Using Multi-Criteria Decision Analysis (MCDA) maps to enhance data interpretation and decision making to manage geotechnical risks.

S.G. Waters
Central University of Technology, Free State, Bloemfontein, South Africa

E. Theron
Central University of Technology, Free State, Bloemfontein, South Africa

ABSTRACT: Infrastructure is highly susceptible to damage caused by expansive soils. A geodatabase was developed for managing and storing large datasets obtained from geotechnical reports for this soil type. These datasets will be used to create an MCDA map applicable to South Africa. This paper discusses the systematic approach to creating this map. The MCDA maps will include an exhaustive analysis considering multiple criteria that impact soil behaviour, stability, and suitability for geotechnical design and construction for risk mitigation.

1 INTRODUCTION

1.1 *South Africa's Problem with Expansive clays*

South Africa faces various challenges and issues in the field of geotechnical engineering. One significant problem is the diverse geological composition across the country, which includes expansive clay soils, weak rock formations, and complex geological structures. One significant problem is the diverse geological composition across the country, which includes expansive clay soils, weak rock formations, and complex geological structures. Being made aware of these problems early could allow geotechnical engineers to plan ap-propriate countermeasures to save time and costs; and ensure safe structures for societal use (NHBRC, 2015). Essentially assisting in risk assessment and incident prevention. In-frastructure is highly susceptible to damage caused by expansive soil.

These geotechnical problems need to be identified by a competent geotechnical engineer who applies the guidelines and codes of South Africa for geotechnical investigations. These investigations play a crucial role in evaluating the geological or geotechnical properties of a site. Experts involved in these investigations provide specialized insights into the potential problems posed by geotechnical conditions (Whitlow, 2000; Calitz, 2023). Geotechnical engineers in South Africa rely on standards, manuals, and experience to make informed decisions during their investigation to plan the construction and design phases. During site investigations, the geotechnical engineer is expected to have sound knowledge of engineering geology and geotechnical engineering, adequate experience in identifying potential practices, conditions, or materials, and be able to effectively sample and request the correct laboratory testing for the site.

Geological materials originate under a diverse range of intricate physical circumstances, often with unknown histories, resulting in substantial geotechnical uncertainties (Phoon et al., 2022; Chen et al., 2022; Feng et al., 2023). Understanding these uncertainties is crucial for accurate risk assessment and effective project planning.

The importance of understanding and addressing various uncertainties (such as variability of soil, high plasticity, collapsible soil, etc.) associated with geotechnical design properties should be emphasized. It is widely acknowledged in geotechnical engineering design that uncertainties are an inherent aspect. There are numerous practical benefits to be gained if these uncertainties and the associated risks can be quantified (Yang et al., 2022). Risk management, which involves identifying, evaluating, and prioritizing risks in a project, is crucial. It encompasses not only structural safety but also economic, environmental, and operational considerations, as well as potential negative outcomes like injuries, cost overruns, and delays (Taherizadeh et al., 2023). Geotechnical risk management involves a standardized approach to handling uncertainties that could impact project goals in geotechnical engineering.

A pivotal undertaking within the realm of geotechnical risk management involves comprehending and interpreting the manner in which existing uncertainties might impact the feasibility of attaining a project's objective (Spross et al., 2022; Azougay et al., 2020). There is, however, often a limited amount of test data of geotechnical properties for site characterization (Gong et al., 2017). This leads to further uncertainty (Phoon et al., 2021).

A system for sharing risk-related information is essential due to the prolonged duration of geotechnical projects and the need for knowledge transfer across projects. Such a system could improve decision-making by availing all the relevant information in an integrated manner (Larsson, 2018). The engineer will be able to view the numerical data on a map with selected overlays for geological formations or mineral groups, climatical or interpolated maps (Weidman & Maloney, 2019; Makki & Abdulaal, 2023; Schweiger et al., 2019; Schweiger, 2023). Such a tool would enable engineers to input project-specific data, adhere to industry standards, and generate comprehensive reports and design recommendations based on multiple criteria. The more information available to an engineer about their site, the better-informed decisions they can make. This can be achieved by use of Geographical Information Systems (GIS) (Darwish, 2023; Shawky & Hassan, 2023; Ponnusamy et al., 2021).

The objective of this study is to develop a comprehensive framework for geotechnical risk management in South Africa, incorporating the use of GIS and AHP mapping techniques to produce MCDA maps using multiple criteria that influences geotechnical engineering problems. By integrating these tools, the study aims to enhance the accuracy and efficiency of site investigations, improve risk assessment processes, and provide a systematic approach to managing geotechnical uncertainties. This will contribute to safer and more cost-effective engineering practices in South Africa.

2 LITERATURE REVIEW

2.1 *Geological Mapping in South Africa*

Civil constructions projects will primarily use detailed or semi-detailed soil maps, but these maps are limited. Land type maps of the whole South Africa provide useful soil information as an alternative with a combination of topography, climate, and soil patterns. Twenty-eight broad soil pattern groups were chosen as the basis of South African soil mapping. In combination with topography and climate, these provide the land types. These maps are provided by the Agricultural Geo-references Information System (ARC-ISC) and Council of GeoScience (CGS) in South Africa. These maps are produced at 1:250 000 scales which assist engineers but do not deliver enough site-specific context. Significant differences in depth and nature of soil can occur over

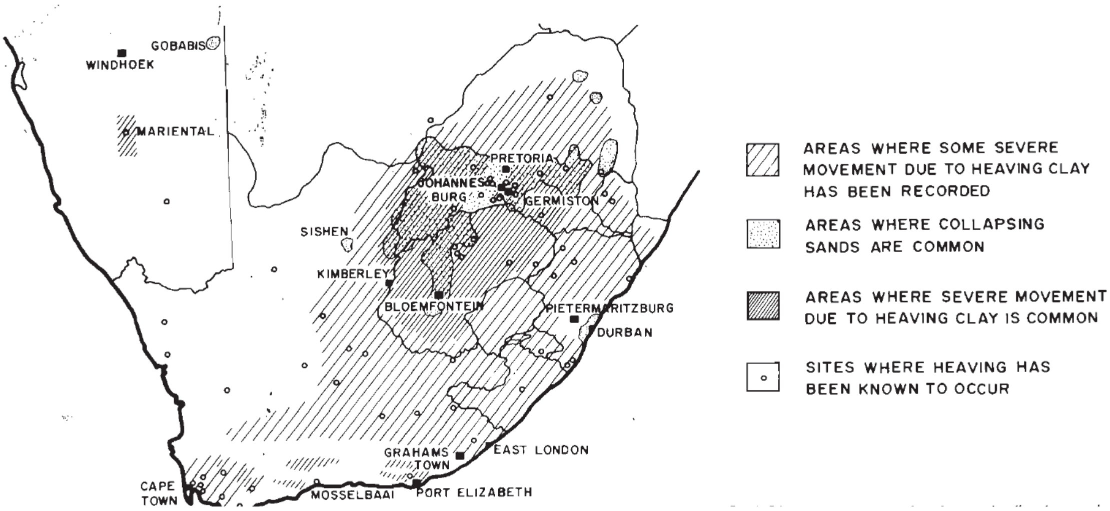

Figure 1. Problematic soils map in South Africa.

short distances. These maps cannot consider geological background, experience, profiling, and terminology that is beneficial for successful infrastructure development. (Paige-green, 2008).

2.2 *Expansive Soils in South Africa*

Expansive clays are likely the most prevalent problematic soils in South Africa (Williams et al., 1985). Damage to structures erected on potentially active soils may occur if the expansiveness is not quantified and appropriate remedial measures are not taken (Weaver, 1990). The volume of most clayey soils fluctuates with seasonal changes in moisture content, with the extent of this change determined by the type and quantity of swelling clay present in the soil. Shrinkage primarily occurs during the dry season, while swelling occurs during the wet season. The most active soils with a plasticity index (PI) exceeding 32, tend to cover much of north-eastern South Africa and central regions like the Free State.

Semi-arid and dry sub-humid regions in South Africa and various other parts of the world are recognized for experiencing significant foundation challenges. The combination of intense seasonal rainfall and prolonged periods of drought results in soil fluctuations between desiccation and saturation. Certain types of clay minerals, notably those in the smectite group, undergo substantial volume changes with fluctuations in moisture content (Stott & Theron, 2015). Figure 1 shows the most used problematic soil map in South Africa where expansive soils areas are indicated visually. These size maps provide limited information for geotechnical engineers working on construction site size projects.

2.3 *Expansive Soil Parameters*

Several studies have been performed on expansive soils in South Africa in which parameters for the identification of these soils were explored. Atterberg Limit parameters were predicted for most expansive soils, liquid limits were given to be more than 30%, plasticity index more than 12, linear shrinkage more than 8% and clay content more than 12%. The type of soil was also shown to play a role. Large proportions of smectite group clays have been identified as high shrinkage and swelling materials (e.g. montmorillonite). Andesite and dolerite could present expansive material as well (Williams et al., 1985).

Site investigations, especially trial/test pit assessments, assist engineers in identifying potentially expansive material. Expansive soils are often recognized as black, dark grey, red, or mottled yellow-grey, brown or white in color and may have a slickensliding or shattering type soil structure. Ferricrete layers that overly residual expansive soils may reduce heave.

Engineers should also consider the climate and topography of the area. Volumetric changes could occur due to seasonal rainfall changes. Original moisture content may be used in swell percentage function. Low-lying areas (floodplains, pans, and drainage channels). Expansiveness increases downwards on a hill. Original void ratio may be used in swell percentage function.

Van der Merwe's method (van der Merwe, 1964) offers a means to assess the potential heave of soil samples, categorizing it as low, medium, high, or very high. Despite its extensive utilization in South Africa, there's a noted tendency for this method to overestimate expansive potential. This is attributed to its reliance on the plasticity index and clay percentage (portion of soil passing through a 2-micron sieve), wherein the clay fraction often includes a substantial proportion of non-swelling minerals like quartz and calcite.

2.4 *Multi-criteria Decision Analysis*

Multiple-criteria decision analysis (MCDA) assists decision makers in evaluating potential actions or alternatives based on multiple factors or criteria that may not be directly comparable, using decision rules or weightings to combine these criteria and assess the alternatives (Eastman, 2009), (Figueira et al., 2005), (Malczewski 1999). MCDA researchers and practitioners don't approach it solely as a quantitative optimization problem aimed at finding the best solutions but focuses on presenting the data for better comprehension of the varied data.

One of MCDA's greatest strengths lies in its capacity to simultaneously consider both quantitative and qualitative criteria, provided that the qualitative aspects can be expressed using an ordinal or continuous scale. (Belton & Stewart 2002; Roy, 2005)

Multiple-criteria decision analysis encompasses several approaches for managing different decision challenges. One such technique is the Analytic Hierarchy Process (AHP), pioneered by Saaty et al., which aims to address a variety of decision problems by assigning relative preferences to individual criteria to achieve specific objectives. AHP functions as a systematic method to compute a numerical ranking for each decision option, reflecting their alignment with the decision maker's prioritized criteria for each factor. (Saaty, 1980)

2.5 *Geographic Information Systems*

Developing a software tool could assist engineers in decision-making by availing all the relevant information in an integrated manner. The engineer will be able to view the numerical data on a map with selected overlays for geological (formation or mineral groups), climatical or interpolated maps (Weidman & Maloney, 2019; Makki & Abdulaal, 2023), (Schweiger, et al., 2019), (Schweiger, 2023). Such a tool would enable engineers to input project-specific data, adhere to industry standards, and generate comprehensive reports and design recommendations based on multiple criteria. The more information available to an engineer about their site, the better-informed decisions they can make. This can be achieved by use of Geographical Information Systems (GIS) (Darwish, 2023; Shawky & Hassan, 2023; Ponnusamy, et al., 2021).

A Geographic Information System (GIS) is technology developed for the purpose of capturing, storing, verifying, and exhibiting data pertinent to Earth's surface positions (Kim & Ji, 2022; Webber & Kijek, 2022). This technology facilitates efficient management and organization through attribute tables, where tabulated data is intricately linked with geographic features (Yasin & Woldemariam, 2023). This linkage accommodates a diverse range of both quantitative and qualitative information, adding depth and context to the spatial insights derived from the technology (Ali, et al., 2020).

The utilization of GIS has streamlined the presentation of geotechnical properties. With GIS, researchers can effortlessly create graphical maps that effectively convey the obtained results. Parameters such as geotechnical parameters can all be conveniently visualized through the power of GIS (Adulraheem, et al., 2019). Additionally, one can use GIS-AHP to determine even more in-depth analysis.

Geographic Information System (GIS)-based Analytic Hierarchy Process (AHP) computations hold significant importance in showing spatial trends and interdependencies among geospatial data. (Eisa & Fattouh, 2023). This process plays a pivotal role in extracting valuable information crucial for informed decision-making. Performing AHP calculations within a GIS framework plays a crucial role in unveiling spatial patterns and interconnections among geospatial data. This method yields valuable insights that are essential for making informed decisions (Awange & Kiema, 2019), (Calitz, 2023) while offering advantages by amalgamating qualitative and quantitative procedures and preventing subjective judgments from decision makers (Xu, et al., 2020).
Multicriteria Geographic Information System Decision Analysis (GIS-MCDA) stands out as a widely employed approach for susceptibility modeling across a spectrum of scientific disciplines (Domazetovic, et al., 2019). Using GIS interpolation to systematically produce maps pertaining to diverse thematic content contingent upon soil properties, in an effective and efficient manner (Adam, et al., 2018; Alkaradaghi, et al., 2022).

3 METHODOLOGY AND DATA

The methodology entails the creation of a comprehensive geodatabases that will be incorporated with various spatial datasets essential for analyzing expansive soils in South Africa. These datasets include topography, Weinert N-value, land type maps, and geological maps. These datasets will be incorporated as shapefiles or line data in GIS. Datasets will be retrieved from the ARC-ISC and CGS public available data while data for the GeoDatabase is a collection of geotechnical engineering site reports and laboratory papers.

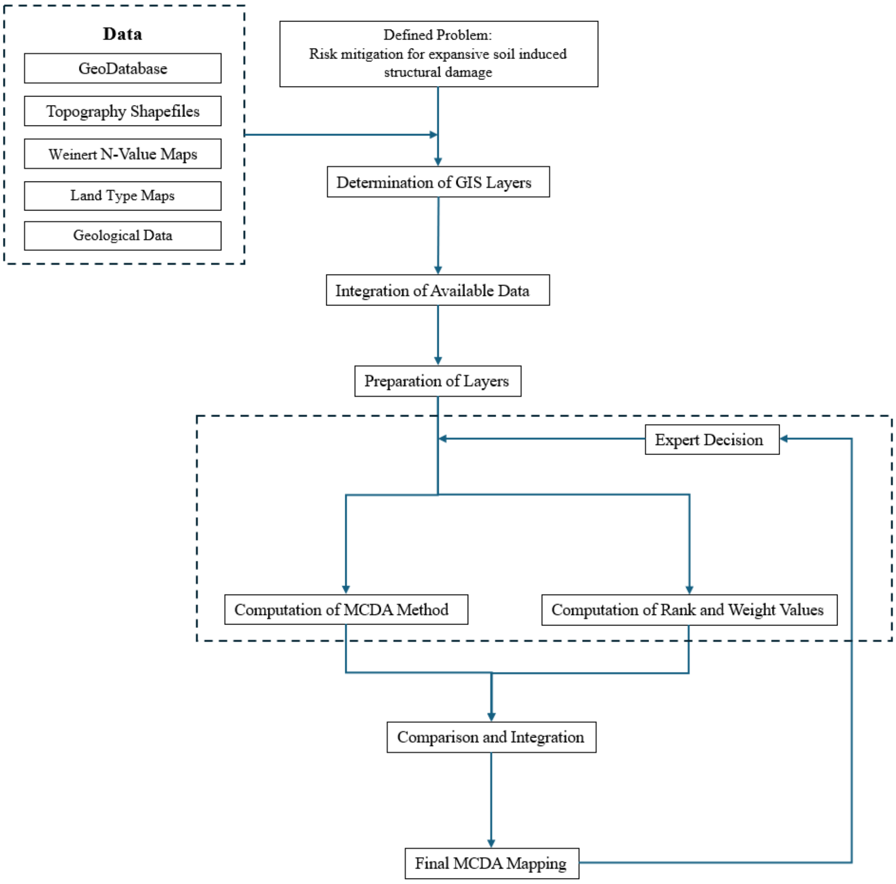

Figure 2. Methodological plan for the development of an expansive potential integrated map

3.1 *GeoDatabase*

The GeoDatabase was created based on the expansive soil parameters. Microsoft Access was used to create a database to store all the data and information of the selected tests. Microsoft Access was based on the ease of use and general accessibility of Microsoft Office tools to professionals expected to make use of this software.

The tables in the database are linked to the sample data table where the primary information for a soil sample is stored. Tables were created for the test pit, density, particle size distribution and Atterberg Limit datasets. These were all linked to ensure proper data storage, collection and management for any sample data that will be imported into the GIS for MCDA incorporation. These tables with the relationships are the foundation of the database. Relationships are vital to preventing data loss and were required to make the database a relational database management system (RDMS). Once the tables with their fields had been created, they needed to be linked through

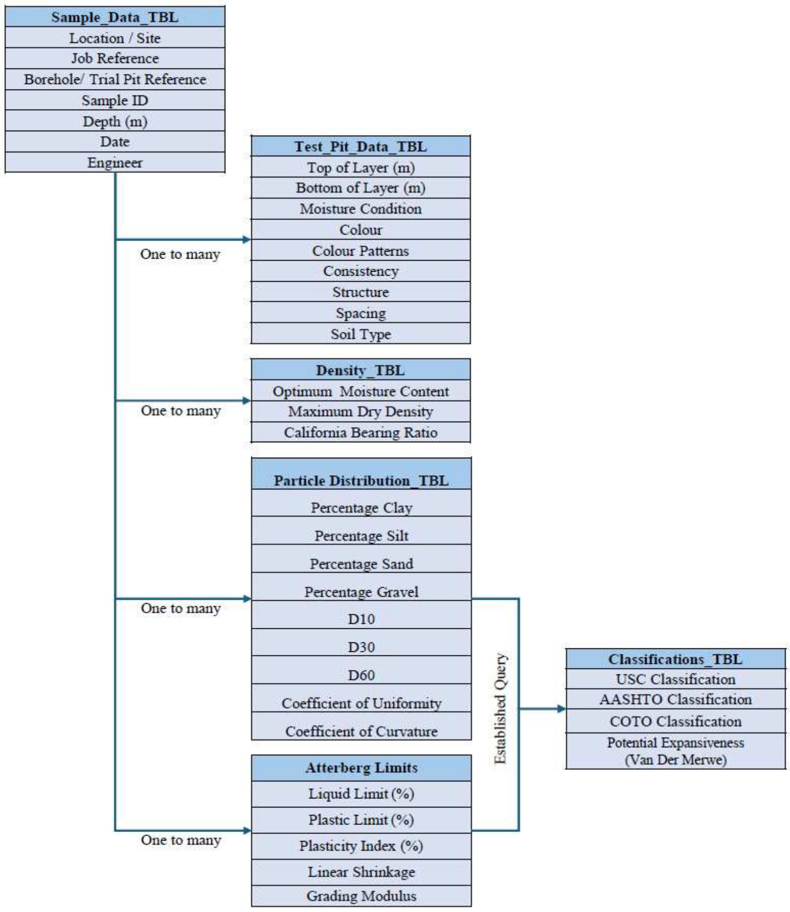

Figure 3. Relationship links for tables in GeoDatabase

relationships. Most tables were related to the sample information table. The relationships between the tables and the sample information table allowed each sample to have more than one result. These relationships are called one-to-many relationships.
Each of these tables with the fields and records allows querying of data for analysis. This is significant to GIS maps that requires certain information from several tables to perform certain manipulations or when a decision needs to be made using specific data from multiple tests.

3.2 *GIS Layer Preparation*

The GIS layer preparation phase involves the transformation of raw data into usable layers for analysis. This includes deriving topographic attributes such as slope, aspect, and elevation from digital elevation models for the topography layer. Additionally, integrating geotechnical engineering data into its own point file layer, while incorporating information on land cover, land use, and soil classification into land type maps. Geological maps are also included to provide insights into rock types, fault lines, and geological hazards.

3.3 *Weight and Ranking Assignment*

Weight assignment is a crucial step in the methodology for Multi-Criteria Decision Analysis (MCDA), involving the identification of evaluation criteria pertinent to addressing expansive soil issues that will undermine infrastructure development. The Analytic Hierarchy Process (AHP) is then employed to hierarchically structure criteria (the expansion criteria parameters) and determine their pairwise comparisons, facilitating the derivation of priority weights for each parameter.

Rank calculation involves the normalization of data to a common scale for consistent comparison. Criteria layers are overlaid to generate composite layers representing the overall values of expansion potential.

MCDA calculation utilizes the weighted sum method to combine normalized the point, line and shape file layers using assigned weights (which will be determined through a re-iterative process of comparing results to expert decision-making, producing an integrated map.

Subsequently, expansive soil identification and construction recommendations involve establishing threshold values (e.g. Atterberg limit minimum values) for identifying areas of high, moderate, and low expansion. Spatial analysis tools are utilized to identify clusters of high expansion areas for targeted solution implementation. Recommendations for construction solutions, such as implementation of foundation types or soil stabilization measures, are generated based on the analysis results.

Validation and verification of the methodology are critical to ensuring its reliability and accuracy. This involves cross-validation by comparing model predictions with field observations, competent expert assessment and historical data. Additionally, expert review is sought to verify the relevance and accuracy of the recommended solutions, providing further confidence in the methodology's effectiveness.

4 CONCLUSION

The challenges posed by expansive soils in South Africa underscore the importance of proactive measures in geotechnical engineering. The development of a GeoDatabase to manage extensive geotechnical datasets and the creation of MCDA maps tailored to the region represent significant steps towards mitigating risks associated with infrastructure development. These initiatives aim to provide engineers with comprehensive insights into soil behavior, stability, and suitability for construction, thereby facilitating informed decision-making and risk assessment early in the project lifecycle. Furthermore, the integration of geospatial technologies such as GIS and the utilization of land type maps offer additional context for site-specific considerations, essential for successful infrastructure development in diverse geological and climatic conditions. By addressing the complexities of expansive clay soils, these efforts contribute to the resilience and longevity of civil constructions projects in South Africa.

5 REFERENCES

Adulraheem, S., Alasadi, Z. & Alhkalidy, A., 2019. The geotechnical maps for physical and engineering properties by using GIS. Journal of Engineering and Applied Sciences.

Awange, J. & Kiema, J., 2019. Fundamentals of GIS in Environmental Geoinformatics. Springer, Issue Envronmental Science and Engineering, pp. 203-212.

Azougay, A., Rezqi, H. & Oujidi, M., 2020. The use of a geographic information system to study geotechnical problems in urban areas. Web Conference, E3S Web of Conferences.

Belton, V. and Stewart, T., 2002. Multiple criteria decision analysis: an integrated approach. Boston, MA: Kluwer Academic Publishers.

Calitz, F., 2023. Using pedological information in preliminary stage geotechnical investigations for strategic urban planning in South Africa. Journal of the South African Institution of Civil Engineering, March, pp. 19-34.

Chen, Z., Ni, P., Zhu, X. & Mei, G., 2022. Using Boundary Transform Method to Solve Geotechnical Problems with Mixed-Type Boundary Conditions. American Society of Civil Engineers, 148(12).

Darwish, K., 2023. GIS-Based Multi-Criteria Decision Analysis for Flash Flood Hazard and Risk Assessment: A Case Study of the Eastern Minya Watershed, Egypt. s.l., 7th International Electronic Conference on Water Sciences.

Domazetovic, F., Šiljeg, A., Loncar, N. & Maric, I., 2019. GIS automated multicriteria analysis (GAMA) method for susceptibility modelling. Elsevier, Issue MethodsX 6.

Eastman, J. R., 2009. IDRISI Taiga: guide to GIS and image processing. Worcester, MA: Clark Labs.

Eisa, A. S. & Fattouh, M., 2023. Hybrid MCDM Model of ARAS TOPSIS GRA for Materials Selection Problem. Journal of Engineering Research (ERJ), Volume 7.

Feng, C., Broggi, M., Faes, M. & Beer, M., 2023. Geotechnical uncertainty analysis with sparse data using interval field method. Dublin, 14th International Conference on Applications of Statistics and Probability in Civil Engineering.

Figueira, J., Greco, S. and Ehrgott, M. (eds), 2005. Multiple criteria decision analysis: state of the art surveys. New York: Springer.

Gong, W., Tien, Y.-M., Juang, H. & Martin II, J., 2017. Optimization of site investigation program for improved statistical characterization of geotechnical property based on random field theory. Bulletin of Engineering Geology and the Environment.

Kim, H.-S. & Ji, Y., 2022. Three-dimensional geotechnical-layer mapping in Seoul using borehole database and deep neural network-based model. Elsevier, Issue Engineering Geology 297.

Larsson, L., 2018. Slope Stability Evaluation from a Risk Management Perspective. Case Study: The Slussen project in Stockholm. In: Stockholm: KTH Royal Institute of Technology.

Makki, A. & Abdulaal, R., 2023. A Hybrid MCDM Approach Based on Fuzzy MEREC–G and Fuzzy RATMI. Mathematics, Volume 3373, p. 11.

Malczewski, J., 1999. GIS and multicriteria decision analysis. New York: J. Wiley & Sons.

NHBRC, 2015. A Guide to the Home Building Manual. Johannesburg: National Home Builders Registration Council.

Paige-green, P., 2004. The Geology and Engineering Geology of Roads In South Africa. Pretoria, Document Transformation Technologies cc.

Phoon, K.-K., Ching, J. & Shuku, T., 2021. Challenges in data-driven site characterization. In: Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards. s.l.:Taylor and Francis, pp. 114-126.

Phoon, K.-k.et al., 2022. Geotechnical uncertainty, modeling, and decision making. Elsevier, Issue Soils and Foundations 62.

Ponnusamy, D. et al., 2021. Mapping of Potential Groundwater Recharge Zones: A Case Study of Maputaland Coastal Plain, South Africa. Research Square.

Roy, B., 2005. An overview of MCDA techniques today: paradigms and challenges. In: Figueira, J., Greco, S. and Ehrgott, M. (eds) Multiple criteria decision analysis: state of the art surveys. New York: Springer, pp. 3–24.

Saaty, T. The Analytic Hierarchy Process (AHP) for Decision Making; McGraw-Hill: London, UK, 1980; pp. 1–69.

Schweiger, H. F., 2023. Numerical modelling of complex geotechnical problems - Three examples. In: Smart Geotechnics for Smart Societies. s.l.:Taylor & Francis.

Schweiger, H. F., Fabris, C., Ausweger, G. & Hauser, L., 2019. Examples of successful numerical modelling of complex geotechnical problems. Innovative Infrastructure Solutions, Issue 2.

Shawky, M. & Hassan, Q. K., 2023. Geospatial Modeling Based-Multi-Criteria Decision-Making for Flash Flood Susceptibility Zonation in an Arid Area. Remote Sensing, Volume 2561, p. 15.

Spross, J. et al., 2022. Risk management procedure to understand and interpret the geotechnical context. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, Volume 250, p. 235.

Stott P., Theron E., 2015 Some shortcomings in the standard South African testing procedure for assessing heaving clay. J S Afr Inst Civ Eng 57(2):36–44

Taherizadeh, M., Niknam, A., Nguyen-Huy, T. & Mezosi, G., 2023. Flash flood-risk areas zoning using integration of decision-making trial and evaluation laboratory, GIS-based analytic network process and satellite-derived information. Natural Hazards, Volume 118, pp. 2309-2335.

Van der Merwe, D.H., 1964, Prediction of Heave from the Plasticity Index and Percentage of Clay Fraction of Soils. Transactions of the South African Institution of Civil Engineers, 6, 103-107.

Webber, S. M. & Kijek, K., 2022. Applying 3D Geological Modelling Techniques to Geotechnical Engineering Problems – Advantages, Pitfalls, and "Getting the Geology Right".

Weidman & Maloney, T. R., 2019. Geotechnical data synthesis for GIS-based analysis of fault zone geometry and hazard in an urban environment. Sand Diego (California): Department of Geological Sciences, San Diego State University.

Whitlow, R., 2000. Basic Soil Mechanics, Third Edition. Harlow: Addison Wesley Longman Limited.

Williams, A.A.B. 1985. Expansive soils. In ABA Brink (ed.) Engineering geology of southern Africa, 4, Pretoria: Building Publications, 23-26.

Yang, R., Huang, J. & Griffiths, D. V., 2022. Optimal geotechnical site investigations for slope reliability assessment considering measurement errors. Elsevier, Issue Engineering Geology 297.

Yasin, K. H. & Woldemariam, G. W., 2023. GIS-based ecotourism potentiality mapping in the East Hararghe Zone, Ethiopa. Heliyon, Volume 9, pp. 1-18.