HIGH-SPEED OCTREE DATA STRUCTURE FOR THREE-DIMENSIONAL (3D) GEOGRAPHICAL INFORMATION SYSTEM (GIS) SPATIAL ANALYSIS IN SLOPE STABILITY APPLICATION

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by

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LIST OF SYMBOLS

(ϕ)	Friction angle
W	Weight of the slice
θ	Angle of inclination
p	Depth level of the node
X_p	X axis
Y_p	Y axis
Z_p	Z axis
0d0	Decimal numbers
0b000	Binary Address
$\cup$	Union operation in set theory

LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AMD	Advanced Micro Devices
ASCE	American Society Of Civil Engineers
AVX	Advanced Vector Extensions
BEM	Boundary Element Method
BMI2	Bit Manipulation Instruction Set 2
CF	Carry Flag
CPU	Central Processing Unit
CSG	Constructive Solid Geometry
DEM	Digital Elevation Model
DEST	Destination
DOSM	Department Of Statistics Malaysia
DT	Delaunay Tetrahedralization
DTM	Digital Terrain Modellings
ESRI	Environmental Systems Research Institute
FEM	Finite Element Method
FOS	Factor of Safety
GDAL	Geospatial Data Abstraction Library
GIS	Geographic Information System
GRASS	Geographic Resources Analysis Support System
GSI3D	Geological Surveying And Investigation In 3-Dimensions
HSO	High-speed Octree
IDW	Inverse Distance Weighted
LEM	Limit Equilibrium Method

LIDAR	Light Detection And Ranging
LSB	Least Significant Bit
MSB	Most Significant Bit
PDAL	Point Data Abstraction Library
PDEP	Parallel Bits Deposit
PEXT	Parallel Bits Extract
ROC	Receiver Operating Characteristic
SDG	Sustainable Development Goal
SRC	Source
TEMP	Temporary
TEN	Tetrahedral Network
TIN	Triangular Irregular Networks
TP	Tri-Prism
TZCNT	Trailing Zero Count
VD	Voronoi Diagrams
WDI	World Development Indicators
XML	Extensible Markup Language
ZF	Zero Flag

STRUKTUR DATA OCTREE BERKELAJUAN TINGGI UNTUK ANALISIS SPATIAL SISTEM MAKLUMAT GEOGRAFI (GIS) TIGA-DIMENSI (3D) DALAM APLIKASI KESTABILAN CERUN

ABSTRAK

Sistem Maklumat Geografi (GIS) mampu memodelkan kompleksiti dunia sebenar dengan lebih tepat melalui analisis spatial tiga-dimensi (3D) berbanding pendekatan dua-dimensi (2D) tradisional, namun pendekatan ini memerlukan keperluan algoritma dan pengkomputeran yang tinggi, terutamanya untuk tugas kritikal seperti penilaian kestabilan cerun. Kebanyakan platform GIS semasa, mampu mengurus data 2D/2.5D secara efektif, tetapi kurang berupaya mengendalikan struktur data 3D sebenar dan sering memerlukan proses penukaran data kepada raster. Octree merupakan struktur asas untuk perwakilan tiga-dimensi tetapi implementasi Octree klasik menunjukkan prestasi lemah dalam pencarian jiran melalui kaedah rentasan pepohon (*tree traversal*) yang perlahan. Penyelidikan ini memperkenalkan struktur data Octree Berkelajuan Tinggi (HSO), yang direka untuk mengatasi batasan ini dengan mengintegrasikan prinsip Octree dengan teknik pengkomputeran moden. Pendekatan asas HSO menyimpan maklumat spatial tiga-dimensi secara langsung di dalam struktur data. Ia menggunakan sistem pengekodan binari 3-bit yang efisien pada setiap tahap hierarki untuk menentukan laluan nod. Implementasi 64-bit menjadi fokus penyelidikan ini kerana alamat nod dikodkan menggunakan integer 64-bit. Pilihan ini sangat penting; ia menyokong perwakilan hierarki yang mendalam sehingga 21 tahap dan memanfaatkan seni bina CPU 64-bit moden. Pengekodan 64-bit HSO membolehkannya memanfaatkan keupayaan CPU khusus melalui arahan BMI2 (*Bit Manipulation Instruction 2*) yang merangkumi arahan TZCNT, PEXT dan PDEP.

Arahan ini melakukan operasi peringkat bit (*bitwise*) berkelajuan tinggi secara langsung pada alamat nod 64-bit, membolehkan HSO menentukan alamat nod jiran, induk atau anak tanpa perlu melakukan operasi rentasan pepohon yang memakan masa. HSO mencapai kerumitan masa malar O(1) (constant time *complexity*) untuk penemuan jiran pada sebarang kedalaman Octree, yang mengatasi peningkatan kerumitan yang diperhatikan dalam kaedah klasik. Struktur HSO telah diuji pada analisis kestabilan cerun 3D dengan membandingkan keputusannya dengan modul GRASS GIS r.slope.stability yang sedia ada. Analisis empirikal mengesahkan bahawa analisis berasaskan HSO menghasilkan output yang setara dengan algoritma asal sambil mengekalkan ketepatan analisis. Ujian prestasi mendedahkan HSO berprestasi lebih baik daripada Octree tradisional dengan mempercepatkan penukaran data spatial ke dalam struktur Octree sebanyak 65% dan penukaran data spatial daripada data Octree memerlukan 85.84% kurang masa pemprosesan. Secara keseluruhan, keputusan menunjukkan HSO mencapai prestasi sehingga 7.06 kali lebih baik, khususnya bagi set data yang lebih besar, hasil daripada reka bentuk 64-bit yang dioptimumkan dan penggunaan arahan CPU moden.

HIGH-SPEED OCTREE DATA STRUCTURE FOR THREE-DIMENSIONAL (3D) GEOGRAPHICAL INFORMATION SYSTEM (GIS) SPATIAL ANALYSIS IN SLOPE STABILITY APPLICATION

ABSTRACT

Geographic Information Systems (GIS) can more realistically model real-world complexity through three-dimensional (3D) spatial analysis than traditional two-dimensional (2D) approaches, but this approach requires significant algorithmic and computational resources, particularly for critical tasks such as slope stability assessment. Most current GIS platforms effectively manage 2D/2.5D data but they experience difficulties when dealing with true 3D data structures and often need data conversion processes to the raster. The Octree stands as a basic structure for three-dimensional representation, but standard Octree implementations demonstrate poor performance in neighbour searches through their slow tree traversal method. This research introduces the High-Speed Octree (HSO) data structure, designed to overcome these limitations by integrating Octree principles with modern computational techniques. The fundamental approach of HSO stores three-dimensional spatial information directly within the data structure. The system uses an efficient 3-bit binary encoding system at every hierarchical level to determine node paths. The 64-bit implementation serves as the research focus since node addresses receive their encoding through 64-bit integers. This choice is pivotal; it supports deep hierarchical representation up to 21 levels and uses the capabilities of modern 64-bit CPU architectures. The 64-bit encoding of HSO enables it to use specialized CPU capabilities through BMI2 extensions which include TZCNT, PEXT and PDEP instructions. The instructions operate at high-speed to perform direct bitwise operations on 64-bit node addresses thus HSO avoids time-consuming tree traversal operations to determine neighbour, parent or child node addresses. The HSO achieves O(1) constant time complexity for neighbour discovery at any Octree depth which surpasses the complexity increase observed in classical methods. The HSO structure was tested on 3D slope stability analysis by comparing its results to the established GRASS GIS r.slope.stability module. The empirical analysis confirmed that HSO-based analysis generated outputs equivalent to the original algorithm while maintaining analytical accuracy. Performance tests revealed HSO performs better than traditional Octrees by speeding up spatial data conversion into the Octree structure by 65% and spatial data conversion from Octree data required 85.84% less processing time. The overall results showed HSO achieved better performance by 7.06 times compared to larger datasets because of its optimized 64-bit design and CPU instruction use.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Geographic Information Systems, commonly referred to as GIS, have undergone a profound transformation in how spatial data is collected, stored, and analysed. Initially perceived primarily as tools for map creation, GIS has evolved into entities that serve as nexuses for various disciplines, including environmental science, urban planning, and more (Longley et al., 2015). The utilization of GIS encompasses skills related to the manipulation, visualization, and analysis of spatial data, making them indispensable instruments for researchers, decision-makers, and industry professionals.

In the realm of geospatial information, GIS can be likened to substantial storage facilities. They enable the spatial linkage of diverse datasets, a pivotal aspect when addressing the intricacies of real-world issues (Goodchild, 2010). Such issues invariably involve multifaceted components that demand consideration, and GIS plays a vital role in offering a comprehensive perspective.

The core function of Geographic Information Systems (GIS) lies in spatial analysis, a wide-ranging field that uses various mathematical and statistical methods to derive insights from geographic data (Berry et al., 2007). While early techniques often involved simple tasks like point-in-polygon tests, advancements in computational power have enabled more complex operations such as kriging and network analysis. These techniques do not just manipulate geographical features; they also consider additional factors like attributes, topology, and time.

Nevertheless, two-dimensional (2D) spatial analysis has limitations. It struggles to fully capture complex geographic phenomena especially the conditions that occur on the sub-surface and are interacted with changes on the surface of the earth, such as landslides (Yanbing et al., 2007). With the rapid development of computer science and spatial information technology, has led to the integration of a multi-dimension in GIS, enabling three-dimensional (3D) spatial analysis. This analysis allows for more comprehensive and detailed understanding of geographical phenomena making it particularly valuable in fields such as geology, flood modelling and urban planning (Billen et al., 2008). This 3D approach also necessitates the development of algorithms and data structures to handle the increased computational complexity.

In the realm of construction engineering for large scale projects like highways and dams, accurate assessments of slope stability are absolutely vital. Incorrect evaluations can lead to loss of life and significant economic losses. Additionally mining and environmental studies highlight the importance of precise slope stability analyses due to their impacts, on both humans and ecosystems. Researchers analysing slope stability have traditionally used data structures like grids and TINs. The existing structures provide useful benefits, yet they produce substantial challenges. The computational inefficiency of these structures prevents timely analysis especially when applied to real-time applications. The representation of complex 3D terrains through these structures becomes problematic for precise geological modelling. The high memory requirements become a limitation when working with detailed data because it restricts the level of detail that can be achieved. The system encounters difficulties when dealing with complex spatial phenomena which prevents complete understanding of geospatial interactions. The inherent difficulties in these data structures have motivated researchers to investigate alternative data structures, including the Octree (Wu, 2010).

Octrees are specifically designed for managing 3D spaces. Efficiently divide these spaces into smaller sections making it easier to store and retrieve data. Their hierarchical design is particularly advantageous when dealing with tasks that require levels of detail. As real-time applications become increasingly important the need for fast data processing is also growing. In the context of slope stability real-time monitoring can provide warnings about potential failures and enable swift preventive actions. Octrees are well-suited for real-time applications due to their efficient architecture.

In summary, this research aims to combine Octree data structures with GIS to enhance slope stability assessments. While Octrees, GIS and slope stability have been studied before (Wu, 2010), their integration represents an innovative and potentially groundbreaking field. By bringing these elements, this research aims to develop a powerful and reliable tool for thorough slope stability evaluations. The potential impacts of this research extend beyond slope stability and could influence other areas.

1.2 Problem Statement

The technology behind Geographic Information Systems (GIS) has experienced continuous development throughout the years. GIS started as a tool for mapping but has transformed into a system which performs sophisticated spatial analysis. Three-dimensional (3D) spatial data represents a significant advancement in this field. The development has shown particular value in specific fields including geotechnical engineering where slope stability analysis is essential for construction engineering, mining and environmental science applications (Longley et al., 2015).

When it comes to slope stability analysis there are analytical requirements that set it apart from many other fields. This distinction stems from the nature of factors that influence slope stability. Elements such as layers, their orientation, moisture levels and seismic activities all contribute to the complexity of understanding slopes accurately. To achieve a precise understanding it is necessary to conduct 3D analysis (Cheng & Tong, 2019). However, transitioning from two-dimensional (2D), to three-dimensional (3D) spatial analysis does come with its challenges. The primary challenge lies in the demand it entails. Analysing data requires significantly more computational resources compared to its 2D counterpart. This demand becomes especially critical in real-time slope stability monitoring systems where rapid data processing's crucial.

In these systems the speed at which data is processed is not about being efficient; it has a direct impact on public safety. Currently the available tools for analysing slope stability are not satisfactory due to their nature. While some tools excel in collecting data others may be optimized for storage or analysis. The lack of a platform that effectively combines these functions creates challenges. This lack of integration hinders collaboration among experts from disciplines such as engineers, geologists, and policymakers. Consequently, there can be analyses that may lead to suboptimal or even hazardous decisions.

The research holds significant importance because of its social impact. Slope stability analyses that are inaccurate or delayed lead to catastrophic outcomes in both engineering and environmental science fields. The consequences of these events include both human casualties and property destruction as well as economic losses and environmental damage. Research needs to focus on resolving these essential problems. The findings from this research extend their value beyond the specific application in slope stability analysis. The development of data structures and algorithms for this research could help advance knowledge about 3D spatial analysis in GIS.

This research has the potential to impact the advancement of algorithms and computational methods in fields that heavily rely on spatial data, including urban planning, environmental monitoring and even disaster management. Considering the challenges and gaps identified, the main goal of this research is to develop an efficient Octree data structure specifically designed for 3D spatial analysis. The new structure has been designed to address the problems of the current methods such as grids. It promises a more efficient and flexible way of dealing with complex spatial data which is very useful in real-time processing applications.

This research has the potential to impact the advancement of algorithms andcomputational methods in fields that heavily rely on spatial data, including urbanplanning, environmental monitoring and even disaster management. However, significant challenges remain in efficiently handling complex 3D spatial data for such applications. Current methods using regular decomposition, like grids or voxels, present difficult trade-offs. Using coarse resolutions can obscure important terrain details vital for accurate analysis, such as those needed for slope stability assessment. Conversely, employing very fine resolutions to capture detail leads to substantial computational expense and large data volumes (Zhao et al., 2022). This highlights a critical gap: the need for data structures that offer a more efficient and flexible way to represent complex spatial data at varying levels of detail, particularly for demanding real-time or large-scale analyses.

1.3 Research Questions (RQ)

The research questions are addressed as follows:

RQ1. What is the most effective data structure for handling three-dimensional spatial data in slope stability analysis?

RQ2. Why are current data structures computationally inefficient when applied to 3D spatial analysis in slope stability, and how critical is this limitation?

RQ3. How can the selected data structure be effectively integrated into 3D slope stability analysis methodologies?

1.4 Research Aim

The main aim of this research is to make a pivotal contribution to the field of 3D spatial analysis, with a particular focus on its application in 3D slope stability analysis, through the identification, optimization, and effective integration of a suitable data structure. This research is driven by pressing needs in public safety and environmental conservation. Existing data structures often lack the computational agility and flexibility required for complex 3D spatial data, which becomes especially apparent in the specialized domain of 3D slope stability analysis. To navigate these challenges, the research initially aims to identify a data structure that is inherently aligned with the requirements of 3D slope stability analysis.

This identification will be informed by an exhaustive comparative analysis of existing data structures, concentrating specifically on their computational limitations when applied to 3D spatial analysis in 3D slope stability contexts. After identifying a suitable data structure, the research will pivot toward its optimization, focusing on enhancing computational efficiency by reducing time complexity and maximizing space utilization. Both theoretical modelling and empirical evaluations will be conducted to validate that the optimized data structure is mathematically rigorous and practically effective for 3D slope stability analysis. The culminating stage of the research will centre on the meticulous integration of this optimized data structure into existing frameworks tailored for 3D slope stability analysis.

This will necessitate scrutiny of algorithmic compatibility, data interoperability, and practicality. Prototypes will be developed to empirically validate this integration, establishing that the optimized data structure significantly elevates both the speed and reliability of 3D slope stability analyses. By addressing these specific challenges, the research aims to advance not only the academic landscape but also practical applications, notably in enhancing public safety through more reliable and efficient 3D slope stability assessments.

1.5 Research Objectives (RO)

Aligned with the overarching aim of advancing 3D spatial analysis in the specialized domain of 3D slope stability analysis, the research has established the following primary objectives:

RO1. To analyse existing data structures by conducting a comprehensive comparative study that evaluates their suitability for 3D spatial analysis in the context of 3D slope stability.

RO2. To propose an optimized data structure based on the analysis, focusing on improving key performance metrics such as speed, complexity and accuracy.

RO3. To apply the optimized data structure by implementing it into existing systems and methodologies used in 3D slope stability analysis, giving special attention to algorithmic compatibility and practicality.

1.6 Research Scope

This study aims to develop a High-Speed Octree (HSO) data structure by implementing it into 3D slope stability analysis. The research was conducted a thorough evaluation of available data structures. This part of the research relies on a variety of sources, including academic articles, foundational works, and case studies, to assess factors like speed, flexibility, and scalability.

Another key part of the research scope is computational efficiency. This is not just about how fast a system can run but also about the quality of the decisions it enables, particularly in situations with safety implications. To address this, the study uses both mathematical models and synthetic slope tests to measure performance, particularly focusing on time and memory usage.

The final aspect of the scope is the actual application of the chosen data structure. This involve using actual data or case studies related to slope stability to assess the structure's practical effectiveness. This step ensure that the research does not just remain a theoretical exercise but has practical implications for the field.

By focusing on these key areas, the research scope provides a clear plan for the study. It helps guide all phases of the research, from initial data gathering and analysis to the final, testing of the optimized data structure. Nevertheless, this study was subject to several limitations:

a) The research focuses on case studies or data sets relevant to 3D slope stability.

b) The study does not look at 2D models of spatial analysis, focusing solely on 3D analysis.

c) The research relies on both mathematical models and synthetic slope tests.

1.7 Research Contributions

The research contributions aim to address gaps and challenges in Geographic Information Systems (GIS) specifically focusing on three-dimensional (3D) spatial analysis in slope stability application. These contributions align with the objective of advancing the field of GIS and geotechnical engineering with a focus on both academic progress and societal impact.

Firstly, this study aims to advance methodologies in GIS in transitioning from two-dimensional (2D) to three-dimensional (3D) spatial analysis. Current methods often face limitations in efficiency and adaptability especially when it comes to specialized areas like slope stability analysis. This study tackles this issue by developing an optimized data structure called High-speed Octree (HSO) which is specifically designed for spatial analysis. The HSO data structure aims to overcome the limitations of existing approaches such as grids offering an effective and flexible method for handling complex spatial data.

Secondly the research contributes to the field of engineering by integrating the HSO data structure into 3D slope stability analysis using a GIS platform. This integration is significant because slope stability analysis requires analytical considerations due to various factors, like layers orientation, moisture levels and seismic activities. The integrated platform not only improves the speed and reliability of slope stability assessments but also has direct implications for the safety of the public and the conservation of the environment.

Another important contribution is how it helps experts from fields collaborate effectively. The current lack of tools that integrate all functionalities makes it difficult for engineers, geologists and policymakers to work together efficiently. This lack of integration can result in even dangerous decisions. The proposed HSO data structure aims to create a platform that combines data collection, storage and analysis seamlessly enabling better collaboration among interdisciplinary experts.

Moreover, this study seeks to have impacts beyond just slope stability analysis. The advancements in data structures and algorithms developed here could be applied to domains heavily reliant on spatial data like urban planning, environmental monitoring and disaster management. This can be particularly significant given the implications associated with these fields where inaccurate or delayed analyses can lead to severe consequences such as loss of life or economic and environmental damage.

Likewise, this study offers academic and practical contributions that are relevant towards the realization of a 3D GIS environment. It addresses existing gaps in spatial analysis methodologies while facilitating interdisciplinary collaboration and extending the applications to wider fields. This study has the ability to establish benchmarks for computational effectiveness and analytical precision in GIS and geotechnical engineering thus leaving a lasting impression on both the academic community and society, as a whole.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews existing studies relevant to this research. The goal is to provide a solid background by exploring the key areas that structure this chapter in a logical order. Understanding the current knowledge in these areas helps set the context for the research problem and highlights the specific areas this study aims to improve.

The review begins with the fundamentals of slope stability analysis. It follows the development from traditional two-dimensional methods to more advanced three-dimensional methods, which represent complex geological terrains more realistically. Different established methods in both two-dimensional and three-dimensional approaches are examined to understand their basic ideas, assumptions, and limitations, providing a necessary foundation for understanding the challenges in the field.

Building on this foundation, the chapter then explores the important role of Geographic Information Systems technology in slope stability assessment and geological modelling. It discusses how Geographic Information Systems helps combine, manage, and analyse different spatial datasets, which improves the accuracy and range of stability evaluations. This part also covers progress in three-dimensional geological modelling within Geographic Information Systems, noting the advancements made and the ongoing difficulties in achieving true three-dimensional analysis capabilities.

To effectively utilize Geographic Information Systems for these complex analyses, the way data is structured is critical. Therefore, the next important section focuses on how data is represented in Geographic Information Systems models. Since the quality of spatial analysis depends heavily on the underlying data structure, this part explores various models used to show three-dimensional geographic and geological features. It carefully reviews surface models, volumetric models, and hybrid approaches, assessing their strengths and weaknesses in showing complex underground details and how well they perform in tasks needing significant computer power, like slope stability analysis. This discussion includes specific attention to previous research on the Octree data structure, examining existing methodologies for its implementation and use.

Finally, by bringing together the information from these interconnected topics, this chapter provides the necessary theoretical background. It identifies the weaknesses in current methods and emphasizes why more efficient data structures, like the High-Speed Octree proposed in this research, are needed to improve three-dimensional Geographic Information Systems spatial analysis for slope stability applications.

2.2 Background and Importance of Slope Stability

According to reports from the (World Bank, 2021) and the Department of Statistics Malaysia (DOSM, 2021), there is a demand for land leading to the exploration and utilization of hilly terrains and slopes for various purposes like residential projects, agriculture and industrial setups. However, this development also brings about challenges related to slope stability and an increased risk of landslides in areas to geological and climatic vulnerabilities.

Ensuring slope stability is crucial when it comes to land development in regions with hills or mountains. Neglecting evaluations of slope stability can result in devastating landslides that have far reaching consequences such as loss of human lives damage to property and disruptions in infrastructure including transportation and utilities. Moreover, landslides can worsen environmental disasters by causing soil erosion lowering the water table and triggering flash floods thus contributing to cycles of environmental degradation.

A recent report, from Utusan Malaysia published on 12th March 2022 highlighted the existence of 1,045 slopes that need immediate attention. The estimated cost of RM978.8 million for surveillance preventive measures and repairs highlights the nature of this challenge and the need for adequate resources to mitigate risks. Given the relationship between population growth, land use and slope stability it is crucial to adopt a comprehensive interdisciplinary strategy for evaluating and preventing landslide risks. This strategy involves integrating surveys, hydrological modelling and engineering assessments from the early stages of development projects. Additionally, it is important to establish frameworks that enforce strict land use protocols and construction standards prioritizing slope stabilization and landslide prevention (Akter et al., 2019; Kirschbaum et al., 2010).

Kerja pencegahan seluruh negara perlu kos RM978.8 juta

1,045 cerun dikenal pasti berisiko runtuh

Utusan Malaysia 12 Mac 2022

Oleh MASZUREEN HADZMAN dan MOHAMAD HAFIZ YUSOFF BAKRI

utusannews@mediamulia.com.my

PETALING JAYA: Kedudukan pokok yang condong dan juga terdapat jatuhan batu-batu kecil di cerun antara tanda-tanda awal runtuhan tanah kemungkinan akan berlaku.

Bukan itu sahaja, hasil kajian Pasukan Bomba dan Penyelamat Malaysia mendapati, aliran air yang keluar dari tebing cerun selain bunyi pelik seolah-olah pokok tumbang dan batu jatuh juga antara petanda awal kejadian tanah runtuh.

Perkara ini jelas membimbangkan apabila melalui pemetaan bahaya dan risiko yang dibangunkan oleh Jabatan Kerja Raya Raya mendapati, sebanyak 1,045 cerun yang berada sepanjang Jalan Persekutuan di Semenanjung Malaysia berada dalam kategori berisiko tinggi untuk runtuh.

Mendedahkan kepada *Utusan Malaysia*, Menteri Kanan Kerja Raya, Datuk Seri Fadillah Yusof berkata, cerun-cerun yang dikenal pasti memerlukan pelaksanaan kerja-kerja pencegahan atau *preventive works* dengan menelan belanja yang tinggi dengan sekitar RM974.8 juta.

Kata beliau, apabila berlaku kejadian tanah runtuh, kebiasaannya kerja-kerja pembersihan akan mengambil masa selama tiga minggu.

"Selain itu, bagi proses perolehan bagi kerja-kerja pembaikan adalah selama tiga bulan dan kerja-kerja pembaikan akan mengambil masa dalam tempoh 10 bulan," katanya di sini semalam.

Mengulas lanjut, kata Fadillah, bagi mengenal pasti sama ada kawasan tersebut serta yang berhampiran benar-benar selamat diduduki atau tidak pemantauan akan dilakukan JKR bersama agensi-agensi lain berkaitan kerana ianya melibatkan kawasan pihak berkuasa tempatan.

"Untuk kejadian tanah runtuh di Ampang, JKR hanya dijemput oleh pihak PBT berkenaan untuk membantu mengenalpasti punca kejadian sahaja.

"Kawasan kejadian adalah di bawah bidang kuasa PBT," jelasnya.

Sementara itu, Pengarah Operasi Jabatan Bomba dan Penyelamat Malaysia (JBPM), Datuk Nor Hisham Mohammad ketika dihubungi *Utusan Malaysia* berkata, sebanyak 51 panggilan kecemasan diterima pihaknya membabitkan kegiatan tanah runtuh di seluruh negara sejak awal tahun ini sehingga 9 Mac lalu.

Kata beliau, daripada jumlah itu, panggilan tertinggi diterima adalah di Sarawak apabila sebanyak 21 kes dilaporkan diikuti masing-masing sembilan di Selangor dan Sabah.

"Selain itu, sebanyak lima panggilan kecemasan di terima di Kuala Lumpur diikuti Johor dan Negeri Sembilan masing-masing dua kes selain Pahang, Perak serta Pulau Pinang masing-masing satu.

"Sepanjang tempoh itu tiada kemalangan jiwa dilaporkan dan hanya membabitkan dua kecederaan sahaja," jelasnya.

Terbaharu, dalam kejadian kira-kira pukul 5 petang semalam, empat maut manakala seorang cedera selepas tertimbus dalam runtuhan tanah di Taman Bukit Permai 2, Ampang dekat sini.

Empat mangsa disahkan maut iaitu Chong Siew Kim, 85, diikuti E. Ramasamy, 58; A. Mahendran, 36, dan Mohd. Saiful Ridzuan Ishak, 37.

Sementara itu, seorang lagi mangsa yang cedera iaitu Cheng Kim Cheng, 85 tahun dan masih menerima rawatan di Hospital Ampang.

Source: Maszureen & Mohamad Hafiz Yusoff (2022, March 12). 1045 Cerun Dikenal Pasti Berisiko Runtuh. Utusan Malaysia.

Considering these projections urban planning and environmental stewardship require an approach. It is necessary to implement strategies that strike a balance between population growth, economic development, and environmental preservation. These strategies should go beyond engineering solutions by incorporating policy frameworks that prioritize long term environmental health over short term benefits. Therefore, collaboration among policymakers, urban designers and environmental advocates is crucial in creating plans that combine feasibility with ecological sustainability.

Slope failures primarily manifest as landslides characterized by the movement of soil, rocks and debris under gravitational forces. Various factors can trigger these movements including occurrences like prolonged rainfall leading to soil saturation (Iverson, 2000) or human induced activities such, as deforestation (Muñoz-Torrero Manchado et al., 2022). The phenomenon of slope instability leading to landslides has gained attention in both academic and policy making circles (Bouajaj et al., 2016; Gebreyohannes et al., 2024; He et al., 2022; Jia et al., 2012, 2015; Mergili, Marchesini, Alvioli, et al., 2014; Mitani, 2004; Safaei et al., 2011; Tiwari & Douglas, 2012; Van Westen et al., 1997; Yu et al., 2020).

2.3 Slope Stability Analysis

Slope stability analysis plays a role in engineering practice as it assesses the resilience and safety of slopes to determine potential failure scenarios. This analysis is vital across sectors such as civil engineering, mining, and environmental studies. The main goal is to assess the likelihood of a slope or embankment experiencing failure typically caused by forces leading to mass movement (Chakraborty & Dey, 2022). Traditional approaches to determining slope stability have relied on analyses primarily focusing on the concept of Factors of Safety (FoS) along with equilibrium principles (Brabb, 1984). A Factor of Safety (FoS) is calculated by dividing the forces resisting movement by the forces driving movement. However, advancements in based models (Van Westen et al., 2006) and innovative techniques by geotechnical engineers have contributed to enhancing these analyses.

In particular the Limit Equilibrium Method (LEM) stands out as an approach that deconstructs slopes and applies equilibrium equations to identify potential failures (Deng et al., 2017). Limit equilibrium methods are techniques that geotechnical engineers use to investigate the balance of a soil mass when it is inclined to move due to gravitational forces. These methods examine whether the forces driving movement usually gravity related are counteracted by the forces resisting movement typically originating from the soils shear strength. When these forces reach an equilibrium; the soil mass is at its stability "limit." This implies that even a slight additional force could trigger movement or failure. The application of this approach plays a role, in assessing slope stability embankments integrity and other earthen structures. It ensures safety. Minimizes the risk of landslides or collapses (Hungr et al., 2014).

Historically, the analysis of slope stability largely relied on a two-dimensional (2D) approach. Even though the natural configurations of slopes inherently possess a three-dimensional (3D) geometry, the analytical methodologies often gravitated towards the simplicity of 2D structural models. Such models aimed to capture the essence of the entire 3D slope by converting it into a 2D representation, a practice supported by studies from Bishop (1955), Morgenstern and Price (1965), and Spencer (1967). In these analyses, under the constraints of plane-strain conditions, slopes were often visualized as symmetric structures. This broad generalization, however, could lead to analytical inaccuracies, especially since many real-world slope failures are distinctly 3D. To address these shortcomings, there has been a significant push towards the development of optimization-based techniques in structural modelling (Leong & Rahardjo, 2012).

The transition to 3D slope stability analyses has gained momentum in recent years, primarily due to its superior ability to depict complex terrains more authentically as compared to the 2D approach (Hutchinson et al., 1985). Studies, such as the one by Hicks et al., (2014), have highlighted that 3D slope stability analyses often yield results that are notably more accurate than their 2D counterparts. Hovland (1977) is credited with being among the pioneers in this realm, having introduced the analysis of 3D slope stability using the column method, which has since gained widespread popularity. Both Lam and Fredlun, (1993) and Ahmed et al., (2012)have emphasized the reasons for its widespread adoption: the method's inherent capability and its practicality for real-world engineering applications.

2.3.1 2D Slope Stability Analysis

The use of two (2D) limit equilibrium techniques has become essential in geotechnical and structural engineering. While these methods are based on mechanics, they exhibit different characteristics in their application and interpretation. One key difference lies in the equilibrium assumptions they rely on; some are based on force equilibrium equations while others focus on moment equilibrium equations. The choice of these assumptions can significantly impact the results, and it is often influenced by specific problem conditions and the analysis preferences.

Moreover, there are variations in the assumptions related to the positioning and direction of forces within material or structural slices. Decisions about where and how these forces act can have an effect on stability outcomes. While certain techniques assume that these forces operate at a slices centroid others suggest they act at its base. The direction of these forces whether vertical, horizontal or at an angle further adds complexity to the matter. It is important to note that some methods may not strictly adhere to all equilibrium conditions those focused on force equilibrium. Deviations from adherence might result from simplifications made for analysis purposes or due, to inherent methodological constraints. Several 2D slope stability analysis methods will be stated as below.

2.3.1(a) Swedish Circle / $\phi = 0$ Method

The Swedish Circle technique, which assumes a friction angle (ϕ) of zero focuses on achieving moment equilibrium around the centre of a slip surface. As the name suggests this method considers the slip surface to be circular (Fredlund & Krahn, 1977). While this assumption simplifies calculations it may not accurately represent all real-world scenarios. Additionally, the lack of friction in this method makes it suitable for analyses but may be less applicable in other situations. This approach is particularly relevant when analysing slopes with a friction angle of zero which's common in evaluations of undrained slopes in saturated clays. Since saturated clays often exhibit a lack of friction the Swedish Circle technique becomes a choice. However, it is crucial for practitioners to understand and acknowledge the assumptions and limitations associated with this method.

2.3.1(b) Logarithmic Spiral Method

The Logarithmic Spiral Technique aims to fulfil the condition of moment equilibrium while focusing on the centre point that defines the shaped slip surface. This method considers the slip surface, as a spiral to facilitate calculations. However, it's important to note that this mathematical representation may not always fully capture the complexity of real-world conditions (Albataineh, 2006). The Logarithmic Spiral Technique is highly effective when analysing slopes with properties making it a popular choice for creating slope stability charts. Additionally, this technique is often integrated into software used for designing reinforced slopes making it a valuable tool for engineers specializing in this field.

2.3.1(c) Friction Circle Method

Ensuring both moment and force equilibrium conditions, the Friction Circle method offers an exhaustive framework for slope stability evaluations. Its underlying assumptions, particularly the proposal that the resultant of the shear strength's normal and frictional components is tangent to a designated friction circle, provide a geometrically intuitive method to address the interplay of these forces (Baker & Garber, 1978). This geometric representation, while streamlining computations, may not encapsulate the full complexity inherent in diverse real-world contexts. The Friction Circle method is invaluable due to its approach to stability analysis. However, it's crucial to evaluate its foundational assumptions in relation to the specific analysis at hand in order to ensure precise and reliable results.

2.3.1(d) Ordinary Method of Slices

Another used method is the Ordinary Method of Slices which focuses on moment equilibrium, around the slip surface defined by the circles centre. The approach represents the slip surface as circular assuming that there are no forces acting on the sides of each slice. This assumption is commonly made to simplify the analysis. Another assumption relates to the forces acting on the base of each slice with the force represented by "$W\cos\theta$" and the shear force represented by "$W\sin\theta$," where "W" is the weight of the slice and "θ" is its inclination angle. While these assumptions make calculations easier, they do have limitations. For example, neglecting forces on slice sides may not always be an approximation especially when interslice forces significantly affect overall stability. This method is mainly suitable for analyses that provide quick assessments. However, its inherent limitations make it less suitable for final stability evaluations.

2.3.1(e) Simplified Bishop Method

The Simplified Bishop method ensures both moment equilibrium in a comprehensive framework for analysing slope stability. A key assumption in this method is that interslice forces are horizontal meaning that all shear forces, between slices are considered negligible. This simplification greatly simplifies calculations. Comes with its own set of challenges. In real life situations especially when shear forces have an impact on overall stability it is important to consider that interslice shear forces may exist and should not be disregarded. Neglecting these shear forces can lead to results that deviate from the conditions.

2.3.1(f) Morgenstern and Price's Method

The Morgenstern and Price method is an analytical approach used for slope stability analysis taking into account all equilibrium conditions. Its versatility is an advantage as it can accommodate various slip surface shapes making it suitable for different slope configurations and soil profiles. This method assumes there is a relationship between interslice shear and normal forces while also assuming the normal force operates at the centre of the slice base. However, despite its robustness this method has its challenges. One such challenge lies in the calculation of interslice forces requiring intricate mathematical procedures and significant computational power. The method is particularly well suited for projects that demand analytical rigor especially when unconventional slip surface shapes or diverse soil profiles are involved.

2.3.1(g) Sarma's Method

In Slope Stability Analysis, Sarmas Method is a technique used in slope stability analysis meticulously designed to satisfy all equilibrium conditions. One notable feature of this method is its adaptability. The technique is designed to handle any shape of a slip surface, which makes it extremely valuable for dealing with complex geological formations and various slope geometries. This method focuses on shear strength as the basis of its analysis, which is influenced by factors. These factors include strength parameters, pore water pressure and the horizontal component of interslice force. Another key assumption in Sarmas Method is that the normal force is concentrated at the base of each slice. However, like any method Sarmas Method comes with its own set of challenges. Its detailed nature and the need for data on soil and water parameters can make it time consuming and computationally demanding.

Additionally, inaccuracies in assumptions related to shear strength parameters or pore water pressure can cause variations in the models results affecting its accuracy. In terms of applications Sarmas Method excels in addressing complex challenges. It is particularly suitable when dealing with slip surfaces that have shapes or when slice boundaries are not strictly vertical. Another notable application of this method is its ability to determine the coefficient needed for a specific level of safety factor. This feature makes it invaluable, in earthquake areas. Essentially Sarmas Method is a technique that is often used for projects requiring a high level of precision. It is particularly useful, in situations where other methods may not provide the depth and accuracy needed for comprehensive solutions.

2.3.2 3D Slope Stability Analysis

3D slope stability analysis methods have evolved from 2D techniques providing a more comprehensive and detailed perspective. However, these advanced 3D methods require assumptions to make the mathematical calculations manageable (Sun et al., 2011). These assumptions aim to simplify the variables or strengthen the equations to ensure a determinate system. The need for analysis becomes apparent in complex situations where 2D methods struggle to accurately replicate reality (Hicks & Spencer, 2010).

Such situations may involve slopes with changing geometry or failure surfaces along their length well as inconsistent soil properties in different sections. Additionally, when external factors, complex shear strength characteristics and varying pore water pressure conditions come into play 3D analysis becomes more valuable. This advanced approach enables a precise estimation of safety factors and even facilitates the backward analysis of shear strength parameters (Kumar et al., 2023) .

Numerous 3D slope stability analysis methods have been introduced since the 1960s. Choosing the suitable method requires careful consideration of its capabilities in relation, to the unique characteristics of the slope. However, it's important to acknowledge that while 3D techniques provide improved accuracy and depth, they also require expertise. This expertise involves data collection, computational proficiency, and a keen ability to interpret the results. Therefore, when navigating geological terrains, it is crucial to carefully consider the advantages and limitations of employing 3D analysis methods (Stark, 2003; Stark & Eid, 1998).

2.3.2(a) Anagnosti

Anagnostis (1969) approach marked a milestone in analysing the stability of slopes in three dimensions. One of its remarkable features is its capability to intricately represent complex geological conditions that might be beyond the scope of simpler 2D models. The strength of this method lies in its precision in accounting for soil types, rock masses and slope configurations. Moreover, it can integrate factors such as anisotropy and inhomogeneity into its calculations. However, this level of precision comes at a cost; extensive computational resources are required along with data collection and expertise in both geotechnical and computational domains. While this method is well suited for representing slopes with geometries and varying material properties it is essential to be aware of its inherent complexities and demands.

2.3.2(b) Baligh and Azzouz

The method introduced by Baligh and Azzouz in 1975 has gained recognition, for delving into shear strength mobilization and the evolution of failure surfaces. The meticulous consideration of soil structure interactions in this approach leads to a precise representation of complex situations. Its strengths lie in its examination of anisotropic behaviour and its ability to accurately capture the transient effects of changing conditions. However, it is important to note that this method requires computational resources and extensive data which may make it less suitable for smaller projects.

2.3.2(c) Hovland

The analytical approach developed by Hovland in 1977 has been widely recognized for its contributions to three-dimensional slope stability analysis. Hovlands method introduced a perspective on 3D slope stability analysis during a time when computer-based techniques were still emerging. While maintaining a level of accuracy this method is computationally more manageable making it well suited for practical applications. It specifically caters to soil structures and can handle both isotropic and anisotropic conditions. However, its usage should depend on the availability of computational resources and the relevance of its assumptions to the specific slope being analysed (Hovland, 1977).

2.3.2(d) Chen

Chen's method from 1981 stands out due to its mathematical foundation and incorporation of intricate geological factors. It is adaptable to slip surface shapes and can account for both drained and undrained conditions, which makes it a versatile tool. However, it should be noted that this method requires computational resources due to its rigorous mathematical approach, as well as comprehensive data availability in order to achieve precision (Chen, 1981).

2.3.2(e) Chen and Chameau

Chen and Chameaus (1983) approach also deserve attention for its qualities. Its adaptability allows it to handle slip surface shapes effectively while considering important geological aspects. Similar to Chens method, employing this approach necessitates advanced computational resources due to its reliance, on intricate mathematics and comprehensive data requirements. The approach presented in the Chen and Chameau study from 1983 provides a framework that focuses on factors like seepage forces and pore water pressures.

Its strength lies in its ability to model hydrogeological conditions and analyse incremental loading. Although valuable this method requires computational resources due to its complexity and it can be time consuming to collect all the necessary data (Chen & Chameau, 1983).

2.3.2(f) Leshchinsky and Baker

The method developed by Leshchinsky and Baker in 1986 stands as a significant contribution to the field of slope stability analysis and this method is known for its ability to consider geometry and various material properties. Its adaptability and