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Geotechnical Analysis of Mining Based on Topography and Geomorphology for Estimation of Limestone Resources and Reserves

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Abstract

Reef limestone is an industrial mineral with high economic value that is widely utilized in construction and cement industries. North Moyo District, Sumbawa Regency, contains tectonically uplifted limestone deposits, yet quantitative assessments of rock mass continuity and resource–reserve estimation remain limited. This study aims to identify geological characteristics, lithology, and fracture structures, and to estimate limestone resources and reserves using digital three-dimensional modeling. The research was conducted using a descriptive, geotechnical, and quantitative approach through the collection of primary data, including outcrop observations, elevation measurements, and fracture mapping, as well as secondary data such as regional geological maps, geomorphological information, and satellite imagery. Surface elevation data were processed using three-dimensional modeling to generate existing and design pit surfaces, and volumetric analysis was performed using the cut and fill method. Resource classification was divided into inferred, indicated, and measured categories, while reserve estimation applied a loss factor correction. The results show that the reef limestone exhibits a massive structure, porous texture, and fossil fragments with an effective thickness exceeding five meters. Fracture patterns are dominated by northwest–southeast and northeast–southwest orientations, consistent with regional tectonics. The estimated measured resource volume is 234,977 cubic meters, while proven reserves reach 226,643 cubic meters after correction. The limestone demonstrates strong lateral and vertical continuity, indicating a stable and homogeneous rock mass suitable for quarry mining. Three-dimensional modeling effectively represents field conditions and confirms the potential of reef limestone as a sustainable industrial material in North Moyo District.

Introduction

Infrastructure development in Sumbawa Regency is entering an accelerated phase, particularly in supporting regional connectivity activities, strategic road construction, and transportation construction projects targeted at enhancing regional competitiveness. The local government, through its regional development theme, has emphasized infrastructure strengthening and the provision of basic services, which directly creates increased demand for rock materials, particularly limestone as a raw material for road construction. Data from the SIPB document shows that rock extraction activities in North Moyo District are under the national Samota Road access project, which directly utilizes limestone material from the quarry site as embankment and road foundation material. This underpins the urgency of the availability of local geological resources to support long-term development projects (Li & Huang, 2023; Dou et al., 2023; Liang & Pan, 2024). Martadiastuti et al. (2022) stated that the availability of limestone reserves in locations adjacent to infrastructure areas provides significant advantages in the supply chain, reducing transportation costs and the risk of delays in material distribution.

The geomorphological conditions in North Moyo District were formed through the history of the regional geological evolution of Sumbawa Island, which has experienced tectonic activity, uplift, and sedimentation from the early Miocene to the present. Local geomorphological studies indicate the dominance of landscapes in the form of raised coral terraces at an elevation of 11–50 meters above sea level with a slope of 16–25%, proving that this area is the result of the uplift of coral reefs from the seabed to the surface due to endogenous tectonic processes. Geomorphological and topographic maps in the SIPB document strengthen this conclusion by visualizing the mining area as a stretch of reef limestone parallel to the Sumbawa coastline. A study by Febrian & Idarwati (2025) emphasized that the interpretation of geomorphological landscapes has direct implications for the character of soil stability and environmental risk scenarios in open-pit mining areas, especially in carbonate medium.

The lithological distribution of reef limestone in the SIPB North Moyo area is not only partial, but rather massive and continuous laterally from west to east of the mine site, indicating the presence of a broad and homogeneous limestone unit. Field observations show a creamy white-brownish color, massive structure, high porosity with mollusk fragments and coral fragments, which are indicators of biogenic carbonate. At the base of the layer, conglomerate and sandstone were found, which form the stratigraphic boundary between the limestone and tuffaceous mudstone units. The unit thickness was confirmed to exceed 5 meters in open outcrops on the cliffs of the former quarry and, based on other carbonate studies, can reach more than 15 meters. Oktavian's (2021) study in Banyumas on fossil reef limestone provides analogous evidence that older carbonate units often have thicknesses far exceeding surface observations. These observations provide a scientific basis for the limestone reserves in North Moyo to have economic and geotechnical significance for long-term mining.

The resource estimation methodology was conducted using Surpac 7.2.0 with a cut and fill approach based on 3D elevation modeling, starting from topographic data extraction through coordinates (X,Y,Z) from Google Earth imagery and field verification via GPS. Resources were classified into inferred, indicated, and measured categories based on the density and quality of control data. The results showed inferred resources of 382,236 m^3, indicated resources of 355,076 m^3, and measured resources of 293,717 m^3. Abadi et al. (2018) confirmed that Surpac is an industry standard tool with a high level of accuracy in limestone pit design models and is capable of producing realistic reserve estimates in carbonate quarries. This approach provides scientific assurance that the calculated reserve estimates have a valid volumetric geometric basis.

The geotechnical design of the mine slope adopts a 1:2 slope with a 1-meter berm width and a 9-meter ramp to ensure excavation stability during production operations. Slope stability in porous carbonate rock is crucial because limestone has variable strength depending on the degree of weathering, porosity, and moisture levels. Andera (2023) in a study of mine slope design concluded that a limit equilibrium approach considering local geotechnical parameters can minimize the risk of landslides in the pit area. Fanani et al. (2021) added that slope safety factors must take into account heavy equipment operating loads and environmental conditions, including rainfall. Referring to local climatological data, North Moyo District experiences high rainfall during the January–February period, which has the potential to increase water content in rock pores, thus becoming a structural factor influencing slope stability.

Geological structure plays a crucial role in interpreting the rock mass stability in North Moyo. The SIPB document notes the presence of northwest-southeast and northeast-southwest-trending cracks resulting from regional tectonic activity. These cracks have the potential to act as groundwater flow pathways and structural weaknesses that could impact the stability of the mine slope (Raza et al., 2025). In a study of Wonosari karst groundwater, Bikwanto & Firmansyah (2011) demonstrated that carbonate rocks with active fracture systems facilitate rapid subsurface water transport, which in turn influences pore water pressure and potentially reduces rock mass cohesion. These conditions make hydrogeological and mine drainage studies integral components of pit design.

The legal and governance aspects of mining provide operational legitimacy. PT Ekatama Megah Konstruksi has obtained a Rock Mining Permit (SIPB), accompanied by a National Land Use License (NIB), and an official work contract for the national road project. The company has also prepared a Environmental Impact Assessment (DPLH) as a form of accountability for environmental impact management, and this process complies with national mining regulations and the principles of good mining practice. Arif (2016) emphasized that mining geotechnical engineering encompasses more than just slope technical analysis, but also encompasses the integrity of the mining management system, environmental impact monitoring, and post-mining reclamation processes. In the context of North Moyo, the approximately 20 cm layer of stripped topsoil is planned to be reused in the reclamation process for vegetation restoration.

The presence of limestone mining in North Moyo has significant regional economic implications. This activity creates job opportunities, strengthens the local construction material supply chain, and reduces the cost of importing materials from outside the island. From a long-term resource management perspective, the integration of geomorphological analysis, elevation modeling, structural geological evaluation, and hydrological monitoring provides a scientific foundation for sustainable mining development. Burhan (2025), in his study of slope stability in Lombok, emphasized that field calibration of geotechnical models must be a continuous evaluation cycle to ensure the mine remains safe throughout its operational life. Therefore, this research is not merely descriptive but also provides academic and technical contributions to the development of responsible carbonate mining.

This study aims to obtain a geological understanding and quantitative estimation of limestone resources in North Moyo District through topographic analysis, geomorphology, and Surpac-based volume modeling; with specific scopes: (1) identifying geological characteristics, lithology, fracture structures, and lateral distribution of reef limestone to determine the quality and continuity of the rock mass; (2) calculating the estimated volume of limestone resources spatially using the cut and fill method based on three-dimensional topographic elevation data; and (3) determining the estimated limestone reserves (proven and estimated) that can be mined economically by considering a 1% loss factor as a basis for realistic, safe, and sustainable mining production planning.

Methods

Research Design

This research uses a descriptive-geotechnical-quantitative approach that combines field observations, geological mapping, geomorphological analysis, and volumetric modeling of resources and reserves. The research design follows a methodological flow: identification of lithology and topography, verification of geological structure data, spatial measurement, and data processing using Surpac 7.2.0 software. The main focus is to produce a 3-dimensional model of limestone blocks as a basis for accurate volumetric calculations of resources and reserves and assessment of rock mass continuity both laterally and vertically. This research is applied research because the results are directly used as a technical basis in planning limestone mining operations, including estimating the potential of mining materials and scheduling production in a realistic and measurable manner.

Location and Time of Research

The research was conducted in North Moyo District, Sumbawa Regency, West Nusa Tenggara, in the SIPB area designated as a limestone mining zone. This location was selected based on key geological indicators, including laterally distributed reef limestone outcrops in the region, and the uniformity of carbonate character on the surface. Administratively, the research area covers approximately 3.44 hectares, which was the focus of topographic and rock body geometry model analysis. The research lasted approximately 10 weeks, encompassing technical preparation, field surveys and outcrop documentation, three-dimensional topographic data acquisition, spatial modeling using Surpac, and quantitative analysis of resource and reserve estimates. This duration and workflow align with standard procedures for limestone exploration modeling in the carbonate-based mining industry.

Data collection technique

The data collection technique in this study was carried out comprehensively through a combination of field observations, digital topographic data acquisition, regional geological document review, and lithology and rock structure mapping to build a valid and representative geotechnical database. Data were collected using a source triangulation approach through cross-verification between field-based primary data, secondary data based on geological literature, and Surpac-based computer modeling data. The main objective of this data collection technique is to ensure that the 3-Dimensional model of reef limestone truly represents the actual distribution of rock mass in the mining zone so that resource and reserve estimates have a high level of accuracy.

Table 1. Data Types and Collection Methods

Data Types	Data Description	Collection Method	Output
Surface morphology	Relief elevation and surface geometry	Field survey & contour interpretation	Existing surface model
Topographic elevation X,Y,Z	Elevation data per coordinate point	Google Earth & GPS Extraction	Digital contour and surface maps
Limestone lithology	Texture, color, coral fragments, thickness	Outcrop documentation & stratigraphic sketch	Outcrop profile & lithology character
Geological structure	Fracture orientation and strike direction	Geological compass & field mapping	Fracture structure pattern
Geological & geomorphological maps	Miocene–Recent regional stratigraphy	Literature study & geological database	Interpretation of stratigraphic position
Mining operational data	SIPB area & prospect boundaries	Permit documents & area delineation	Boundary polygon for Surpac
Surpac input data	Point coordinate & elevation data	Import to Surpac 7.2.0	3D model of rock body

Primary data were collected directly from the research site through observation and recording of limestone outcrops, including the physical properties of carbonates, texture variations, fracture patterns, and thickness estimates of rock units. These primary data were supported by secondary data in the form of a geological map of the Sumbawa Island sheet, carbonate stratigraphy literature, and geomorphological analysis of the area, so that the regional geological context could be compared with local conditions. Digital data of X, Y, Z elevation coordinates generated existing surfaces in Surpac, which were used for spatial resource volume calculations. Through this systematic data collection method, the results of limestone resource and reserve estimates are not only based on computer modeling, but also have a strong geological foundation and are verified through actual field data.

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Data Analysis Techniques

The data analysis techniques in this study were carried out systematically and based on a scientific approach to ensure that all geological and topographic information obtained was processed accurately towards valid limestone resource and reserve estimates. Data analysis included geomorphological interpretation, lithological characterization, fracture structure identification, topographic surface modeling, and volumetric modeling using Surpac 7.2.0 software. This analysis combined descriptive-geological, quantitative-volumetric, and 3-D spatial modeling techniques, so that the final results represent the actual condition of the rock mass in North Moyo.

Table 2. Data Analysis Stages and Technical Methods

Analysis Stage	Technical Process	Device / Method	Objective
Geomorphologic al Analysis	Evaluation of surface shape and elevation patterns	Interpretation of contours and DEM	Identification of coralline landforms and terraces
Geological Structure Analysis	Identification of fracture and joint orientation	Geological compass & structural pattern analysis	Determination of dominant crack direction
Lithological Analysis	Evaluation of the physical properties of limestone	Field exposure & visual description	Determination of carbonate quality
Stratigraphic Analysis	Correlation of geological units from old to young	Regional geological map study	Placement of limestone in the Miocene–Recent context
Existing Surface Modeling	Formation of topographic surface model	Surpac 7.2.0	Digital representation of surface geometry
Resource Estimation	Volume modeling with the Cut & Fill method	Surpac 7.2.0	Resource volume calculation
Reserve Estimate	Volume correction with a loss factor of 1%	Numerical calculations	Determination of proven & probable reserves
Data Validation	Field & model cross-check	Data triangulation	Spatial and geological verification

Topographic data in the form of X, Y, Z coordinates were processed to construct an existing surface that represents the actual surface conditions before mining. This model was then compared with the design pit surface to determine the difference in vertical elevation, which became the basis for volume calculations using the cut and fill method in Surpac software. The estimated results in volume units (m^3) were then converted to tonnage using the average limestone density value according to the literature and empirical data. Fracture structure analysis was conducted to understand the rock block-fracture pattern, which is related to the nature of carbonate compaction and the lateral continuity of limestone. Through this integrated analysis process, the research produced a valid, geologically verified estimate of limestone resources and reserves that can be used directly as a basis for technical planning of limestone mining in North Moyo District.

Results and Discussion

General Condition of the Research Location

The research location is in North Moyo District, Sumbawa Regency, which is geomorphologically dominated by lowlands of carbonate rock with a landscape character of uplifted coral terraces. This area covers approximately 3.44 hectares of operational area listed in the SIPB and has been verified in the field using GPS coordinates. Access to the location is relatively easy because it is connected by local roads and a material mobilization network to the national road construction area, including distribution routes to the Samota region. Land cover in the area around the study is a combination of shrubs, exposed soil resulting from carbonate weathering, and exposed limestone surfaces. The climate conditions of North Moyo are tropical semi-arid with a dominant rainy season occurring between December and March, so hydrological factors and surface water infiltration have a direct influence on the stability of carbonate rocks in the mine opening area.

The rock environment character at the research site is represented by outcrops of creamy white-brownish reef limestone that exhibits a massive porous structure with mollusk fragments and coral fragments, a strong indication that this rock is the result of shallow marine biogenic sedimentation. The surface morphology is dominated by elevations between 11 and 50 meters above sea level with slopes varying from 16 to 25%, which impacts the planning of the mine pit design, benching system, and material disposal direction. The geological structure indicates the presence of northwest-southeast and northeast-southwest trending fracture paths, which are visually visible in the outcrop flake pattern and micro-slope contours in the field. These conditions serve as an important basis for geotechnical analysis, including in mapping potential slip planes and the direction of rock mass weakening. Thus, understanding the general conditions of the research site serves as an interpretative foundation for every mine design decision, slope stability analysis, and validation of the reserve estimation model in subsequent chapters.

Figure 1. Spatial Information Map of PT Ekatama Megah Perkasa in the Spatial Planning Map of Sumbawa Besar Regency

Identification of Geological Characters, Lithology, and Distribution of Limestone

Local Geological Analysis (Topography)

The topography of Sumbawa Island is controlled by geological processes that occurred during the early stages of its formation, from the Early Miocene to the modern period. These geological processes produce various surface features, or geomorphologies. The geomorphologic features on the island represent the various geological processes that occurred during its formation. These processes include volcanic activity, as well as tectonic activity (the uplift and subsidence of the land surface). Most of North Moyo District has a topography consisting of plains spread across the north, west, and central areas, while hills occupy the southern part. The lowlands are at an altitude of 0–75 meters above sea level, while the hilly areas are at an altitude of 76–500 meters above sea level (masl).

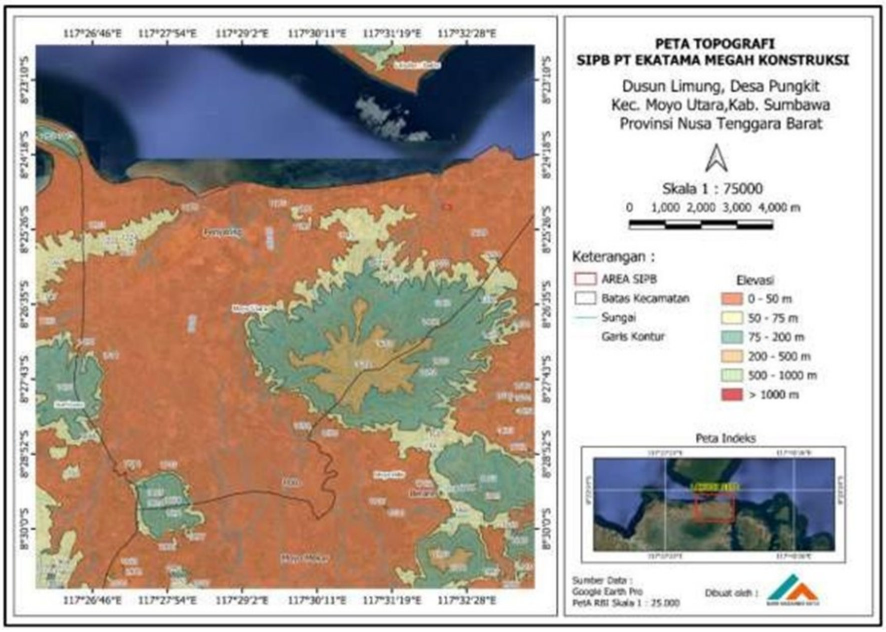

Figure 2. Topographic Map of North Moyo District

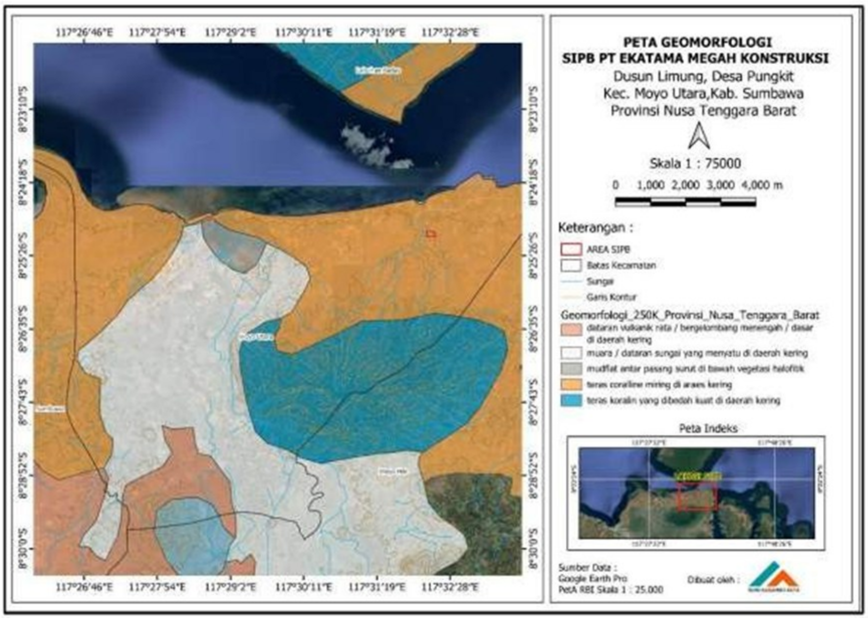

Figure 3. Geomorphological Map of North Moyo District

The geomorphology that occupies the lowland area consists of lowlands in river valleys, tidal areas, and plains on sloping coralline terraces with a land slope of <2%-5%. In general, the topography of the research area is a lowland in the form of sloping coralline terraces, a slope of 16-25% at an altitude of 11-50 meters above sea level with a stretch parallel to the coastline. The coralline terrace plains were formed from an uplift process by endogenous forces from tectonic activity that plays a role in the formation of the morphology and topography of Sumbawa Island.

Lithological Analysis

North Moyo District generally refers to the Geological Map of Sumbawa Island Sheet (A. Sudrajat, S. Andi Mangga and N. Suwarna 2012) composed of alluvium, sedimentary rocks, and volcanic rocks of Tertiary – Quaternary age, which were deposited in the early Miocene to Recent. The youngest rock unit in North Moyo District is composed of Alluvium deposits (Qal) from the decomposition of surrounding rocks transported by water flow and deposited along river meanderings and floodplains and river estuaries. While the oldest rock unit is composed of the Tuffaceous Sandstone Unit (Tms). Above the Tuffaceous Sandstone Unit (Tms) deposited unconformably is the Tuffaceous Claystone Unit (Tpc). The following is the stratigraphic sequence of rock layers in North Moyo District from Oldest to Youngest:

Tuffaceous Sandstone Unit (Tms): composed of tuffaceous sandstone, mudstone, tuff, and breccia. The sandstone unit is well-bedded and contains limestone lenses (Tml). The tuff weathers into green clay containing pyrite. Breccia is exposed.

Tuffaceous Claystone: This rock unit was deposited unconformably on older rocks. The Tms consists of tuffaceous claystone, interbedded layers of sandstone and gravel resulting from the decomposition of volcanic rocks. This unit is quite well layered. Its age is estimated to be Late Tertiary (Brouwer, 1915).

Uplifted Coral Reef Unit (Ql): composed of limestone in the form of coral reefs and coral limestone fragments. In some places, it contains volcanic rock fragments in the form of andesite, pyroxene andesite, and hollow andesite. The lower part of the unit contains conglomerate, sandstone, and a thin layer of magnetite sand. The age of the unit, based on analysis of planktonic foraminifera fossils found in the rocks, is Late Miocene and Pistocene (Kadar 1972).

Alluvium Unit: composed of gravel, sand, clay, mud and sand, mainly composed of andesite and locally containing magnetite.

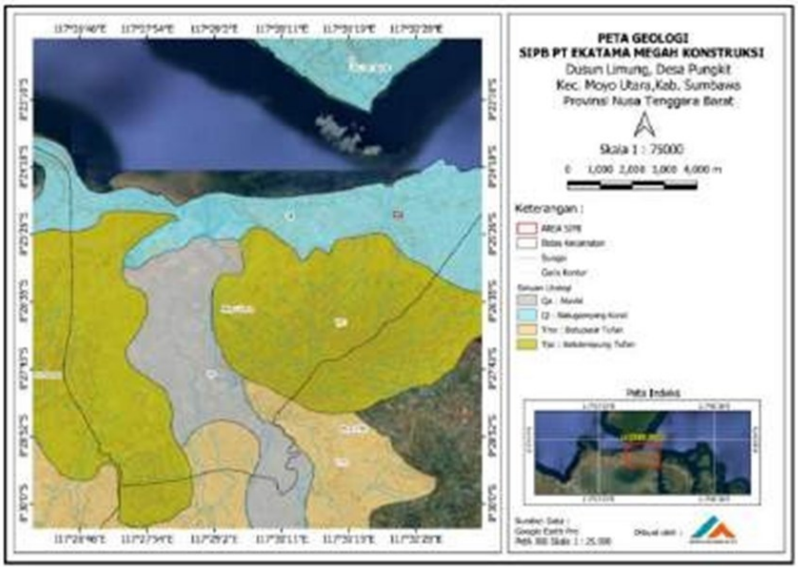

Figure 4. Local Geological Map of Moyo Hilir District

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Field observations in the study area revealed that the rock lithology consists of reef limestone, distributed throughout the SIPB area. The distribution of the rock extends from west to east. The reef limestone exposed on the cliffs of the former excavation is characterized by a creamy white to brownish white color, porous texture, mollusk skeletons/shells, coral fragments, and massive structures. This rock unit is part of the uplifted reef limestone unit.

Figure 5 Outcrop of reef limestone on the cliff to the west of the SIPB area

Figure 6. Coral reef outcrop in a corn field within the SIPB area

From the outcrops found in the field, it is known that the rock layer has a thickness of more than 5 meters. Based on literature studies from various sources, it is known that the reef limestone unit in this unit has a potential thickness of more than 15 meters. Field data in Figures 5 and 6 show a very clear visual character regarding the reef limestone lithology at the SIPB location, where on the western cliff there is a massive outcrop with a structure that indicates laterally continuous carbonate compaction, while in the corn field area the outcrop shows a porous surface texture with fragments of marine biota skeletons such as corals and mollusk shells preserved in the rock matrix. These indications confirm that the limestone found is a product of shallow marine biogenic sedimentation that underwent diagenesis and compaction over a fairly long geological period until it was finally lifted into a coral terrace due to tectonic activity. The measured limestone thickness of over 5 meters in exposed outcrops provides a strong basis for interpreting the greater vertical potential, especially when correlated with carbonate literature that indicates that reef limestones in such units often reach tens of meters in thickness. This condition has a direct impact on mining strategies, as the lateral and vertical homogeneity of the carbonate mass allows for stable and continuous extraction processes, while minimizing the potential for internal weak zones in the rock body. These observations together confirm that geologically, the study site possesses carbonate resources that are not only volume-wise feasible but also geotechnically stable for limestone quarry operations.

Geological Structure

The geological structures developing in the study area are generally influenced by those on Sumbawa Island. The island's structure primarily consists of a northwest-southeast and northeast-southwest trending rift system, with less significant rifts trending north-south and west-east. These rifts are eroded areas that form deep valleys, such as those found in North Moyo District. These valleys have north-south river flow.

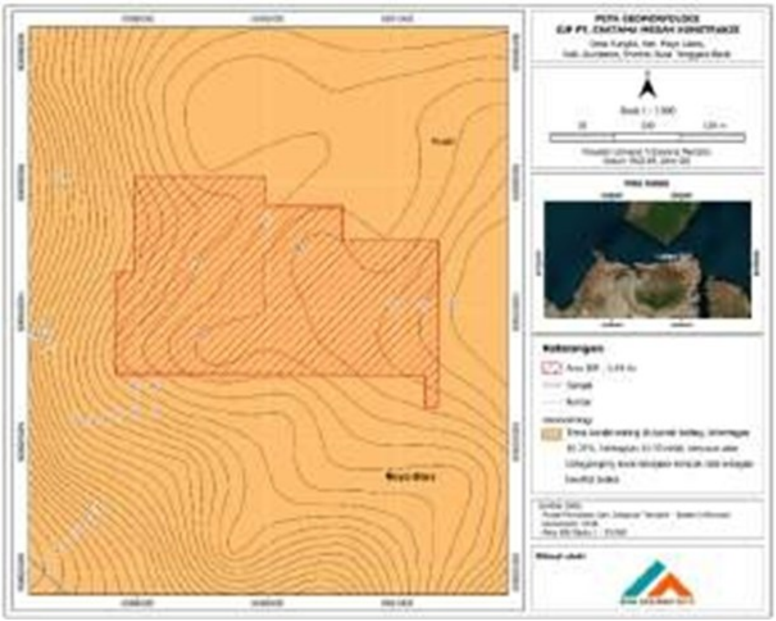

Figure 6. Geomorphological Map and Elevation Contour of SIPB Area

The fracture structures that develop in the mine area not only reflect the regional tectonic patterns of Sumbawa Island but also have direct implications for the mechanical properties of the rock mass in the context of mine geotechnical engineering. The predominantly northwest-southeast and northeast-southwest-oriented fractures are the result of repeated tectonic strain, and in reef limestone, these patterns serve as natural weakening pathways that affect the rock's ability to withstand both lateral and vertical loads during mine opening. The fractures, which function as water infiltration channels, also accelerate microweathering in the fracture zone, causing cohesion differences between the compacted rock and the carbonate-decomposed portions. This makes geological structural data crucial for mine slope design, as potential slip surfaces can be anticipated early through bench orientation, excavation direction, and material disposal patterns. By understanding the dominant fracture orientation, mine operators can direct cliff cutting activities parallel to or perpendicular to the fracture system to minimize the potential for undetected local landslides.

Resource Volume Estimation

Estimation Method

The resource estimation calculation for the investigation area was performed using the Surpac 7.2.0 software application. This application was selected based on its functionality in resource modeling and mining planning, which is the most widely used for resource projects globally. The volume calculation method used is the cut and fill method. In volume calculations using the cut and fill method, three pieces of data are required: existing topographic data, area boundaries, and topographic data for the excavation plan. The stages in this resource calculation require several preparations, including: 1) Topographic data retrieval: in this process the topographic data used is topographic data resulting from the extraction of Google Earth satellite image data in the form of 3-dimensional coordinates (x,y,z) with the UTM coordinate system; 2) The image data used is Google Earth Satellite imagery from 2019; 3) Other data is in the form of topographic mapping data in the field using GPS.

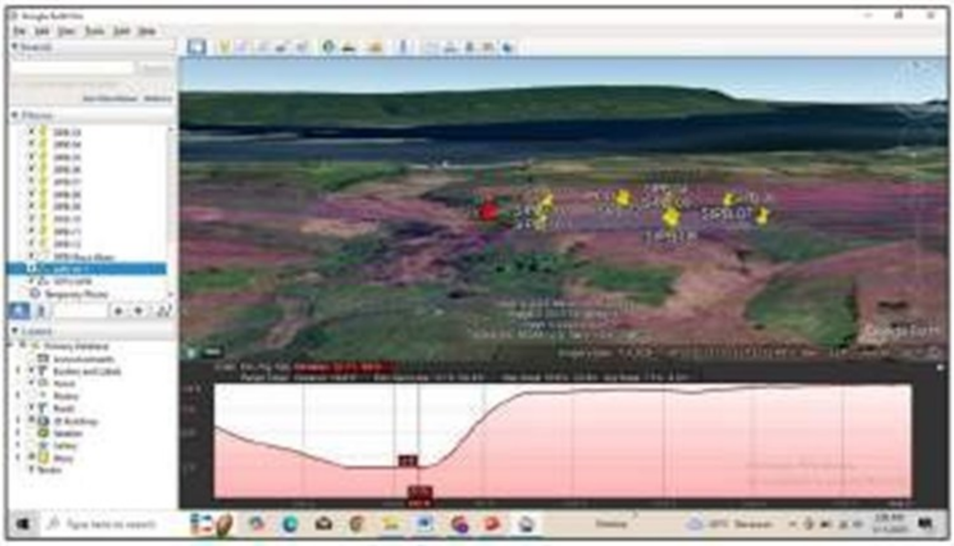

Figure 7. Topographic Data Extraction via Google Earth Satellite Imagery

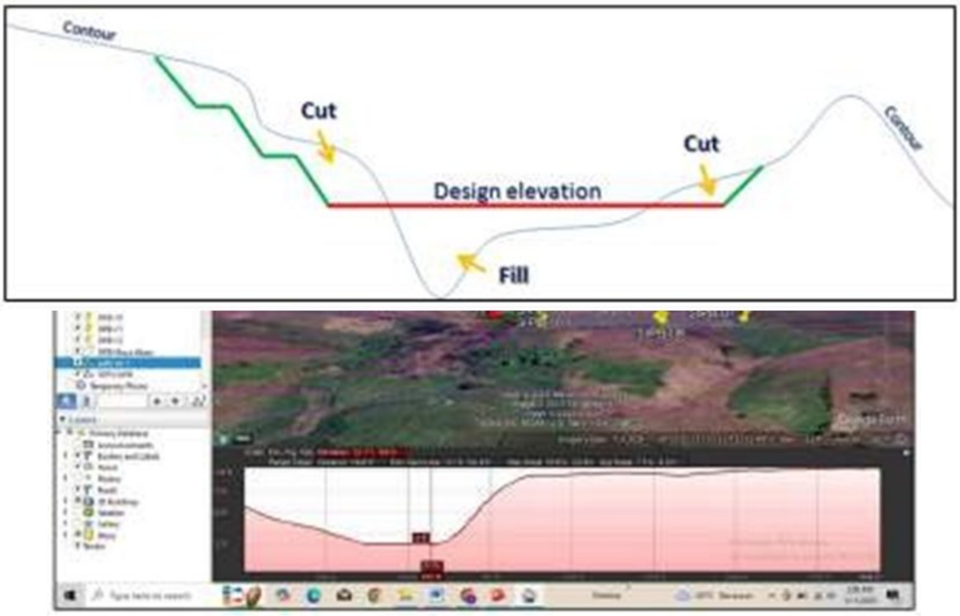

Figure 8. Volume Calculation with the Cut and Fill Method

The calculation of limestone resources and reserves is carried out through a series of structured technical steps to ensure that the estimated material volume reflects the actual conditions of the rock body geometry in the field. This volumetric modeling approach is carried out numerically by operating on elevation data (x, y, z) as the basis for the formation of a digital surface (surface model). The entire process is carried out within a Surpac-based geospatial computing system environment, which allows the integration of existing topographic data, mine design elevation plans, and work area boundaries. In this way, resource calculations are obtained not only through mathematical estimates, but through spatial representations that reflect the actual geological conditions of the mining area. Calculation Steps: 1) Plotting existing topographic data, Extracting elevation data (x,y,z) from Google Earth imagery and field measurements are processed into existing contour and surface maps to depict the original surface shape before mining; 2) Plotting topographic data from field mapping results, Coordinate data from field measurements is entered into the model to visualize the actual conditions of the mine opening and changes in elevation after excavation activities; 3) Cut and fill method (cutting and filling), Volume calculation is done by comparing the existing surface and the design surface (design elevation), where all material above the design elevation is calculated as the cut volume, and the part below the design elevation is calculated as the fill volume. The three main inputs required in this method are: Existing surface, Boundary polygon, Design pit surface.

The schematic depicts the concept of design elevation as an ideal reference line for mining operations, where the surface area above that elevation is considered cut (material to be excavated), while the area below that elevation is treated as fill (topographically filled or ignored in reserve estimation). This visual representation emphasizes that the volume estimation process considers not only the mine area but also the micro-elevation variations that determine the effective thickness of limestone that can be economically mined. With this understanding, the cut and fill calculations in Surpac reflect the spatial and vertical dimensions of the resource, thus providing a basis for accurate reserve estimation for life-of-mine planning and production capacity.

Resource Estimation Parameters

PT Ekatama Megah Konstruksi's resource estimation parameters are based on the accuracy of both field and other data. The estimated rock resources are calculated over a 3.44-hectare investigation area. Resource estimation classification at the exploration stage is categorized into three types: inferred, indicated, and measured resources. These three types of resources refer to the quality of the data and the reliability of the geological interpretations performed. The resource estimation calculation refers to the following aspects:

WIUP Topography The results of topographic data extraction are in the form of 3-dimensional coordinates (x, y, z). The coordinate data is then prepared for processing using measurement data processing software, in this case using Surpac Software. 7.2.0. The software selection is based on the objective of calculating Rock Volume. The results of the data processing produce a pattern of elevation lines or contours that connect points of equal elevation. These contour lines are then used as surface boundaries.

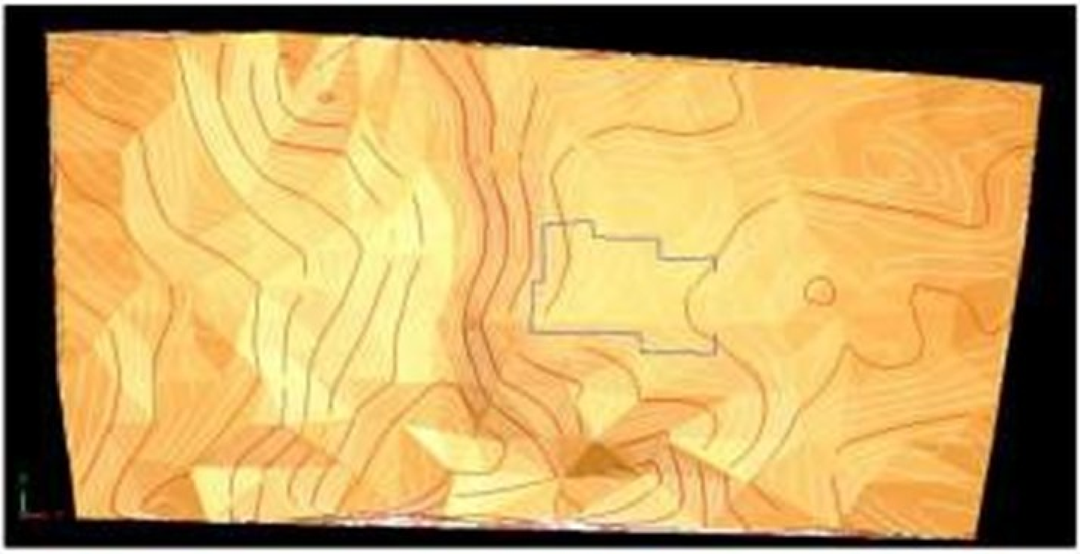

Figure 9. Topography of the SIPB Region area

Mine Design

Existing top elevation: 30.40 m;

Base elevation of excavation: 13.4 - 15.4 m;

Excavation slope: 1: 2;

Berm Width: 1 m; • Ramp Width: 9 m

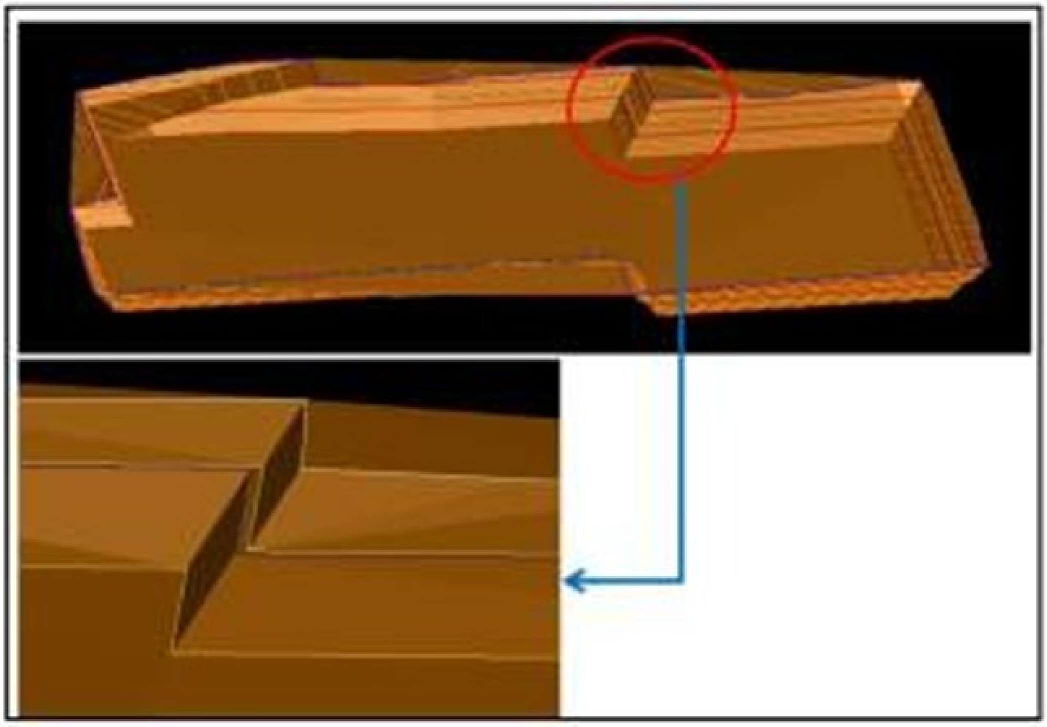

Figure 10. Cross-section of Mine Plan Design

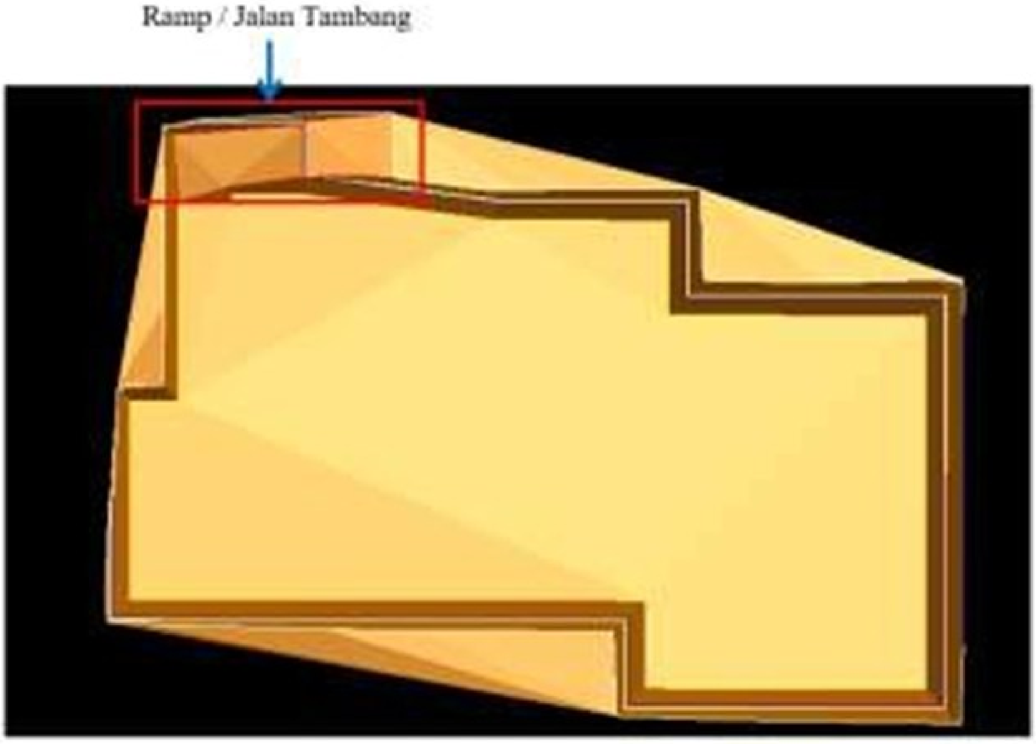

Figure 11. Mine Design View

Prospect Block Limit

Inferred Resources: WIUP Boundaries;

Designated Resources: WIUP Boundaries;

Measured Resources: 5 meters from the WIUP boundary

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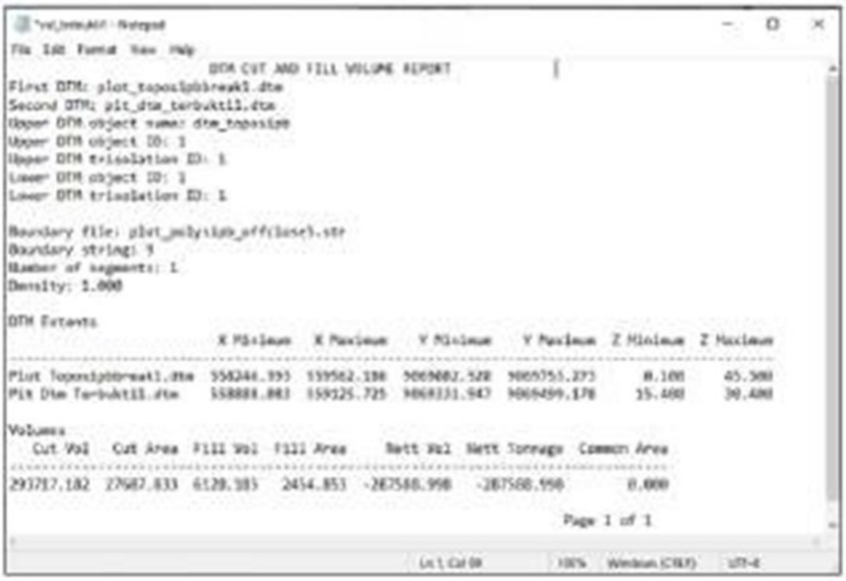
Top Soil Volume, Top soil volume is obtained from the calculation of excavation volume according to the mine design with the assumption of a soil thickness of 20 cm from the surface;

Rock Specific Gravity, The rock specific gravity used in the tonnage calculation refers to data from previous research.

Amount and Classification of Resources

Calculation of the estimated volume of SIPB resources of PT Ekatama Megah Konstruksi with a total area of 3.44 Ha of SIPB Block using the Surpac 7.2.0 cut and fill method. From this calculation, the inferred resource value was obtained at 382,236 m3, the indicated resource volume was 355,076 m3 and the measured resource volume was 293,717 m3.



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Lower DTM object ID: 1
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Number of segments: 1
Density: 1.000

DTM Extents
                         X Minimum   X Maximum   Y Minimum   Y Maximum  Z Minimum  Z Maximum
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Volumes
   Cut Vol    Cut Area   Fill Vol   Fill Area     Nett Vol   Nett Tonnage  Common Area
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293717.182  [illegible]  [illegible]  [illegible]  [illegible]  [illegible]        0.000

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Figure 12. Hail Calculation of measured volume using Surpac 7.2.0

Limestone resource estimation in the SIPB area was conducted by separating the primary material, reef limestone, and the overlying weathered material, topsoil. Resources were classified into three classes based on their geological confidence level: Inferred, Indicated, and Measured, in accordance with the classification standards used in industrial mineral exploration activities. Data were calculated in volume units (m³) and converted to tonnage based on the average density of the carbonate limestone, thus providing a quantitative overview of the potential exploitable resources. This classification is the result of volumetric modeling conducted using the cut and fill approach described previously.

Table 3. Estimated SIPB Resources of PT Ekatama Megah Konstruksi

No.	**SIPB Block**	**Estimated Volume (m³)**	**Estimat ed Tonnage (tons)**	**Indicated Volume (m³)**	**Indicated Tonnage (tons)**	**Measure d Volume (m³)**	**Measured Tonnage (tons)**	**Area (Ha)**
1	Rock	313,538	783,845	290,352	725,880	228,993	572,482	3.44
2	Topsoi l	6,794	18,378	5,984	16,187	5,984	16,187	–
	Total	320,332	802,223	296,336	742,068	234,977	588,670	3.44

The estimated data in the table shows that the volume of measured and indicated limestone resources is much more significant when compared to topsoil, which has practically no economic value in quarry operations. In the measured category, the value of 228,993 m³ or equivalent to ±572,482 tons indicates the highest level of confidence in the reserve estimate

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because it is supported by more solid field geological control data. The difference between the Inferred, Indicated, and Measured categories reflects the increasing level of geological certainty as data validation and outcrop mapping increase. The total resource value represents a significant accumulation for sustainable mining operations and has strategic implications for mine life, annual production estimates, and the feasibility of material supply for infrastructure projects in the Sumbawa region.

Topsoil in mining areas plays a crucial role in the context of environmental management because it represents the productive soil horizon that will be reused during post-mining land reclamation. Field observations indicate that topsoil averages approximately 20 cm in thickness, ranging from dark brown to grayish brown in color, and is composed of organic material, weathered carbonate rock, and the root systems of plants growing on the surface. Therefore, accurate estimation of topsoil volume is essential as a basis for backfilling and rehabilitation planning in mining areas.

Table 4. Volume of Topsoil

No	Resource	Thickness (m)	Opening Area (m²)	Volume (m³)
1	Inferred	0.2	33,971	6,794
2	Designated	0.2	29,921	5,984
3	Measurable	0.2	29,921	5,984

The data in the table shows that the relatively thin topsoil layer of only 0.2 m or approximately 20 cm results in a much smaller cover volume compared to the volume of the reef limestone beneath. In total, the topsoil volume is only around ±6,000–7,000 m³, with the highest value in the Inferred category due to the larger opening area before more detailed outcrop mapping was carried out. This small topsoil volume indicates that the portion of the organic soil surface in the mining area is not dominant, so that the mine opening process will directly encounter compact limestone units at shallow depths. This finding supports an operational strategy where topsoil will be systematically stripped, stored in stockpiles, and reused to cover excavated land during the reclamation process, while ensuring the sustainability of post-mining vegetation in accordance with the principles of good mining practice.

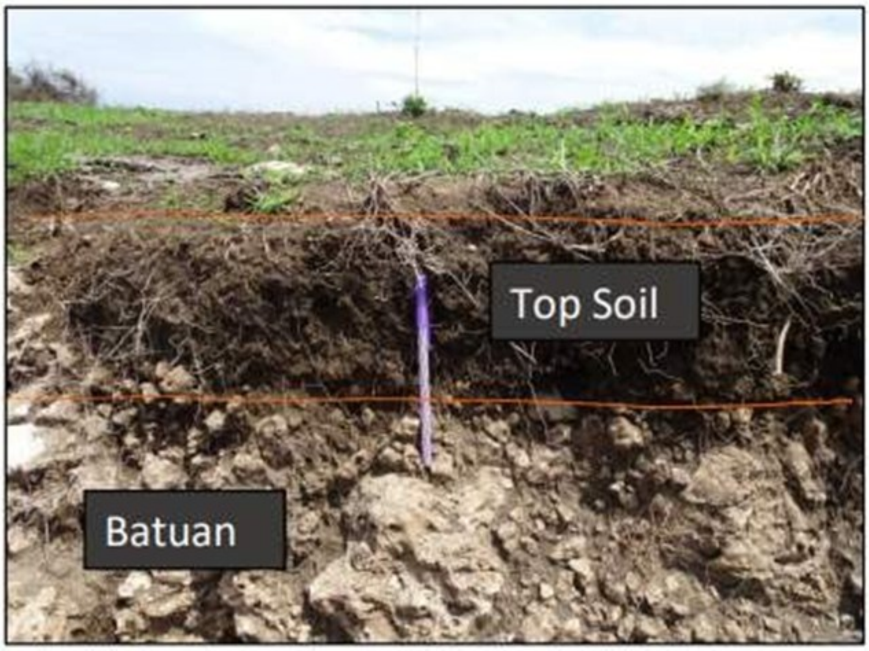

Figure 13. Vertical outcrop of soil and rock layers

Limestone Reserves Estimate

Limestone reserve estimation in the mining area is carried out as the final part of the geological and geotechnical evaluation stage with the aim of determining the amount of material that is technically and economically feasible to mine. These reserves are the result of the final screening of resources, where the measured and indicated resource values are corrected through technical reduction factors that reflect the reality of operations, including excavation, loading, and material transportation activities. In an area of 2.99 hectares, reserve calculations are carried out for two material components: carbonate rock layers (the main mining product) and topsoil (overburden), with classification separation based on Probable Reserves and Proven Reserves. With this analysis, the final results not only provide material volume figures, but also provide a basis for projecting the life of the mine and potential production levels.

Limestone Reserve Calculation Method

Reserve calculations were performed using the cut and fill method in Surpac 7.2.0 software, which integrates topographic surface data with the design pit diagram elevation model. Surpac is used to create a three-dimensional digital model of the rock body, measure the actual volume above the design elevation, and convert it to tonnage based on the density of the carbonate rock. The reserve model is calculated not as a rough estimate, but as an accurate geometric volume representation, in accordance with the surface contours of the mine opening and the local morphology of the North Moyo area. With this method, reserve interpretation becomes more realistic because it is based on geologically verified spatial data.

Estimation Parameters

The main parameters in reserve estimation refer to Measured and Indicated class resources.

Measured Resources are used as the basis for calculating Proved Reserves, because they have the highest level of geological confidence.

Indicated Resources form the basis for calculating Probable Reserves, as they have moderate geological certainty.

In the process of separating proven reserves, a correction factor of 1% is applied to compensate for material loss during excavation, fragmentation, stacking, and transportation. This factor is common practice in the mining industry to ensure that reserve estimates reflect actual conditions during mining. Example calculation:

Proved resources (before correction): 234,977 m^3

Loss factor 1% = 234.977 × 0.01 = 2,350 m^3

Final proven reserves = 234,977 – 2,350 = 226,643 m^3

This value ensures conservative reserve results and is in accordance with good mining practice.

Amount and Classification of Reserves

Proven reserves totaled 226,643 m^3, while probable reserves totaled 296,336 m^3, reflecting both material that can be mined with certainty and material that has the potential to be mined at a lower geological confidence level. Within this, proven reserves are almost entirely rock (limestone), while topsoil serves only as cover material that will be reused during the reclamation phase.

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Table 5. Estimated Limestone and Topsoil Reserves in the SIPB Area

No	SIPB Block	Estimated Volume (m³)	Estimated Tonnage (tons)	Proven Volume (m³)	Proven Tonnage (tons)	Area (Ha)
1	Rock	290,352	725,880	220,871	552,178	2.99
2	Topsoil	5,984	16,187	5,772	15,613	–
	Total	296,336	742,068	226,643	567,791	2.99

The reserve value shows the dominance of limestone as the main commodity with total proven reserves of ± 552 thousand tons, indicating the availability of material in significant quantities for mining operations in the medium to long term. The relatively small volume of topsoil does not contribute to production tonnage, but rather serves as a stock of reclamation material that has important environmental value. The difference between proven and probable reserves shows different levels of geological certainty, where proven reserves have been strongly validated by field data and Surpac modeling, while probable reserves still contain uncertainty related to rock continuity that has not been granularly mapped. These results provide a strong foundation for mine design, sequence mining planning, and operational life estimation based on monthly production targets.

The geomorphology of North Moyo, composed of inclined coralline terraces with slopes of 16–25%, strongly indicates tectonic uplift, as described in preliminary topographic observations. This condition is consistent with the geomorphological findings of karst terraces in other regions of Indonesia, where tectonic processes play a significant role in the evolution of carbonate morphology (Arief 2024; Febrian & Idarwati 2025). The limestone thickness of more than 5 meters measured in outcrops strengthens the interpretation that the reef limestone unit is a compact and laterally continuous carbonate unit. This is consistent with carbonate layer thickness models in similar areas, such as the Rembang carbonate quarry (Martadiastuti et al. 2022), Karang Dawa (Abadi et al. 2018), and Banyumas (Oktavian 2021), which show similar biogenic sedimentation patterns, including the presence of coral and mollusk fragments as indicators of shallow marine paleoenvironments. This comparison shows that the limestone units in North Moyo have a similar geological basis to other productive carbonate mining areas in Indonesia.

The northwest-southeast and northeast-southwest trending fracture patterns in the SIPB area demonstrate regional continuity with the geological structures on Sumbawa Island previously reported in geotectonic studies of the area (Rahma 2025; Fatih Qodri et al., 2024;). This fracture system is recognized as a controlling factor in rock mass stability and slope behavior, as it serves as a pathway for water infiltration and internal weakening of carbonate rocks. Integrating these results with slope stability studies in carbonate and coal mines in Indonesia suggests that the presence of dominant fractures should be incorporated into mining geometry design to avoid potential landslides (Fanani et al. 2021; Burhan 2025; Andera 2023; Parissing et al. 2024). Understanding this fracture structure strengthens the argument that mine slope design must consider the dominant fracture direction and the properties of porous carbonate materials to achieve optimal safety factors according to mining geotechnical principles (Arif 2016).

The resource estimation data obtained through the cut and fill method and Surpac modeling demonstrate methodological compatibility with modern mineral exploration practices, where 3D modeling approaches are now standard in volumetric resource estimation (Utama 2023; Royer et al., 2015; Unver, 2018). The use of topographic data extracted from satellite imagery and field measurements represents an efficient multi-data-source exploration approach, consistent with iron ore and nickel exploration practices conducted using similar methodologies (Analiser 2021; Dullah et al. 2023; Ilham et al. 2025). Surpac modeling also allows for a higher level of geological confidence in the measured resource category compared to the inferred and indicated categories, in accordance with the principles of staged evaluation of mining resources (Sari 2020). The high measured resource value indicates sufficient and convincing field data quality in determining reserves.

The interpretation of reserves that separates primary limestone and topsoil materials aligns with responsible mining practices, where overburden is considered an environmental reclamation material, not a primary mining commodity (Rezky & Zulkarnaen 2023; Pakniany et al. 2023). The topsoil thickness of ~0.2 m obtained in this study aligns with the characteristics of thin carbonate soils in karst areas, as also recorded in the Wonosari karst groundwater study (Bikwanto & Firmansyah 2011) and carbonate hydrogeochemical studies in Aceh (Yuranda 2020; Riyadi 2025). This reinforces the conclusion that the carbonate rock layer in North Moyo dominates volumetrically and is the primary exploitation target, while overburden functions in the context of post-mining land restoration in accordance with good mining practice guidelines.

The implications of this research indicate that North Moyo has the potential for carbonate mining with nationally competitive resource quality. Proven reserves of approximately 552,178 tonnes demonstrate adequate economic value for medium- to long-term mining operations, similar to carbonate quarries in Banyumas (Oktavian 2021), Karang Dawa Tegal (Abadi et al. 2018), and Rembang (Martadiastuti et al. 2022). With stable geology, compact lithology, predictable fracture structures, and accurate reserve modeling through Surpac, this area is ready for mining operations that meet technical, geotechnical, and environmental requirements. This discussion confirms that North Moyo limestone is not only geologically feasible to mine but also has a strong technical basis for implementing sustainable mining based on modern geotechnical engineering.

Conclusion

This study shows that the SIPB area of PT Ekatama Megah Konstruksi in North Moyo District has significant geological and economic reef limestone resource potential, where compact carbonate lithology character, predictable fracture structure, and volumetric quantitative modeling results indicate the availability of sustainable mining materials for long-term operations; the main findings can be summarized as follows:

The geological and lithological characteristics show a compact, moderately porous reef limestone mass containing fragments of coral and mollusk biota, with an effective thickness of >5 meters and extending laterally from west to east, thus indicating strong rock continuity and mining value.

The resource estimate yields a measured volume of approximately 234,977 m³ (≈588,670 tonnes), indicating a high level of confidence in the availability of carbonate material and is suitable for use as a basis for assessing mining potential.

The reserve estimate yields a proven volume of 226,643 m³ (≈567,791 tonnes) after a 1% loss factor correction, confirming that mineable material is available in significant quantities, and can be used as a reference for mine production planning and operating life.

The results of this study are expected to be the initial technical basis for detailed planning of limestone mining operations, so that in the next stage it is necessary to measure further rock density at various elevation points to improve the accuracy of tonnage conversion, more granular 3D modeling to ensure the vertical and lateral distribution of carbonate material, as well as additional micro geophysical or geotechnical surveys to support environmentally friendly mine design and ensure the reuse of topsoil in post-mining reclamation according to the principles of good mining practice.

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