Identification of variables and methods for the development of MCDA maps for predicting problematic soils

S.G. Waters & E. Theron
Central University of Technology, Bloemfontein, South Africa

Geotechnical investigations play a critical role in infrastructure development in South Africa, particularly in regions with diverse and complex geological conditions such as the central plateau. This study focuses on identifying variables that could predict problematic soils in the development of Multi-Criteria Decision Analysis (MCDA), including expansive clays, collapsible soils, soft clays, and dispersive soils, which pose risks to infrastructure stability. Early identification of these risks is essential for implementing mitigation strategies and optimizing geotechnical design. These variables will be used to generate MCDA maps that integrate key geotechnical variables and provide insights into soil behaviour. The study identifies the primary geotechnical variables necessary for MCDA-based geotechnical investigations in South Africa. By leveraging Geographic Information Systems (GIS); environmental, topographical, geological, and geotechnical datasets are systematically analysed to enhance geotechnical risk assessments. The integration of multiple datasets enhances decision-making for engineers and planners, reducing costs, mitigating delays, and improving infrastructure resilience. This approach advances geotechnical engineering by quantifying risks associated with various soil types, ensuring proactive infrastructure planning in central South Africa.

1 INTRODUCTION

South Africa's central plateau presents significant geotechnical challenges due to its diverse geological conditions. Geotechnical investigations are essential for identifying these hazards and implementing mitigation strategies to reduce construction failures, particularly in South Africa, where diverse geological conditions present varying geotechnical risks. Expansive clays, collapsible soils, soft clays, dolomitic sinkholes, and erodible soils are prevalent in regions such as Gauteng, Free State, and North West, posing significant challenges to infrastructure development (Brink 1985). By integrating comprehensive geotechnical assessments with risk mitigation strategies, engineers can enhance the resilience of developments in South Africa's geologically complex environments. Traditional site investigations in geotechnical engineering are indeed essential but can be both costly and time-consuming. To enhance efficiency and comprehensiveness, integrating Geographic Information Systems (GIS) with Multi-Criteria Decision Analysis (MCDA) could offer a systematic approach to geotechnical risk assessment. This integration enables the incorporation of diverse datasets, enhancing the accuracy and comprehensiveness of decision-making processes. However, given the variety of MCDA methods available, a critical evaluation of their suitability was essential before selecting an approach for this study.

2 LITERATURE REVIEW

Multi-Criteria Decision Analysis (MCDA) is a structured approach used to evaluate complex decision-making problems that involve multiple, often conflicting, criteria. It is widely applied in various disciplines, including environmental management, engineering, economics, and risk assessment to systematically assess different alternatives and support decision-making. (De Monti et al. 2023) MCDA provides a framework for integrating both quantitative and qualitative data, enabling decision-makers to prioritize, rank, or classify options based on predefined objectives. (Kolat 2006)

The fundamental principle of MCDA is to break down a decision problem into a hierarchical structure, where criteria and sub-criteria are assigned weights according to their relative importance. These weights help in comparing and evaluating multiple alternatives against each criterion. The process typically involves gathering expert input, assigning preference values, and applying mathematical models to determine the most suitable option. (Liang et al. 2017)

MCDA techniques vary in complexity and methodology, but they share common steps, including problem definition, criteria selection, data collection, weighting of criteria, and ranking of alternatives. Some methods use pairwise comparisons to determine relative importance, while others rely on scoring models or distance-based ranking techniques. The choice of method depends on the nature of the decision, data availability, and the level of subjectivity involved in assigning weights. (Zhang 2022)

In geotechnical engineering, MCDA is particularly useful for risk assessment, site selection, and decision-making in soil analysis. By integrating spatial data with MCDA techniques, engineers can systematically evaluate factors such as soil stability, groundwater conditions, and geological risks, leading to more informed and objective decision-making. To determine the most suitable approach, it was first necessary to identify the key variables required for predicting problematic soils and assess the additional data needed for comprehensive analysis (Alkaradaghi et al. 2022)

2.1 *Problematic Soils in South Africa: Geotechnical Challenges and Engineering Solutions*

South Africa's geological diversity has led to the formation of various problematic soils that present significant geotechnical challenges. These include expansive clays, collapsible sands, dispersive soils, and soft clays, each requiring specialized engineering solutions to mitigate infrastructure risks (Brink, 1985; Partridge et al., 2009). The behaviour of these soils is influenced by multiple factors, including climate, geology, topography, and weathering processes, which dictate their distribution and geomechanical properties (Jennings & Brink 1975, Paige-Green 2008).

Expansive clays exhibit shrink-swell behaviour due to changes in moisture content, leading to differential movement and ground heave (Brink 1985; Diop et al. 2011). These soils are predominantly associated with high montmorillonite content and occur in regions where chemical weathering is dominant (Brink 1985). Their swelling potential is quantified using plasticity index values, while engineering solutions focus on moisture control, chemical stabilization, and deep foundations (Collins 1958).

Collapsible soils have an open structure with high void ratios, causing them to undergo sudden volume reduction upon wetting (Diop et al. 2011, Richards et al. 2006). These soils are typically found in semi-arid environments with intermittent moisture availability and are common in wind-deposited loess, weathered granite, and residual sandstones (Paige-Green 2008). Their collapse potential is evaluated using dry density and oedometer testing, and mitigation strategies include pre-wetting, compaction, and foundation reinforcement (Elges 1985).

Dispersive soils are highly susceptible to erosion and piping failure due to their high sodium content, which weakens interparticle bonding (Elges 1985, Brink 1985). They are prevalent in semi-arid and arid regions, where sodium accumulation and deflocculation increase their erodibility (Partridge et al. 2009). Dispersive behaviour is assessed using the Emerson Crumb and Double Hydrometer tests, while engineering measures focus on chemical stabilization, controlled drainage, and erosion control (Richards et al. 2006).

Soft clays are highly compressible with low shear strength, posing settlement and stability risks in construction (Paige-Green 2008). They are typically found in coastal and estuarine environments, where fine-grained sediment accumulation in low-energy settings leads to prolonged consolidation times (Diop et al. 2011, Partridge et al. 2009). Their bearing capacity limitations necessitate engineering solutions such as pre-loading, vertical drains, and deep foundation systems (Elges 1985).

The formation and distribution of problematic soils in South Africa are strongly influenced by geology, climate, and topography. The Weinert N-Value serves as an indicator of weathering potential, with low N-values (humid climates) favouring expansive clay formation, while high N-values (arid climates) promote soil dispersivity (Brink 1985). Problematic soils are often found in low-lying floodplains, plateaus, and valley floors, where groundwater fluctuations and seasonal moisture changes exacerbate their geotechnical risks (Paige-Green 2008, Partridge et al. 2009).

3 METHODOLOGY

This study aimed to identify the most relevant variables for assessing geotechnical risks within a Geographic Information System (GIS) framework using a MCDA approach. Through a review of existing literature and engineering practices, key geotechnical, geological, hydrological, climatic, and topographical variables influencing soil behaviour and associated risks were identified and categorized. Data sources included field surveys, remote sensing techniques, and existing geotechnical investigations to ensure a comprehensive dataset for analysis. By selecting appropriate variables, this study establishes a foundation for integrating MCDA with GIS to enhance geotechnical risk assessments and support infrastructure planning (Zhang 2022).

The study identified key geotechnical characteristics of problematic soils in South Africa, focusing on expansive clays, collapsible soils, dispersive soils, and soft clays. Each soil type exhibits distinct physical, mechanical, and environmental properties that influence its behaviour and associated risks in infrastructure development. The distribution and severity of these problematic soils are further controlled by topography, climate, hydrology, and geological setting, which play a critical role in geotechnical risk assessment and mitigation.

Expansive clays are characterized by a plasticity index (PI) exceeding 12, with higher values indicating greater swelling potential. Slickensliding and shattering are common indicators, particularly when the PI exceeds 17, while soils with a PI greater than 32 pose a high risk of heave (Brink 1985, Diop et al. 2011). Their liquid limit surpasses 30%, and clay content exceeds 12%, indicating their ability to retain moisture and undergo volumetric changes. These soils predominantly originate from Karoo sedimentary rocks, dolerites, and shales, forming vertisols rich in montmorillonite (Brink 1955, Paige-Green 2008).

Expansive clays are commonly found in low-lying areas and valleys, where poor drainage and high clay content exacerbate swelling potential. Their behaviour is influenced by seasonal moisture fluctuations, particularly in semi-arid to humid climates, where alternating dry and wet seasons trigger shrink-swell cycles (Jennings & Brink 1975).

The Weinert N-Value, a key climatic indicator of weathering potential, plays a crucial role in expansive clay behaviour. Areas with N-values below 5 indicate humid conditions, where chemical weathering dominates, promoting the formation of expansive clays. In contrast, regions with N-values above 5 experience drier conditions, reducing their activity. The presence of water networks such as rivers, groundwater seepage zones, and seasonal wetlands further influences clay expansion, as moisture availability directly affects shrink-swell behaviour (Brink 1985).

Testing methods such as the Atterberg Limits, Van der Merwe method, and Brackley equation help assess expansion potential (Collins 1958). The engineering impact of expansive clays is severe, with differential heave reaching up to 300 mm within days, leading to damage in roads, foundations, and pipelines (Brink 1985).

Collapsible soils are defined by a dry density below 1600 kg/m³, typically ranging from 900 to 1600 kg/m³ (Richards et al. 2006). These soils, commonly found in wind-deposited loess, weathered granite, and sandstones, exhibit an open structure that remains stable when dry but collapses upon wetting, leading to sudden settlement (Diop et al. 2011).

Collapsible soils are mostly present on straight slopes, plains, and well-drained terrains, where their loose structure is maintained (Paige-Green 2008). The semi-arid climate of South Africa, characterized by seasonal rains followed by prolonged dry periods, significantly influences their behaviour. These soils remain stable during dry conditions but rapidly lose strength when saturated.

Regions with Weinert N-Values between 5 and 10, indicating moderate to high weathering potential, are particularly susceptible to collapsible soil formation. Seasonal groundwater recharge, stormwater runoff, and irrigation can trigger sudden collapses, affecting infrastructure stability (Elges, 1985). Water infiltration from rivers, wetlands, and seepage zones increases the collapse potential, necessitating proper drainage control.

The double oedometer test and moisture content analysis is critical in evaluating collapse susceptibility (Elges 1985). Engineering challenges associated with collapsible soils include sudden settlement of up to 300 mm in structures, leading to instability and potential failure (Brink 1985). Engineering interventions include pre-wetting, dynamic compaction, vibro-replacement, and reinforced foundations to improve stability before construction.

Dispersive soils are distinguished by high smectite content, making them highly susceptible to internal erosion and piping failure (Elges 1985). They are commonly associated with the Karoo Basin, weathered shales, and mudstones, where high sodium levels (>2 Weinert N-Value) reduce soil cohesion and increase erodibility (Brink 1985, Paige-Green 2008).

Dispersive soils predominantly occur in low-lying areas, floodplains, and valley bottoms, where water accumulates and enhances erosion processes. They are widespread in semi-arid and arid climates, where low rainfall and sparse vegetation increase vulnerability to gully erosion and piping failures (Partridge et al. 2009).

The Weinert N-Value for dispersive soils typically exceeds 2, indicating drier regions where physical weathering dominates. However, seasonal flash floods, poor drainage design, and proximity to rivers or artificial irrigation accelerate soil deflocculation and erosion. These factors contribute to embankment failures, road degradation, and agricultural land loss (Richards et al. 2006).

Their susceptibility is assessed using the Emerson Crumb Test and the Double Hydrometer Test, which help determine dispersivity levels (Elges 1985).

Soft clays pose risks due to their low dry density and high moisture content, making them highly compressible with low shear strength (Paige-Green, 2008). They are primarily found in coastal and estuarine deposits, where fine-grained sediments accumulate in low-energy environments (Diop et al. 2011).

Soft clays are commonly observed in floodplains, deltas, and gentle coastal slopes, where prolonged water saturation reduces soil strength. The humid climate of South Africa's coastal regions, particularly along the east coast, increases the water retention capacity of these soils, leading to long-term settlement issues (Partridge et al. 2009).

Soft clays are typically found in regions with low Weinert N-Values (< 2), indicating dominant chemical weathering and high groundwater activity. These areas experience seasonal flooding, tidal influences, and groundwater fluctuations, making foundation stability a major challenge.

Consolidometer testing is essential for predicting settlement behaviour (Elges 1985). The engineering impact of soft clays includes long-term settlement, slope instability, and poor bearing capacity, posing significant challenges for infrastructure development (Paige-Green 2008). Engineering solutions focus on pre-loading, vertical drains, geotextile reinforcement, and deep foundation systems such as pile foundations to transfer loads to more stable substrata.

Based on this research the following variables will be considered in the MCDA analysis:

Geotechnical Variables (Previous site investigations):

- Soil Depth
- Soil classification
- Soil Colour
- Soil Texture
- Soil Structure
- Soil Consistency
- Moisture content

Geotechnical Variables (Previous laboratory investigations):

- Plasticity Index
- Clay content
- Shrinkage Limit

Geology:

- Parent material
- Origin (transported or residual)
- Rock type
- Mineralogical composition

Hydrological Variables:

- Water table depth
- Buffer areas around rivers

Climatic and Topographical Variables:

- Weinert N-Value
- Rainfall variability
- Slope gradient
- Elevation
- Aspect

Each of these variables will be integrated into a GIS environment as geometric data—represented as points, lines, or polygons, and interpolated where necessary to ensure spatial continuity. A geotechnical database (Waters, 2022) has already been developed to support the structured accumulation and management of these datasets. In addition, a comprehensive collection of geopackages and shapefiles covering South Africa has been assembled to support spatial analysis and visualization.

The AHP method will be applied and tested with varying hierarchical structures and weighting schemes. The outputs from these iterations will be evaluated against known geotechnical failure locations, including roads and foundations affected by problematic soils, as well as verified against existing site investigation reports and laboratory data.

This process will initially focus on the Free State province and selected areas within the central plateau, where problematic soils are prevalent and well-documented. The results of the different MCDA configurations will be compared, and the most effective setup—determined through spatial correlation with known failures—will be selected for further application. This optimal configuration will then be expanded and applied at a national scale to refine and enhance geotechnical risk mapping across South Africa.

To validate the predictive accuracy of the selected MCDA configuration, targeted fieldwork will be undertaken. Test pits will be excavated at locations identified by the MCDA model as high-risk for problematic soils. These field investigations will provide ground-truth data to confirm the reliability of the model and guide further refinement of the methodology.

4 CONCLUSIONS

Geotechnical challenges in South Africa including expansive clays, collapsible soils, dispersive soils, and soft clays, would benefit from a systematic, data-driven risk assessment approach. These problematic soils pose significant infrastructure risks, influenced by geology, climate, topography, and hydrology. While traditional site investigations are effective, they are resource-intensive, highlighting the need for Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) for improved decision-making.

By identifying and categorizing these variables, the study plans to enhance soil risk prioritization, supporting site selection, foundation design, and targeted mitigation strategies. This would refine MCDA weighting, incorporate additional environmental variables, and validate the model through field investigations and comparison of existing data. The proposed methodology contributes to sustainable infrastructure planning, improving resilience in geotechnically complex regions of South Africa.

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