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EXCAVATABILITY CLASSIFICATION OF SOFT SEDIMENTARY FORMATIONS: A CASE STUDY ON OPEN-PIT COAL MINES IN THAR, PAKISTAN

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Abstract

This research explores the limitations of traditional excavatability assessment methods which predominantly focus on muck pile characteristics and offer limited insights for pre-excavation equipment selection. To address this gap, a novel empirical model was developed using key rock properties and shovel performance indicators, with Total Loading Time (TLT) as a critical metric. Regression analysis revealed a strong linear relationship between TLT and rock properties, with an R-squared value of 0.99 ($p < 0.001$), highlighting the predictive power of the model. Cohesion and Weight Bulk Density were identified as statistically significant predictors, validated within a 95% confidence interval. Additionally, a new excavatability classification system was proposed, integrating shovel performance and rock properties. Using a K-means clustering algorithm, three distinct excavatability classes were identified, ranging from easily excavated to difficult-to-excavate materials. This research provides a more comprehensive approach for excavation planning, facilitating more accurate equipment selection and operational efficiency in mining practices.

Index Terms: Excavation planning, Excavatability classification, Shovel performance, Soft Sedimentary Formations, Total Loading Time (TLT).

1. INTRODUCTION

The economic, technological, and geopolitical developments has increased the current demand for mineral and ore production globally [1]. Surface mining techniques are well considered for their higher production rates and ease of operation as compared to underground mining techniques [2]. Open pit mining is a commonly practiced surface exploitation technique, which involves construction of benches (levels) within the earth crust to uncover the targeted mineral, and subsequently excavate it [3]. The open pit mining process includes three major operations, i.e., removal of the overburden, extraction of the targeted mineral, and transportation of the overburden and mineral to

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their corresponding destinations. These operations require heavy equipment such as draglines, hydraulic excavators, and bucket wheel excavators to accomplish the production demands [4]. A substantial capital investment is made in the procurement of mining equipment. Hence, the effective utilization of these equipment is one of the main economic consideration in every surface mining project [5, 6]. Equipment utilization indicates how effectively it is deployed and its contribution to overburden removal and the excavation of mineral [7]. The rockmass behavior significantly affects the excavation performance of mining equipment. The deployment of equipment must take into account the geological and geomechanical characteristics of the rockmass to meet production requirements at each bench and simultaneously maintain the overall slope of the pit [8].

Excavators, notably the hydraulic shovels, have gained widespread popularity due to their variety in terms of scale of operation, especially when used for excavating soft sedimentary rocks. Hydraulic-operated shovels are now commonly employed in mining and civil worksites, playing a crucial role in both, the drill-blast excavation, and the mechanical excavation methods [9].

The optimization of shovel utilization is contingent upon correlating the variability in rockmass properties with its performance parameters. This variation needs to be addressed by considering the lithological heterogeneity. Lithological heterogeneity is the variation in the rockmass properties at different working levels of the pit. The material being excavated and loaded by the shovel may vary from sandy, unconsolidated mass to soundly compacted rock mass. Additionally, high-strength rock layers may be interbedded with lower-strength layers, or vice versa. In either case, the excavation performance of the hydraulic shovel significantly varies. Therefore, the shovels working at various levels will take different loading times to excavate the material from the bench-face and load it into the truck.

Excavatability refers to the effort with which a particular material, typically rock or soil, can be excavated or dug up using machinery such as shovels, or other earth-moving equipment. It is an important parameter used in the field of mining and geotechnical engineering to designate the rock or soil material being excavated, in terms of its resistance to excavation or digging. The rock excavatability depends on the rockmass parameters and affects the operational parameters of the excavating equipment (figure 1).

The Rockmass parameters include the mechanical, physical, and structural properties of rock. Literature indicates that the mechanical or strength properties are of particular importance while assessing the excavatability. For a Shovel-truck mining system, the operational parameters include the shovel cycle time, number of cycles to fill one truck, and bucket fill factor. Comprehending rock excavatability is a fundamental element in planning and executing excavation projects efficiently, safely, and cost-effectively. Additionally, it contributes to project success by optimizing resources and mitigating potential risks associated with mining activities.

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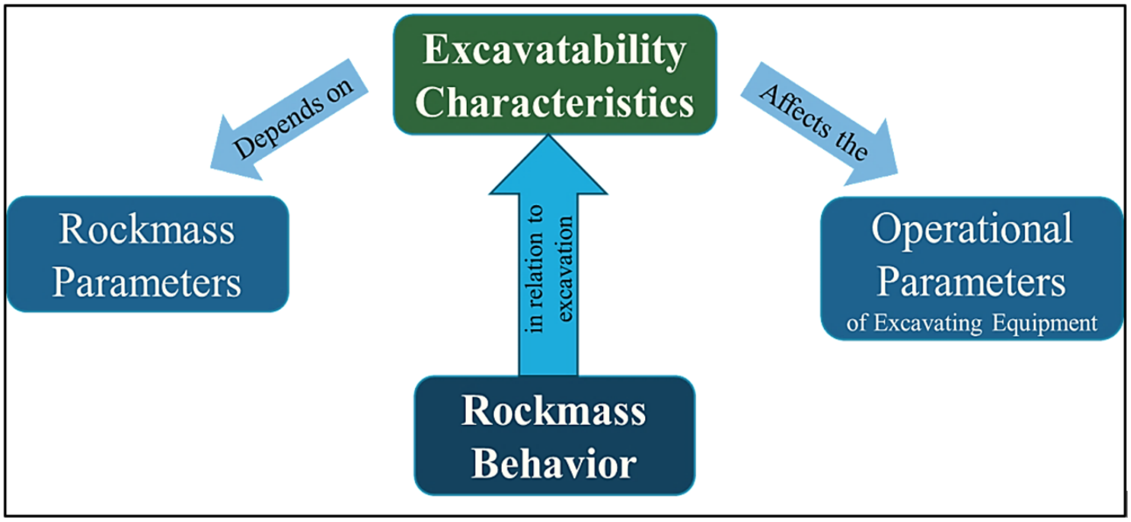

Fig. 1. Conceptualization of Excavatability Characteristics

Empirical models, such as the rockmass classification systems are commonly used methods for the assessment of excavatability characteristics and shovel performance [10]. These assessments rely on geotechnical site characterization and on-site monitoring of shovel performance.

A variety of factors affect the excavatability of geomaterials, and numerous methods and principles have been developed for the assessment of excavatability. A diggability index, incorporating rock parameters such as weathering, uniaxial compressive strength, joint spacing, and bedding plane spacing, was developed [9]. Another excavation rating system was proposed, considering rock mass properties that influence excavation performance, including uniaxial compressive strength, hardness, discontinuity spacing, degree of weathering, and seismic wave velocity [11].

Some Researchers correlated the Specific Cutting Energy (MJ/m^3) obtained from the standard cutting test, and the cutting resistance measured through the Orenstein and Koppel (O&K) Wedge test. This model was then used to establish a diggability classification. The proposed classification provided guidelines pertaining to the ease or difficulty of excavating various types of rocks using a bucket wheel excavator based on their specific cutting energy and cutting resistance characteristics [12].

Physical properties such as hardness, density, moisture content, grain size, and fragmentation characteristics also play an important role in determining how easily material can be excavated. Studies have also been conducted indicating the bucket fill factor as a significant scale for measuring excavatability [13].

The bucket fill factor is expressed as the percentage of the volume of excavated material being carried by a bucket in relation to its theoretical capacity. However, when assessing excavatability, it's important to consider physical properties for an accurate assessment.

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These physical properties affect the bucket fill factor and, consequently, the excavatability of the material. Excavatability can also be indicated in terms of digging rate, payload frequency and shovel productivity [14]. Among these, the digging ratio is most critical, as it considers the other two parameters.

Digging rate is the ratio of payload to the time taken for digging. This indicates that the digging component of shovel is of utmost importance while analyzing the shovel cycle time. It accounts for about 50% of the cycle time and therefore the largest component of shovel loading cycle [15].

The dig time, or excavation time, is defined as the time taken by a shovel to cut the material from the bench and subsequently load it in its bucket. It does not include the swing time and dump (unloading) time components of the shovel cycle time, which are not significant while assessing the excavation performance of shovel. The overall lithology of the Thar coal basin is mainly composed of three types of materials. The overlying sand dunes, alluvial materials, and loosely consolidated sedimentary rocks, containing the coal seams of lignite origin. These loosely consolidated sedimentary rocks have low compressive strength values and thus considered as soft sedimentary rocks [16].

The diggability indices and the excavability classifications previously develop, fail to characterize the excavatability behavior of Thar basin. To address this problem, this research aims to quantify the geological and geotechnical characteristics that affect the excavation performance of shovel, and to develop an excavatability classification for the soft sedimentary formations at Thar Coalfield. The performance parameters of backhoe type hydraulic shovel with 7 m^3 bucket were investigated in different rock and soil layers.

The formation characteristics such as, unconfined compressive strength, ultimate tensile strength, cohesion, internal friction angle, density, rock quality designation, and moisture content were determined for each rock and soil layer. Based on the shovel performance in various rock and soil layers, an excavatability classification is proposed in this study.

2. STUDY AREA DESCRIPTION

The Thar coalfield is situated in the Thar desert of Sindh province of Pakistan. It has about 175 billion tons of lignite type coal making it one of the largest coal deposits in the world. The Thar coal is currently the most essential and sustainable energy source for Pakistan. The discovery of coalfield dates back to late 1980's, however the resources were confirmed through a detailed exploration of the area in 1994 [17].

The coalfield is divided into 13 blocks numbered in roman as per their exploration sequence. Figure 2 presents the layout of the Thar coalfield area [18]. The Thar coal project is currently the major coal producing project in Pakistan, which is focused on the utilization of indigenous coal reserves for electricity generation.

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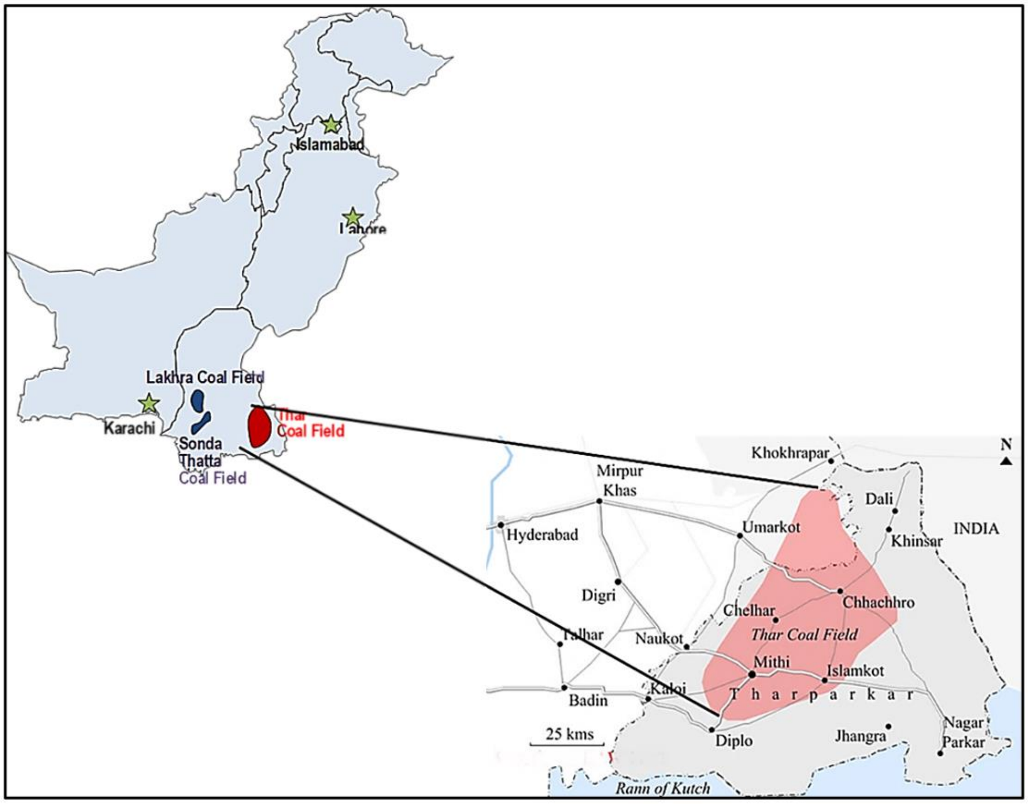

Fig. 2. Location of the study area

The Thar coalfield is comprised of three geological formations [19]. The top surface of the coalfield is composed of undulating and thick sand dunes of Recent formation deposited during Quaternary period. Lithologically, the Recent formation is composed of a blend of sand, silt, and clay [2].

The Subrecent formation underlying the Recent formation, also deposited during the same period. These are alluvial deposits comprising of silty sand, sandstone, siltstone, and claystone. Then meets the coal bearing formation, the Bara formation, deposited during the tertiary period of Cenozoic era. The coal bearing formation consisted of a sequence of coal seams of varying thickness, deposited at about 130 meters and 250 meters deep, with a cumulative seam thickness of 1.45 – 42.6 meters [20]. This entire strata is slightly dipping at about 2º, which makes it structurally simple and no major fault zones are encountered within the coalfield.

The Bara formation rests upon the major unconformity, underlain by the granite basement zone deposited during the Precambrian era [21]. Due to a long and consistent period of erosion and non-deposition, the basement granite is highly weathered, medium compacted composed of coarse to fine quartz grains, and a little amount of rhyolite and diorite. Figure 3 presents the generalized lithology and stratigraphy of the Thar coal basin.

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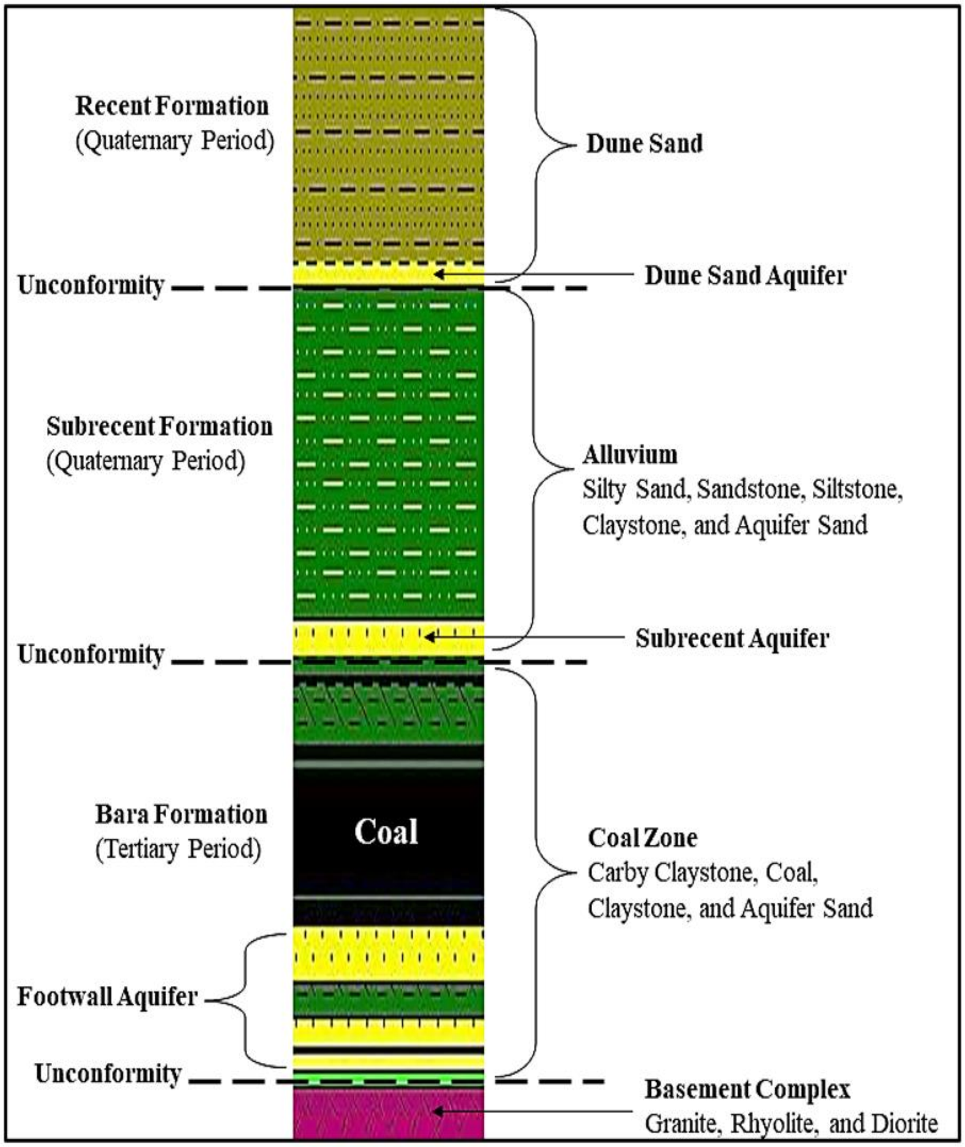

Fig. 3. Generalized lithology and stratigraphy of Thar coal basin

At the base of the Recent formation lies the dune sand aquifer. This aquifer is present all over the Thar desert and at the Indian side. The water column in this aquifer is only around one to five meters at maximum. The Subrecent aquifer is located at the base of the Subrecent formation. It is spread out all over the Thar area, having a thickness from almost 0 to about 12 m with an average of about 6 m. The footwall aquifer lies at the base of the Bara formation. This aquifer covers the whole Thar area. It has a varying thickness about 30 m to 50 m.

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3. METHODOLOGY

Real time field investigation was conducted, recording the videos of shovel excavation and loading operation on the site. The shovels were backhoe type hydraulic operated, with a bucket capacity of 7 m^3, filling two different types of trucks i.e. 34 m^3 for overburden and 54 m^3 for coal. The operational parameters were then extracted from the videos, which include, shovel cycle time (SCT), number of cycles to fill a truck (N), total loading time of a truck (TLT), and bucket fill factor (BFF). Table 1 presents the nomenclature of the operational parameters of shovel used in this study. The operational parameters were then correlated with the rockmass parameters, including RQD, Unconfined Compressive Strength (UCS), Tensile Strength (TS), Cohesion (C), Internal Angle of Friction (ϕ), Wet Bulk Density (WBD) and Moisture Content (M), which were acquired from the previous studies conducted [2]. These rockmass properties were determined on 'as received' basis, following ASTM and ISRM compliant methods [22-24].

Table 1: Nomenclature of The Operational Parameters for Excavatability Assessment

Parameter	Notation	Unit	Description	Equation
Truck Capacity	C_{truck}	m^3	Max. Total volume of material that can be filled in a truck.	-
Bucket Capacity	C_{bucket}	m^3	Max. Total volume of material that can be filled in a Shovel Bucket.	-
Number of Cycles	N	-	The total number of loading cycles a shovel takes to fill one truck.	-
Shovel Cycle Time	SCT	sec	The time taken by a shovel to load one bucket, swing towards the truck position and empty the bucket in truck and swing back to a position for next loading.	-
Spotting Time	T_{spot}	sec	The time taken by a truck to spot itself at loading position.	-
Leaving Time	T_{leave}	sec	The time taken by a truck to leave the loading spot.	-
Bucket Fill Factor	BFF	%	The percentage of available volume in an excavator bucket that is actually filled.	$BFF = \frac{C_{truck}}{N \times C_{bucket}} \times 100$ (1)
Total Loading Time of Truck	TLT	sec	The total time a Shovel takes to fill one truck including its spotting and leaving times at loading point.	$TLT = (SCT \times N) + T_{spot} + T_{leave}$ (2)

Excavation performance of Shovel is analyzed for various rocks and soil layers having different excavatability characteristics, which have a significant effect on the operational parameters of Shovel. The total loading time (TLT) of a truck is considered as a major

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indicator of excavatability in this study. It is the sum of truck loading time, truck spotting time and truck leaving time (Table 1). The spotting and leaving times of the truck are incorporated into the TLT because the shovel is typically involved in excavation work as the loaded truck departs from the loading spot, while an empty truck positions itself for reloading. The TLT is correlated with the rock properties at different working levels to analyse the significance of rock parameters as a predictor of excavatability. The linear multiple regression analysis was performed for TLT and corresponding rock properties of each working level (bench). The proposed model is validated by using the rock properties to evaluate the performance of shovel in terms of TLT and compared with the actual performance. Additionally, the overall strata is classified into distinct categories based on the TLT, using K-means clustering analysis technique. Finally, an excavatability classification is proposed describing the ease of excavation for each class. Figure 4 presents the detailed methodology adapted for this study.

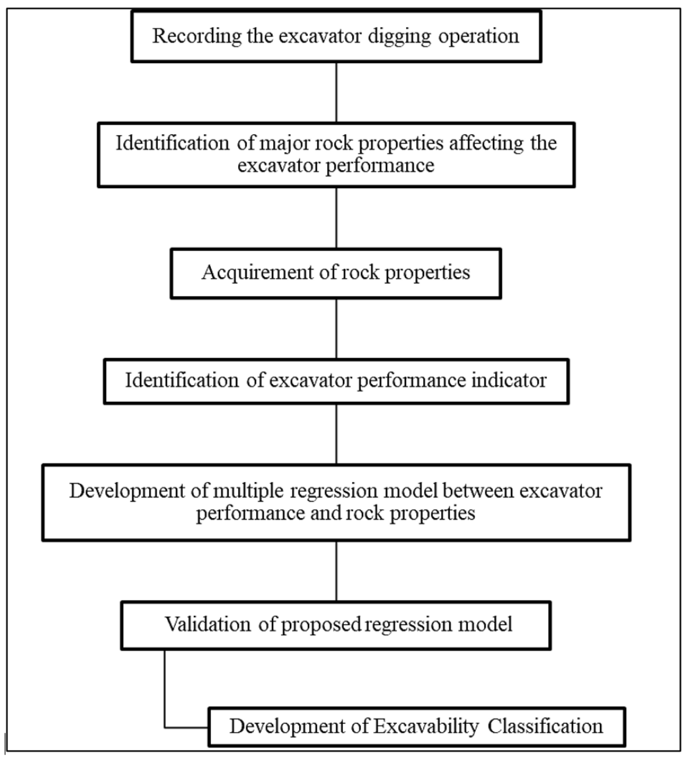

Fig. 4. Methodology flowchart

4. EXCAVATION PERFORMANCE ASSESSMENT

The shovel operation data was acquired through real-time performance assessment by recording the videos of the excavation and loading operation for 10 working shifts, equal to 80 working hours. A total of 40 shovels were recorded during the stated time duration, and the operational parameters were extracted from the recorded videos that are presented in table 2, along with the respective rockmass properties. A significant variation in the shovel operating parameters was observed, as summarized in figure 5 (a-d).

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Table 2: Average Values of Operational Parameters of Shovel and Respective Rockmass Properties

Rock type	Formation	Thickness (m)	No. of Shovels recorded	N	SCT (sec)	TLT (sec)	BFF (%)	UCS (MPa)	TS (MPa)	C (kPa)	ϕ (deg.)	M (%)	WBD (t/m3)	RQD (%)
Dune Sand	Recent	40	3	6	25	178	79	0.00	0.00	51.3	38	20.2	2.00	0.0
Sandstone	Sub-Recent	12	2	8	31	260	65	2.00	0.27	79	42	21.8	2.04	53.7
Silty Sand	Sub-Recent	10	4	6	26	162	89	0.47	0.06	67.25	40	17.5	2.06	45.2
Siltstone-1	Sub-Recent	23	6	7	26	207	70	0.80	0.16	104	36	16.6	2.10	81.1
Claystone-1	Sub-Recent	15	5	9	25	241	57	0.60	0.15	148.2	35	18.0	2.15	79.3
Siltstone-2	Sub-Recent	10	4	8	28	252	62	0.66	0.08	126.1	31	13.5	2.20	81.6
Claystone-2	Sub-Recent	14	7	7	28	216	73	1.17	0.17	92	36	12.2	2.30	73.8
Aquifer Sand-1	Bara	15	3	7	29	228	73	0.50	0.07	108	41	21.2	1.99	0.0
Carby Claystone	Bara	10	2	8	30	279	62	1.30	0.24	191	39	35.6	1.57	75.5
Coal-1	Bara	23	2	12	25	307	67	1.87	0.22	235.4	45	46.8	1.29	89.0
Coal-2	Bara	10	2	10	24	255	83	1.81	0.21	188.4	48	40.6	1.26	84.6
Claystone-3	Bara							PIT BOTTOM						

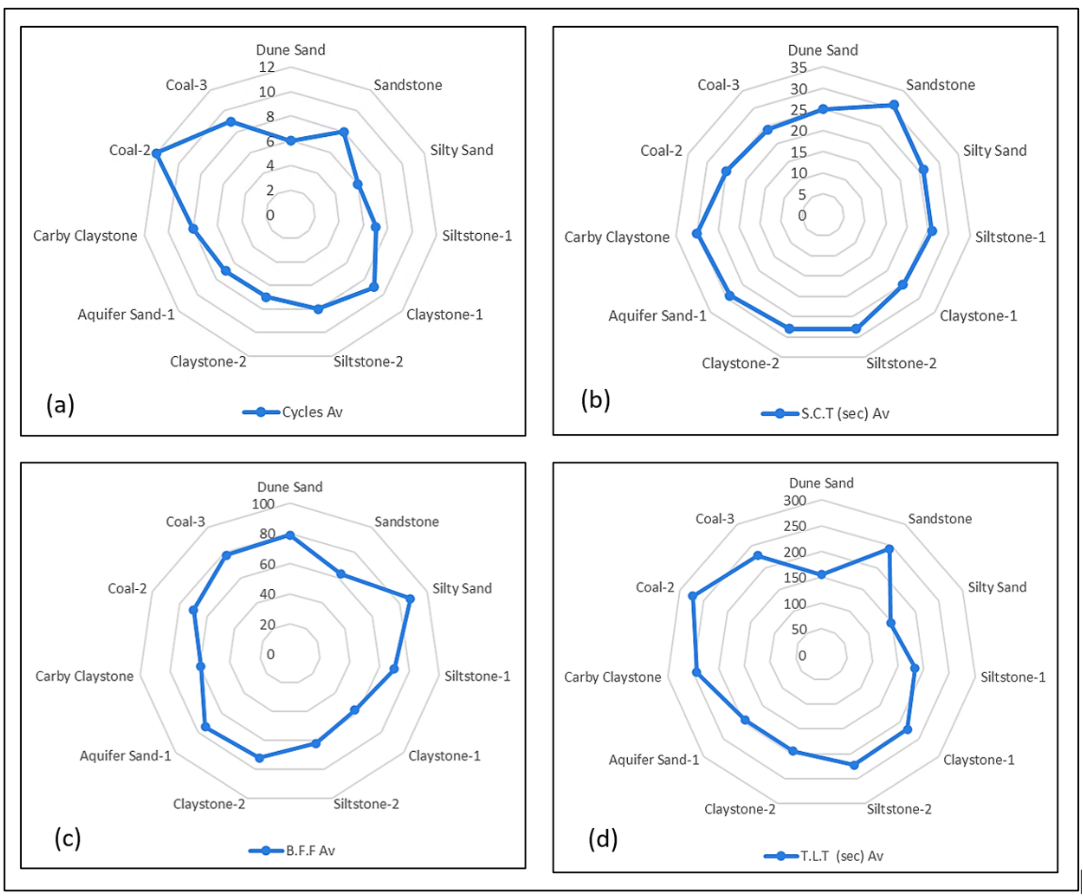

Fig 5. Shovel operational parameters in different rock and soil formations

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The rock properties presented in table 2 were compared with the respective TLT values by a correlation analysis to check the impact of individual rock property on the excavatability. The results of the correlation analysis are presented in figure 6. From the correlation analysis it was observed that most of the correlation coefficients lie between 0.5 – 1. This shows that there is a significant positive relationship between TLT and unconfined compressive strength (UCS), tensile strength (TS), cohesion (C), moisture content (M), and rock quality designation (RQD). An inverse correlation was observed between the TLT and wet bulk density (WBD). However, the correlation coefficient of 0.31 was obtained for TLT and friction angle (ϕ), indicating a moderate relationship.

	TLT	*UCS*	*TS*	*C*	*ϕ*	*M*	*WBD*	*RQD*
TLT (sec)	**1**							
UCS (MPa)	0.74	**1**						
TS (MPa)	0.74	0.92	**1**					
C (kPa)	0.84	0.58	0.57	**1**				
ϕ (deg.)	0.31	0.61	0.41	0.41	**1**			
M (%)	0.68	0.64	0.52	0.82	0.79	**1**		
WBD (t/m3)	-0.60	-0.59	-0.45	-0.79	-0.81	-0.98	**1**	
RQD (%)	0.55	0.58	0.64	0.63	-0.03	0.29	-0.27	**1**

Fig. 6. Correlation coefficients of various parameters

Additionally, the Pareto analysis was performed to assess the significance or impact of each individual rock property on the excavation performance of shovel. For this reason, the TLT was compared with rock properties that shown a strong correlation. Figure 7 presents the pareto chart showing the analysis results. It can be observed that cohesion has the highest impact (0.84), contributing to 20% of the total cumulative effect.

This indicates that cohesion is the most significant rock property influencing excavation performance. The UCS has an impact of 0.75 and brings the cumulative percentage to 38%. It is the second most influential factor. Tensile strength has an impact of 0.74, bringing the cumulative to 56%, showing it is another important factor after UCS. The moisture content has an impact of 0.68 and pushes the cumulative percentage to 72%, indicating that moisture also plays a considerable role. The WBD shows an impact of 0.60, increasing the cumulative percentage to 87%. Its contribution is significant but lower compared to the previous factors. The RQD has the lowest impact (0.55) but raises the cumulative percentage to 100% indicating that it is the least significant factor among those analysed.

Therefore, the RQD and the friction angle (ϕ) are not considered for analysis of excavatability. The red line represents the cumulative percentage. As more rock properties are considered, the cumulative impact on excavation performance increases, with cohesion, UCS, and tensile strength contributing the most to the total impact.

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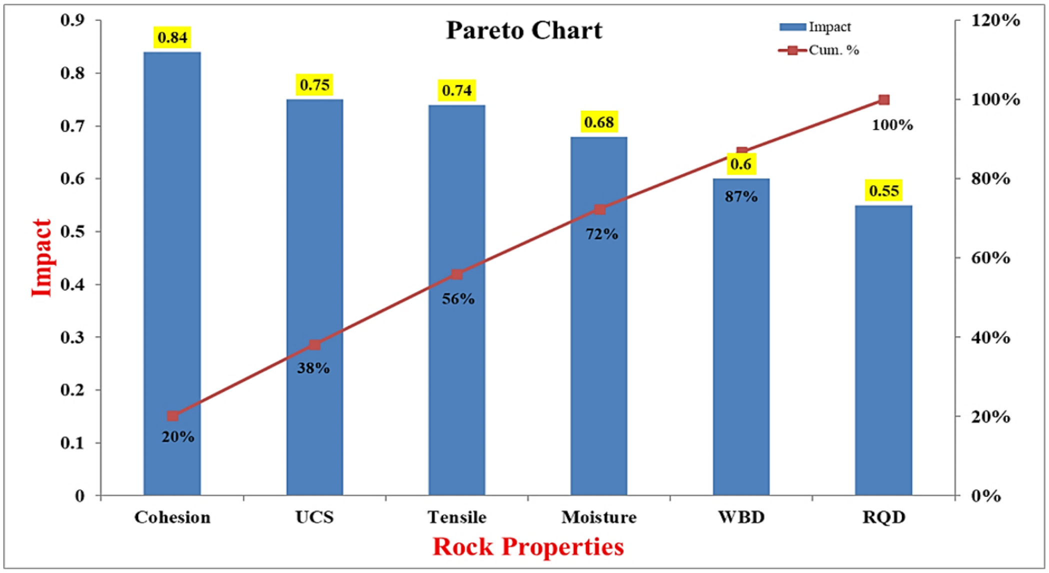

Fig. 7. Pareto analysis for impact of rock properties on excavation performance of shovel

To predict the excavatability using the rockmass properties, a multiple regression analysis approach is effective, as it allows for the combination of various rock characteristics to develop an empirical model. In this context, the model was created using the excavation performance data from the shovel (TLT) as the dependent variable, and rock properties as independent variables, such as cohesion, uniaxial compressive strength, tensile strength, moisture content and weight bulk density (Table 2). The developed model has a strong correlation between TLT and rock properties, as indicated by the high R-squared value in the analysis. This suggests that the linear combination of these rock properties can explain a large portion of the variability in TLT. The results are significant within a 95% confidence interval, implying that the predictions made by the model are statistically reliable. Table 3 presents the validation of the regression model and interpretation of corresponding metrics. The developed regression model for the estimation of TLT from rock properties is expressed in equation 3:

$$TLT = 38UCS - 32TS + 0.6C + 0.3M + 57WBD \quad (3)$$

Where, TLT = Total truck loading time (sec),

UCS = Uniaxial Compressive Strength (MPa),

BTS = Brazilian tensile strength (MPa),

C = Cohesion (kPa),

Φ = Internal angle of friction (degrees),

M = Moisture content (%),

WBD = Wet Bulk density (t/m^3).

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Table 3: Validation of The Multiple Linear Regression Model

MODEL VALIDATION COMPONENTS	VALUE	INTERPRETATION
REGRESSION STATISTICS		
Multiple R	0.998	Very strong correlation between predicted and actual values of TLT
R-square	0.996	99.6% of variability in TLT is explained by model.
Adjusted R -square	0.993	Slightly for the number of predictors, still very high, showing minimal over fitting
Standard Error	19.61	Acceptable given the high R-squared but could be reduced with more data.
Observations	11	A small sample size, more data would improve robustness.
ANOVA (ANALYSIS OF VARIANCE)		
Regression SS (sum of squares)	623,409.07	Most of the variation in TLT is explained by the model.
Residual SS (sum of squares)	2307.93	Unexplained variation is very low, indicating a good fit
F - statistics	324.14	Indicates over all significance of model.
Significance F	3.28E-07	Very significant that the showing the model is valid
PREDICTOR COEFFICIENTS		
Unconfined compressive strength (UCS)	37.92	A positive relationship with TLT, but not statistically significant (p-value = 0.24).
Tensile strength (TS)	-32.40	Negative relationship with TLT, but not statically significant (p-value =0.87).
Cohesion (C)	0.66	Positive relation with TLT, statically significant (p-value=0.03).
Moisture (M)	0.29	Positive relationship with TLT, but not statistically significant (p-value=0.83).
Wet bulk density	57.02	Positive and highly significant relationship with TLT, (p-value =7.03E-05).

5. EXCAVATABILITY CLASSIFICATION

In this analysis, the K-means clustering algorithm was applied to classify the digging behavior of the shovel, specifically for understanding the digging ease of the rockmass. This was done by dividing the TLT values into distinct clusters. Each cluster represents different levels of performance in terms of how easily the shovel can dig through various rock and soil zones.

The TLT values reflect the performance of the shovel in different rockmass conditions based on various rock properties (Table 2). K-means clustering was performed using SPSS software. Based on the performance of shovel in different rock and soil zones, the algorithm grouped the TLT values into three clusters (Figure 8). The clustering method minimizes the variability between clusters, ensuring that each cluster is distinct in terms of excavation difficulty.

Figure 8 presents the clustering results based on TLT values are classified into three unique excavatability classes: Easy, Moderate, and Difficult (Table 4). The vertical axis represents the TLT in seconds, while the horizontal axis shows the corresponding excavatability class.

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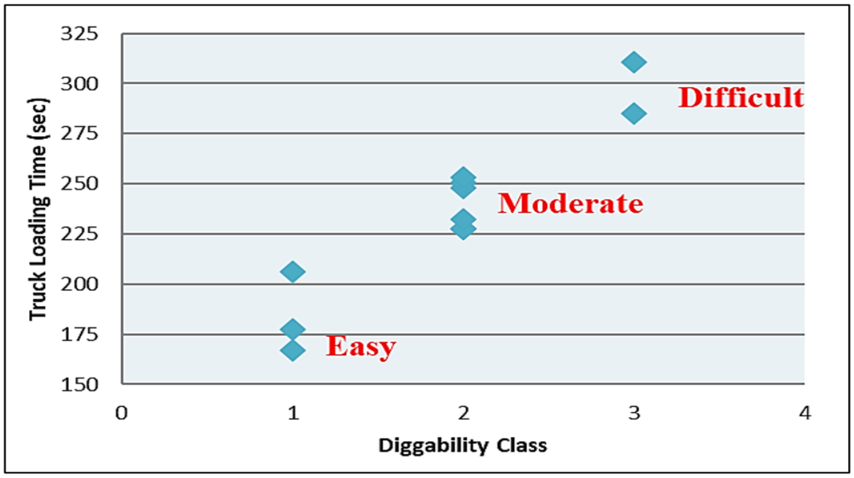

Fig. 8. Graphical representation of clusters

Table 4: Cluster Interpretation and Excavability Classification for Soft Sedimentary Rocks

Cluster	Excavatability Class	TLT Range (sec)	Rock characteristics	Interpretation
1	Class-I (Easy)	< 210	Low UCS, low density, high RQD	Represent zone with the easiest digging condition, shovel performs efficiently with minimal loading time
2	Class-II (Moderate)	215 – 275	Moderate UCS, moderate cohesion, average density	Represent zones with moderate digging difficulty, shovel takes a reasonable amount of time to load material.
3	Class-III (Difficult)	> 280	High UCS, high density, low RQD	Represent zones with the most difficult digging conditions, shovel takes a significantly longer time to load.

6. CONCLUSIONS

This research provides insights into the factors influencing shovel performance and productivity, focusing on the limitations of existing excavatability assessment methods. Previous approaches primarily relied on muck pile characteristics, which only reflect excavatability during or after the excavation, making them inadequate for pre-excavation equipment selection. In contrast, rock properties offer a more effective means of assessing the excavation performance before the start of routine mining operation. To address this gap, an empirical model was developed using rock properties and key shovel performance indicators, with Total Loading Time (TLT) as the critical metric. The regression analysis technique was used to develop a strong predictive model with a linear relationship between TLT and the given rock properties, validated within a 95% confidence interval. The model can be used to estimate TLT based on rock properties, supporting its use in practical mining operations for scheduling and performance assessment. The regression model shown a best fit with high R-squared value (0.99) and significant overall F-statistic ($p < 0.001$). Two predictors, cohesion and wet bulk density are statistically significant, while others are not. The model is valid based on ANOVA results but could be improved by increasing the data. In addition, a new excavatability classification system was proposed, incorporating both shovel performance and rockmass properties, offering a more comprehensive approach for excavation planning. K-means clustering algorithm was used to classify the rock and soil layers into three unique excavatability classes:

- **Excavatability Class-I:** Includes Dune Sand, of Recent Formation, and Silty Sand and Siltstone-1 from Sub-Recent Formation, characterized by easy excavation.
- **Excavability Class-II:** Comprises of Sandstone, Siltstone-2 and Claystones of Sub-Recent Formation, Coal-2 (minor coal seam), and Aquifer Sand of Bara Formation, all of which require moderate excavation effort.
- **Excavability Class-III:** Consists of Carby Claystone, and the Coal-1 (major coal seam) of Bara Formation, representing the rocks which are difficult to excavate.

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