Integrated Rock Mass Classification Approach for Predicting Blasting Behavior of Cambodian Limestone

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Abstract. Limestone deposits as located in the study location exhibit high permeability and clear signs of strong karst development which can be seen across the site from their sinkholes, dolines and interconnected caverns as evidence. These found characteristics result in considerable geological variability and intricate drainage from the subsurface. Regionally, the limestone of Cambodia display lithology of semi-marble, argillaceous, chetty and micritic types, each reflecting mineral compositions and metamorphism levels. The karst landscape resembles Fengcong (cone karst) and Fenglin (tower karst) forms from their clustered hills and isolated towers shape. For quarry operations, understanding blastability is important because each parameter in terms of rock strength, joint spacing, hardness and dry density influence how efficient the rock breaks. This study examines the geological condition of Cambodian limestone and develops a preliminary rock mass classification to support blasting, in which geological and rock mass characterization were carried out by reviewing key blastability related parameters and observing karst features also the weathering patterns. The results show that karstic features and higher weathering grades increase heterogeneity within the rock mass. The preliminary classification proposed provides an initial basis for improving blasting strategies in karstic limestone location.

1 Introduction

The Touk Meas West (TMW) limestone deposit is situated in Cambodia's Kampot Province. The carbonate rocks of Permian age forms as part of the fold belt on its eastern flank. Meanwhile, carbonate rocks of Permian age and Devonian-Carboniferous found at the southern region of Kampot [1]. These formations also overlain by Quaternary deposit comprising of silts, pebbles, clays and slates. The limestone deposits have undergone extensive karstification as in Fig. 1. Thus, it is vital to understand the stratigraphy and mineral composition for extraction.

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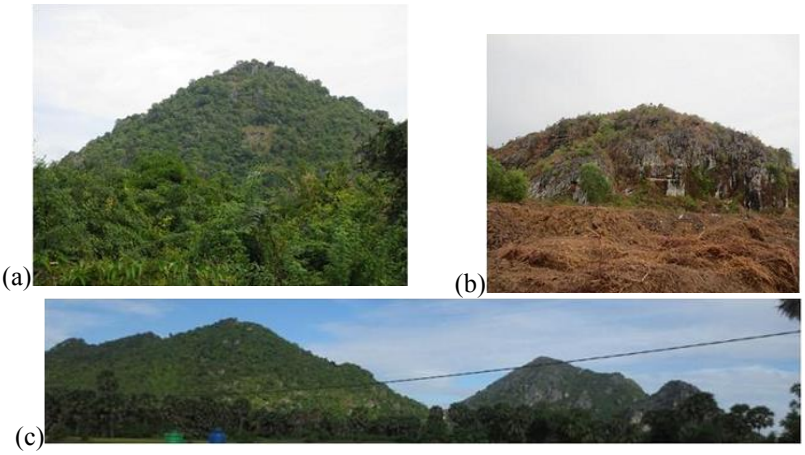


Fig. 1. Distinct Cone karst hills at the Touk Meas West (TMW) limestone deposit, Cambodia, showcasing karstification features and geological formations.

2 Karst Formations

Early studies on karst formations across various climatic and temperature zones have contributed to the development of region-specific terminologies. For example, karst landscapes in Slovenia [2], Bali [3], South Sulawesi [4] and Java [5] (Fig. 2) were initially referred to as Cone karst, a term derived from the earlier Kegel karst, used by German researchers. Additionally, the term Cockpit karst emerged in the literature to describe similar landforms. However, terminological inconsistencies arose across different regions. In Java and Jamaica, the term Cone karst was often applied to any hilly terrain with hemispherical or domed shapes, regardless of geological formation processes. In contrast, following works in Guizhou, China, showed that the area's usual conical hills fit the true idea of cone karst, more in line with the geomorphological definitions.

Fig. 2. Cone karst hills located at Gunung Sewu, Java. It shows the conical peak shapes created from protracted karstification stages [5].

The term Fengcong comes from China and refers to a "cluster of peaks." It describes the grouped conical hills in the area (such as shown in Fig. 3 and Fig. 4), where deep depressions sit between exposed bedrock. These closed depressions are called Fengcong-depressions or Fengcong-dolines. When many of these dolines connect, they form a linked valley system known as Fengcong-valley karst. The slope angles in these hill clusters vary a lot, and some parts are almost vertical.

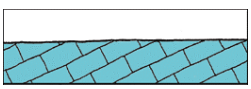
Fig. 3. Cone shaped peaks located at Guilin Yangshuo in Guangxi, China. It shows the deep depressions with steep Fengcong-like karst hills [5].

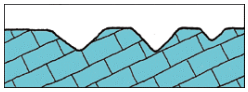
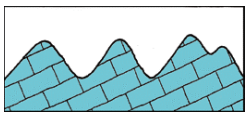
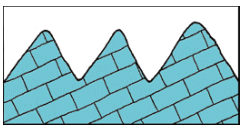
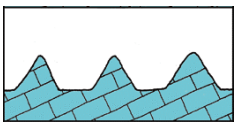
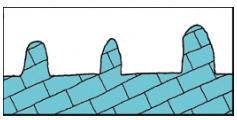
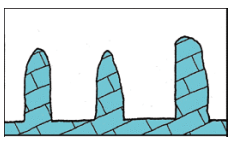
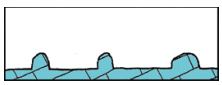
Fig. 4. Fuli and Yangshuo located at Guangxi, China. It shows tall Fenglin-like tower landscape [5].

2.1 Evolution of Fenglin and Fengcong Karst Formations

Karst landscapes begin with plain surfaces, after that doline karst, Fengcong and eventually to Fenglin. The terrain gradually transforms back into a more developed karst plain as it ages. The entire evolutionary process can be described into nine stages as shown in Table 1. When Dolines transform into conical shapes in Phase 3, Fengcong karst formation occurs. The primary component of this process is the dissolution of carbonate rocks, particularly in between fractured areas. The Fengcong karst's conical shapes are the result of this dissolution growing larger as time passed [6]. In contrast, Phase 6 sees the formation of Fenglin karst when the bottoms of conical hills are severely spot-dissolved. It eventually takes the shape of towers with pillars.

Table 1. The evolution of karst landscapes begins with a flat plain. After that, it become Doline karst followed by Fengcong karst. Fenglin karst and karst plain are formed from that in the end [5].

Phase	Visual representation	Description
1		Original surface condition.

2		Formation of Doline karst as depressions when water flows into passages of cave.
3		Formation of Fengcong karst when Dolines undergo dissolution forming conical shapes.
4		Maturation of Fencong karst as dissolution and erosion continues while providing higher relief to the hills.
5		Dolines halts deepening as base level is reached.
6		Formation of Fenglin karst as bottoms of conical hills undercut by severe spot dissolution.
7		Lowering of base level due to slow tectonic uplift which results in higher towers.
8		Erosion and lateral planation shortens and collapses the tower.
9		Formation of karst plain as Phase 8 continues over time.

Yangshuo shows the first until seventh stages of karst development [7]. However, the sequence isn't always straighforward as regional controls and local factors affect this. For example, multi- level summits and tiered conical forms shifts in tectonic activity as well as rock dissolution. The variations found indicate the evolve of karst through the mix of rock type, climate and water flow [8].

3 Surveys and Borehole Logs Data at Kampot Limestone Deposit

Table 2 shows the rock classes. From the blasting assessment, factors that take into account are the weathering grade, hardness and Rock Quality Designation (RQD). Hard solid

rock with high RQD usually needs higher energy for breakage. Meanwhile softer and more weathered rock with low RQD breaks easily. These relationship helps engineers to set safer blasting work.

Table 2. Rock classification system for geological evaluation of the Kampot site [9].

Weathering degree	5	4	3	2	1
	Completely hard rock	Fresh Rock	Slightly weathered rock	Moderately weathered rock	Highly weathered rock
Hardness	5	4	3	2	1
	Very hard rock	Hard rock	Medium hard rock	Soft rock	Very soft rock
RQD	90-100%	75-90%	50-75%	25-50%	< 25%
	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

A high cavity percentage can make blasting harder to control which means extra stabilization works and more charge needed. From the borehole logs, it shows that most subsurface cavities show up in cherty and argillaceous limestone. Roughly 65% or two-thirds of them are filled with clay while the rest are not. One study from Cambodia reported about the same pattern which is 67%. In contrast, Thailand shows the opposite where cavities were mostly empty at around 2%. In Sri Lanka, clay filled plenty of the voids hence making individual cavities difficult to pick out [10]. All this shows that clay accumulation changes how rock behave. Table 3 shows the cavity classes reported from the exploration logs. The said fractured limestone beds often dip between 20° and 80° carrying calcite and clay filling these fractures. In this site, less than 3% of drilling work (74%) hit any cavities. It indicates the limestone is largely solid content. However, only 4% of drilling shows 10-20% cavities while 13% fall into Class 2. Futhermore, 9% of drilling in Class 5 has cavities larger than 20% which is most concerning. High cavity zones particularly in Class 5 poses several difficulties. These include potential instability and increased fragmentation. Careful engineering measures are required for safe and efficient blasting.

Table 3. Distribution of cavities in the Kampot's study area [9].

Class	1	2	3	4	5
Total Drilling (%)	74	13	0	4	9
Overall Cavity Area (%)	0.37	0.59	0	0.64	2.07
Cavity in Individual Borehole(%)	<3	3 to 6	6 to 10	10 to 20	>20

4 Karst Rock Mass Categorization to Provide Blasting

Karst deposits with their natural cracks and cavities affect blasting efficiency. It causes dispute especially in terms of fragmentation and flyrock. Cratering, rock weaknesses, and discontinuities can all cause flyrock, as shown in Fig. 5. To minimize these risks, the proper way to classify the rock mass accurately should be done.

Table 2 and 3 shows the rock mass classification based on cavity formations identified from the borehole logs. Key parameters for this classification include the RQD, hardness and condition of cavity. These factors are critical in understanding their influence on flyrock generation and should be incorporated as criteria for rock mass classification.

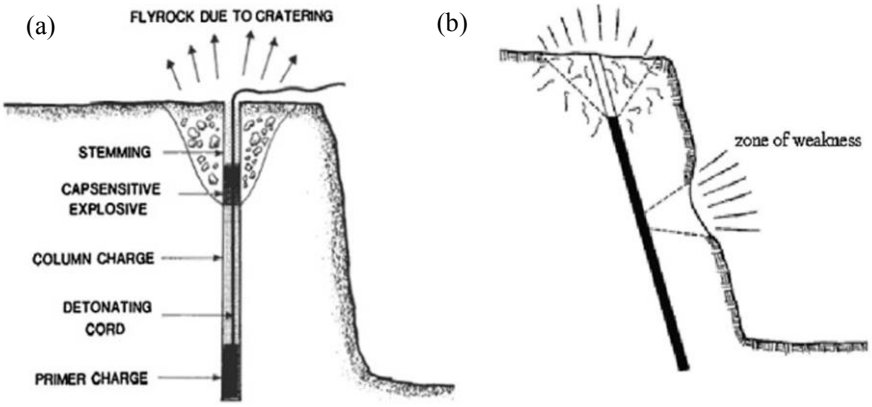


Fig. 5. Common causes of flyrock during blasting operations: (a) The impact of large burden and improper top priming, leading to flyrock or sinkholes, and (b) Crater effects in bench blasting that can result in flyrock dispersion [11]

Density, uniaxial compressive strength or known as UCS along with modulus of elasticity are further significant characteristics of rock that are determined by laboratory testing. These characteristics, which are gathered from rock samples taken from different blocks, are presented in Table 4.

The mechanical characteristics of the underlying carbonate solid mass have the biggest impact on ground stability in karst contexts. Specifically, in caves formed through karst processes, stratified calcareous rock masses often exhibit tensile joints, which lead to rock falls in the form of slabs with varying thicknesses. The degradation of limestone in these settings has been attributed to the combined effects of chemical reactions and moisture, which reduce the rock's tensile strength over time. Dry density matters since compact rock need more charge to open up. The modulus of elasticity shows how stiff the rock is and how blast blasting waves move through it. Meanwhile UCS is the rock strength and the force needed to make it crack. Lab tests has shown that unit weight and UCS decrease as porosity increases among limestone [16, 17]. A lot of studies make a link between UCS and Brazilian Tensile Strength (BTS). These parameters demonstrate that they can indicate rock behavior during blasting [17, 18]. From the observation, UCS data varies across the site. Block 4 has the highest at 75.3 MPa. Meanwhile, Block 1 is the lowest at 43.6 MPa. In comparison, UCS reaches 77 MPa with rock mass quality between 50% and 90% with densities of 2.5-2.7 gm/cc in Thailand. But in Sri Lanka, rocks are weaker and more brittle with UCS 10-15%. Also in the Sri Lanka, the densities of 2.2-2.5 gm/cc and lower rock mass quality are recorded [12]. These UCS differences with elasticity variations suggest weaker rocks fragment more during blasting. Hence, adjusted techniques for better handling are needed.

During data collection, several challenges were faced. Practical constraints such as drilling depth limitations and access issues during fieldwork were encountered. In addition, the heterogeneity of limestone especially with the presence of fractured and weathered zones results in inconsistent measurement during laboratory tests. Several factors shall be considered as countermeasure in this case. This includes classification of limestone based on cave shape and size, sinkhole size, rock density and relief, integration of more boreholes for better spatial representation, utilization of geophysical survey for better imaging and

monitoring of environmental conditions such as temperature which may influence the geomechanical properties of carbonate rocks.

Table 4. Laboratory data for the limestone samples, including physical characteristics of dry density, uniaxial compressive strength and modulus of elasticity [9]

Block	Modulus of Elasticity, E (GPa)	Dry Density (kg/m^3)	UCS, σ_C (MPa)
Block 1	45.2±18.9	2670	43.6±7.1
Block 2	33.8±18.2	2650	52.8±18.4
Block 3	48.9±11.4	2730	52.42±12.4
Block 4	34.8±1.9	2690	75.3±7.7
Block 5	37.0±9.4	2600	51.5±9.5

5 Cost Implications in Blasting Operation of Karst

The breakdown of blasting costs includes expenses for purchasing explosives (62.90%), as well as the total costs associated with transportation, security, personnel, consumption monitoring, and container management (16.80%), blasting company staff salaries (8.50%), secondary fragmentation expenses, and any negative impacts resulting from the blasting process (11.80%) [13].

Stemming refers to the practice of filling the blast hole with inert materials, such as crushed rock, dirt, or other non-explosive substances serves to contain the explosion within the blast hole, ensuring that the energy is directed towards fragmenting the rock. Using a coefficient of 0.94, higher than the others, two algorithms [14] identified stemming as the most important factor among 13 inputs. Its efficiency in maximizing blasting and controlling costs became clear when the used model considered data like a hardness of 3.5 Mhos, a UCS of 65.8 MPa, and a stemming depth of 1 meter [14].

Hardness and UCS are the parameters in the Rock Engineering System-based Blasting Costs model (RES-based BC) for estimating blasting expenses. The model is quite accurate to be used, with a mean square error of 0.00608 [14]. In this, factors affecting blasting costs are rated from 0 (least favorable) to 4 (most favorable). UCS values above 65.77 MPa with the highest tested at 75.3 MPa get the top rating of 4. Limestone hardness usually ranges between 3 and 4 Mhos earning ratings from 3 to 4. Higher ratings reflect lower resistance and the energy required.

Clay-filled cavities absorb explosives energy. This reduces fragmentation efficiently. Essentially, more explosives are needed to break the rock apart. Since 65% cavities contain clay thus the overall blasting cost could be reduced if this factor is accounted for. Additionally, the existence of clay-filled cavities adds uncertainty to cost estimation because the cavity properties in terms of shape as well affect the necessary blasting parameter adjustments. Cavity data is still understudied in the literature. It can be seen that few research integrating it into cost estimating models despite the impact on cost.

6 Conclusion

Therefore, RMC-based system analysed from the karst topography is highly suitable for optimizing blasting operations in the study area. The classification of karst rock masses can be aligned with the evolutionary stages of karst formations, including Fengcong, Fenglin, and Tower karst. This system is beneficial as the physico-mechanical properties of limestone change over time due to weathering, and these changes correspond to the stages of karst

evolution. These variations significantly impact key blasting parameters such as fragmentation, throw, flyrock, and backbreaks.

In this preliminary survey, it has been observed that the majority of cavities (approximately 99%) in the karst limestone are found in Argillaceous and Upper Cherty Limestone formations through surveys. Remarkably, it has been found that about 9% of the area has cavities greater than 20%, and roughly 74% of the drilled points show at least some cavity presence. These high cavity levels raise concerns because they can affect blasting work, especially the risk of flyrock, fragmentation quality and chance of backbreaks.

In short, the block model for blast design guide could be developed using the discussed exploration and survey data. However, it needs further information on discontinuity survey and groundwater conditions for a refined block model. Upon development, this model shall be efficiently used for prediction of environmental issues related to blasting such as flyrock, ground vibrations, backbreaks and air overpressure as well as costing estimation of blasting works.

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