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Numerical Analysis of Soft Soil Stabilization with Iron Slag Using MIDAS GTS NX in Kayonza District Rwanda

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ABSTRACT: This Research project titled "Numerical Analysis of Soft Soil Stabilization with Iron Slag Using MIDAS GTS NX in District Rwanda" investigates the effectiveness of using iron slag as a stabilizing agent for soft soils in Kayonza District. Laboratory experiments, including Atterberg limits, Modified Proctor compaction, and Direct Shear tests, were conducted to evaluate changes in soil properties after stabilization. The untreated soil exhibited low shear strength parameters, with a cohesion of 0.015 MPa and an internal friction angle of 22.4°. Stabilization with 9% GBFS (identified as the optimum percentage) improved these parameters to a cohesion of 0.0237 MPa and a friction angle of 41.3°, indicating a significant increase in soil strength and bonding capacity. Numerical modeling in MIDAS GTS NX was performed for two cases: untreated soil and soil stabilized with 9% GBFS. The respective safety factors obtained were 0.8 (unstable) and 1.54 (stable), in line with Eurocode 7 requirements, which recommend a minimum global safety factor of 1.5 for stable slopes and soil structures. All analyses were conducted using the Mohr–Coulomb constitutive model, with self-weight as the only external load. The results confirm that GBFS is an effective material for improving the stability of soft soils, making this method suitable for preliminary stabilization works prior to the application of structural or traffic loads.

KEYWORDS: soil stabilization, iron slag, GTSNX, numerical simulation

1. INTRODUCTION

In geotechnical engineering, soft soil presents a persistent challenge due to its weak mechanical properties. Such soils are typically characterized by low shear strength, high compressibility, and low bearing capacity. These characteristics make them unsuitable for supporting structural loads without ground improvement. When subjected to loads, soft soils often experience excessive settlement, which can lead to foundation instability and structural failure.

Table 1-1: Characteristics and impact associated with soft soil

Characteristics of Soft Soil	Associated Engineering Effects
Low shear strength	Weak structural support
High compressibility	Excessive settlement
High water content	Increased risk of failure
Low bearing capacity	Difficulty in supporting loads

This problem is particularly relevant in areas experiencing rapid urban development, such as Kayonza District in Rwanda, where increasing demand for land has driven construction into areas with suboptimal ground conditions. Traditional stabilization methods, such as lime or cement treatment, soil replacement, preloading, and deep foundation systems (e.g., piles), have been used to improve such soils. However, these methods present environmental and cost challenges. The production of cement and lime releases significant amounts of carbon dioxide, contributing to climate change (Higgins, 2005). Additionally, some of these treatments may cause cracking due to shrinkage and moisture loss during curing (Christopher D.F. Rogers, 2022). In response to these limitations, recent studies have explored industrial by-products as sustainable alternatives for soil stabilization. One such

material is Granulated Blast Furnace Slag (GBFS), commonly referred to as iron slag. This non-metallic by-product of steel manufacturing is rich in calcium and silica, giving it cementitious properties. When mixed with soil in an alkaline environment, iron slag undergoes pozzolanic reactions that enhance soil strength and durability (Yadu, 2013). Compared to other alternatives like fly ash, iron slag offers higher hydraulic reactivity and greater long-term strength gains.

Although iron slag production is increasing globally due to steel industry growth, its application in geotechnical engineering remains limited in many developing countries. Utilizing this material for soil stabilization not only reduces industrial waste but also aligns with sustainable development goals by converting a waste product into a valuable construction input.

In addition to material-based solutions, advances in numerical modeling now allow engineers to simulate soil behavior under various conditions before field implementation. MIDAS GTS NX, a finite element–based geotechnical software, enables accurate modeling of soil–structure interaction and assessment of slope stability, settlement, and deformation. Combining experimental soil stabilization with numerical modeling offers engineers a reliable method to predict performance, optimize designs, and reduce costly trial-and-error in the field.

This study focuses on evaluating the effectiveness of iron slag in stabilizing soft soil and analyzing its performance through numerical modeling in MIDAS GTS NX, using Kayonza District as a case study.

2. REVIEW OF LITERATURE

In geotechnical engineering, soft soils present significant challenges due to their low shear strength, high compressibility, and poor bearing capacity. These characteristics make construction on such soils difficult and often require intervention through soil improvement techniques (Karl Terzaghi, 1996). Over the years, engineers and researchers have explored various approaches to improve the mechanical behavior of soft soils, ranging from traditional chemical stabilization methods to modern, sustainable alternatives. Simultaneously, the advancement of computational tools has enabled more detailed modeling of soil behavior under different loading and environmental conditions, contributing to more informed and cost-effective design decisions (Budhu, 2011).

This chapter presents a comprehensive review of relevant literature to contextualize the current research. It begins with an overview of soft soil characteristics and the challenges they pose in construction. Following that, traditional soil stabilization techniques and their limitations are discussed. The chapter then explores the potential of using industrial by-products, particularly iron slag, as a sustainable stabilizer. In addition, it highlights the growing role of numerical modeling in simulating geotechnical problems, with particular attention to the capabilities of MIDAS GTS NX software. Finally, the review identifies existing research gaps, especially the limited integration of laboratory-based stabilization with advanced numerical simulations, which this study seeks to address.

2.1 Characteristics and Challenges of Soft Soil

2.1.1 General Properties of Soft Soils

Soft soils, particularly clayey and organic soils, are characterized by high water content, low shear strength, and high compressibility. These soils typically exhibit low permeability, making drainage slow and consolidation time prolonged. The particle arrangement in soft soils often results in a weak skeletal structure, making them prone to deformation under low loads (Budhu, 2011). Additionally, soft soils are often sensitive to changes in stress conditions, which may lead to large settlements or even slope failure.

Another key property of soft soils is their plasticity, especially in clays, which influences their behavior under different moisture conditions. Plasticity Index (PI), Liquid Limit (LL), and Shrinkage Limit (SL) are common indicators used to evaluate the consistency of such soils (BRAJA M. DAS, 2018). These indices provide vital input during geotechnical investigations to determine the soil's suitability for construction.

2.2 Soil Stabilization Techniques

Soil stabilization is a critical process in geotechnical engineering, aiming to improve the engineering properties of weak or problematic soils to enhance their performance under structural loads. The primary objective of stabilization is to increase soil strength, reduce permeability, and improve durability under varying environmental conditions (Budhu, 2011). Various methods have been developed and utilized over time, broadly categorized into mechanical, chemical, and additive-based techniques.

2.3 MIDAS GTS NX and Its Capabilities

MIDAS GTS NX (Geotechnical and Tunnel System) is a specialized finite element software developed for advanced geotechnical and underground structure analysis. It is particularly well- suited for problems involving complex soil-structure interaction, seismic loading, tunnel analysis, and slope stability.

One of the key strengths of MIDAS GTS NX is its user-friendly interface combined with high computational performance as it shown in Figure 2.1. The software supports 2D and 3D FEM analyses and includes advanced features such as consolidation, seepage, dynamic analysis, and construction stage simulation (IT, 2020). These capabilities make it a preferred choice for academic research and professional engineering applications where accurate modeling of soil behavior is required.

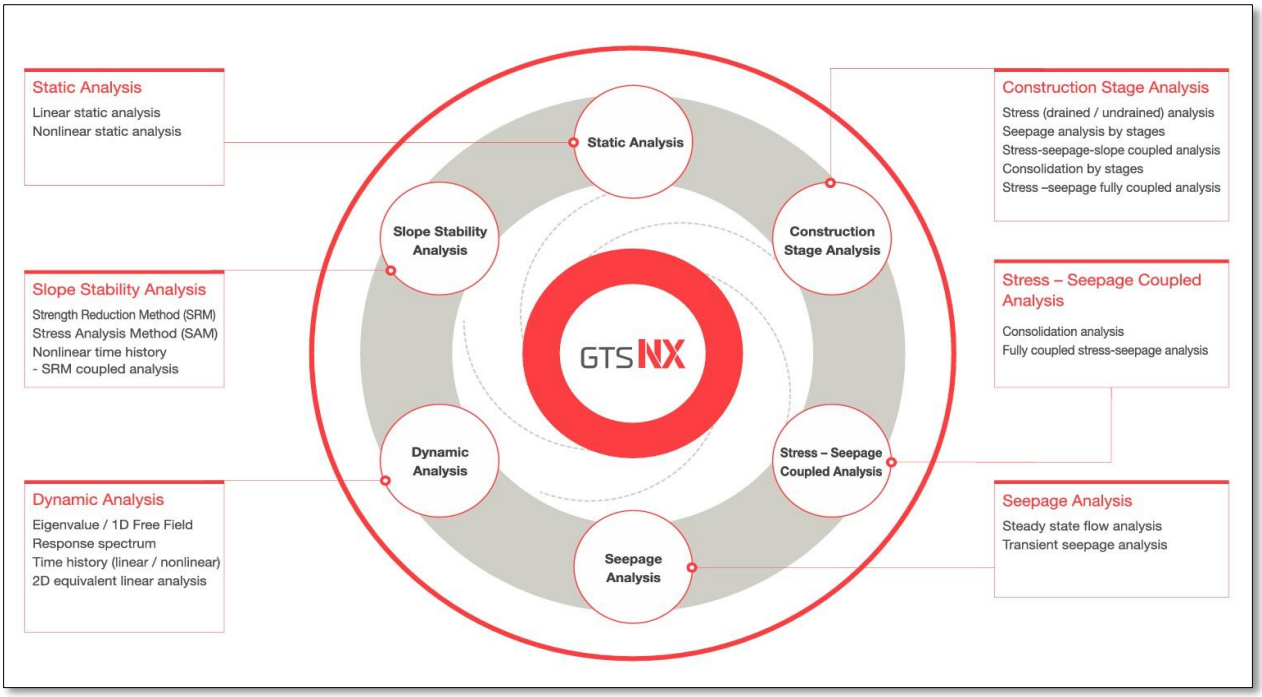


Figure 2.1: MIDASGTS NX Analysis Methods

3. METHODOLOGY

This chapter presents the methods used to investigate the effectiveness of soft soil stabilization using iron slag, along with the application of numerical modeling techniques. The research approach combines laboratory experiments and finite element simulations to analyze and compare soil behavior before and after stabilization. The aim is to assess the performance of iron slag as a stabilizing agent and evaluate how well numerical models can replicate the results observed in the laboratory. This chapter outlines the research design, describes the study area, details the materials and testing procedures, explains the modeling approach, and discusses how data will be collected, analyzed, and interpreted. It also highlights the key limitations and assumptions considered in the study.

3.1 Research Design

This study follows an experimental and comparative research design aimed at evaluating the effectiveness of soft soil stabilization using iron slag. It combines both laboratory testing and numerical modeling to analyze soil behavior before and after stabilization. The research involves collecting soil samples from the site, conducting laboratory tests to determine the effect of iron slag, and simulating the same conditions in MIDAS GTS NX to compare results. The study follows a step-by-step structure as illustrated in Figure 3.1

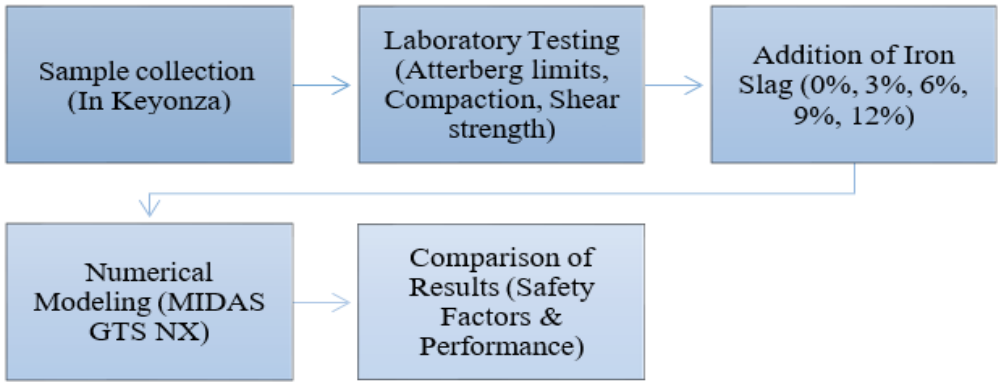


Figure 3.1: Flowchart of the Research Methodology

3.2 Study Area

The study was based on a proposed construction site located in Kayonza District, in Rwanda's Eastern Province. The selected site lies within the Rwinkwavu Sector, approximately 7 kilometers from the entrance to Akagera National Park, near the main access road that connects Kayonza town to the park. The site occupies an estimated 3,600 square meters (60m × 60m) and is intended for the construction of a G+1 guest house facility designed to host travelers, tourists, and local events. The proposed development will include accommodation rooms, a reception area, and a garden space suitable for small parties and community gatherings.

This location was strategically chosen due to its proximity to a major tourism hub, making it ideal for commercial hospitality development. The land in this area is mostly flat with small gentle slopes. The soil is soft and contains a lot of clay, especially in places near natural water channels and marshy areas. This poses challenges for traditional shallow foundation systems, hence the need to explore reliable soil stabilization methods.

In this study, the plot was conceptually analyzed as a soft soil site requiring foundation enhancement. The soil for laboratory testing was extracted from this area using standard open pit techniques, and all geotechnical evaluations were carried out accordingly. The site's characteristics including its semi-rural setting, commercial potential, soft subgrade, and hydrological conditions made it a suitable case for evaluating ground improvement using iron slag as an industrial by product and modeling stabilization performance by soil nailing method through MIDAS GTS NX software.

3.3 Materials and Tools

The materials used in this study included disturbed soft soil obtained from the Kayonza site and iron slag (specifically granulated blast furnace slag) sourced from IMANA Steel Ltd located in Bugesera District. The laboratory work involved the use of equipment for standard geotechnical tests such as Atterberg limits, sieve analysis, moisture content, compaction, and direct shear tests. The numerical modeling part of the study was performed using MIDAS GTS NX, a finite element analysis software capable of simulating complex soil-structure interactions and slope stability conditions.

4. RESULT DISCUSSION AND INTERPRETATION

4.1 Introduction

This chapter presents the results, discussion, and interpretation of both the laboratory tests and numerical modeling related to soft soil stabilization. Laboratory testing was conducted on untreated soft soil and on soil samples treated with various percentages of iron slag. These tests included sieve analysis, Atterberg limits, compaction, and direct shear tests. Among the treated samples, the one that achieved the maximum dry density and optimum moisture content was selected as the most effective for stabilization.

The selected treated soil sample was then modeled in MIDAS GTS NX, alongside the untreated soil, to compare their behavior under similar conditions. The aim was to evaluate and compare the safety factor of the two conditions; untreated, and treated with iron slag, under identical loading and boundary conditions.

4.2 Interpretation

The Atterberg limits test results revealed that the liquid and plastic limits of the soil fall within a moderate range, indicating a gradual transition between the liquid and plastic states. With a plasticity index (PI) of 12.92%, the soil demonstrates medium plasticity, suggesting that while it is not overly soft or brittle, it still lacks the necessary strength and consistency required for safe construction. Based on the liquid limit and PI values, the soil is classified as CL (inorganic clay of medium plasticity) according to the Unified Soil Classification System (USCS). This classification confirms that the soil has cohesive characteristics but requires stabilization to improve its load- bearing capacity and overall performance for construction applications.

4.3 Compaction test results and interpretation

The compaction test was performed to evaluate the relationship between moisture content and dry density of soft soil both in its natural state and after stabilization with various percentages of Iron Slag. This test was conducted following the Modified Proctor method under BS 1377-4:1990, which provides insights into the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) required for achieving proper field compaction.

Tests were conducted for soil samples treated with 0%, 3%, 6%, 9%, and 12% GBFS, and each sample was compacted at varying moisture contents of 0%, 2%, 4%, and 6%. The dry densities corresponding to each moisture content were calculated and used to plot compaction curves. The goal was to identify the point at which each sample achieved its highest dry density, this point indicates the OMC and MDD.

The peak dry density was observed at 9% iron slag, where the soil reached a maximum dry density of 1.8 g/cm³ at an OMC of 16.1%. This suggests that 9% Iron slag provides the most efficient packing of soil particles under modified Proctor energy. Beyond this

percentage, a slight drop in dry density was noted (1.77g/cm³ at 12% iron slag), indicating that further addition of iron slag may result in less effective compaction. From the results founded this figure 4.1, present the relationship between Dry density and moisture content we can get a combined graph showing how the varying percentage of Iron slag affects both the maximum dry density and the optimum moisture content.

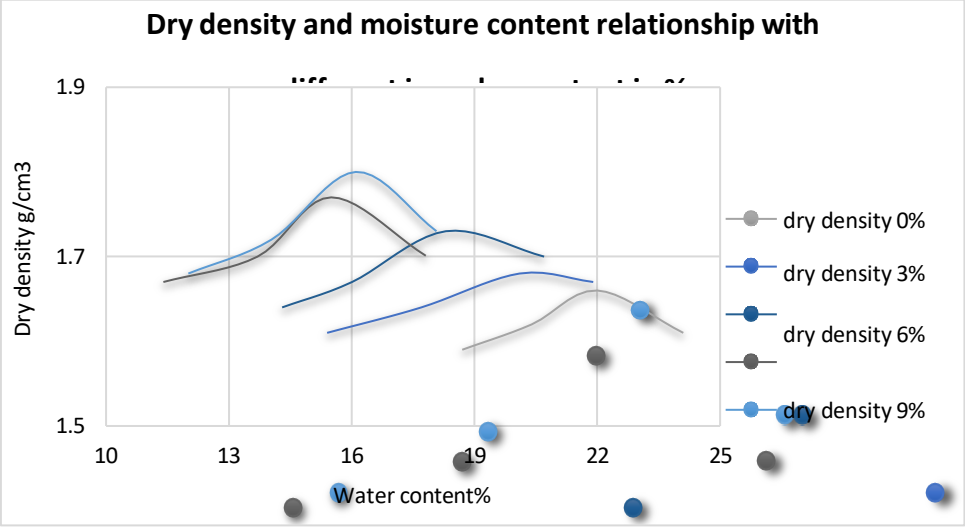


Figure 4.1: Graph combining findings on different iron slag content

The summarized results are presented in table 4.1

Table 4-1: Relationship between OMC and MDD for Varying Iron slag Content

% Iron slag	Optimum Moisture Content (%)	Maximum Dry Density (g/cm³)
0	22	1.66
3	20.1	1.68
6	18.3	1.73
9	16.1	1.80
12	15.5	1.77

From the results, it is evident that the addition of Iron Slag influenced both the compaction characteristics and strength of the soil. The untreated soil (0% iron slag) exhibited the lowest dry density at a relatively high moisture content of 22%. As Iron slag was added, there was a gradual increase in the dry density accompanied by a decrease in the moisture content needed for optimal compaction.

4.4 Numerical simulation results in terms of displacement, plane stresses and grid forces before using iron slag

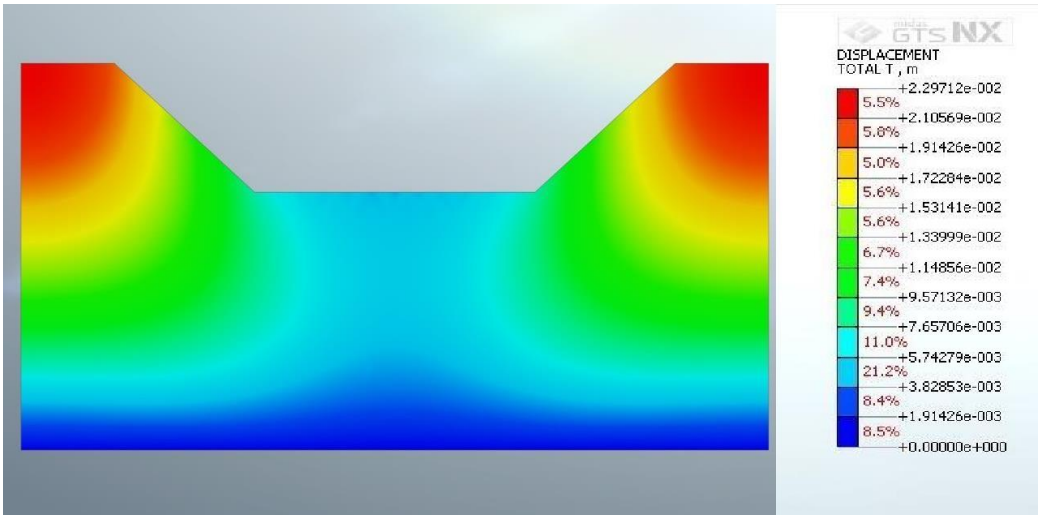


Figure 4.2: Untreated soil, INCR=2 (FOS=0.8000) Displacements_TOTAL TRANSLATION

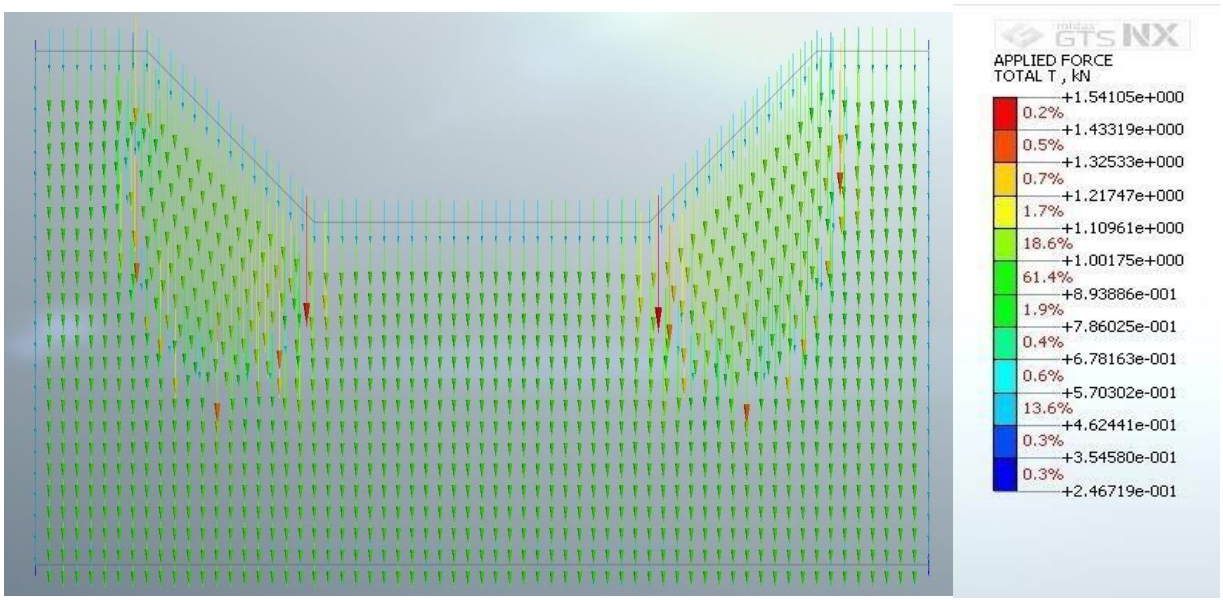


Figure 4.4: Untreated soil, INCR=2 (FOS=0.8000) Grid Forces_TOTAL APPLIED FORCE

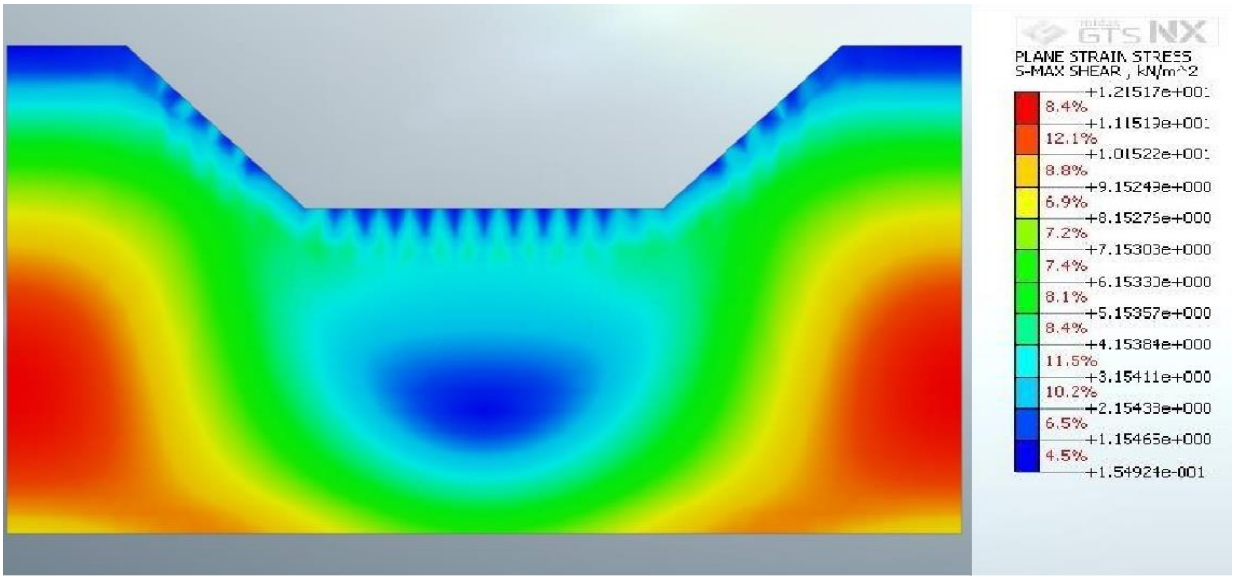


Figure 4.3: Untreated soil, INCR=2 (FOS=0.8000) Plane Strain Stresses-MAX SHEAR

4.5 Numerical simulation results in terms of displacement, safety factor and grid forces after using 9% of iron slag

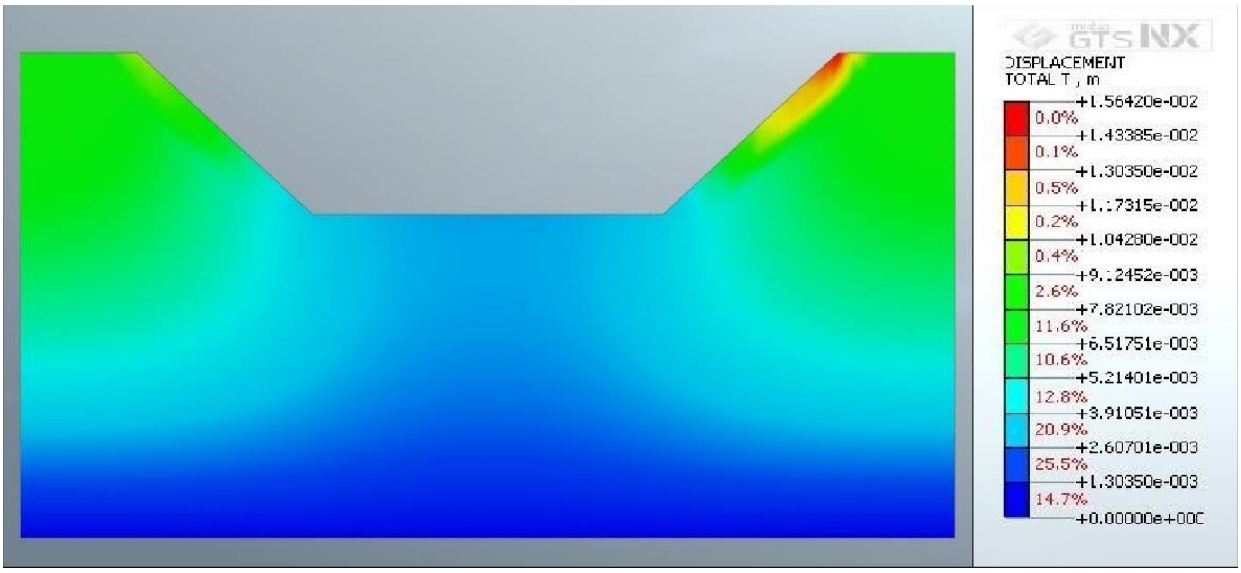


Figure 4.5: 9% Iron slag, INCR=12 (FOS=1.5441) Displacements_TOTAL TRANSLATION

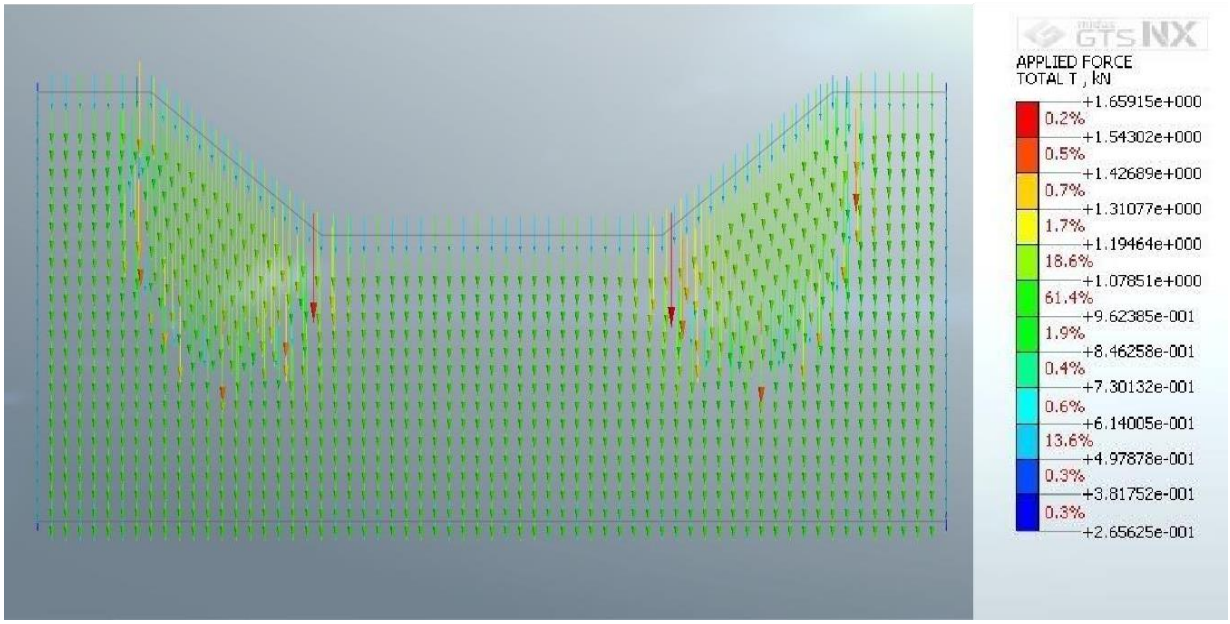


Figure 4.6: 9% Iron slag, INCR=12 (FOS=1.5441) Grid Forces_TOTAL APPLIED FORCE

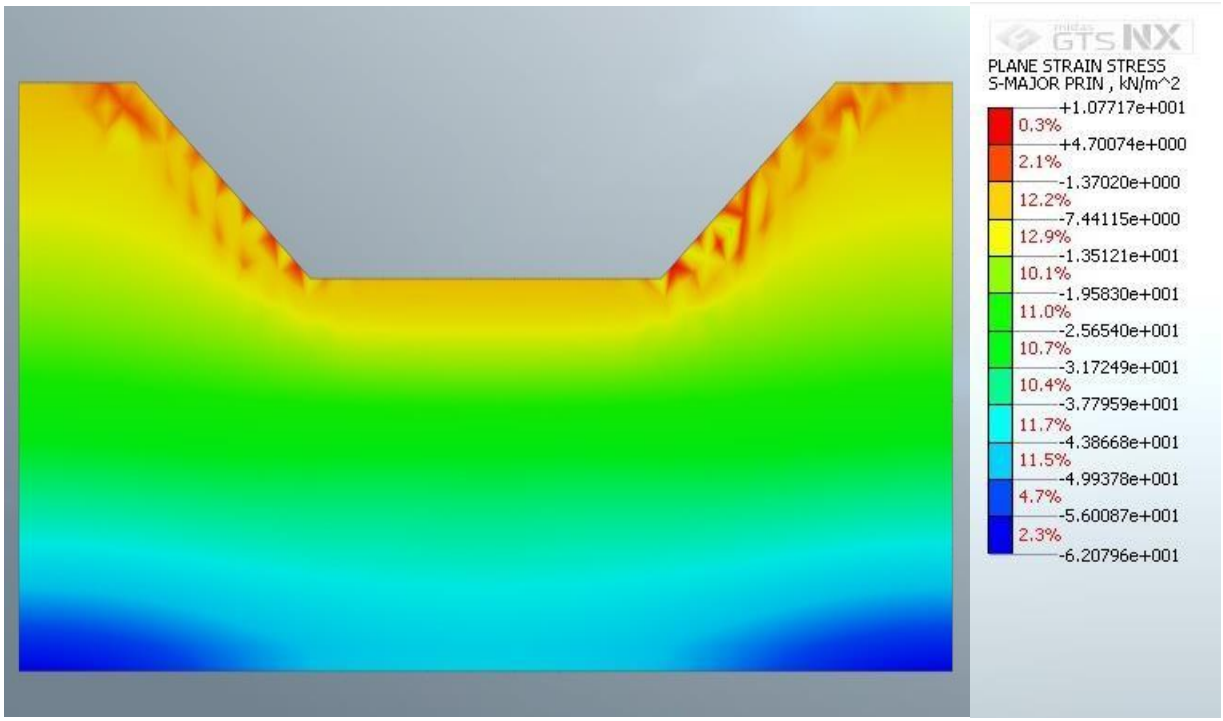


Figure 4.7: 9% Iron slag, INCR=12 (FOS=1.5441) Plane Strain Stresses-MAJOR PRINCIPAL

4.6 Interpretation of Results

From the numerical simulation results, it was evident that stabilization significantly improved the safety and performance of the soft soil model.

Model 1 (Untreated Soil): The computed safety factor was 0.80 as it shown in Figure 4.2 to Figure 4.4, which is far below the generally accepted minimum value of 1.50 for construction. This indicates that the natural soil is unstable and unsuitable for supporting loads without failure, even under its own self-weight. The failure surface observed in the output confirms a shallow and extended slip circle, typical of weak, soft clay soils.

Model 2 (9% Iron Slag): After treating the soil with 9% iron slag, which was previously determined as the optimum percentage from the compaction and shear strength tests, the safety factor improved to 1.54 as it shown in results of Figure 4.5 of total displacement using iron slag, Figure 4.6 of grid force and Figure 4.7 showing plane strain stress. This value satisfies the basic requirement for stability, indicating that the addition of iron slag significantly enhanced the soil's strength parameters. The internal friction angle and cohesion both contributed to the observed improvement, reducing the risk of failure under natural loading

conditions.

- These results validate the effectiveness of chemical (iron slag) methods for stabilizing soft soils. The highest safety factor was observed in the soil treated with iron slag model (1.54), by the 9% iron slag. On the other hand, untreated soil demonstrated unsafe conditions, emphasizing the necessity for stabilization in soft clay deposits.

The highest strength was recorded at 9% Iron slag, with a cohesion of 0.0237 N/mm² and an internal friction angle of 41.3°. This notable peak in strength parameters confirms 9% Iron slag as the optimum content, resulting in the most significant enhancement of soil resistance to shear failure. The increase in both cohesion and friction angle reflects the optimal pozzolanic reaction and particle interlock, contributing to maximum strength gain.

However, at 12% Iron slag, a slight reduction was observed, with cohesion dropping to 0.0208 N/mm² and the friction angle decreasing to 35.6°. This decline indicates that excessive slag content may lead to over-stabilization, disrupting soil structure and reducing shear strength.

In summary, the test confirms that the addition of iron slag significantly improves the shear strength of soft soil, particularly at 9% Iron slag, which delivers the best balance between cohesion and internal friction, making it the most effective stabilization ratio for safe construction.

5. CONCLUSION

This study evaluated the stabilization of soft soil using granulated blast furnace slag (iron slag) and assessed its performance through laboratory testing and numerical analysis using MIDAS GTS NX. The primary objective was to determine the improvement in soil stability and safety factor after treatment with iron slag, particularly under conditions representative of preliminary construction evaluations.

Laboratory tests on untreated soil revealed low shear strength parameters, with cohesion and internal friction angle values indicating poor load-bearing capacity. Upon stabilization with 9% iron slag identified as the optimum proportion the soil exhibited significant improvements in both cohesion and friction angle, demonstrating enhanced strength and bonding capacity.

Numerical modeling in MIDAS GTS NX was conducted for two scenarios: untreated soil and soil stabilized with 9% iron slag. The Mohr–Coulomb material model was applied in all simulations, and self-weight was considered as the only external load. The untreated soil recorded a safety factor of 0.8, indicating a critically unstable condition, whereas the stabilized soil achieved a safety factor of 1.54, surpassing the Eurocode 7 minimum threshold of 1.5 for stable slopes and soil structures.

These results confirm that iron slag is an effective stabilizing agent for improving the geotechnical performance of soft soils. The integration of laboratory findings with numerical modeling provides a reliable approach for predicting field performance, supporting the adoption of iron slag stabilization in similar geotechnical environments. This method offers a sustainable, cost-effective alternative to traditional chemical stabilizers, while contributing to the reuse of industrial by- products in construction.

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