dumpsite's pre-failure and post-failure sl profile, while the original ground was approximately at elevation +330 m MSL. The dashed blue lines displayed the water level obtai from the piezometer monitoring. It was seen from the slope prof before and after the failure that the main slumping block moved ve cally at the highest elevation (+465 m MSL in 2018), acting as an act wedge. The translation occurred in horizontal movement as a pass wedge shortly thereafter, and its debris spread to the toe of the wa dump area.

The waste dump materials at Borehole B2 were mostly clayst fragments, classified as poorly graded sand (SP) based on the Unif Soil Classification System (USCS). Furthermore, a depth of appro mately 3 m of weak clay layer was found above the existing origi ground level (at elevation of +331 m MSL). At Borehole B3, wa gushed out within the deposit during the drilling process for about 3 82 m from the top evaluation of +420 m MSL and about 10 m above existing ground level (elevation of +331 m MSL). This might be due the high excess pore water pressure, which is one of the main fact triggering landslide failure (Ouyang et al., 2017; Wang and Sassa, 200 The topsoil profile at Borehole B4 (top elevation +360 m MSL), abou m in thickness, was claystone, and below this topsoil, the medium clay about 10 to 15 m was found during the drilling process. In additi about 2 m of weak clay was found above the existing ground level. It i interest to note that the medium clay and weak clay were located at existing swamp area, as described in the topography evolution of waste dumpsite (Fig. 3). The typical soil profile at the toe of the wa dumpsite obtained from the group of boring logs (Borehole S2–1, S2 and S2–3) indicated that the overburdened materials about 10 m thickness were relatively moist claystone, and the underlying layer w clayey soils of approximately 10 to 12 m in thickness. In addition, weak material (swamp clay) layers of about 3 to 5 m were found ab the original ground foundation at the elevation of approximately +3 m to +327 m MSL.

The vibrating-wire piezometer boreholes were fully backfilled w cement-bentonite grout (B2, B3, WD16, and WD8). Piezometers w installed at different locations and various depths as described in Fig The vibrating-wire piezometers were denoted as B-V, where B stands the name of the borehole and V for the position of the vibrating-w piezoelectric sensor, i.e., B2-V2, B3-V3, WD16-V3, and WD8-V3.

Fig. 8 shows the pore water pressure observed from the piezomet at various locations. The water levels were changed insignifican during the year of observation. The piezometer monitoring at B2-V2, V3, WD16-V3, and WD8-V3 close to the original ground level dem strated that the pore water pressures within the failure zone (B3-V3 a WD16-V3) were higher than those out of the failure zone (WD8-V3)



(b)

Fig. 4. The Unmanned Aerial Vehicles (UAVs) images of waste dump area: (a) before failure in November 2016 and (b) after failure in March 2018.

3.3. *Electrical resistivity tomography (ERT) method*

To understand the overall subsurface conditions in the waste dumpsite, the electrical resistivity tomography (ERT) technique was used in conjunction with the geophysical and geotechnical investigations. The ERT is a geophysical imaging technique used to determine the electrical resistivity of subsurface materials. Since different materials have different electrical resistivities, the electrical resistivity values can be used to examine the subsurface condition. This technique can be used in various applications, including mineral exploration, groundwater monitoring, and geotechnical engineering (Al-Fares and Al-Hilal, 2018; Suzuki et al., 2000; Thompson et al., 2012).

The ERT technique involves injecting an electrical current into the ground through a pair of electrodes and measuring the resulting voltage between another pair of electrodes. By varying the electrodes' positions and the current's direction, multiple measurements were taken at different points and depths beneath the surface. Based on Ohm's law, the voltage was then converted to apparent resistivity values for the ground between the two potential electrodes. The resistivity model of the subsurface (pseudo-section) is generated using the input current, measured voltage, and array geometry (Edwards, 1977). The subsurface ground resistivity image can be interpreted to identify variations in soil or rock properties.

In this study, 4 ERT profiles (LINE A, LINE B1, LINE B2, and LINE D within the failure zone and 2 ERT profiles (LINE C1 and LINE C2) clos to the failure zone were investigated as shown in Fig. 9. The ERT profile were designed to cross the boring logs prescribed in Fig. 6 to ascertai the soil profiles. The ERT profiles indicated that the resistivity value ranged from 2 to 40 Ohm.m (Ωm). Based on the resistivity values, th subsurface materials can be classified into three main groups, i.e., cla and silt materials (2–8 Ωm), clayey-sand materials (12.5–17.5 Ωm), an sandstone or lignite materials (23–40 Ωm) (Al-Fares and Al-Hilal, 2018 Pasierb et al., 2019; Porras et al., 2022).

Fig. 10 illustrates the ERT profile of the cross-section Line C1, indi cating the inhomogeneous waste dump materials. The resistivity value were used to verify the waste dump materials' subsurface properties an groundwater level. The resistivity values were calibrated with so properties at boring log B2. From the elevation +342.02 m MSL to th existing ground elevation +330 m MSL, the resistivity values range from 12.5 to 17.5 Ωm, defined as the clayey-sand materials. In additio the water table was detected at an elevation of approximately +440 r MSL, which is in agreement with the detected level obtained from th piezometer analysis. Since the water table was located in the wast material and higher than the ground surface, this water table is desig nated as perched water table.

Similarly, the ERT profile presented by the resistivity values alon the longitudinal cross-section of the failure zone (Line D) was depicte

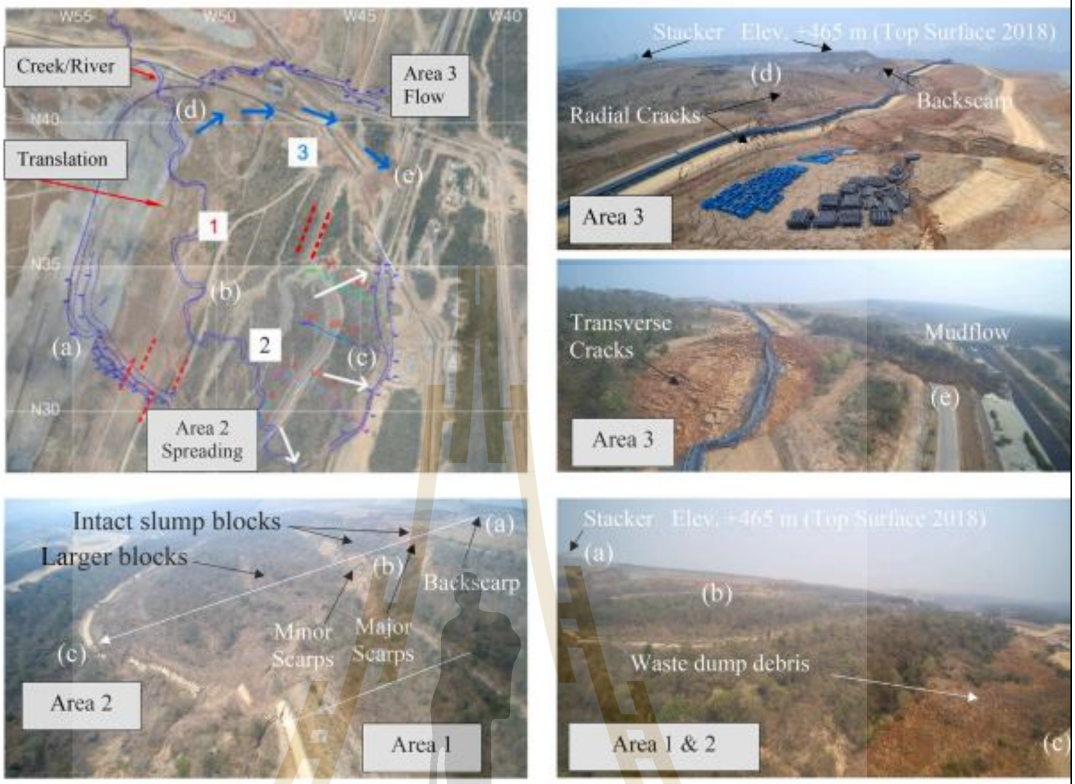


Fig. 5. Development of the West waste dump collapsed in the failure zone.

Fig. 6. The locations of boring logs and piezometers monitoring.

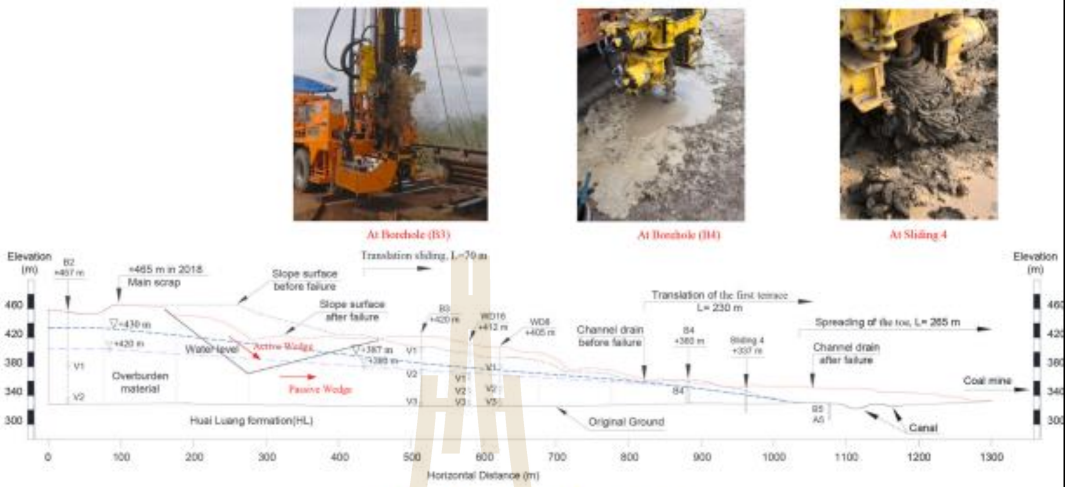


Fig. 7. The slope profile of the waste dump.

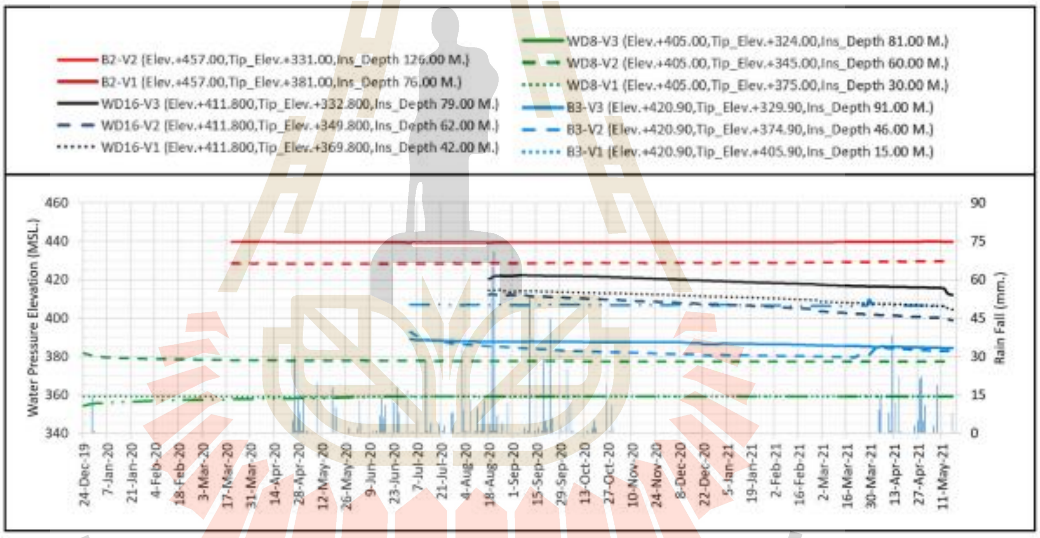


Fig. 8. Water pressure elevation observed from piezometers monitoring.

in Fig. 11. The perched water table gradually lowered down from the top elevation (WEST) to the lowest elevation (EAST). To compare with the soil profile from boring log B3, the resistivity values from the elevation +346.9 m MSL to the existing ground elevation +330 m MSL were studied. The resistivity values ranged from 5 to 10 Ωm obtained from the ERT analysis indicated the clay materials with high moisture content, which were consistent with the soil properties obtained from the boring log.

Fig. 12 presents the ERT profile (the transverse cross-section Line A) at the lower part of the slope within the failure zone. The resistivity values in this profile were used to benchmark with the soil profiles obtained from the boring logs B4, In J1, and In M1. The results for both the ERT analysis and boring log indicated that the waste dump materials were inhomogeneous materials with various moisture contents. How ever, in order to simplify the cause of failure analysis by the fini element method, the waste dump materials were assumed to be h mogenous, as described in Fig. 6.

4. Stability analysis by the finite element method

This investigation aims to determine the cause of the waste dum slope failure, in which the stability of a waste dumpsite was analyz based on the geometry and construction sequence. The analysis resu was compared with the minimum stability acceptance criteria explicit developed for mine waste dumpsite and published by well-know research and practical work. Analytical techniques were used

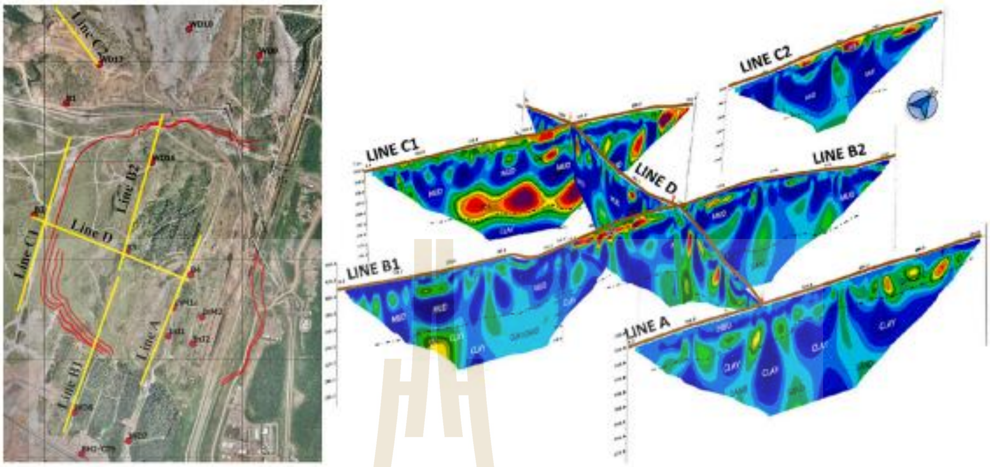


Fig. 9. The locations of the electrical resistivity tomography (ERT) profiles in this study.

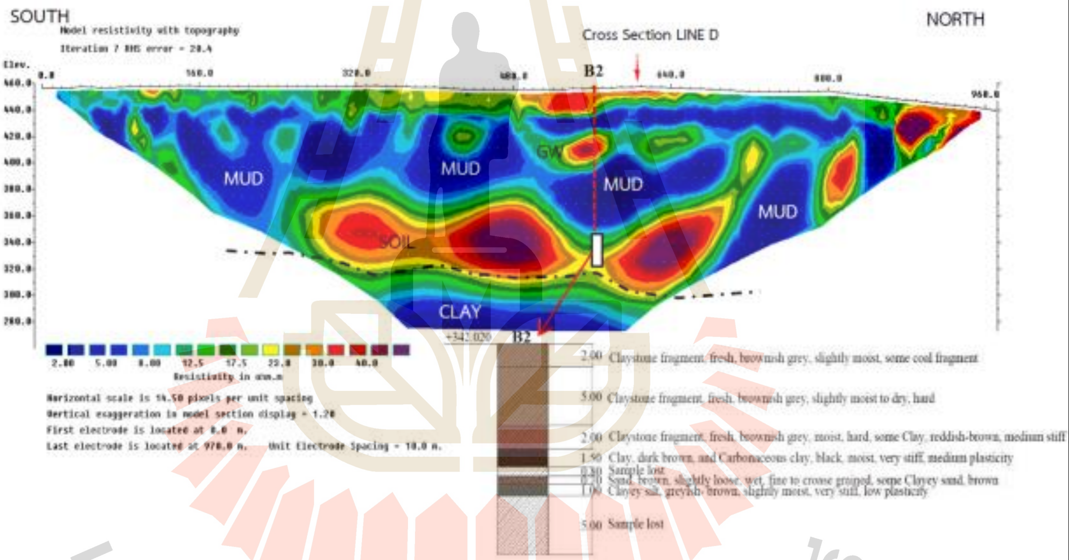


Fig. 10. ERT profile of a cross-section Line C1.

analyze the stability of a waste dumpsite, which can be classified into two main groups: deterministic and probabilistic. The deterministic method is designed to determine the specific index value that represents stability, such as the factor of safety (FS) or strength reduction factor (Goh et al., 2019; Zhang and Goh, 2012). This technique is more commonly associated with numerical modeling techniques, including finite element and distinct element methods. The probabilistic techniques determine a probability of failure (PF), which represents the likelihood that a failure of a given magnitude could occur based on the variability of the input parameters (Giasi et al., 2003; Xu and Low, 2006). The relationship between the factor of safety and probability of failure of overall static stability was summarized as follows: FS < 1.1, PF $> 20\%$, FS $= 1.1$–1.2, PF $= 10$–20%, FS $= 1.2$–1.3, PF $= 5$–10%, FS $= 1.3$–1.5, PF $= 1$–5%, and FS > 1.5, FS $<1\%$ (Jefferies et al., 2008; Rea and Stacey, 2009; Tapia et al., 2007).

In geotechnical engineering practice, a parametric study is general used to evaluate the stability of natural and man-made earthworks. Th slope stability is conventionally defined based on the factor of safe using the limit equilibrium method. The limit equilibrium methods we proposed by Janbu (1954), Bishop (1955), and Morgenstern and Pri (1965) based on the method of slices. Despite the long-standing exp rience with limit equilibrium analysis, this method presented sever drawbacks, such as the assumption of the shape of the failure plane an the force acting between the slices. The strain and displaceme compatibility was not considered (Krahn, 2003). Consequently, the hig reliability of this method still needs to be discovered. On the other han

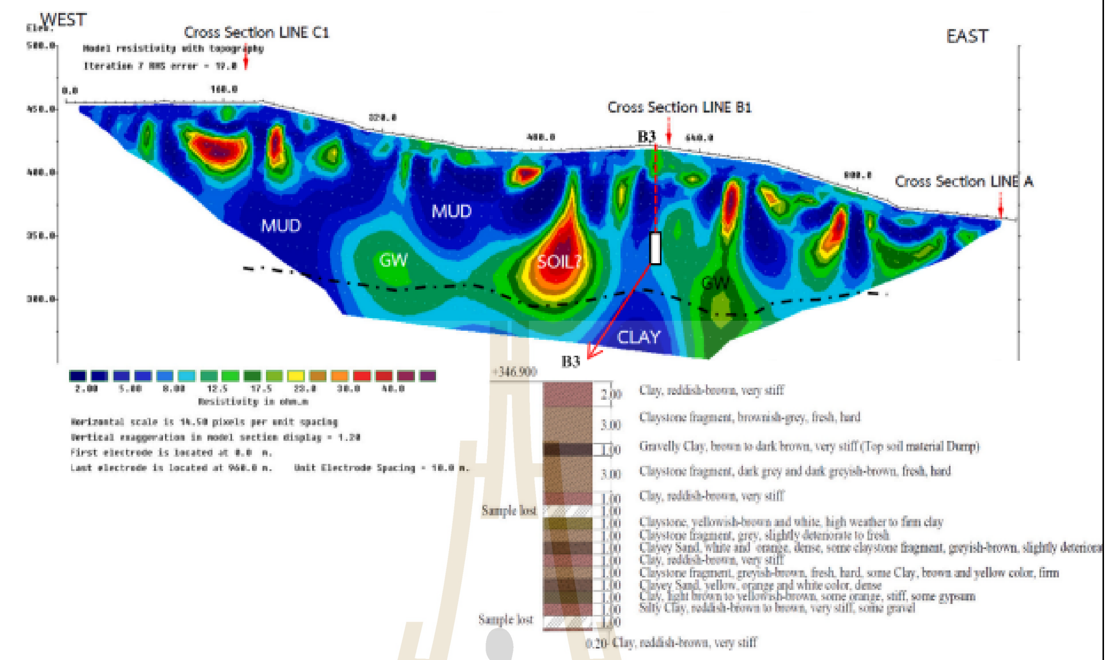


Fig. 11. ERT profile of a cross-section Line D.

the finite element method using a strength reduction technique has increasingly become popular over the last few decades. The strength reduction technique was proposed by Zienkiewicz et al. (1975) to estimate the safety factor by a simultaneous reduction in effective friction angle and effective cohesion of the soil material.

Therefore, the finite element method using computer software Plaxis 2D was carried out to investigate the waste dump slope failure in this research. Plaxis 2D is a common practice software for solving complex geotechnical and mining problems, which provides the high accuracy in modeling the soil behavior (Afiri and Gabi, 2018; Albataineh, 2006; Udomchai et al., 2017).

Generally, several factors can affect the stability of mine waste dumpsite. However, based on the site investigation and ERT profiles in this study, these can be categorized into three main factors. The first factor is the foundation geometry and condition; second factor is the waste dumpsite geometry and material properties and construction sequence; and the last but not least factor is perched water conditions. This study performed three different possible cases for examining the cause of the failure of the waste dump. For the first case, the dry waste dump materials with the dumping consequences were studied. Similar to the first case, the increase of the perched water table was simulated in the second case. These two cases were compared and used to investigate the influence of the perched water table on waste dump failure. In the waste dump mining area, the perched water table can be formed when impermeable materials like clay or waste rock create a barrier that prevents downward water movement. The recorded rainfall data (Fig. 8) indicated that the heavy rainfall was not detected prior to the slope failure incident; the failure occurred in dry season. It is therefore implied that the rainfall causes water to infiltrate through the waste dump and to get trapped above less permeable layers, leading to the formation of the perched saturated zones. With progressive saturation and waste material alterations over long time periods (many wet-dry seasons), the expansion or merging of existing perched zones formed a large interconnected perched water table. The degradation of the waste dump material (claystone), which deposited in the swamp area and discovered duri the geophysical and ERT investigation, could cause the sliding failure the dumpsite. Therefore, the thin and weak basal layer above the ha foundation and beneath the waste dump materials was included in ca 2 for the simulation case 3.

The finite element modeling was based on the geological a perched water condition as shown in Fig. 13 where the maximum heig of the waste dump material was 135 m with an average inclination slo of 10% (horizontal to vertical ratio of 1:6). The original ground w assumed to be a horizontal line. The waste dump materials of four su layers were studied based on the history of the waste dumping proce Based on the field and geotechnical investigation, the 4-m basal lay was assumed to be a weak clay layer. The foundation layer w considered a hard stratum. The waste dump material was normal consolidated material as it was not subjected to any stress history a compaction.

The constitutive model used in finite element analysis was select based on stage construction and soil material characteristics, where the Mohr-Coulomb model was used for the studied soil materials. Th model was chosen because of its simplicity and ability to approxima the behavior of the specific soil types found at Mae Moh Mine, employed in similar mining studies (Afiri and Gabi, 2018; Albataine 2006; Udomchai et al., 2017). The Mohr-Coulomb model requires fi soil parameters: friction angle, cohesion, Young's modulus, Poisso ratio, and dilatancy angle. The value of the dilatancy angle was zero f clay soils. The dilatancy angle of soil was set as zero when the fricti angle was < 30 degrees and equal to the friction angle minus 30 degre when the friction angle was higher than 30 degrees (Brinkgreve, 200 There were six stages in the construction process: (1) the generation initial stresses and installation of the first terrace, (2) the installation the second terrace, (3) the installation of the third terrace, (4) t installation of the fourth terrace, (5) the installation of the fifth terrac and (6) the determination of the factor of safety (FS). The soil param ters of the waste dump materials obtained from the laboratory testi

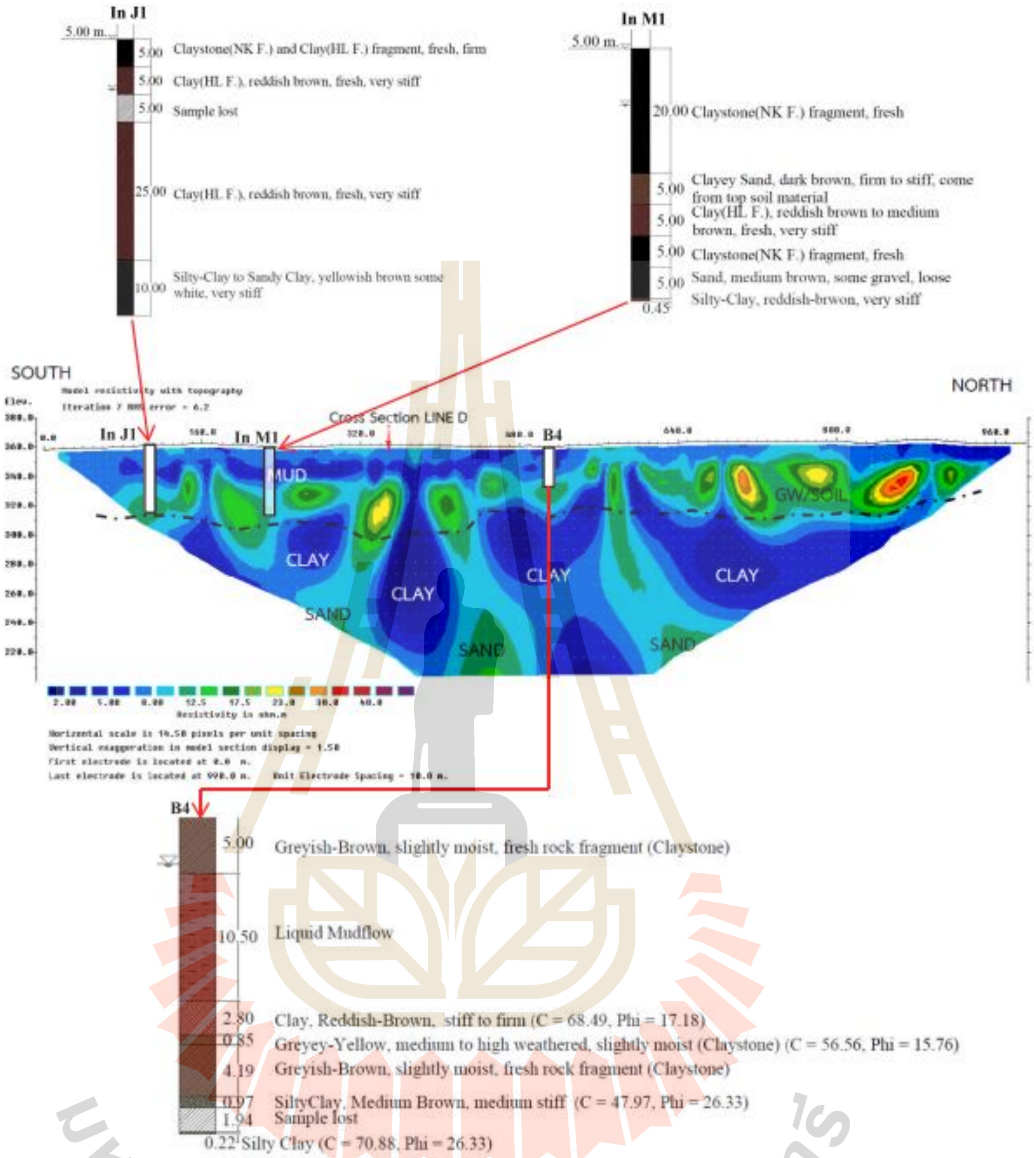


Fig. 12. ERT profile of a cross-section Line A.

required for finite element analysis are presented in Table 1. Undisturbed samples of the basal soil were collected using thin wall tube samplers according to ASTM D6519. It was found that the samples were clayey sand with high organic content. Hence, it was impossible to obtain the undisturbed sample for laboratory triaxial tests.

The calibration of the constitutive model was a crucial step in ensuring accurate simulation results. This process involved adjusting model parameters to match the observed behavior. The calibration aimed to achieve a close match between the simulated and observed behavior of the failure mechanisms (deformation patterns). The good agreement achieved through calibration indicates that the constitutive model and parameters were appropriate for the conditions leading to the waste dump failure. With the validated model, a parametric study was then conducted to further investigate the essential causes of failure.

Fig. 14 shows the finite element analysis results for all three cases. For case 1, Fig. 14a indicated the minor slope sliding mechanism with the factor of safety equal to 1.51, in other words the waste dump slope did not fail in the dry condition. With the influence of the perched water

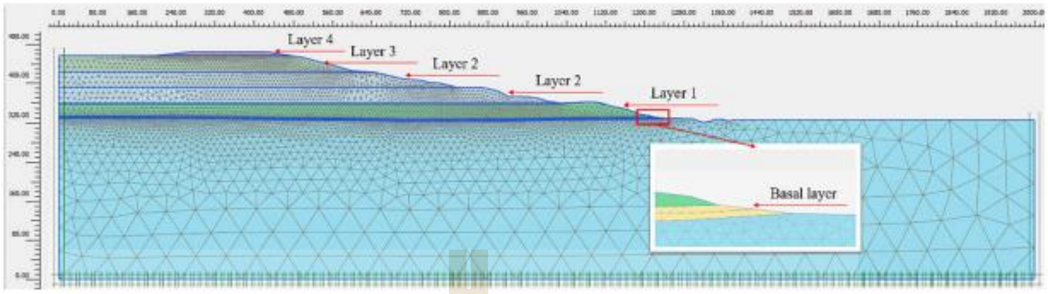


Fig. 13. Finite element modeling of the waste dump slope.

Table 1
Soil parameters of the waste dump materials for finite element analysis.

Soil Parameters	Dump soil (Layer 4)	Dump soil (Layer 3)	Dump soil (Layer 2)	Dump soil (Layer 1)	Basal soil[a]	Foundation soil	Units
Material model	M-C	M-C	M-C	M-C	M-C	M-C	-
Drained type	Drained	Undrained (A)	Undrained (A)	Undrained (A)	Undrained (A)	Undrained (A)	-
Unsaturated unit weight, γ_{unsat}	18	18	18	18	18		kN/m^3
Saturated unit weight, γ_{sat}	20	20	20	20	20		kN/m^3
Young's modulus, E'	20	40	45	60	60		MPa
Poisson's ratio, υ'	0.25	0.3	0.3	0.3	0.3		-
Initial void ratio, e_{init}	1	1	0.8	0.8	0.8		-
Cohesion, c'	1	35	50	70	1–20		kPa
Friction angle, ϕ'	25	15	17	20	12–20		Degree
Permeability, k	-	6.00E-03	6.00E-04	5.50E-04	5.50E-04		m/day

[a] Note: the shear strength parameters (c' and ϕ') of the basal soil layer were varied for case III finite element analysis.

table for case 2, Fig. 14b indicates the major sliding failure mechanism of the waste dumpsite and the factor of safety was equal to 1.11. It was also indicated that the failure mechanism was well associated with the field observation of the soil movement at the toe and along the base of the dump. Furthermore, the soil mass movement at the top of the model specified the formation of the active and passive wedges described in the previous studies (Richards et al., 1981; Zhan et al., 2018). This confirmed that the perched water table significantly influenced the stability of the waste dumpsite, which could be one of the leading causes of waste dump failure.

Based on the field and geotechnical laboratory investigation, the soil properties of the weak soil at basal layer above the original ground level might also influence the cause of the waste dump failure. Therefore, the shear parameters: effective friction angle, and effective cohesive values, were varied to examine its effect. In this case, the effective cohesion was assumed to be 1 kPa, while the effective friction angle values were varied in order to find its minimum value when the factor of safety was >1. Once the minimum effective friction angle was determined, the effective cohesion values were varied to examine its influence on the waste dump slope stability.

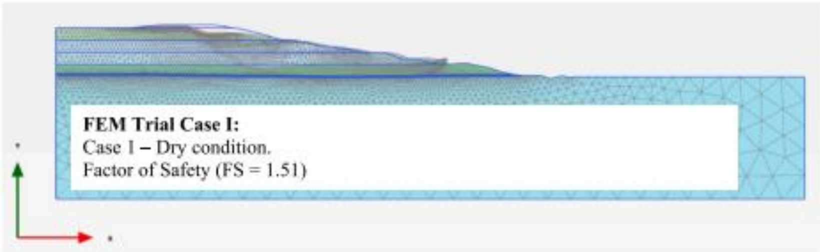
Fig. 14c showed that the waste dump slope failed when the effective friction angle of the weak clay layer was <12°, and the failure mechanism was found to be similar to case 2 while the factor of safety was <1.0. Fig. 15 shows the relationship between the shear strength parameters (effective friction angle and effective cohesion) and the factor of safety of the waste dump slope. It was evident that the stability of the waste dumpsite was more significantly influenced by the effective friction angle than the effect of the effective cohesion. This finding was found to be strongly associated with the previous research for high waste dump slope failure (Poulsen et al., 2014). Therefore, the failure of the waste dump was also due to the thin degraded soil layer above the hard foundation which was weaker than the waste dump materials and the sliding failure may occur in the formation of active and passive wedges.

This was similar to the previous studies on waste dump failures reported by several researchers (Kasmer et al., 2006; Poulsen et al., 2014; Steiakakis et al., 2009; Wang and Griffiths, 2019; Zevgolis et al., 2019). The base layer might result from the degradation of claystone waste in the swamp area over time and becomes clayey soil.

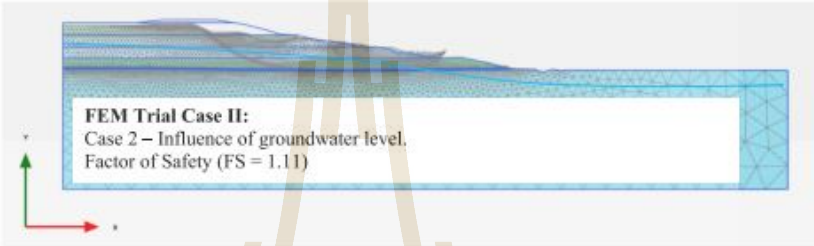
Based on the site investigation and finite element analysis results, the possibility of the causes of waste dump failure could be attributed to two main factors, which were the perched water table associated with the high pore water pressure and/or the degradation of waste dump materials at the interface between the foundation and the waste dump materials. Failure of the dump basal zone can be classified in the mode of wedge failure, which causes the kinematics with the horizontal translation of a passive wedge and vertical subsidence of an active wedge.

Based on this study, the soil improvement techniques, including vertical drains or horizontal drains to reduce the water pressure inside the waste dump material are suggested to improve the stability for further dumping to the target height. Moreover, periodic measurement of pore-water pressures and deformations using an inclinometer during the field dumping would greatly support anticipating any impending stability problems.

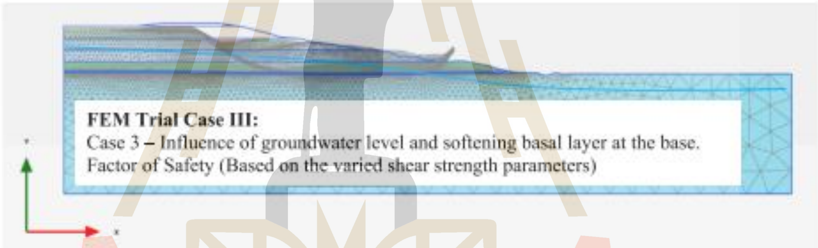
This study provides new insights into the cause of the catastrophic waste dump slope failure at the Mae Moh Mine, Thailand. While previous failures case studies have highlighted factors like excess pore water pressure, weak foundation layers, and wedge failure mechanisms, the specific combination of causal factors for the Mae Moh dump failure has not been fully documented. This investigation applies an integrated approach using electronical resistivity tomography imaging in combination with geotechnical filed data to characterize the complex stratified waste layers and hydrogeological conditions. The data-driven 2D finite element stability analyses quantify the relative contribution of elevated perched water table and strength loss in a thin degraded soil layer above the stiff foundation. The findings will facilitate targeted remediation plans to improve stability as dumping resumes to the ultimate height.



(a)



(b)



(c)

Fig. 14. Finite element analysis results of the waste dump slope: (a) case 1 – dry condition, (b) case 2 – influence of groundwater level, and (c) case 3 – influence groundwater level and softening basal layer at the base.

5. Conclusions

Based on the data from the Electricity Generating Authority of Thailand (EGAT), the Mae Moh Mine in the northeast of Thailand will be excavated on a larger and deeper scale up to a depth of 500 m. Hence, the waste material was designed to dump up to 260 m in the waste dump site. However, the large-scale failure occurred and covered an area of about 1.56 km^2 when the dump reached a height of only 135 m from the original ground. The cause of a catastrophic waste dump failure at Mae Moh Mine was investigated in this research. The slope stability of the waste dumpsite was conducted based on a comprehensive geophysical investigation using electrical resistivity tomography and geotechnical investigation, including field observation, borehole exploration, remote-sensing technique, geotechnical laboratory tests, and finite element analysis.

The geophysical and geotechnical investigation results indicated that the waste dump subsoil profile was inhomogeneous and had various moisture contents. Different types of mine waste materials have been deposited in the dumpsite over time. This variation in waste dump material types can cause inconsistencies in the subsoil profile. T deposition of waste materials within the swamp areas in the mine dur led to the presence of weak degraded claystone layer above the ha foundation. In the waste dump mining area, the perched water table c be formed when impermeable materials like clay or waste rock create barrier that prevents downward water movement. Rainfall over t catchment area caused water to infiltrate through the waste dump and get trapped above less permeable layers, leading to the formation of t perched saturated zones over time, resulting in a significant rise in t perched water surface. The inadequate drainage system of the dumpsi was found during the investigation. Hence, the seepage force or the fect of the perched water might be the cause of the slope failure.

The reduced shear strength of the degraded clay layer, which exist between the original foundation and the waste dump body, might be t other potential cause of slope failure. The waste dump slope's ma failure mode was an active/passive wedge failure, the slide of which w initiated at the toe of the slope and moved along the clay baseme Tension cracks were then generated at the rear part of the slope. U stable mass collapsed along tension cracks. The moving mass w

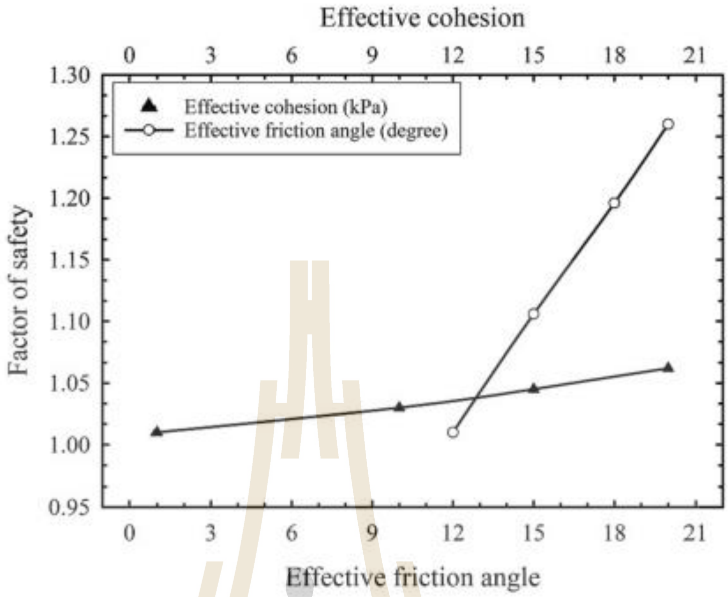


Fig. 15. Influence of effective cohesion and friction angle of weak clay layer on the factor of safety of waste dump.

divided into an upper active and lower passive wedges. The active wedge pushed a passive wedge horizontal movement in the two-wedge failure mode.

This study will provide more guidance to facilitate the geotechnical and mining engineering team to efficiently find short-term and long-term remediation solutions and to access the long-term implications for waste dump up to the target height.

CRediT authorship contribution statement

Menglim Hoy: Writing – original draft, Supervision, Formal analysis. **Cong Bien Doan:** Writing – original draft, Investigation. **Suksun Horpibulsuk:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Apichat Suddeepong:** Methodology, Conceptualization. **Artit Udomchai:** Methodology, Investigation, Data curation, Conceptualization. **Apinun Buritatum:** Methodology, Investigation, Formal analysis. **Apipat Chaiwan:** Investigation, Data curation, Conceptualization. **Prajueb Doncommul:** Project administration, Funding acquisition. **Arul Arulrajah:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was financially supported by Electricity Generating Authority of Thailand under contract no 64-G201000-11-IO. SS03G3008566 and Suranaree University of Technology.

References

Afiri, R., Gabi, S., 2018. Finite element slope stability analysis of Souk Tleta dam by shear strength reduction technique. Innov. Infrastruct. Solut. 3 (1), 1–10.

Albataineh, N., 2006. Slope Stability Analysis Using 2D and 3D Methods. University of Akron.

Al-Fares, W., Al-Hilal, M., 2018. Integration of electrical resistivity tomography with electromagnetic and soil radon measurements for characterizing the leakage problem in Afamia B dam, Syria. Geofis. Int. 57 (4), 275–287.

Bishop, A.W., 1955. The use of the slip circle in the stability analysis of slopes. Geotechnique 5 (1), 7–17.

Brinkgreve, R.B., 2005. Selection of soil models and parameters for geotechnical engineering application. In: Soil Constitutive Models: Evaluation, Selection, and Calibration (pp. 69–98).

Edwards, L., 1977. A modified pseudosection for resistivity and IP. Geophysics 42 (5), 1020–1036.

Giasi, C., Masi, P., Cherubini, C., 2003. Probabilistic and fuzzy reliability analysis of a sample slope near Aliano. Eng. Geol. 67 (3–4), 391–402.

Goh, A.T., Zhang, W., Wong, K., 2019. Deterministic and reliability analysis of basal heave stability for excavation in spatial variable soils. Comput. Geotech. 108, 152–160.

Janbu, N., 1954. Application of composite slip surface for stability analysis. In: Proceedings of European Conference on Stability of Earth Slopes, Sweden, 1954.

Jefferies, M., Lorig, L., Alvarez, C., 2008. Influence of rock-strength spatial variability on slope stability. In: Hart, R., Detournay, C., Cundall, P. (Eds.), Continuum and Distinct Element Numerical Modeling in Geo-Engineering. Proceedings first International FLAC/DEM Symposium on Numerical Modeling.

Kasmer, O., Ulusay, R., Gokceoglu, C., 2006. Spoil pile instabilities with reference to a strip coal mine in Turkey: mechanisms and assessment of deformations. Environ. Geol. 49 (4), 570–585. https://doi.org/10.1007/s00254-005-0092-1.

Krahn, J., 2003. The 2001 RM Hardy Lecture: the limits of limit equilibrium analyses. Can. Geotech. J. 40 (3), 643–660.

Mikkelsen, P., Green, G.E., 2003. Piezometers in fully grouted boreholes. In: FMGM-field Measurements in Geomechanics, Oslo, Norway.

Morgenstern, N.U., Price, V.E., 1965. The analysis of the stability of general slip surfaces. Geotechnique 15 (1), 79–93.

Ngo, D.H., Horpibulsuk, S., Suddeepong, A., Samingthong, W., Udomchai, A., Doncommul, P., Arulrajah, A., Bo, M.W., 2020. Full scale consolidation test on ultra soft soil improved by prefrabricated vertical drains in Mae Moh mine, Thailand. Geotext. Geomembr. https://doi.org/10.1016/j.geotexmem.2020.09.005.

Ouyang, C., Zhou, K., Xu, Q., Yin, J., Peng, D., Wang, D., Li, W., 2017. Dynamic analysis and numerical modeling of the 2015 catastrophic landslide of the construction waste landfill at Guangming, Shenzhen, China. Landslides 14 (2), 705–718.

Pasierb, B., Grodecki, M., Gwóźdź, R., 2019. Geophysical and geotechnical approach to a landslide stability assessment: a case study. Acta Geophys. 67 (6), 1823–1834.

Porras, D., Carrasco, J., Carrasco, P., González, P.J., 2022. Imaging extensional fault systems using deep electrical resistivity tomography: a case study of the Baza fault, Betic Cordillera, Spain. J. Appl. Geophys. 202, 104673. https://doi.org/10.1016/j.jappgeo.2022.104673, 2022/07/01/.

Poulsen, B., Khanal, M., Rao, A.M., Adhikary, D., Balusu, R., 2014. Mine overburden dump failure: a case study. Geotech. Geol. Eng. 32 (2), 297–309. https://doi.org/10.1007/s10706-013-9714-7.

Read, J., Stacey, P., 2009. Guidelines for Open Pit Slope Design.

Richards, B.G., Coulthard, M.A., Toh, C.T., 1981. Analysis of slope stability at Goonyella Mine. Can. Geotech. J. 18 (2), 179–194. https://doi.org/10.1139/t81-023.

Simmons, J.V., McManus, D.A., 2004. Shear strength framework for design of dumped spoil slopes for open pit coal mines. In: Advances in Geotechnical Engineering: The Skempton Conference. Thomas Telford Publishing, pp. 981–991. https://doi.org/10.1680/aigev2.32644.0026.

Songtham, W., Ratanasthien, B., Watanasak, M., Mildenhall, D.C., Singharajwarapan, S., Kandharosa, W., 2005. Tertiary basin evolution in northern Thailand: a palynological point of view. Nat. Hist. Bull. Siam Soc. 53 (1), 17–32.

Steiakakis, E., Kavouridis, K., Monopolis, D., 2009. Large scale failure of the external waste dump at the "South Field" lignite mine, Northern Greece. Eng. Geol. 104 (3–4), 269–279. https://doi.org/10.1016/j.enggeo.2008.11.008.

Suzuki, K., Toda, S., Kusunoki, K., Fujimitsu, Y., Mogi, T., Jomori, A., 2000. Case studies of electrical and electromagnetic methods applied to mapping active faults beneath the thick quaternary. In: Kanaori, Y., Tanaka, K., Chigira, M. (Eds.), Developments in Geotechnical Engineering, vol. 84. Elsevier, pp. 29–45. https://doi.org/10.1016/S0165-1250(00)80005-X.

Tapia, A., Contreras, L., Jefferies, M., Steffen, O., 2007. Risk evaluation of slope failure at the Chuquicamata Mine. In: Slope Stability 2007: Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.

Thompson, S., Kulessa, B., Luckman, A., 2012. Integrated electrical resistivity tomography (ERT) and self-potential (SP) techniques for assessing hydrological processes within glacial lake moraine dams. J. Glaciol. 58 (211), 849–858.

Touch, S., Pongpanlarp, P., Pipatpongsa, T., Takemura, J., 2015. Underground water in open pit mining at Mae Moh mine of Thailand. ASEAN Eng. J. 4 (1), 126–143.

Udomchai, A., Horpibulsuk, S., Suksiripattanapong, C., Mavong, N., Rachan, R., Arulrajah, A., 2017. Performance of the bearing reinforcement earth wall as a retaining structure in the Mae Moh mine, Thailand. Geotext. Geomembr. 45 (4), 350–360. https://doi.org/10.1016/j.geotexmem.2017.04.007, 2017/08/01/.

Wan, M.S., Standing, J.R., 2014. Lessons learnt from installation of field instrumentation. Proceed. Inst. Civil Eng. Geotech. Eng. 167 (5), 491–506.

Wang, J., Chen, C., 2017. Stability analysis of slope at a disused waste dump by two-wedge model. Int. J. Min. Reclam. Environ. 31 (8), 575–588. https://doi.org/10.1080/17480930.2016.1270498, 2017/11/17.

Wang, W., Griffiths, D.V., 2019. Case study of slope failure during construction of an open pit mine in Indonesia. Can. Geotech. J. 56 (5), 636–648. https://doi.org/10.1139/cgj-2017-0662.

Wang, G., Sassa, K., 2003. Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content. Eng. Geol. 69 (1), 109–125. https://doi.org/10.1016/S0013-7952(02)00268-5, 2003/04/01/.

Xu, B., Low, B., 2006. Probabilistic stability analyses of embankments based on finite-element method. J. Geotech. Geoenviron. Eng. 132 (11), 1444–1454.

Zarlin, N., Sasaoka, T., Shimada, H., Matsui, K., 2012. Numerical study on an applicable underground mining method for soft extra-thick coal seams in Thailand. Engineering 04 (11), 739–745. https://doi.org/10.4236/eng.2012.411095.

Zevgolis, I.E., Deliveris, A.V., Koukouzas, N.C., 2019. Slope failure incidents and other stability concerns in surface lignite mines in Greece. J. Sustain. Min. 18 (4), 182–197. https://doi.org/10.1016/j.jsm.2019.07.001, 2019/11/01/.

Zhan, L.-T., Zhang, Z., Chen, Y.-M., Chen, R., Zhang, S., Liu, J., Li, A.-G., 2018. The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. Eng. Geol. 238, 15–26.

Zhang, W., Goh, A.T., 2012. Reliability assessment on ultimate and serviceability limit states and determination of critical factor of safety for underground rock caverns. Tunn. Undergr. Space Technol. 32, 221–230.

Zienkiewicz, O.C., Humpheson, C., Lewis, R.W., 1975. Associated and non-associated visco-plasticity and plasticity in soil mechanics. Geotechnique 25 (4), 671–689. https://doi.org/10.1680/geot.1975.25.4.671.

KKU International Engineering Conference 2021 (KKU-IENC2021)
May 12-14, 2021 - Khon Kaen, Thailand

Large scale failure of waste dump at the Mae Moh open-pit lignite mine, Thailand

Bien Cong Doan[1)], Suksum Horpibulsuk*[1, 2, 3)], Menglim Hoy[1, 2)]

[1)]School of Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand
[2)]Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand
[3)]Academy of Science, Royal Society of Thailand, Bangkok, 10300, Thailand

*Corresponding author. Tel.: +08 9767 5759
Email address: suksun@g.sut.ac.th

Abstract

This paper presents the failure mechanism of a waste dump of the Mae Moh Mine, the largest open-pit mine in Thailand. The spoil material excavated from the mine was deposited in a dumping area where is around a coal mine. The rapid dumping rate of 20 m in a month caused the accumulation of excess pore water pressure in the low permeability of mine soils. The absence of compaction on fill materials leads to low relative density and is more likely to displace vertically at the crest. The high moisture content at the base of the dump and the giant of the deposit, forming the development of pore water pressure of clayed soil in the base. As a consequence, a huge mass of overburden over an area of 1.56 km2 occurred during the routine activity of dumping at the 6th-bench of the slope. After the waste dump failure event, the in-situ investigation was performed and geotechnical instrumentation was carried out. This research study confirms the potential factors that developed in the deposit led waste dump to failure.

Keywords: Coal mine, Slope stability, Waste dump failure, Mae moh mine

1. Introduction

The Mae Moh Mine is one of the currently largest open-pit lignite mines in Southeast Asia. It is situated in the Mae Moh District, Lampang Province, Thailand. The surface lignite mine area and external spoil dumping area approximate 38 km2 and 42 km2, respectively (Fig. 1). At the present rate of extraction, nearly 45,000 tons of produced annually, which accounts for 70% of the total lignite production of Thailand [1]. The mine has been commencing since 1955. The Electricity Generating Authority of Thailand (EGAT) owns and manages the Mae Moh Mine as well as its operation of the power plant to generate electricity of 2,400 Megawatts, which contributes to 20-30% of domestic electricity command [2].

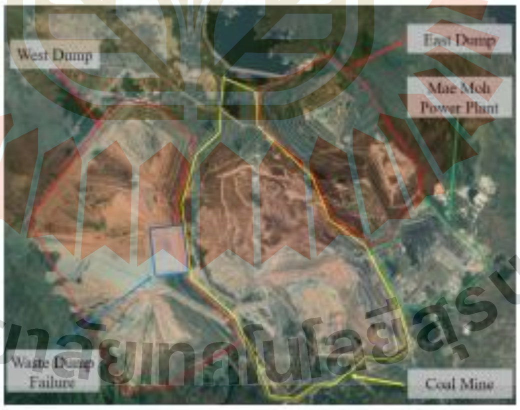


Figure 1 Location of Mae Moh Mine

On 18th March 2018, as reported by EGAT, a massive scale failure occurred in system A of the west dump area (Fig. 2). The instability initiated as the excavated soil was spreading at the 6th-bench slope. The high of dumping area is approximately 135 m from the base of the deposit, a width of 1300 m and 1200 m in length. The landslide involved the mobilization of debris in the order of 70,000,000 m3. The central failure was moved away and reached a distance of 250 m from the original location. The inclination of the lignite interface is about 3 degrees.

Figure 2 Aerial view of the large West waste dump failure at Mae Moh Mine

From literature review, several researchers have reported that there is increasing the failure of open-pit dumps in the world [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. For instance, the overburden dump failed at Indian Colliery was documented that the spoil was displaced about 70 m from the original foot by reason of foundation soil failure, sufficient spoil strength [17]. A large scale of the external waste dump in Northern Greece was taken place in 2004 [18]. It was found that increase in pore water pressure caused the deposit to flow a mass of 40,000,000 m3 up to 300 m from the foot. The Hellenic Public Power Corporation (PPC) lignite mines in Greece revealed that the majority factor induces instability of waste dump is the inclination of original ground and clayed soil strata placed either marginally above or below the toe [19]. The spoil piles failure at the Gooneylla Mine in central Queensland, Australia was studied using accurate surface surveying and it was stated that the collapse developed along bi-linear surface (Fig. 3). This is because of the two reasons that reduction in shear strength of moisture sensitive material at the toe and cracking at the upper of waste dump due to consolidation [20]. Groundwater infiltration is partly responsible for slope instability. It was mentioned in some previously studies that water infiltrated into open faults and joints, as a result, causing serious movement problems on the deposit [21, 22]. Based on comprehensive review of field study and laboratory testing, the cracking on the crest and heaving at the toe of slope might be derived from mining activities as horizontal stress relief [23].

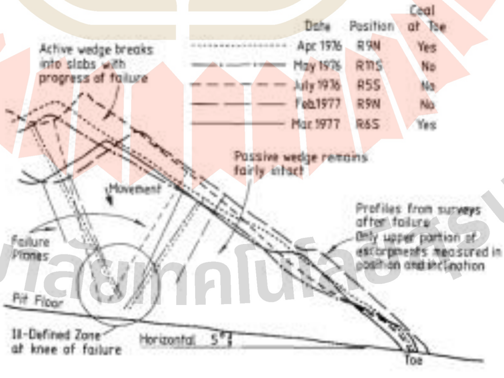


Figure 3 Monitoring results of a large overburden dump failure at Goonyella Mine, Australia [20]

As claimed by the planning of EGAT, the mine will be extracted down to a depth of closely 500 m from the original surface in the next four decades and will become the deepest surface lignite in the world. The coal by-products from mining activities will be transferred to the external waste dump area by a conveyor system and spreaders are used for dumping. As a result, the stability problems of the waste dump are becoming a challenging issue for EGAT from a geotechnical perspective. From these considerations above, it is apparent that the extensive implementation of geotechnical engineering plays the leading role in the stabilization of the dumping area for the future.

2. Field case study

2.1 Description of the failure

The west dump site was started to put into use in 1992. The enormous proportion of excavated soil was placed into a river and caused the elevation of water flow from +326 m to approximately +340 m in 1995. The northwest dump failure collapsed on 18th March 2018 in the dry season, measuring about 1.2 km by 1.3 km and 135 m high. Prior to failure, the stacker was fed with excavated material from the belt conveyor at roughly +465 m at the crest while the dump toe was approximately +330 m. According to EGAT's estimation, the failure mass was 70,000,000 m^3 which divided into three main areas (Fig. 4).

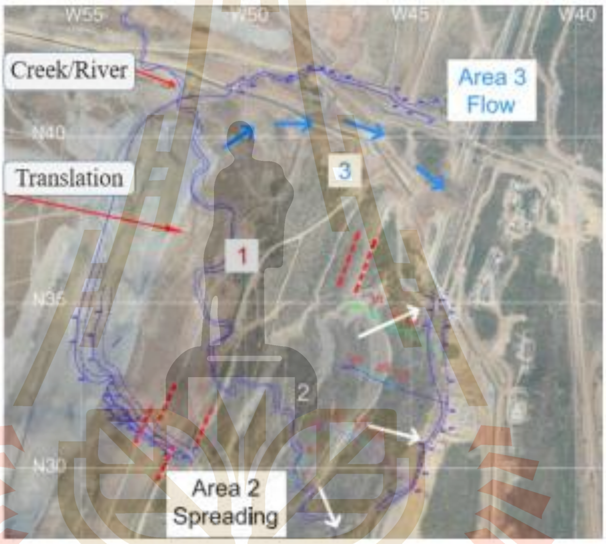


Figure 4 Development of west waste dump failure

As field observations declared that the main body Area 1 stayed intact and slipped between 35 and 50 m by lateral translation sliding. Area 2 failed by spreading from 200 to 300 m compared with the original location and a sigh of mudflow was visible at the toe of the deposit. Area 3 collapsed immediately after the main body had moved and mudflow also showed on the surface. As specified that it was a river beneath the dump. From that it can be explained why water flow presented at the base. The geotechnical investigations have confirmed that the basal dump layer was predominantly clayed soil. Based on borehole data obtained from the Electricity Generating Authority of Thailand (EGAT), the spoil waste layer commonly comprises of friable clay and the excavated material in the deeper layers showed the higher moisture content and higher degree of saturation.

KKU International Engineering Conference 2021 (KKU-IENC2021)
May 12-14, 2021 - Khon Kaen, Thailand

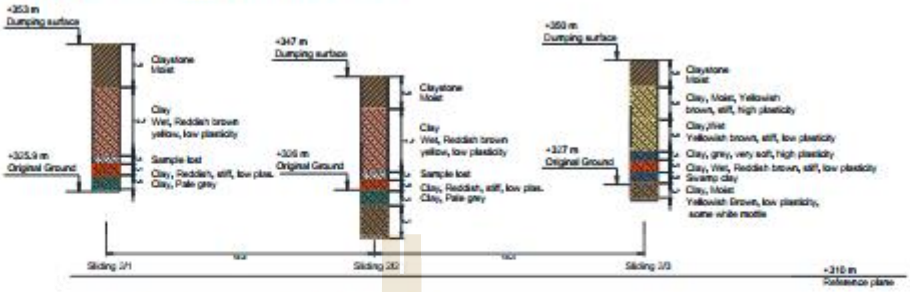


Figure 5 Soil boring log of sliding borehole at row 2

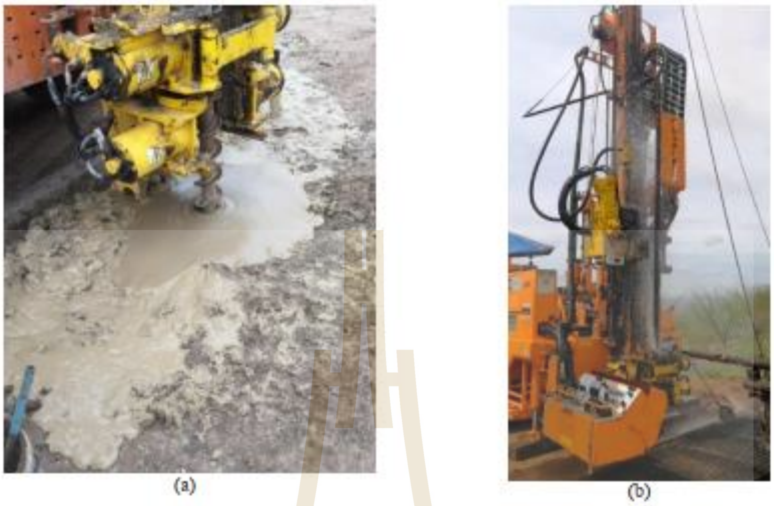
The location of sliding borehole at row 2 is shown in Fig. 4. It can be seen that figure 5 illustrates soil profile of the first bench slope after the failure event. The borehole indicated that the fill materials within a depth of 0-8 m were relatively moist claystone. Underneath the claystone is approximately 12 meters of clay. The 3-5 m thickness of soft soil is above the original ground (Fig. 6).

(a) (b) (c)

Figure 6 Soil exploration of sliding 2/3 borehole (a) 0-8 m thickness Claystone (b) 12-13 m thickness Clay (c) 3-5 m thickness softclay

The mudflow yellow clay appeared during drilling by the auger hole method at the first bench which has an overall thickness of from 10 to 20 m (Fig. 7 a). Borehole samples of toe layer were wet and loose to medium state sandy soil with the value Standard Penetration Test (SPT-value) from 8 to 30 blow counts. At the borehole B3 (figure 8), water within the deposit was gushed due to high excess pore water pressure (Fig. 7 b).

KKU International Engineering Conference 2021 (KKU-IENC2021)
May 12-14, 2021 - Khon Kaen, Thailand



(a) (b)

Figure 7 Photos of representative borehole installation: (a) At the first bench; (b) At the B-3 borehole

2.2 Early studies and investigations

After the occurrence of slope failure, in-situ surveying was carried out to characterize the failure mechanism of west dumping area. A layout of the instrumentation is presented in Fig. 8.

Figure 8 A layout of instrumentation at waste dump failure

At location within collapse region, a total of 23 boreholes were conducted, nine of which enable pore water pressure measurement to be installed, including four boreholes of vibrating-wire piezometer and five of standpipe piezometer boreholes, each borehole has one or more instruments. Figure 9 shows the detailed piezometers descriptions. Among other boreholes, Standard Penetration Test (SPT) was carried out in accordance with ASTM – D 1586, in order to specify the state of overburden soil. To perform SPT, a borehole was explored by drilling rigs and then 5.1 cm diameter of a slit-spoon sampler was lowered into the borehole. The number of blows is the sum of last two increments of 30 cm, guided by a 63.5-kg of doughnut hammer falling from a height of 67 cm.

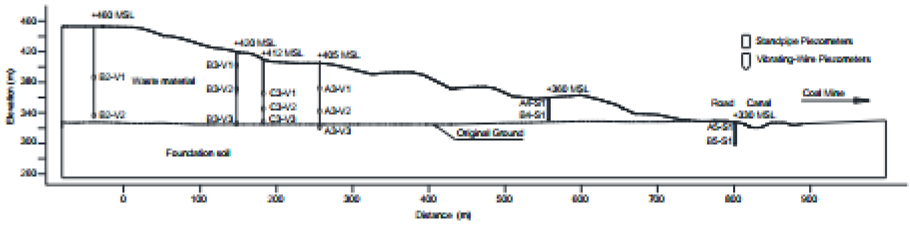


Figure 9 Cross-section of installed piezometers of the waste dump failure

In this project, the vibrating-wire piezometer boreholes were backfilled fully with cement-bentonite grout (B2, B3, C3, and A3). A cement-bentonite grout mixture is one of the most dependable method to measure pore water pressure as a reading of piezoelectric sensor without notable time-lag [24, 25]. 11 piezometer sensors at different depths, were positioned within overburden material and at the original ground (B2-V2, B3-V3, C3-V3, and A3-V3). The standpipe piezometer consists of 21 m of riser pipe made from PVC plastic pipe and filter tips backfilled with sand to generate 8 m long of granular filters. Cement grout was refilled into the remaining length of the borehole. The four conventional standpipe piezometer boreholes were mostly placed at the first bench (B4, A4) and at the foot (A5, B5) to observe water level.

3. Results and discussion

With the aim of obtaining information on the relative density of fill materials, four standard penetration tests were conducted at the toe of the slope to identify the number of blows (N) with depth (Fig. 10). The location of standard penetration tests is marked in Fig. 8.

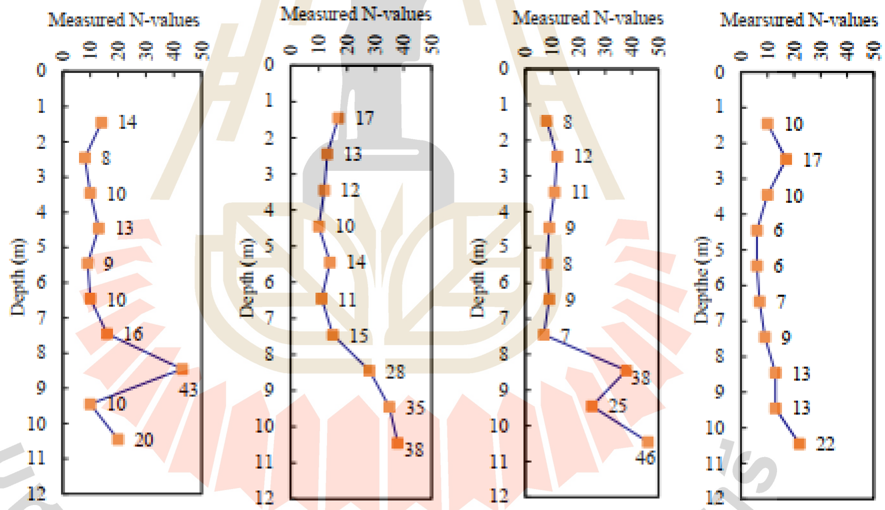


Figure 10 The number of blows with depth at the toe of the deposit from stadard penetration tests

Based on the field investigation, the soil layer at the toe of the deposit above the sliding surface indicated saturated state. It is noted that the number of SPT blows increased slightly from the ground surface to a depth of 10 m. The N-value measured from ground surface to a depth of 8 m was generally 6 to 10. It is classified as a loose state. At the depth deeper than 8-10 m where is diversion canal was mostly greater than 10, expressing as medium-dense sate. Some abnormal measured points with an extremely high N-value might be attributed to a sizable rigid material such

KKU International Engineering Conference 2021 (KKU-IENC2021)
May 12-14, 2021 - Khon Kaen, Thailand

as claystone, rock. For example, at a depth of 8.45 m in the drilled hole SPT-1, the cone tip came up against big-size claystone and reached a number of blows of 43 and then dropped to 10 blows at a depth of 9.45 m.

Piezometers were placed at different depths as well as at various locations. The vibrating-wire piezometer is denoted as B-V which stands for the name of the borehole and the name of vibrating-wire piezoelectric sensor position. Similarly, the other B-S is also the name of the boreholes and the name of the standpipe piezoelectric sensors spot. The ratio of measured water level to ground elevation versus rainfall monitoring using vibrating-wire piezometer is represented in Fig. 11.

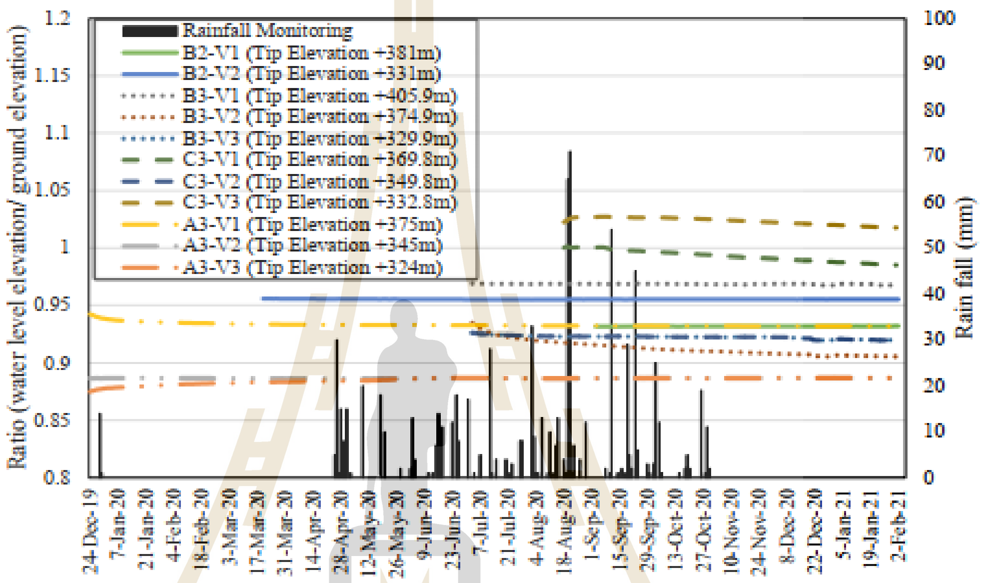


Figure 11 Measurements of water level using vibrating-wire piezometers

As it can be seen that figure 11 shows the ratio of boreholes inside the failure area is higher than that outside. All of sensors show that the water level remains unchanged during a year. The record from piezoelectric sensors of C3-V1 and C3-V3 installed in the borehole C3 indicated that high excess pore water pressure appeared during the process of dumping of excavated material, about 0.98 and 1.01, respectively. The ratio of water level to ground elevation of B3-V3 and C3-V3 sensors inside the failure area are higher than A3-V3, where is located out of that area. It was around 0.92 of B3-V3 in comparison with 0.88 of A3-V3.

The relationship between ratio of water level elevation to ground elevation and rainfall monitoring using standpipe piezometers is described in Fig. 12. From the graph, it is conspicuous that the water level appeared closely beneath the ground level. For instance, the proportion at borehole B-4 was approximately 1, around +354 m at the first bench slope, about 6 meter under the ground surface. A +329 m of water level observed while the elevation of toe of slope was +330 m as the ratio is relatively 1. It is noted that water level increased slightly during the dry season due to the low permeability of waste material. From that, slope failure incidents might take place after raining season[26].

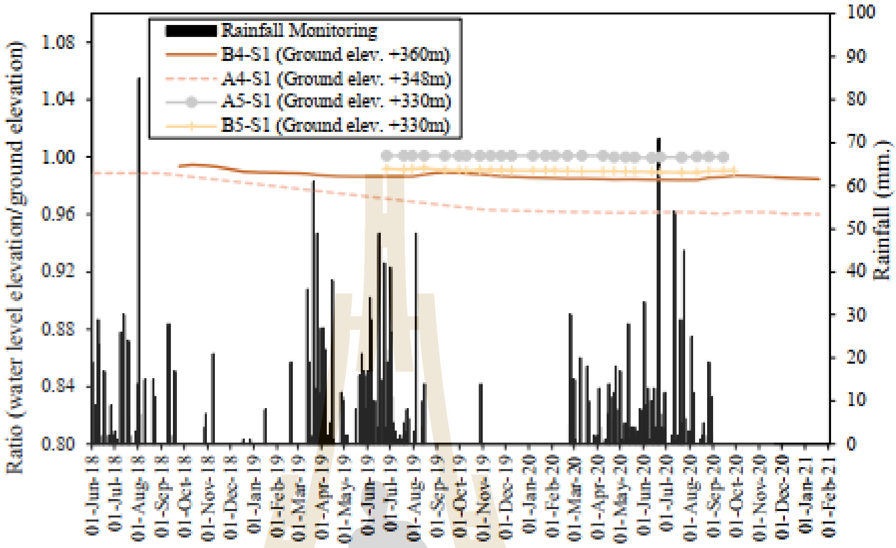


Figure 12 Measurements of water level using standpipe piezometers

4. Conclusions

In an effort to investigate the failure of waste dump, the primary conclusions from this study can be drawn as follows:

- As mentioned by the Electricity Generating Authority of Thailand (EGAT), the mine will be excavated larger and deeper up to the depth of 500 m. As a result, the planning and operation of waste dump are becoming more demanding and challenging in order to prevent any failure.
- Inadequate drainage system was established at the dumpsite. A great quantity of water from catchment area flowed into the dump, resulting in a significant rise in the water surface. From that, seepage failure might occur at the bottom of the dump.
- Based on geotechnical instrumentation, it is revealed that a reduction in shear strength of basal soil and mudflow occurred at the base of the dump due to wetting. Furthermore, dumping activity at the crest raised by 20 m of material in one month which may lead to growth of high excess pore water pressure. The emergence of wet excavated soil and the high water pressure of the deposit caused the overburden dump to collapse.

5. Acknowledgments

This work was supported by Electricity Generating Authority of Thailand (EGAT) and completed under the assistance of Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology.

6. References

[1] Udomchai A, Horpibulsuk S, Suksiripattanapong C, Mavong N, Rachan R, Arulrajah A. Performance of the bearing reinforcement earth wall as a retaining structure in the Mae Moh mine, Thailand. Geotextiles and Geomembranes. 2017;45(4):350-60.

[2] Punyawadee V, Pothisuwan R, Winichaikule N, Satienperakul K. Costs and benefits of flue gas desulfurization for pollution control at the Mae Moh power plant, Thailand. ASEAN Economic Bulletin. 2008:99-112.

[3] Kasmer O, Ulusay R, Gokceoglu C. Spoil pile instabilities with reference to a strip coal mine in Turkey: mechanisms and assessment of deformations. Environmental geology. 2006;49(4):570-85.

[4] Dassanayake A, Phien-Wej N, Giao P. Groundwater flow modeling and slope stability analysis for deepening of Mae Moh open pit lignite min. Geotechnical Engineering Journal of the SEAGS and AGSSEA. 2016;47(3):101-15.

[5] Ngo DH, Horpibulsuk S, Suddeepong A, Hoy M, Udomchai A, Doncommul P, et al. Consolidation behavior of dredged ultra-soft soil improved with prefabricated vertical drain at the Mae Moh mine, Thailand. Geotextiles and Geomembranes. 2020;48(4):561-71.

[6] Bar N, Baczynski N, editors. Understanding and modelling a highly ductile 25+ years old active-passive landslide at Ok Tedi Mine in Papua New Guinea. Workshop on World Landslide Forum; 2017: Springer.

[7] Zhan L-t, Zhang Z, Chen Y-m, Chen R, Zhang S, Liu J, et al. The 2015 Shenzhen catastrophic landslide in a construction waste dump: Reconstitution of dump structure and failure mechanisms via geotechnical investigations. Engineering Geology. 2018;238:15-26.

[8] Tzampoglou P, Loupasakis C. Evaluating geological and geotechnical data for the study of land subsidence phenomena at the perimeter of the Amyntaio coalmine, Greece. International Journal of Mining Science and Technology. 2018;28(4):601-12.

[9] Leonardos M, Terezopoulos N. Rim slope failure mechanism in the Greek deep lignite mines–a case study. Mining Technology. 2003;112(3):197-204.

[10] Kainthola A, Verma D, Gupte S, Singh T. A coal mine dump stability analysis—a case study. Geomaterials. 2011;1(01):1.

[11] Igwe O, Chukwu C. Slope stability analysis of mine waste dumps at a mine site in Southeastern Nigeria. Bulletin of Engineering Geology and the Environment. 2019;78(4):2503-17.

[12] Koner R, Chakravarty D. Numerical analysis of rainfall effects in external overburden dump. International Journal of Mining Science and Technology. 2016;26(5):825-31.

[13] Rajak TK, Yadu L, Chouksey SK, Dewangan PK. Stability analysis of mine overburden dump stabilized with fly ash. International Journal of Geotechnical Engineering. 2018:1-11.

[14] Wang Y-k, Sun S-w, Liu L. Mechanism, Stability and Remediation of a Large Scale External Waste Dump in China. Geotechnical and Geological Engineering. 2019;37(6):5147-66.

[15] Zarlin N, Sasaoka T, Shimada H, Matsui K. Numerical study on an applicable underground mining method for soft extra-thick coal seams in Thailand. 2012.

[16] Prountzopoulos G, Fortsakis P, Marinos V, Marinos P. A large scale landslide in a coal mine in marly formations: Evaluation, analysis and rehabilitation. ISSMGE International Journal of Geoengineering Case Histories. 2017;4(1):29-45.

[17] Poulsen B, Khanal M, Rao AM, Adhikary D, Balusu R. Mine overburden dump failure: a case study. Geotechnical and Geological Engineering. 2014;32(2):297-309.

[18] Steiakakis E, Kavouridis K, Monopolis D. Large scale failure of the external waste dump at the "South Field" lignite mine, Northern Greece. Engineering Geology. 2009;104(3-4):269-79.

[19] Kavvadas M, Roumpos C, Schilizzi P. Stability of Deep Excavation Slopes in Continuous Surface Lignite Mining Systems. Geotechnical and Geological Engineering. 2020;38(1):791-812.

[20] Richards B, Coulthard M, Toh C. Analysis of slope stability at Goonyella Mine. Canadian Geotechnical Journal. 1981;18(2):179-94.

[21] Vassilis M, Theodoros T, Spyridon P, Panagiotis T, Alexandros C, Konstantinos V. Large Induced Displacements and Slides Around an Open Pit Lignite Mine, Ptolemais Basin, Northern Greece. Engineering Geology for Society and Territory-Volume 2: Springer; 2015. p. 311-5.

[22] Anagnostopoulos A. The Mechanical Behaviour of the Megalopolis Lignites: Thesis presented to the National Technical University of Athens for the ...; 1979.

[23] Monopolis D, Stiakakis E, Agioutantis E, Kavouridis C. Geotechnical investigation at lignite mines. Mineral Resources Engineering. 1999;8(04):405-18.

[24] Wan MS, Standing JR. Lessons learnt from installation of field instrumentation. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering. 2014;167(5):491-506.

[25] Mikkelsen P, Green GE. Piezometers in fully grouted boreholes. FMGM-field measurements in geomechanics, Oslo, Norway. 2003.

[26] Rahardjo H, Nio AS, Leong EC, Song NY. Effects of groundwater table position and soil properties on stability of slope during rainfall. Journal of geotechnical and geoenvironmental engineering. 2010;136(11):1555-64.

BIOGRAPHY

Mr. Cong Bien Doan was born on November 25, 1996, in Nam Dinh province, Vietnam. He obtained a Bachelor’s degree in Transportation Engineering, Vietnam-English Road & Bridge Construction program from the University of Transports and Communications, Ha Noi, Vietnam. After graduation, he studied at "Dunărea de Jos” University of Galati in Romania as an exchange student. In 2019, he received the award “Vithedbundit scholarship” for 2-year of master’s degree in the academic year 2019-2021, and studied at the School of Civil Engineering, Suranaree University of Technology, Thailand. During his master’s program, he first conducted research on recycled asphalt pavement project. Then he made a decision to take over an interesting geotechnical project “Investigation of a large-scale waste dump failure at the Mae Moh mine in Thailand” under an advisor of Assoc. Prof. Dr. Menglim Hoy and Co-advisor Prof. Dr. Suksun Horipibulsuk. During his master's program, he published one leading international journal paper and one international conference paper. He has worked at Nui Phao Mine in Vietnam, the world’s largest tungsten mine outside of China, as a senior geotechnical engineer since 2023.