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Kayusi Ondabu Fredrick
M.Sc., School of Environmental and Earth Sciences, Pwani University, P.O Box 195, Kilifi, Kenya

Maarifa Ali Mwakumanya
Ph.D., Lecturer and Professor, Department of Environmental Sciences, Pwani University, P.O Box 195, Kilifi, Kenya

Mwakio P Tole
Ph.D., Lecturer and Professor, Department of Environmental Science, Pwani University, P.O Box 195, Kilifi, Kenya

Corresponding Author:
Kayusi Ondabu Fredrick
M.Sc., School of Environmental and Earth Sciences, Pwani University, P.O Box 195, Kilifi, Kenya

Slope stability analysis at soapstone mining sites in Nyamarambe, Kisii County, Kenya

Kayusi Ondabu Fredrick, Maarifa Ali Mwakumanya and Mwakio P Tole

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Abstract
Soapstone mining designs cause slope instability, resulting in quarry accidents causing injuries, and death to artisanal miners. Slope destabilization of soapstone strata and sliding of rock masses into open pits are common in soapstone mines. This study assessed the influence of slope angles and heights on the slope gradient, safety factor and instability of the excavated mine slopes. This paper outlines unstable slopes at the mining sites. Studies on soapstone mining in Kisii have mostly focused on socio-economic aspects but very little has been reported on slope instabilities that are common in soapstone rocks mining geosites. Kisii soapstone quarries were examined as several slope failure accidents have been encountered during mining. Field surveys made to the quarries enabled the collection of geomorphometric field data on soapstone quarries and potential slope failure zones. A digital inclinometer and tape measure were used to collect geometric data from the quarries. LEM was used to compute and analyze the factor of safety of slopes to predict the slope instability risks. The findings reveal that unsafe mining designs increase slope angles and heights, inducing instability geohazard risks. The soapstone rock mass in the opencast mines is weak and prone to slope failure. The means of slope angles and heights of the sampled quarries were 69.1° and 6.19 meters with the safety factor mean value of 0.565 indicating that all the examined quarry slopes are unstable. The results reveal that increasing slope angles and heights in soapstone mines decreases the factor of safety resulting in slope failure geohazards. The study recommends that artisanal miners should always mine under optimized slope angles and heights and suggests slope stabilization geotechniques for further scientific and academic research works. This paper provides a significant database for slope failure mitigation, sustainable soapstone mining, post-mining phaseout transformations and management.

Keywords: Soapstone rocks, soapstone mining, slope stability, factor of safety, slope angle and height, slope failure

Introduction

A slope is a surface or plane's upward or downward inclination. An earth slope is an unsupported, inclined soil mass surface (Salunkhe *et al*., 2017) [38]. Slopes are distinct geomorphic structures that can be found not just in mountainous and hilly areas but also in quarries (Atmaja *et al*., 2019) [4]. A slope is an inclined topography or terrain of the surface of the earth which occurs naturally or is anthropogenically excavated (Abramson *et al*., 2001) [1]. Slope geometry is deformed and configured by both natural and artificial forces causing instability (Earle *et al*., 2015) [16]. Slope instability and slope failures are common in many parts of the world.

The type and extent of rock structural control which can be split into numerous categories determines how often a rock slope fails (Böhme *et al*., 2011) [5]. Many rock slope failures exhibit ground movements that indicate escalated velocity trends (Du *et al*., 2022) [15]. The types of rock slope failures including rotational, translational, toppling, circular and planar collapses are common in quarries (Braathen *et al*., 2004) [6]. Surface drainage, groundwater conditions, geometry and characteristics of possible slope failures are the main internal factors influencing the stability of the mass of soil and rock slope (Sengani & Allopi, 2022) [39]. Precipitation, seismic activity and human activities are examples of external intervening variables. Human activities such as quarrying make the slopes of mines unstable, hence causing them to collapse (Böhme *et al*., 2011) [5].

Globally, the high demand for minerals in the twenty-first century has forced the expansion of mining activities leading to the excavation of minerals in large capacities into deeper levels (Kolapo *et al*., 2022) [28]. Most minerals that are mined and produced globally do so in open pits using surface mining methods. The opencast method exposes the surface and rocks around the open pit walls to become free to move towards the direction of the face of the slope over a sizable area (Wesseloo & Dight, 2009) [45]. Surface opencast mining is an effective method because it permits high mechanization degrees and large output quantities (Jotham & Mulinya, 2020) [26]. Opencast mining methods majorly depend on the slope gradient and stability of the open quarries, which must not fail throughout the mines' life.

Opencast mining operations subject natural slopes to deformation due to reduced shear strength causing rock slope failures (Sutejo & Gofar, 2015) [44]. The mass of rocks and soil in and around the mines develop deformations because of the in-situ stress field characteristics (Stacey & Potvin, 2007) [41]. As a result open pit mines frequently face collapsing and sliding of rock masses which grow more inevitable as the quarrying activities go deeper and get more challenging to control (Kolapo *et al*., 2022) [28]. In the worst-case scenario, artisanal miners working immediately below unstable quarry slopes may sustain fatalities (Kramadibrata *et al*., 2012) [29]. Small rockfalls cause fatal injuries to unprotected miners whereas larger landslides harm miners who are confined in larger mining equipment if necessary precautions are not taken (Harries *et al*., 2009) [24].

According to Clark & Small (2006) [13], opencast quarrying operations alter the soil profile and bedrock, triggering geomorphic slope movement processes. The loss of vegetation cover due to quarrying activities accelerates weathering, mass movement and erosion on the exposed slopes.

Zevgolis *et al*. (2019) [47], ascertained that weathering of rocks is slow but constantly accelerates the diminishing of shear strength forces of slope materials.

In Africa, Gumisiriza & Lurd (2014) [22] in a study in Uganda probed the role geomorphological slope processes and anthropogenic activities play in the formation of slopes and the causes of slope instability. Thus, the balance of geomorphic slope processes that erode the parent rock while transporting regolith down the slope determines the steepness of a slope. Increased shear stress force of the slope materials causes instability with slope failure being the result (Ciampittiello *et al*., 2021) [12].

Kenya is rich in mineral resources such as limestone, soda ash, carbon dioxide, diatomite, gold, titanium, silica, gemstones, gypsum, iron ore, fluorite, granite, lead and soapstone. These minerals are mined in various parts of the country including mining of gold in Kakamega and Migori, Titanium in Kwale, Fluorspar in Kerio Valley, limestone in Athi River and Mombasa. In Kisii County, as noted in the annual CIDP, there are two main mineral resources; soapstone and granite (CGK, 2018). The instability of slopes within the quarries is an issue in the quarries of Kisii County. Most mineral production areas are located close to the excavation floor, hence constantly risking the miners and machines used in mining. This sometimes causes loss of lives and property and premature closure of quarries. The Nyamarambe area is characterized by massive soapstone rocks which have been mined since 1885 (GoK, 2016) [19]. According to Kenya's Department of Geology, the soapstone rock is 25 kilometers long and 265 meters deep. Approximately, 20 percent of the soapstone rocks have been mined (Buyeke & Njoroge, 2015) [9, 10]. Dewatering and replanting of vegetation are mostly used to control and manage the instability of slopes in the quarries.

The Slope Concept

The slope of an inclined surface is its resistance to failure due to sliding or collapsing (Salunkhe *et al*., 2017) [38]. Every type of landform on the earth's surface is a component of some scale of a slope that can be assessed in terms of gradient and length, resulting in a variety of gradients and amplitudes in topography (Njue, 2021) [33]. Slopes can be delineated into two types: natural slopes and artificial slopes. The natural slopes are generated by continual erosion processes and deposition by physical forces. They include hillsides, river embankments, ridges and valley escarpments. Artificial slopes are those that are the product of anthropogenic construction efforts. Among them are embarkments, canals, cut slopes and retaining walls (Palaskar, 2016) [48]. Types of slopes are also categorized as finite or infinite. Finite slopes are slopes of a limited extent while infinite slopes are slopes that represent the border surface of semi-infinite masses of soil, where soil characteristics are constant at all identical depths below the surface (Salunkhe *et al*., 2017) [38].

Stability of the Slope

According to research, slope stability is the endurance and shifting capacity of soil covered materials. The stability of a slope refers to the static and dynamic stability equilibrium of earth and rock-fill dam slopes, embankment slopes, engineered slopes, and natural soil and soft rock slopes (Kumar, 2015) [30]. The slope's stability can be calculated using the balance of shear forces and shear strength. Preparation variables may first alter a previously stable slope, making it conditionally unstable (Kumar, 2015) [30]. A slide ensues when a mass of soil beneath a slope fails. It includes the full amount of soil implicated in the collapse flowing downhill and outward. Slope failure is caused mostly by gravity pressures and seepage forces inside the soil (Salunkhe *et al*., 2017) [38].

They may also fail due to foot excavation or undercutting, or when the soil structure slowly deteriorates. Slides can occur in almost every way imaginable, rapidly or gradually, with or without any visible trigger (Salunkhe *et al*., 2017) [38]. Climatic events can be triggering factors for slope failures, making slopes actively unstable and hence causing mass motions. Massive movements of slope materials are caused by increasing shear stress, loads, lateral pressure and transient forces (Kumar, 2015) [30]. Weathering, pore water pressure fluctuations and organic material diminish the shear strength of slope materials.

Factors Causing Slope Instabilities

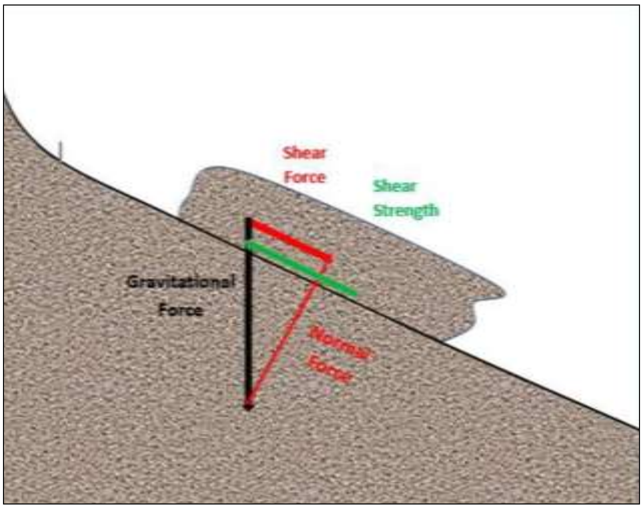
Slope parameters, climatic factors and forces acting on a slope affect its stability. Sliding and collapsing of heaped materials on a slope are influenced by the forces and parameters such as weight, gravity, slope angles and frictional forces acting on a slope as shown in Figure 2.1. Slope instability is a mass of rock, regolith, debris or unconsolidated soil moving down an inclined plane due to gravitational force. Studies have investigated various geomorphic and human factors responsible for slope instability. Many authors such as Kumar (2015) [30]; Palaskar (2016) [48]; Salunkhe *et al*. (2017) [38]; Satyanarayana and Sinha (2018) [49] and Suman (2015) [43], gave special reference to both natural and anthropogenic factors.

In a nutshell, they include slope geometric parameters that alter the stability of slopes. The slope geometric parameters including the slope angle, slope height and the total area of the failure surface cause slope instability. The instability of slopes increases with an increase in height and slope angle. The type of rock (lithology) on open pit slopes determines the strength of rock mass affected by discontinuity, folding, faulting, bedding plane and weathering. Slopes with weathered rocks have weaker shear strength and deteriorate due to seepage of water through them. Geological structures with strata dipping into the excavation and steepening of rock strata affect slope stability hence the slopes become conditionally unstable. Stability is dependent on the shear strength of rock structure orientations.

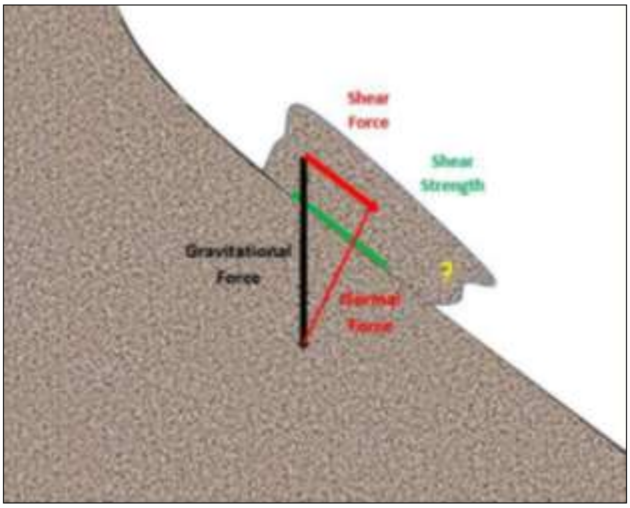
Excess content of groundwater in excavated slopes reduces parameters such as cohesion, adhesive and frictional resistance. This reduces the shearing resistance due to the reduced discontinuity surface friction and effective normal stress. Cohesion is the resistance of slope materials per unit area. It is measured in Pascal (Pa). The lower the cohesion values and frictional condition, the more the slope becomes unstable.

Internal frictional angle is a measure of the angle between the normal force and the resistance force. This angle depends on the size and roundness of the particles. The lower the roundness, and the larger the size of the particles, the larger the frictional angle.

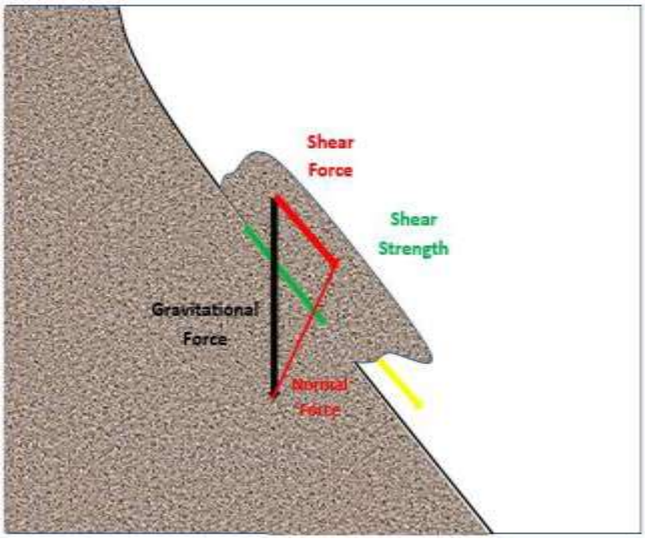
According to Sailaja *et al*. (2021) [37], the instability of opencast mine slopes is significantly affected by the presence of geological disturbances like faults, joints, unconformities and some other man- made mistakes. Surface mining tools and methods in the open pits cause deep cutting and sharply dip the rock strata into the excavation due to greater slope, increasing downward pulling force on the slope, hence causing instability conditions.

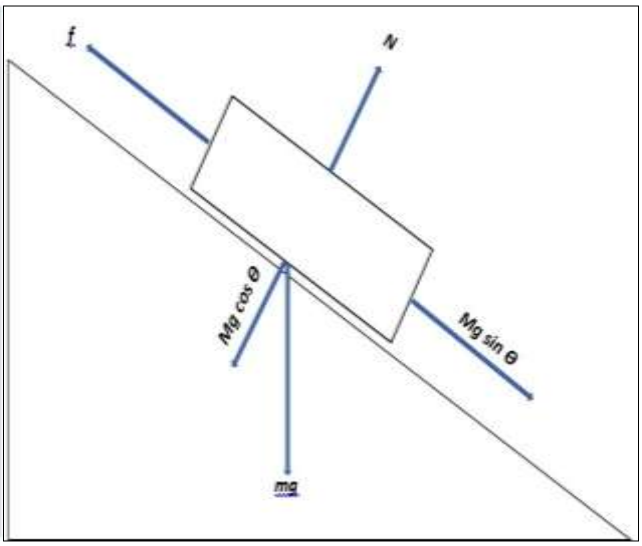


A: Steep-Plane



B: Steeper Plane





Source: Modified from (Earle *et al*., 2015) [16]

C: Steepest Plane

D: Sliding Object on a Sloppy Plane

Fig 1: Forces Acting on a Slope and Stability Conditions

With constant gravitational force in models A to C, in model A the force of shear is less than the tensile shear strength forces, and hence the slope is stable thus the block on it is considered stable.

In model B the shear strength and the shear forces are approximately the same thus the slope and the block on it exhibit intermediate stability conditions, implying that its motion may or may not happen hence the need for slope monitoring. In model C the force of shear is greater than the force of shear strength and hence the slope is unstable thus the block is most likely in motion. Shows a rock bedding to the slope hence considered an unstable slope. Model D shows forces and

parameters that significantly affect slope stability. Where m is the material's mass, g is the force

of gravity, ϴ is the angle of slope, f is the frictional force (mgsinϴ), N is the normal force

(mgcosϴ), mg is the weight of materials, sin is the sine and cos is the cosine.

Slope Measurement and Determination of Slope Instability

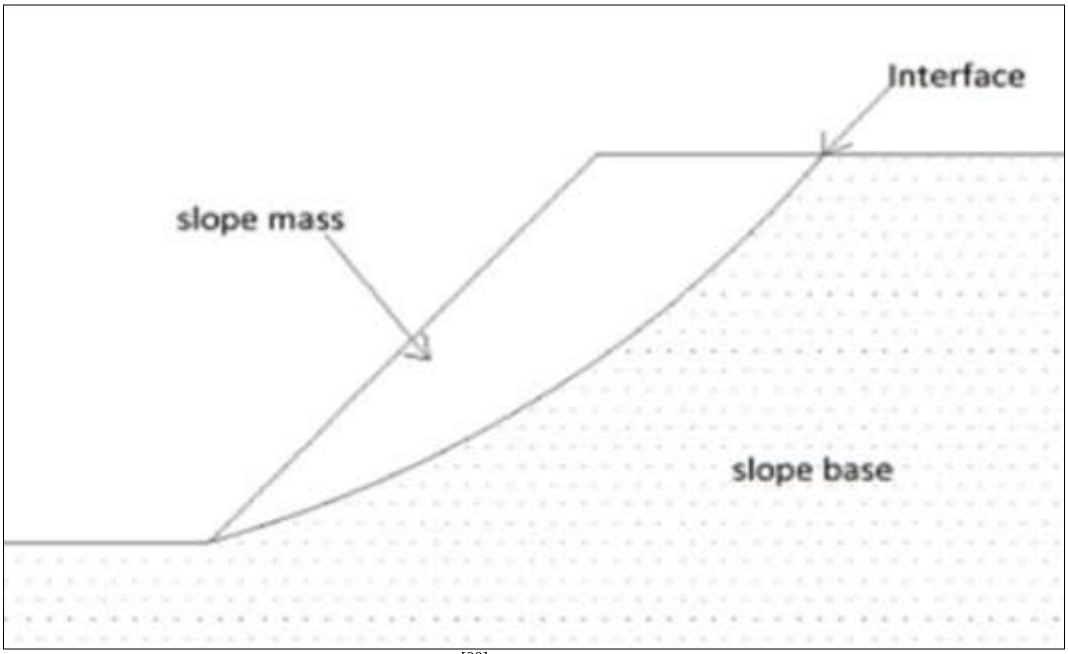
Slope is a measure of how much the height (elevation) of land changes over a certain distance and time (Burles & Huscroft, 2023) [8]. It is a critical parameter in several well-known environmental forecasting models. It is the measurement of how much higher an incline or lower a decline is at a specific point of a surface or plane. Slope is measured with an instrument called an inclinometer. When using an inclinometer, the line of measurement is fixed on the target as the slope percentage is read from the scale (DeYoung, 2016) [14]. The inclinometers and tiltmeters are used in surface movement surveying to record changes in the direction and rate of slope movement depth, as well as the aerial extent of the failure mass (Kumar, 2015) [30].

The equilibrium of shear force and shear strength affects the instability of slopes. The slope is conditionally unstable if the shear strength forces available to prevent movement are less than the forces causing the motion. The two basic methodologies used to determine slope instability are limit equilibrium and finite equilibrium (Salunkhe *et al.*, 2017) [38]. Limit equilibrium methods are used to determine the equilibrium of a mass of soil that tends to slide down a slope due to gravitational force as shown in Figure 2.2. The rotational and transitional motion of slope materials is examined beneath the soil or rock mass on an expected or known probable slip surface. These approaches are particularly crucial in rock slope engineering and the failure of simple blocks along discrete discontinuities.

These approaches rely on a comparison of the forces, moments or stresses that oppose the mass movements with those that potentially cause unstable movements. The LEM analysis produces a factor of safety ratio indices, which are described as the shear strength-to-shear stress ratio indices required for slope equilibrium. The slope is conditionally unstable if the safety factor is less than

1. The force opposing movement is divided by the force driving a movement to calculate the safety factor (Salunkhe *et al.*, 2017) [38]. The factor of safety is expressed as

$$FS = (Shear\ strength\ available) \div (Shear\ strength\ mobilized).$$



Source: Modified from (Salunkhe *et al.*, 2017) [38]

Fig 2: Limit Equilibrium Method (LEM)

Slope Movements and Instabilities

The term "slope movement" refers to the outward and downward displacement of slope-forming materials caused by gravity (Gutiérrez & Gutiérrez, 2016) [23]. Rock masse's movements can be lateral or vertical displacements that are triggered by mining activities beneath the steep open pit final slopes (Xu *et al.*, 2016) [46]. Delineation of slope movement and instability processes are often defined by slope failure mechanism, speed of movement and geological materials (Guerra *et al.*, 2017) [20-21]. Combining well-known geologic, topographic and geomorphic site characteristics with site historical data on previous failures can increase the predictability of a slope failure (Keller, 2017) [27].

The various types of mass movements such as flows, slips, slides and unblock falls, as well as their duration, depend on the slopes, rocks and climatic conditions (Nyaga, 2021) [34]. Any time a slope turns unstable, a mass movement mechanism is triggered and accelerated by climatic, tectonic and human factors. Sometimes a slope is fundamentally unstable during the entire operation, as in the case of soil creep, solifluction and sliding processes, which are continuous (Zevgolis *et al*., 2019) [47]. The benefit of improved slope failure predictability leads to increased safety at the mining site and valuable resources being saved (Bui *et al*., 2020) [7]. In the highlands, slope modification and disturbance, which is primarily caused by deforestation linked to population pressure, causes many slope motions such as slope failures and landslides.

A massive slope displacement of the loose topsoil and quarried regolith materials can re-adjust and modify the cultivated quarry slopes to their repose angle. Slope instabilities in the quarrying areas have been greatly impacted by the use of lands with steep slopes with no soil management techniques, as well as engineering projects for building on steep slopes (Bui *et al*., 2020) [7]. Slope modification by anthropogenic activities or by natural forces can result in the alteration of the slope angle reducing its repose angle. Therefore, it makes sense to associate slope instabilities in such areas with unsafe opencast soapstone mining practices. Gathuru (2012) [18] asserts that soapstone extraction processes also produce molds and boulders made of leftover soapstone ore residual deposits, some of which have incredibly small grains.

By liquefying soil colloids, quarrying triggers and accelerates a variety of slope processes and slope instabilities such as slides, rolling, flows, falls, toppling, tension cracks, scree, surficial and massive creeps (Guerra *et al*., 2017) [20-21]. The likelihood of weathering of exposed soapstone rocks, large-scale slope motions and accelerated soil erosion increases as a result of the mining practices (Londero *et al*., 2021) [31]. In Kisii County, quarrying sites have unstable zones, and hence unexpected earth movement can cause damages and fatalities. Small rock falls can also cause injuries to artisanal miners who are not protected, while larger and massive landslides during rainfall seasons could harm artisanal miners confined in larger mining operations in the underground opencast pits (Palaskar, 2016) [48].

Materials and Methods

The Study Area

Kisii County is one of the 47 counties of the Republic of Kenya. It is located to the South East of Lake Victoria. The County covers a total area of 1,317.5 km2 and is geographically located between latitude 0o 40' 38" to 0o 48' 36" South and longitude 34o 34' 46" to 39o 37'41" East. The location of the Nyamarambe division in Kisii is at latitude 0o 45' to 0o 46' South and longitude 34o 36' to 34o 40' East (Buyeke & Njoroge, 2015) [9, 10] as shown in Figure 3 below.

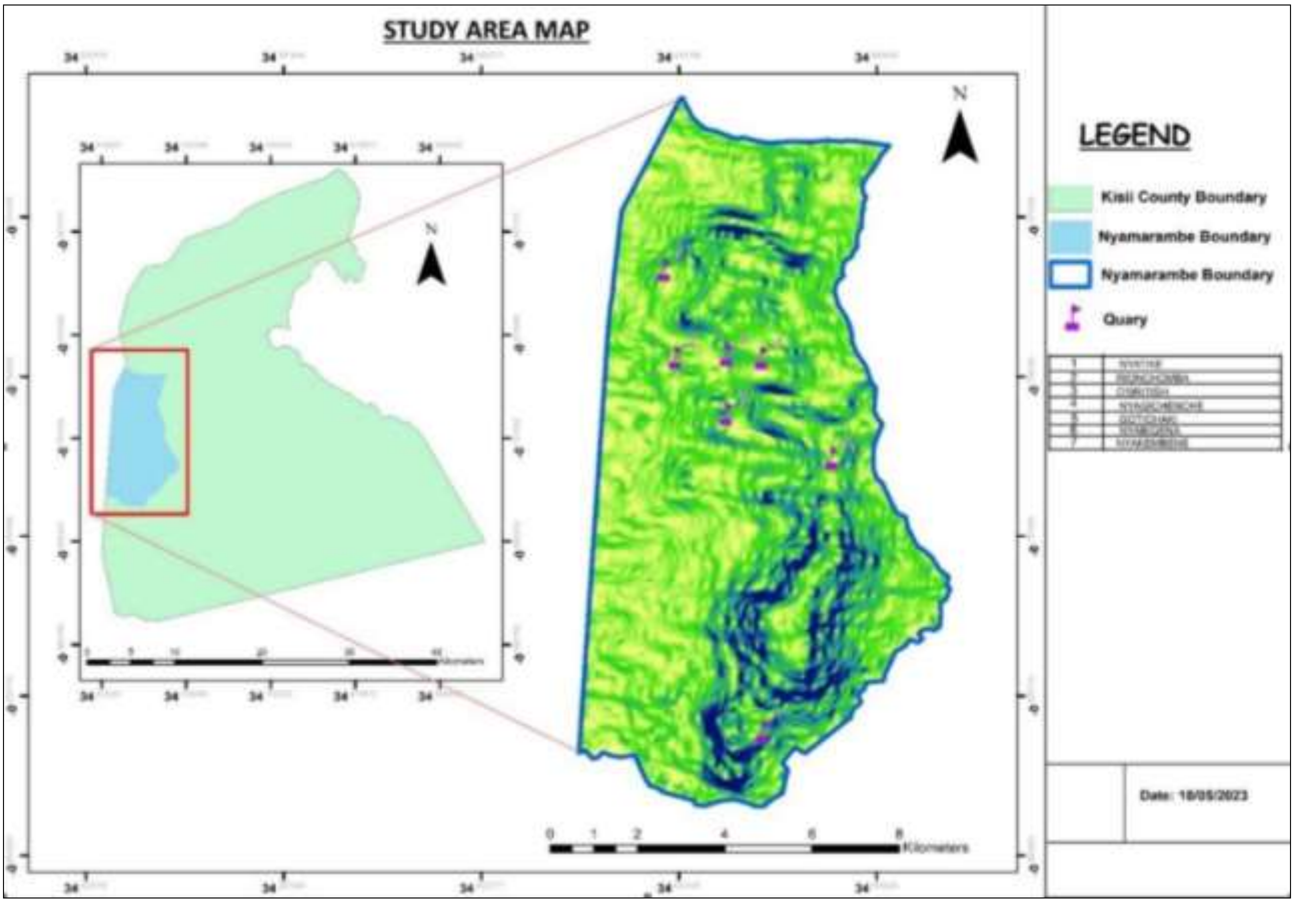
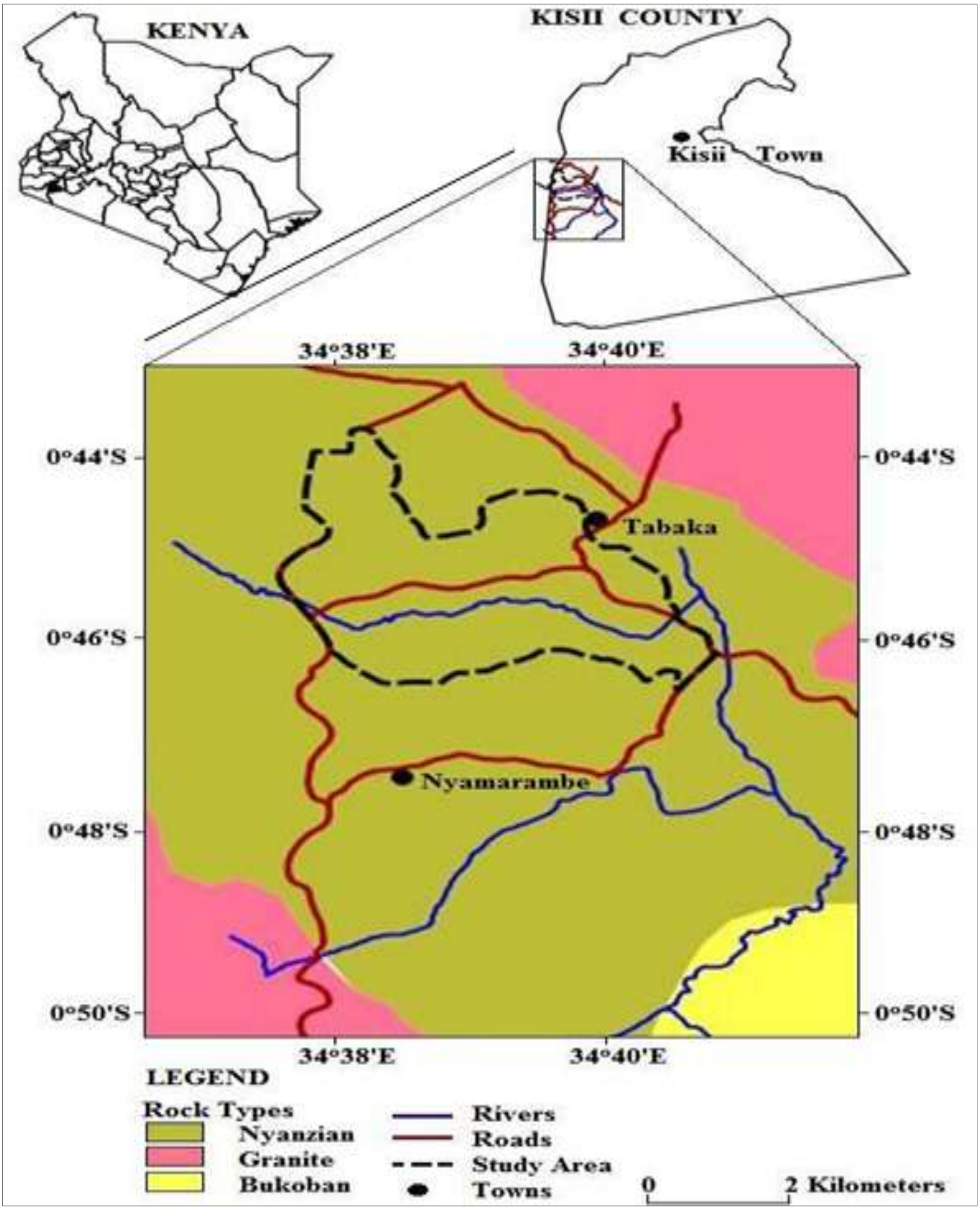


Fig 3: Research Geographical Location Map

Geological Background

The Geological Survey of Kenya carried out the original mapping of the Kisii Series (Shackleton, 1948; Schoeman, 1949; Huddleston, 1951; Sag Gerson, 1952). The Kisii Series is a volcano- sedimentary series, laid unevenly on top of the Mesoarchean-Neoarchean, Bukoban, Nyanzian and

Kavirondian Series. The so-called "Older Granites" (3100-2850 Ma), which intrude upon the schists and gneisses of the Nyanzian System, are uncomfortably overlain by the systems of bi- modal volcanic rocks and banded ironstone formations 2850-2700 Ma (Meert *et al*., 2016) [32]. The primary nature of the geological base of the Nyamarambe region consists of talc soapstone, granite, lava quartzite, sandstones and grits. The area is also covered with brown fertile volcanic soils with some areas dominated by stony and rocky outcrops. Metamorphosis of peridotites exposed to heat and pressure at the intersecting points of the plates form the talc soapstone rock (Rumbe, 2021) [36].



***Source*:** Adopted from Philips (2002)

Fig 4: Geological Map Showing Soapstone Quarry Reserves

Methods

The study combined analytical, experimental and descriptive methods. Field surveys and Longitudinal Cross-sectional methods were used in this study to collect data. A Composite Research design approach is an integration of qualitative and quantitative surveys in a research study (Asenahabi, 2019) [2]. This research design involved field survey, longitudinal cross-sectional and field experimental measurement data methods. The research used field surveys, experimental measurement and observation tools to collect primary data. A digital inclinometer and tape measure were used to measure and record the slope angles and heights of the sampled soapstone quarry slopes. The assessment involved the observation of proxy physical evidence to delineate potentially unstable slopes, stability conditions of slope surfaces and physical geological features. The safety factor values and slope stability conditions were computed by numerical modeling using compressive Limit Equilibrium Slide 6.0 Version software (Sailaja *et al*., 2021) [37].

Data Analysis Method

Slope geometry data was analyzed using Limit Equilibrium Method (LEM) through Mohr Coulomb's (1900) failure equations 1 and 2 (Suhendra *et al*., 2022) [42]. Numerical modeling by Slide
6.0 Version Limit Equilibrium software and a simple design chart methods were applied to
accurately compute and analyze the Factor of Safety, describe and deduce the state of slope stability conditions (Shiferaw, 2021) [40]. This data was analyzed using Bishop's Equation in the LEM numerical modeling Slide 6.0 software.

The stability of quarry slopes was examined using a factor of safety that was computed (Shiferaw, 2021) [40]. The strength of the rock mass was shown to be greater than the stress if the computed FoS is greater than 1.0, indicating that the slope is stable. If the safety factor index is equal to 1.0, this demonstrated that the slope has an equal chance of failing or remaining stable. Additionally, if the safety factor is less than 1.0, this demonstrates that the stress exceeds the rock mass's strength and that the slope is therefore unstable (Fleurisson & Cojean, 2014) [17]. The slope stability analysis is a significant factor for planning and designing mining designs of open pits and mines (Prabowo *et al*., 2023) [35].

Equation (1) $t = c + \sigma_n \tan(\varphi)$ (Mohr, 1900)

Equation (2) $\sigma_n = \sigma_t - u$ (Mohr, 1900)

The shear strength (t), effective stress (σn), total stress (σt), porous water pressure (u), cohesion (c), and frictional angle (φ) are the symbols used to denote the above equations.

Table 1: Stability Condition Analysis

Safety Factor	Stability Conditions	Recommendations
Factor of Safety > 1.0	Stable	None
Factor of Safety = 1.0	Critical	Monitor stability thoroughly
Factor of Safety < 1.0	Unstable	Slope angle and height optimization

Source: Modified from (Stacey & Potvin, 2007) [41]

Results and Discussions

Figure 5 (A&C) shows a large mass of soapstone rock slanting on the quarry slope face after excessive excavation on the hillside. The geological structure of the soapstone slope face exhibits discontinuities, joints, cracks and fissures exposed to weathering agents which accelerate disintegration of the rock mass resulting in weakening its shear strength. Further, the protruding rock outcrops exfoliate from the main soapstone rock mass as shown in Figure 5 (A). Figure 5 (B) shows the mechanical splitting of the large soapstone rock mass into workable sizes. The splitting leaves hanging boulders of rocks and weakens the shear strength of the rock mass causing rock slides and falls. Figure 5 (C) shows unconsolidated topsoil and soapstone rock strata. It also shows traces of topsoil washed down the soapstone rock slopes. Figure 5 (D) shows water infiltration paths through the soapstone rock slope surface and stagnated water in the open pit which reduce cohesion and frictional resistance causing unstable slopes.

A. Rock Discontinuities (joints, cracks)

B. Splitting Soapstone Rocks

C. Loose Topsoil and Soapstone Rocks

D. Water Infiltration through Slope Face

E. Soapstone Cavity and Pits

F. Deep Open Pit and Dumped Debris

G. Hanging Soapstone Rock and Void

H. Crushing Soapstone Rocks

Fig 5: (A, E, & J) shows deep-cut open pits with sharp dipping of soapstone rock bedding planes into the excavated opencast mines. The increased slope angles and heights cause the downward sliding of rock masses on unstable slopes under the influence of the increased force of gravity. Further, Figure 5 (F, G & H) show geological disturbances such as faults, joints, fissures and weathered debris. Steepened weathered rock slopes with dipping geological bedding plane structures cause slope instability in the mines due to weakened shear strength. Figure 5 (H, I & J) shows dangerously overhanging rock masses and topsoil layers with no firm base supporting structures hence at risk of collapsing at any time. The weak weathered rock mass beneath the loose topsoil and rock layers slope becomes unstable and highly susceptible to failure.

I. Underground Pit & Overhanging Rock J. Soapstone Open Pit Slope Face

Fig 5: Geological Properties and Unstable Slopes of Soapstone Mines

Figure 5 (F, G & I) shows caves, cavities and voids. The caves and voids in the soapstone rock mass have developed because of deep excavation into the hillsides. The cave in Figure 5 (I) poses a danger to the safe production of soapstone rocks. The overlying thin roof slab tends to be potentially unstable and may collapse at any time if subjected to high infiltration and content of groundwater and excessive excavation.

Slope Gradients and Percentages

The slope gradients of the sampled quarry slopes of soapstone quarries were determined by dividing the slope height (quarry depth) by the horizontal length of the quarry floor. Results in Table 4.2 that show the slope angle and height of open pit quarries are significant factors for the evolution of slope instabilities and slides. The means of slope angles and heights were 68.3° and
6.35 meters, respectively. The means of slope gradients and percentages of the sampled quarries were 2.597 and 259.7%, respectively. their average slope gradient percentage at 259.7%. All the sampled quarries had a slope gradient percentage above 100% (above 45°) showing a high probability of slope instabilities and slides. Figure 6 shows that the slope gradients are directly proportional to slope angles of quarries. This implies that increase in slope angles and heights increase the slope gradients of the sampled quarry slopes. Therefore, the relative slope stability of open pit quarry slopes is significantly influenced by the slope gradients. The quarry slope gradients determine the strength of gravitational force acting on the slope materials.

Table 2: Soapstone Quarry Slope Geometry Measurements

Quarry Name			Quarry Geometry Parameters			
Slope Angle		Slope Distance	Horizontal Length	Slope Height	Slope Gradient	Gradient Slope %
Rionchomba	70.2°	5.75m	1.95m	5.41m	2.774	277.4%
O' British	68.6°	4.83m	1.76m	4.50m	2.557	255.7%
Nyagichenche	61.7°	5.66m	2.68m	4.98m	1.901	190.1%
Gotichaki	72.5°	8.26m	2.48m	7.88m	3.177	317.7%
Nyabigena	74.8°	9.85m	2.68m	9.48m	3.537	353.7%
Nyatike	67.4°	7.85m	2.84m	6.78m	2.387	238.7%
Nyakembene	66.8°	5.32m	2.10m	4.89m	2.329	232.9%
Mean	68.9°	6.82m	2.45m	6.35m	2.597	259.7%

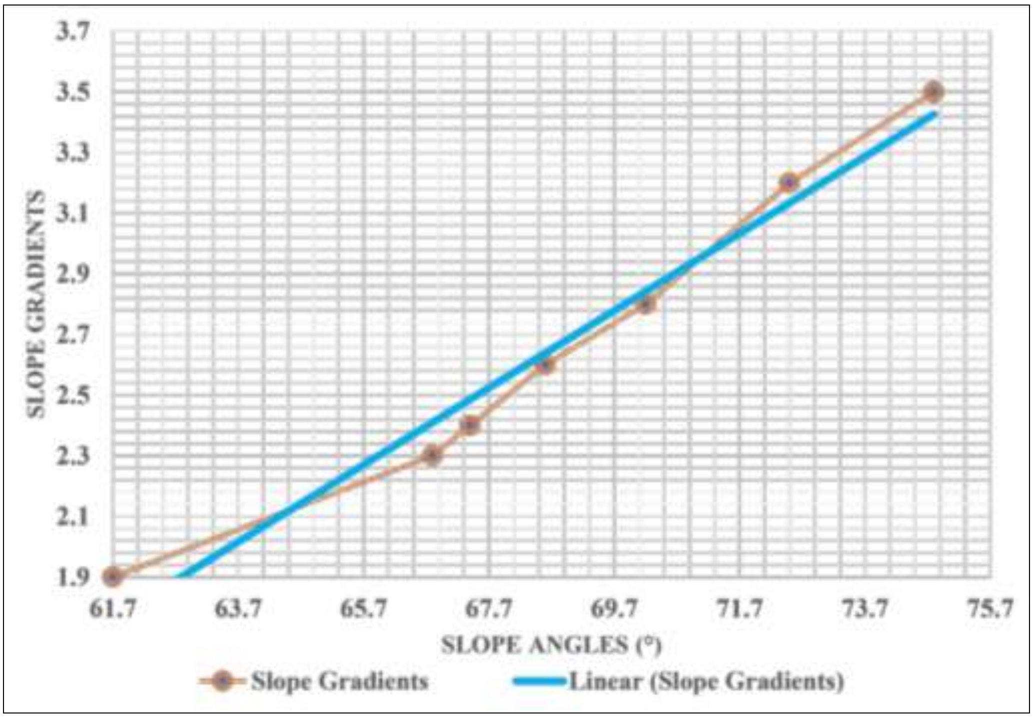


Fig 6: Plot of Slope gradients against Slope Angles

Slope Stability Analysis of Soapstone Quarry Slopes

The slope stability analysis of the sampled soapstone quarries carried out determined the level of the factor of safety of the mining design angles and heights. The Slide Version 6.0 software was used to perform simulations and models. This facilitated accurate and actual description of the soapstone quarry slopes in the mining geosites. The quarry geometry parameters were tabulated in Table 3. The LEM was used to deduce the factor of safety indices of the sampled quarries.

Table 3: LEM Factor of Safety for Sampled Soapstone Quarries

Quarry Name	Quarry Geometry Parameters and Safety Factor			
Slope Angle		Slope Distance	Slope Height	Safety Factor
Nyagichenche	61.7°	5.66m	4.98m	0.676
Nyakembene	66.8°	5.32m	4.89m	0.604
O' British	68.6°	4.83m	4.50m	0.603
Rionchomba	70.2°	5.75m	5.41m	0.578
Gotichaki	72.5°	8.26m	7.88m	0.491
Nyabigena	74.8°	9.85m	9.48m	0.438
Mean	69.1°	6.61m	6.19m	0.565

Source: Author's Calculations

The findings presented in Table 2 above, reveal that the mean slope angles of the sampled six active quarries was 69.1° with 6.19 meters of slope heights. The mean of the factor of safety value was 0.565. The research results also revealed that the Nyabigena quarry had the highest slope angle of 74.8°, and the lowest deduced factor of safety value of 0.438 while the Nyagichenche quarry had the lowest inclined slope angle of 61.7° and the highest factor of safety value of 0.676. The results revealed that increase in slope angles and heights decreased the factor of safety.

A. 2-D Nyabigena Soapstone Open Pit

In constant internal parameters, the value of the factor of safety (FoS) is 0.438 (unstable) with an overall slope angle of 74.8 degrees a height of 9.48 meters and slope distance (hypotenuse) of 9.85 meters.

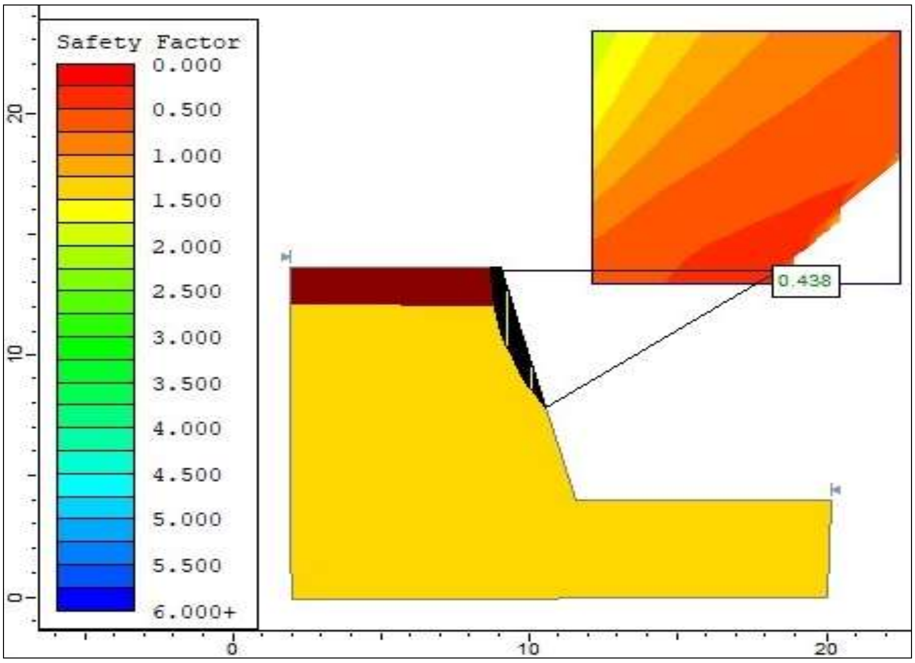


Fig 7: FoS of Nyabigena Quarry Slope

B. 2-D Gotichaki Soapstone Open Pit

In constant internal parameters, the value of the factor of safety (FoS) is 0.491 (unstable) with an overall slope angle of 72.5 degrees, a height of 7.88 meters and slope distance (hypotenuse) of 8.26 meters.

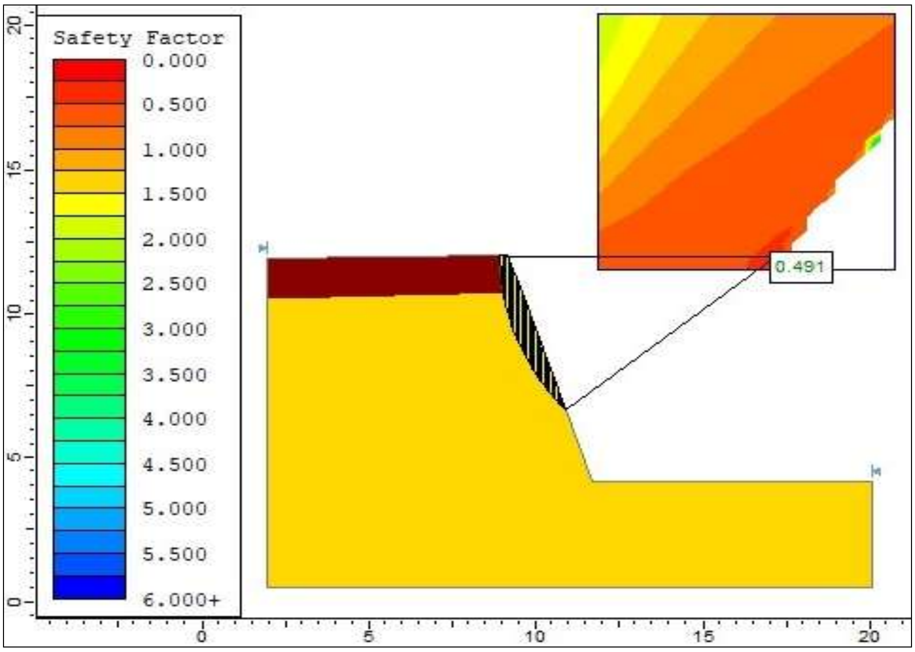


Fig 8: FoS of Gotichaki Quarry Slope

C. 2-D Rionchomba Soapstone Open Pit

In constant internal parameters, the value of the factor of safety (FoS) is 0.578 (unstable) with an overall slope angle of 70.2 degrees, a height of 5.41 meters and slope distance (hypotenuse) of 5.75 meters.

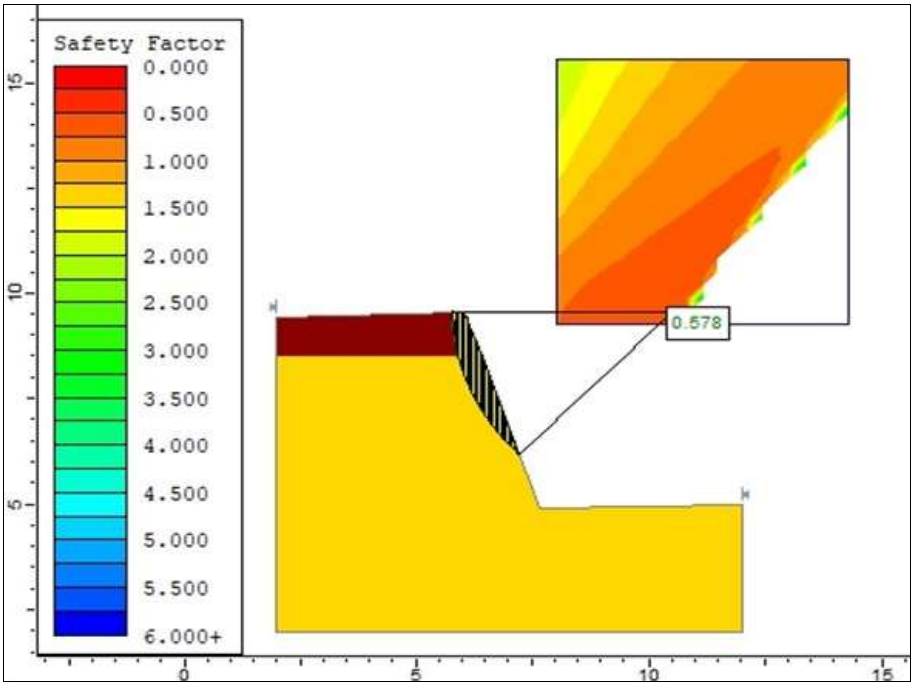


Fig 9: FoS of Rionchomba Quarry Slope

D. 2-D O' British Soapstone Open Pit
In constant internal parameters, the value of the factor of safety (FoS) is 0.603 (unstable) with an overall slope angle of 68.6 degrees, a height of 4.50 meters and slope distance (hypotenuse) of 4.83 meters.

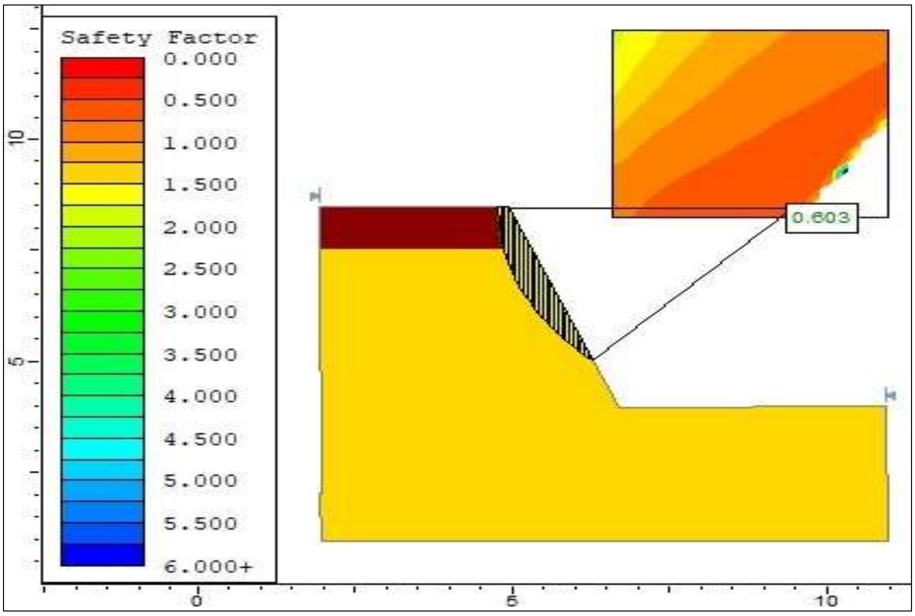


Fig 10: FoS of O' British Quarry Slope

E. 2-D Nyakembene Soapstone Open Pit
In constant internal parameters, the value of the factor of safety (FoS) is 0.604 (unstable) with an overall slope angle of 66.8 degrees, a height of 4.89 meters and slope distance (hypotenuse) of 5.32 meters.

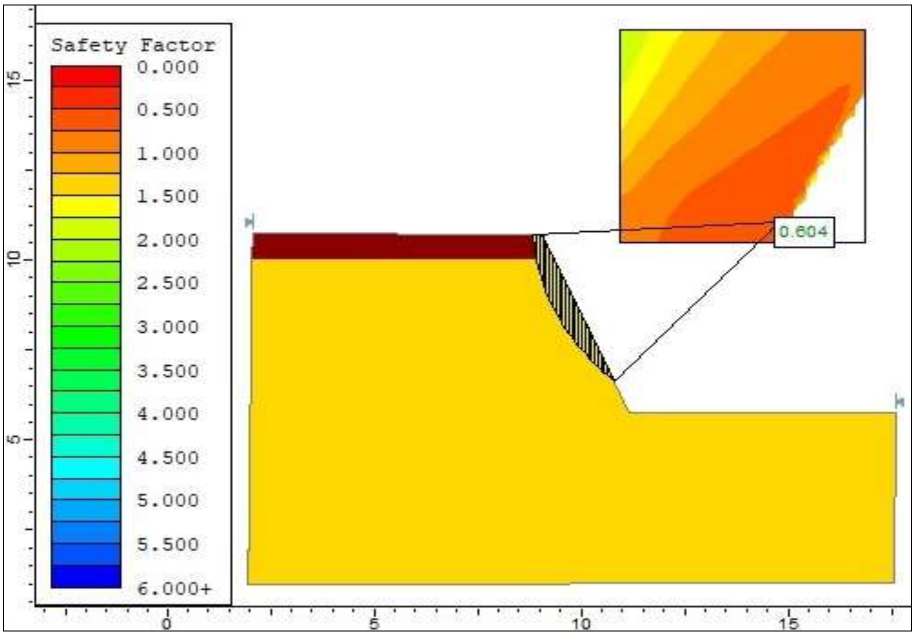


Fig 11: FoS of Nyakembene Quarry Slope

F. 2-D Nyagichenche Soapstone Open Pit

In constant internal parameters, the value of the factor of safety (FoS) is 0.676 (unstable) with an overall slope angle of 61.7 degrees, a height of 4.98 meters and a slope distance (hypotenuse) of 5.66 meters.

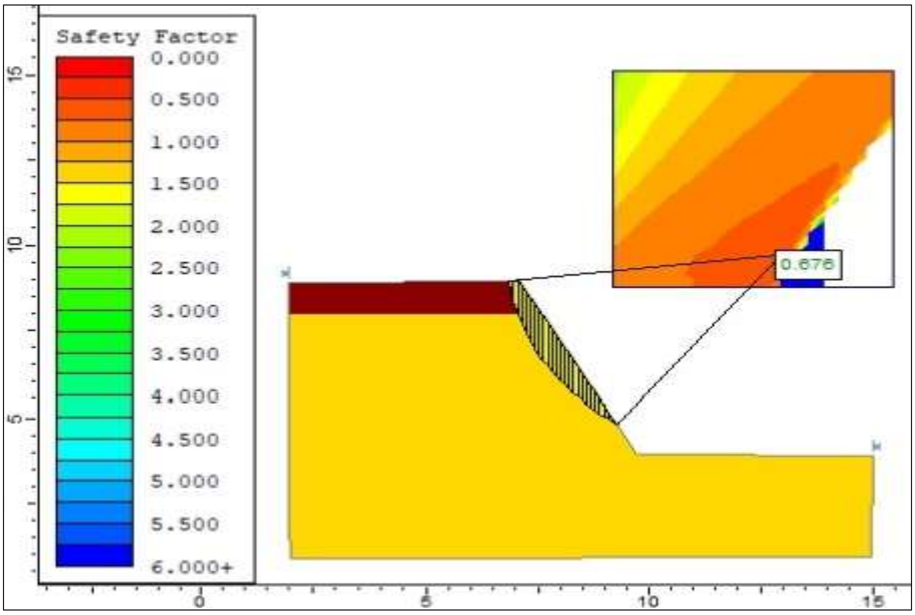


Fig 12: FoS of Nyagichenche Quarry Slope

The Influence Slope Angles and Heights on Safety Factors

The linear trend in Figure 11 shows that the factor of safety values are inversely proportional to the slope angles of the sampled soapstone quarry slopes. This means that an increase in slope angles and heights reduces the values of the slope safety factor values. The results also revealed that a decrease in slope angle and height increases the values of the slope safety factor. The deduced factor of safety values for the six sampled soapstone quarry slopes are below the slope factor of safety of 1.0. This means that all the six soapstone quarries had unstable slopes which are susceptible to slope failure. Optimization of slope angles and heights indicates that the slope safety factors increase by reducing the slope angles and heights of the soapstone mines. This means that the stability conditions of the slopes can be maintained at their equilibrium by slope optimization analysis. Excavated slopes with greater slope heights require less steep angles to maintain the stability of slopes and safety in mining operations (Atieno & Moses, 2021) [3].

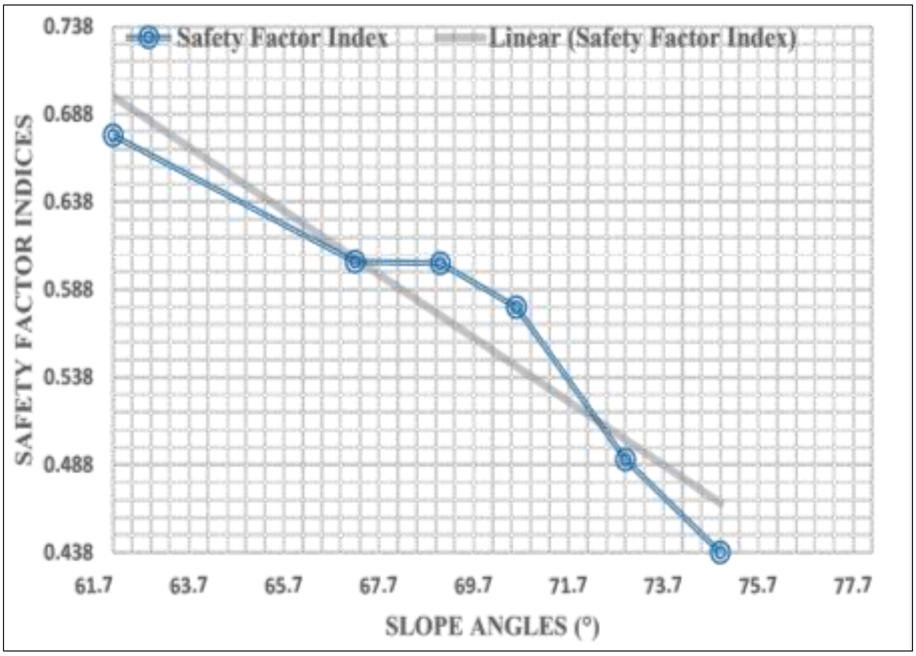


Fig 13: Plot of Factor of Safety indices against Slope Angles

Discussions

The analysis results indicated that increasing the slope angle decreases the safety factor indices nearly linearly while an increase in height decreases the safety factor indices. Slope angle and height increase decreased the stability of the soapstone mine slopes at a higher rate. Slope gradient and percentage increase increased slope instability and failure. The rock falls and slides were observed in at higher slopes of soapstone outcrops while the soil gapping was observed at heterogeneous layers (loose topsoil of 3m and large mass of soapstone rock beneath) slopes. The slope slide was dominant during rain seasons at different slope angles and slope heights. The impact of increasing slope heights and angles was studied by computing the safety factor simultaneously. The most prevalent slope instability and failure in the current study was slope sliding, collapsing of caves and rock falls. The excavation of soapstone rocks is done by opencast method which results in slopes with higher angles and heights making them highly susceptible to failure. Therefore, it is significant to reduce and optimize the slope angles and heights. Undercutting excavation of soapstone rocks as shown in Figure 5 (I) should be avoided and adapt the top-down approach to slope excavations (Atieno & Moses, 2021) [3].

Conclusion

Stability of slopes is a fundamental factor in the planning and operation of soapstone open pits and mines. The study identified slope instabilities and delineated them into two namely unstable slopes (rockfall, rock slides, rock rolling, landslips) and slope failures (collapse of voids, cavities and caves). The development processes of the steep opencast mining design angles and heights have significantly contributed to slope failures and instabilities in this soapstone rock mass. The safety factor computed from Limit Equilibrium analysis is lower than the critical value of 1 thus the soapstone mine slopes are unstable and hence vulnerable to slope instabilities. The greater the excavated slope angles and heights in the soapstone rock mass, the higher the chances of slope instability. The safety factor of mine slopes had decreased with slope angle and height increase. The type of soil and slope geometry influences slope stability. The type and shape of slope instability affect the sliding mass of soil. Using the slope angle and height optimization techniques for slope stabilization should be thoroughly explored to determine the most appropriate geotechniques and installation of monitoring systems to provide slope failure warning signs to mitigate slope failure accidents at the soapstone mines.

Recommendations

Slope stabilization and optimization of slope angles and heights are recommended to mitigate the effects of slope failure and instabilities. Slope heights and slope angles can be optimized to maximize the factor of safety indices of the excavated mine slopes. This paper, which appears to be the first in Kisii in analyzing and documenting slope stability related to mining of soapstone rocks reveals gaps regarding this database in the county and country.

Conflict of Interests

The authors declare that there is no competing conflict of interests that could have appeared to influence the work reported in this paper.

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