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Influence of Crushed Rock Properties on the Productivity of a Hydraulic Excavator

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Featured Application: The presented methodology is a relatively fast and accurate method that provides solid information of the influence of crushed rock properties on the productivity of a hydraulic excavator. The methodology has been tested in quarries of crushed stone but is also applicable to geotechnics, construction works, and other earthworks where hydraulic excavators are used.

Abstract: Among many factors that influence an excavator's performance and productivity, the volume of the bucket load and duration of the excavator working cycle are crucial. In this paper, both factors were investigated, including the granulometric composition of the excavated material. The volume of material in the bucket was determined by photogrammetric analysis while the excavator cycle time was measured by analysis of video recordings captured by a digital video camera during the excavator operation. Interconnections between the angle of repose, slewing angle, particle size distribution of material, and their effects on hydraulic excavator productivity were analyzed. It was found that a larger number of fine particles in granular materials with a higher coefficient of uniformity resulted in an increase in the volume of the bucket load. Correlation analysis revealed significant interconnection between the bucket fill factor and swell factor. It was also found that calculation of the production rate according to ISO (International Organization for Standardization) standards was more accurate for materials with a higher angle of repose while the CECE (Committee for European Construction Equipment) standard was more appropriate for materials with lower angles of repose.

Keywords: hydraulic excavator; bucket volume; particle size distribution; fill factor; cycle time; productivity

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1. Introduction

Hydraulic excavators are common nowadays and are often irreplaceable equipment at the majority of mining and civil worksites [1]. In civil projects, hydraulic excavators are primarily used for earthmoving works. In mining, in open pits or quarries, they are used for many different tasks such as auxiliary equipment or main machinery for non-cohesive mineral raw material excavation. The excavator plays a significant role in the transition from the drill and blast excavation non-blasting methods [2]. Therefore, optimization of efficiency [3] and productivity of the excavators are necessary for on-time availability, cost reduction, and better performance.

Many authors have analyzed the productivity of earthmoving machinery as a system consisting of an excavator and truck [4–9], but calculation of the productivity of only the excavator was not conducted. In numerous studies, authors used miscellaneous statistical methods to model excavator productivity using different independent variables. In [10], multiple regression was used to model excavator productivity by employing the weight of the excavator, depth of digging, and swing angle as independent variables. For calculating excavator productivity, an artificial neural network was applied in [11,12].

Irrespective of the calculation method or model of the excavator productivity used, analyses must begin by determining the technical excavator productivity. This depends on the volume of material in the bucket and the duration of the working cycle as is the case for most cyclical machinery. To obtain effective excavator productivity, technical productivity must be corrected by mainly modifying the estimation factors: operator competence, operator utilization, and excavator efficiency. Excavator efficiency is called "random conditions" [13] and "natural variability" [6] and depends on specific conditions at the work site. Operator competence positively correlates with a higher productivity of the excavator [14]. The impact of operator competence on operator utilization and excavator efficiency is analyzed in detail in [15], and a hybrid factor was developed which can be used to calculate effective excavator productivity as a function of operator competence alone. The cycle time of the excavator is composed of the time needed to fill the bucket, slewing time, and time for unloading the bucket [16]. The cycle time for filling and unloading the bucket is, principally, the consequence of material properties while the slewing time of the excavator depends on size of the machine, slew angle, and height/depth of the working face [17]. This can be monitored by using specific measurement systems [18], but productivity calculations also require material properties. The amount of material in the bucket is a function of the constructional bucket volume and bucket fill factor.

According to an extensive literature review in [19], in the past three decades a significant amount of research has been carried out on the automation of excavating machinery. It has been stated that the capability to fill a bucket with material depends on the same material parameters as those for loosening the material from the ground. The extent of filling is higher for fine grained and homogenous material and lower for material with a high boulder content.

Based on the studies conducted in [20–22], the main factors that govern the interconnection between the heap size distribution resulting from a production blast in surface mines and the productivity of the excavator are the cycle time and the bucket fill factor.

In [23], the relationship between the characteristic heap fragment size and both the excavator cycle time and the bucket fill factor was investigated, and an estimation model was proposed as a tool for determining excavator productivity. The characteristic heap fragment size depends on the coefficient of uniformity of the heap size distribution and the mean fragment size of the heap [24].

Based on blasted rock fragmentation data obtained by using image processing software and dependencies of the bucket fill factor and cycle time of the excavator on these data, the authors in [25] also concluded that excavator productivity directly depends on the granulometric composition of rock. By analyzing the particle size and ratio of bucket volume to truck capacity, the authors in [26] concluded that these properties affect the crowding efficiency, fill factor, and swell factor. Further, the blasting efficiency and operator competence were found to be effective parameters.

In contrast to other research, in [27], the authors investigated the relationship between fuel efficiency (kg/l) and productivity (m^3/h) by monitoring two independent variables, engine speed and bucket cut depth (BCD), in an excavator working with loose dry sand. It has been found that BCD and engine speed can affect the fuel efficiency and productivity of a hydraulic excavator in a way that a half-filled bucket (50% BCD) can have an effect of 30% higher productivity, 24% saving on fuel (l/kg), and 62% more sand moved per hour, in addition to the amount of fuel consumed. Except for granulometric composition, the productivity of the excavator will indubitably depend on the water content of the material. A simple explanation of this is the fact that if the quantity of water is greater, the bucket filling factor will be lower because part of the constructional bucket volume is filled by water [28]. Furthermore, the moisture in some materials causes the appearance of stickiness, resulting in a longer dumping time of the bucket that is longer than the cycle time of the excavator. On the other hand, the moisture in coherent material directly influences the increase in the bucket fill factor.

It is clear from the presented literature review that the productivity of the excavator will strongly depend on the bucket fill factor, and one of the properties with a major influence on it is the particle size distribution of the material being manipulated. The swell factor is also the consequence of the particle size distribution of the material, and it can be hypothesized that there is a connection between them. Besides, the water content in coherent material will increase the fill factor in a way that it will increase the angle of repose of material, which results in expansion of the heaped volume of the bucket. It can be assumed that a higher material angle of repose will cause an increase in the heaped bucket volume and consequently, the productivity of the excavator.

This work aims to determine the strength of impact of the angle of repose of crushed rock material on excavator productivity and to investigate the connection between the bucket fill factor and swell factor of the material being manipulated. Analysis of the simultaneous effect of the angle of repose, slewing angle, and particle size distribution of the material on hydraulic excavator productivity will also be conducted.

Calculations are based on field measurements for determining the volume of the bucket load and the duration of the excavator loading cycle as the main factors that determine the productivity.

2. Materials and Methods of Field Research

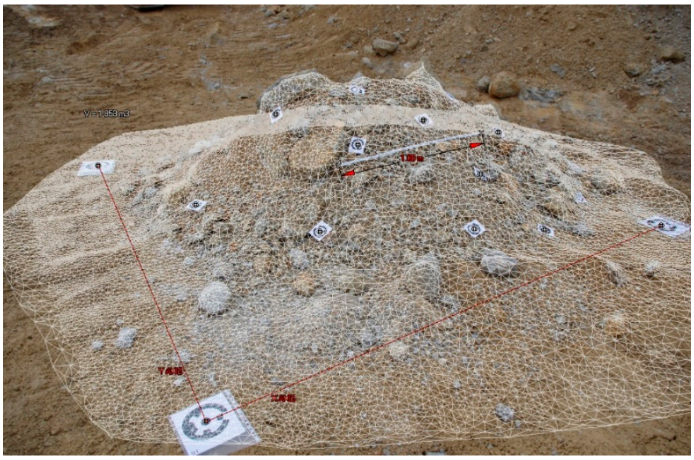
Measurements were performed under field conditions on seven crushed rock quarries. Two of them are diabase quarries ("Žervanjska" and "Hruškovec"), four of them are dolomite quarries ("Zaprešićki Ivanec", "Gradna", "Škrobotnik" and "Očura"), and limestone was excavated at quarry "Špica". The locations of the quarries are shown in Figure 1.

Figure 1. Locations of quarries where field measurements were conducted.

Excavators performed either loading of blasted rock material into trucks or mobile crushers or gravitational transport of overburden. Gravitational transport is throwing of overburden and rock material from excavation into haulage benches, and it is common in most quarries of crushed stone in the Republic of Croatia as the most economical method of transport [29].

The measurement procedure at every location composed of loading the bucket and taking photographs of the top material for measurement of the angle of repose. The next step was taking photographs of the empty ground in the marked area. After unloading the bucket in the same area, the heap was photographed which served as the volume of bucket load determination as well as particle size distribution. Afterwards, a video recording was started and a minimum of 100 excavator cycles were recorded. The procedure was repeated three times and the given results represent average values.

The volume of the excavator's bucket load was determined by using software for photogrammetric analysis from pairs of photographs, Photomodeler Scanner, in this case. The volume was determined as the difference between the heap surface and base surface. Previously fixed marks were used as common reference points for both surfaces (Figure 2a). The angle of repose was measured using the same software but on the surface generated from the material on top of a strike plane of a bucket (Figure 2b). The angle represents the average slope between the top and bottom points on four sides of the surface.



(**a**)

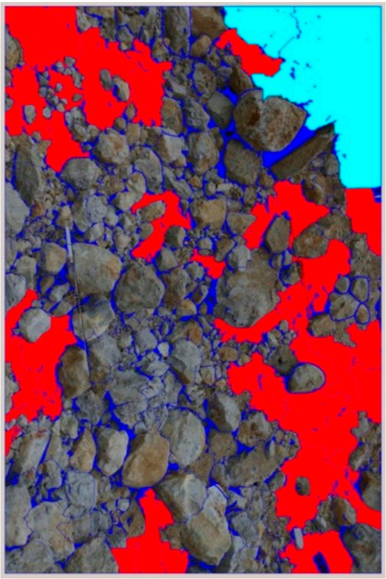
(**b**)

Figure 2. (a) Measuring volume of the bucket load and (**b**) angle of repose of material.

Granulometric analysis of each relevant rock material was performed by taking digital images of a heap, simultaneously with the volume measurement (Figure 2a). Two images from opposite angles were selected for the analysis to give representative parameters of a material. Digital images (Figure 3a) were processed by Wipfrag computer software for granulometric analysis, and parameters of rock particle size distribution were obtained (Figure 3b).

The duration of the excavator loading cycle was measured by analysis of video recordings taken by a digital video camera during the excavator operation. These video recordings, of each observed excavator, were then analyzed in Windows media player, and cycle times were recorded. Table 1 shows the results of field measurements as well as granulometric analyses of the rock material in the bucket.

For convenience, methodology for calculating the excavator's productivity and forming regression equations is presented in the following chapters, in parallel with the analysis.



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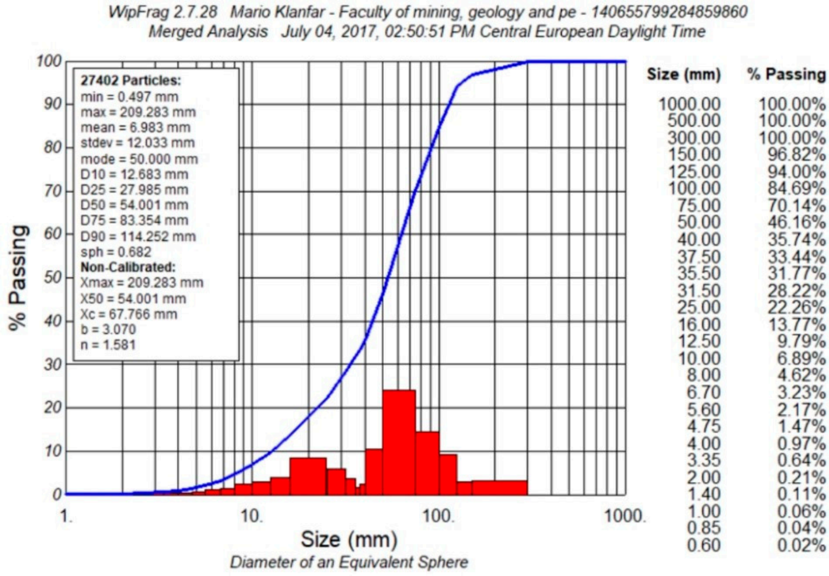

(**b**)

Figure 3. Determination of rock size distribution parameters: (**a**) digital image; (**b**) rock particle size diagram.

Table 1. Results of field measurements and granulometric analysis.

Quarry	Excavator	Material	Task	A_T [°]	V_m [m^3]	A_r [°]	T_c [s]	n	X_c [mm]	d_{50} [mm]	d_{80} [mm]
Žervanjska	Liebherr R944C	Overburden (wet)	Heap shifting	70	2.37	49	14.23	6.59	30.1	29.07	32
Zaprešićki Ivanec	Fiat—Hitachi EX355	Blasted dolomite rock (wet)	Heap shifting	60	2.28	48.6	13:49	3.87	1.305	1.242	1.3
Gradna	Renders RKE 2600	Blasted dolomite rock (wet)	Truck-shovel	35	2.23	44.0	22.70	1.51	34.024	25.7	50
Škrobotnik	Komatsu PC 340 NLC	Blasted dolomite rock (wet)	Crusher-shovel	130	1.95	23.5	20.14	1.274	128.984	96.08	280
Hruškovec	CAT 330D	Blasted diabase rock (wet)	Truck-shovel	171	2.09	39.5	27.62	1.318	91.896	67.6	152
Špica	CAT 336E	Blasted limestone rock (dry)	Truck-shovel	98	2.05	29.2	18.09	1.485	217.461	162.4	295
Očura	Liebher R944C	Blasted dolomiterock (dry)	Truck-shovel	110	2.03	44.1	28.21	1.581	67.766	54	92

A_T—slew angle of the excavator; Vm—measured volume of material in the bucket; Ar—angle of repose; Tc—mean duration of the excavator cycle; n—coefficient of uniformity of the particle size distribution; Xc—characteristic particle size; D50—50% of particles are smaller than this dimension.

3. Calculation of the excavator's Productivity

Calculation of the technical excavator's productivity consisted of determining the volume of material in the bucket and the duration of the cycle. The amount of material in the bucket depends on its geometric volume and the bucket fill factor while the duration of the cycle is a function of the excavator size and working conditions. The general formula for calculation of the excavator's technical productivity can be expressed by (1):

$$Q = (3600\ V\ k_f)/T_c, \tag{1}$$

where Q is the excavator's technical productivity in m^3/h, V is the geometrical volume of the excavator bucket in m^3, k_f is the bucket fill factor, and T_c is duration of the cycle in seconds.

Geometrical Volume of the excavator's Bucket

The method for calculating the geometrical volume of buckets for hydraulic excavators published by the Society of Automotive Engineers (SAE) [30] is representative of the methods used by most heavy equipment manufacturers. This method is technically equivalent to methods described in ISO standard 7451 [31]. Buckets are rated on both their struck and heaped capacities. Struck capacity is the volume actually enclosed inside the outline of the sideplates and rear and front bucket enclosures without any consideration of any material supported or carried by the spillplate or bucket teeth. Heaped capacity is the volume in the bucket under the strike-off plane plus the volume of the heaped material above the strike-off plane, having an angle of repose of 1:1 (45°) regardless of the type of material (Figure 4). The Committee on European Construction Equipment (CECE) rates heaped bucket pay loads on a 1:2 (~27°) angle of repose for material above the strike-off plane. These standard procedures of the excavator bucket volume calculation presume certain errors in results because dissimilar materials have different angles of repose.

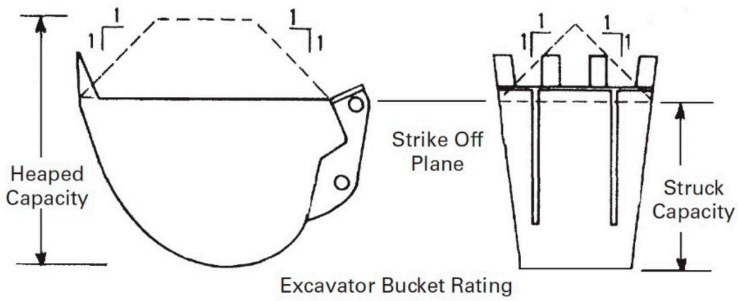

Figure 4. SAE and ISO excavator bucket rating [32].

4. Results and Discussion

4.1. Factors Influencing Excavator Productivity

Most manufacturers of construction and mining machinery give the fill factor in their equipment performance handbook based on data collected from numerous worksites. Table 2 shows values of the bucket fill factor from handbooks of certain heavy equipment producers.

It can be seen from the Table 2 that the lowest fill factor is associated with coarse-grained material and vice versa. This is in conformity with investigations mentioned in the introduction that the bucket fill factor for no coherent material will depend on the granulometric composition. It is also evident that for coherent material, moisture has an increasing effect on the bucket fill factor. In general, coherent material is associated with a higher bucket fill factor than no coherent material.

The fill factor for well blasted rock material, according to all manufacturers, ranges from 0.6 (Caterpillar) to 0.95 (Volvo). The fill factor can be expressed as a ratio (2):

$$k_f = V_a/V, \tag{2}$$

where V_a is the actual volume of material in the bucket and V is calculated the geometrical volume.

During field measurements, when the excavator unloaded material from the bucket on the terrain surface, material from the bucket was additionally loosened, causing an increase in the material volume when it was in the bucket. That additional loosening, V_m, can be expressed by loosening factor k_l with Equation (3):

$$V_m = V_a\ k_l, \tag{3}$$

If it is supposed that the most accurate procedure of bucket geometrical volume calculation is by using the measured angle of repose for volume calculation of heaped material above the strike-off plane and the ISO or CECE method for the struck bucket volume calculation and by taking the bucket fill factor from Table 2, we can calculate the coefficient of additional loosening of material when it is unloaded from the bucket:

$$k_l = V_{m/}(V\ k_f), \tag{4}$$

where k_l is the loosening factor, V_m is the measured volume of the bucket load, V is the geometrical volume of the bucket calculated by the measured angle of repose and ISO calculation procedure, and k_f is the bucket fill factor.

Table 2. Excavator bucket fill factor from manufacturer handbooks.

Source	Material	Fill Factor	Swell Factor
John Deere	Wet Earth, Loam, Sandy Clay Loam	1.2	1.2–1.43
	Natural Bed Clay, Damp Sand, Sand & Clay, Lime Rock w/Fines	1.1	1.05–1.33
	Rock and Earth–25%/75%, Dry Clay, Dry Earth, Topsoil	1.0	1.25–1.56
	Rock and Earth–50%/50%	0.95	1.29–1.38
	Rock and Earth–75%/25%	0.9	1.25–1.42
	Dry Sand	0.9	1.11–1.13
	Broken limestone	0.8	1.63–1.70
Caterpillar	Moist loam or sandy clay	1.0–1.1	1.2–1.43
	Sand and Gravel	0.95–1.1	1.11–1.15
	Hard, Tough Clay	0.8–0.9	1.34–1.43
	Rock—Well Blasted	0.6–0.75	1.49
	Rock—Poorly Blasted	0.4–0.5	1.67–1.80
Komatsu	construction application		
	Excavating natural ground of clayey soil, clay, or soft soil	1.1–1.2	1.22–1.43
	Excavating natural ground of soil such as sandy soil and dry soil	1.0–1.1	1.25–1.46
	Excavating natural ground of sandy soil with gravel	0.8–0.9	1.18–1.41
	Loading blasted rock	0.7–0.8	1.49–1.80
	mining application		
	Excavating natural ground of clayey soil, clay, or soft soil	1.0	1.22–1.43
	Excavating natural ground of soil such as sandy soil and dry soil	0.95	1.25–1.46
	Excavating natural ground of sandy soil with gravel, Loading blasted rock	0.9	1.18–1.80
Volvo	Earth/Sandy Clay	1.0–1.1	1.2–1.375
	Hard and Compacted Clay, Sand/Gravel	0.95–1.1	1.11–1.43
	Rock—well blasted	0.75–0.95	1.49
	Rock—averagely blasted	0.6–0.75	1.58
	Rock—poorly blasted	0.4–0.6	1.67–1.80
Liebherr	Clay and sticky material, clay, sandy loam, moist material	1.1	1.1–1.43
	Sand, sand gravel mixture, moist	1.0–1.1	1.1–1.15
	Hard dry clay	0.9	1.24–1.43
	Rock, well blasted	0.85	1.49
	Rock, poorly blasted	0.6–0.7	1.67–1.8
	Rock, deteriorated, layered shale, not blasted	0.5–0.7	1.33–1.79
	Underwater digging of sand, gravel & sand-gravel mixtures	0.85	-

Table 2 also shows range values of swell factors for respective materials from the literature and web sources [33–43]. The swell factor parameter is used to describe an increase in volume that may occur when a block of rock breaks up to form rubble or when a mass of soil is excavated. It is well known that the swell factor depends on the granulometric composition of the respective material, exactly the same as we stated for the bucket fill factor. If we compare the mean loosening factor for blasted rock materials from Table 3 (k_l = 1.55) and the mean swell factor from Table 2 (k_s = 1.5), they are evidently similar. The loosening factor for overburden material at quarry Žervanjska is the same as the swell factor (k_l = k_s = 1.4). Figure 5 plots dependencies of fill factor on swell factor based on data shown in Table 2.

Table 3. Loosening factor.

Quarry	Excavator	Material	Vm [m^3]	V [m^3]	k_f	k_l
Žervanjska	Liebherr R944C	Overburden (wet)	2.37	1.89	0.9	1.39
Zaprešićki Ivanec	Fiat—Hitachi EX355	Blasted dolomite rock (wet)	2.28	1.77	0.8	1.61
Gradna	Renders RKE 2600	Blasted dolomite rock (wet)	2.23	1.73	0.8	1.61
Škrobotnik	Komatsu PC 340 NLC	Blasted dolomite rock (wet)	1.95	1.46	0.8	1.67
Hruškovec	CAT 330D	Blasted diabase rock (wet)	2.09	1.72	0.8	1.52
Špica	CAT 336E	Blasted limestone rock (dry)	2.05	1.71	0.8	1.50
Očura	Liebher R944C	Blasted dolomite rock (dry)	2.03	1.83	0.8	1.39

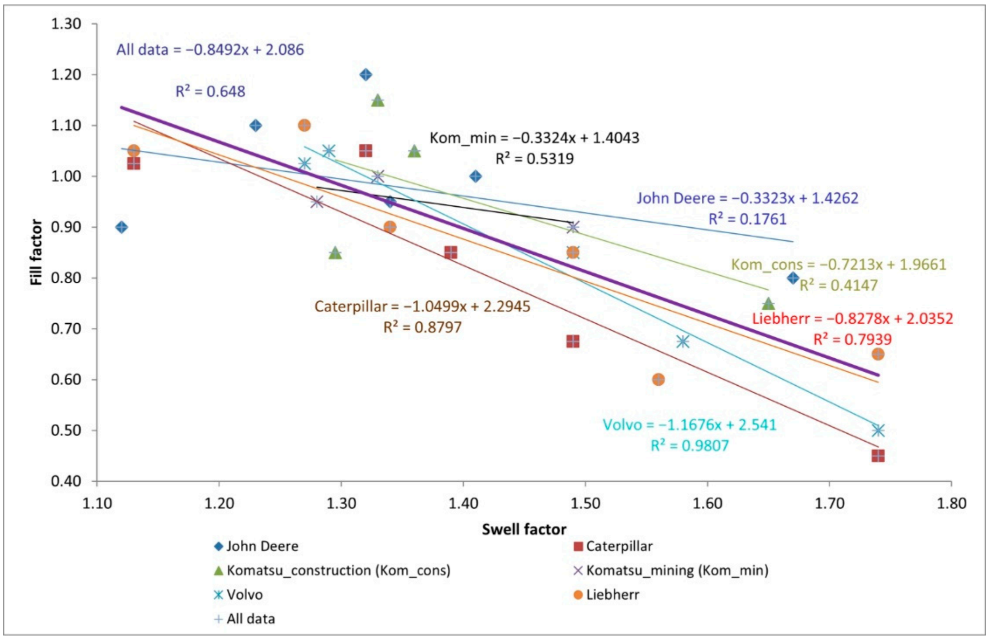

Figure 5. Dependence of the bucket fill factor on the swell factor of the material.

Mean values are taken for range values of the bucket fill factor and swell factor. The coefficients of determination of Volvo's, Liebherr's, and Caterpillar's data on the bucket fill factors and corresponding swell factors (Figure 5) exhibit significant interconnection of these two parameters, as is the case with the correlation of all data whose coefficient of determination also exhibited a significant correlation (R^2 = 0.6483). All trend lines showed a decreasing trend, i.e., with increased swell factors, fill factors decreased. Based on the shown dependencies, it is possible to assume the bucket fill factor if the swell factor is known.

4.2. Analysis of the excavator Productivity Determinants

As we stated several times, all factors that we discussed above (bucket filling, loosening, and swelling) indubitably significantly depend on the granulometric composition of the rock material. Accordingly, the productivity of the excavator must be strongly related to that material characteristic too. Another material property that will surely have a strong influence on excavator productivity is the angle of repose. On that angle will depend the heaped volume of material in the excavator bucket. Except for the material characteristic, organization of the working place, that is the slew angle of the excavator, influences the duration of the working cycle and consequently, the productivity of the excavator.

Table 4 shows a comparison of the excavator productivity for a loose state of the material calculated in three ways: Q_{Vm}—productivity calculated by field-measured volume of the material in the bucket and Q_{ISO}—calculated by the ISO procedure of the bucket volume calculation, and Q_{CECE}—calculated by the CECE procedure of the heaped bucket volume calculated by expression (5):

$$Q_{ISO,CECE} = (3600\ V\ k_f\ k_l)/T_C, \quad (5)$$

Table 4. Comparison of the excavator productivity.

Quarry	Excavator	A_T [°]	A_r [°]	Q_{Vm} [m^3/h]	Q_{ISO} [m^3/h]	Q_{CECE} [m^3/h]
Žervanjska	Liebherr R944C	70	49	600	573	491
Zaprešićki Ivanec	Fiat—Hitachi EX355	60	48.6	608	584	488
Gradna	Renders RKE 2600	35	44	354	357	302
Škrobotnik	Komatsu PC 340 NLC	130	23.5	349	413	356
Hruškovec	CAT 330D	171	39.5	272	290	239
Špica	CAT 336E	98	29.2	408	478	399
Očura	Liebher R944C	110	44.1	259	263	224

Dependence of the excavator productivity on the angle of repose is unquestionably noticeable from Table 4. Productivity calculated by the CECE procedure, which is calculated by an angle of 27 degrees, is in general the lowest except in the case of quarry Škrobotnik where the measured angle of repose is 23.5°.

As can be seen from Figure 6, for materials with a lower repose angle from Škrobotnik and Špica quarries, productivity calculated by the CECE procedure is more accurate. The main reason is that CECE rates the heaped bucket assuming an angle of repose 27°.

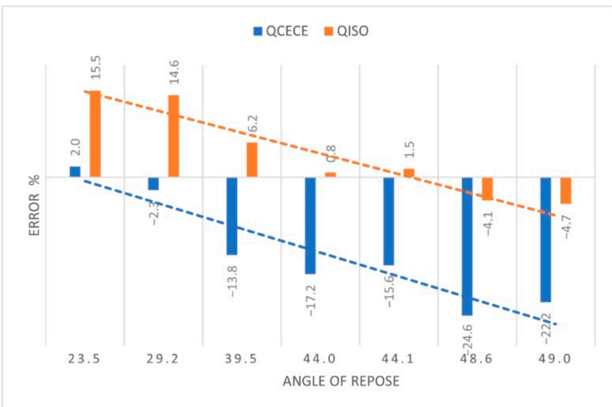

Figure 6. Influence of the angle of repose on the excavator productivity calculation error.

In the case of an angle of repose of 34.6°, both methods are equally precise in productivity calculation. Above this angle, as can be seen, the ISO method is more suitable since the heaped bucket is calculated assuming an angle of repose 45°.

Figure 7 shows the influence of the slew angle on excavator productivity, which is calculated by the measured volume of material in the bucket.

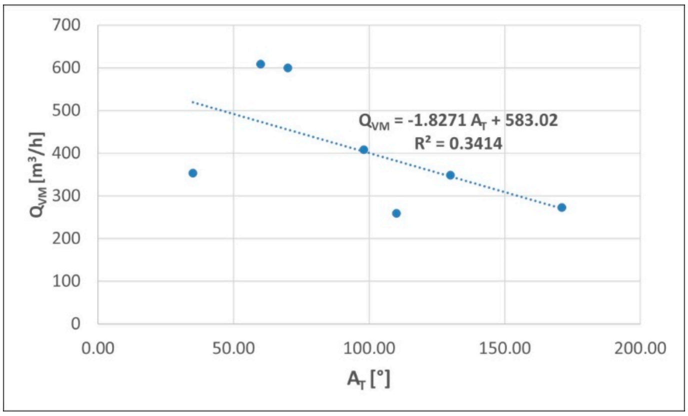

Figure 7. Influence of the slew angle on productivity.

It can be noticed that productivity is inversely proportional to the slew angle. Although a low correlation factor suggests a relatively small dependence between the excavator productivity and slew angle, this is not the case. The total cycle time comprises the time required to load, dump, and maneuver the bucket. A larger angle causes a longer cycle time and thus less productivity.

However, depending on the task of the excavator, the time for maneuvering the bucket depends on the slew angle, but also on the height of lift and digging depth. If there is a large difference in the height of lifting and lowering the bucket, then the overall cycle can be longer regardless of the relatively small slew angle. An example can be seen from Table 2. In the case when the excavator was used to shift the pile, the total time of the cycle was shorter, although the slew angle was higher than in the case of loading the truck. Litvin & Litvin found that under the same conditions of installations of dump trucks for loading, the excavator cycle time decreased exponentially with the slew angle [44].

Since it is evident from the performed analysis that there is a considerable influence of several observed properties on excavator productivity, a multiple regression analysis of the simultaneous influence of multiple properties was conducted.

A linear regression model was assumed in which the excavator productivity for a loose state of material is a dependent variable (6), and all other observed and analyzed properties are independent variables.

$$Q_{Vm} = b_1\,x_1 + b_2\,x_2 + \ldots + b_n\,x_n + \text{Intercept} \quad (6)$$

The independent variables are the results of measurements and granulometric analysis from Table 1. The correlation between these variables is shown in Table 5.

In general, it can be mentioned that A_r and d_{80} have the most significant degree of correlation with all other variables, while d_{50} correlates the least with all other variables. It was determined by conducted analysis that, between the combinations of two properties, largest influence on productivity of the excavator was a combination of the slew angle of excavator A_T and the coefficient of uniformity of particle size distribution n.

The results of the analysis are graphically presented in Figure 8, and the regression summary is shown in Table 6.

Table 5. Correlation between variables.

	A_T	A_r	n	X_c	d_{50}	d_{80}
A_T	1	−0.5	−0.43	0.47	−0.31	0.57
A_r	−0.5	1	0.61	−0.85	0.32	−0.97
n	−0.43	0.61	1	−0.53	0.25	−0.59
X_c	0.47	−0.85	−0.53	1	−0.39	0.95
d_{50}	−0.31	0.32	0.25	−0.39	1	−0.39
d_{80}	0.57	−0.97	−0.59	0.95	−0.39	1

A_T—slew angle of the excavator; A_r—angle of repose; n—coefficient of uniformity of the particle size distribution; X_c—characteristic particle size; $d_{50\text{—}80\,\%}$ of particles are smaller than this dimension

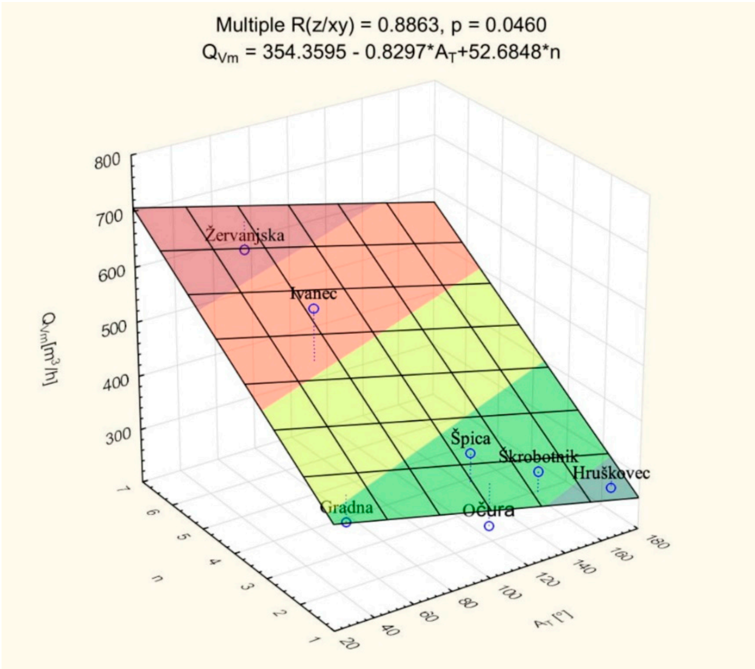

Figure 8. Multiple regression analysis of the dependence of the excavator productivity on the slew angle of the excavator and the coefficient of uniformity of the particle size distribution.

Table 6. Regression summary for dependent variable Q_V.

N = 7	**R = 0.88628382; R^2 = 0.78549901; Adjusted R^2 = 0.67824851; F (2,4) = 7.324 *P* < 0.04601; Std. Error of estimate: 81.529**					
	b *	**Std.Err. of b ***	**b**	**Std.Err. of b**	**t (4)**	***p*−Value**
Intercept			354,3595	110.2472	3.21423	0.032458
A_T [°]	−0.265315	0.256894	−0.8297	0.8034	−1.03278	0.360057
n	0.738543	0.256894	52.6848	18.3258	2.87490	0.045245

R—Pearson correlation coefficient; R^2—Coefficient of determination; Adjusted R^2—Adjusted coefficient of determination; F (2,4)—F-distribution; p−Probability value of error; b—regression coefficients; b*—standardized regression coefficients

It appears from the indicators of reliability of multiple regression analysis from Table 6 that excavator productivity is significantly dependent on the slew angle of the excavator A_T and coefficient of uniformity n. It can be seen from standardized regression coefficients b* that coefficient of uniformity n has a larger influence on excavator productivity. The probability value of error p of the assumed regression model shows that the probability of error is less than 4.601%, from which it can be concluded that the dependence of the excavator productivity on analyzed material characteristics is significant given the usual significance level of 5%. The intercept of the regression plane on the z axis and coefficient n are also significant.

The results of multiple regression analyses with a combination of three, four, and five independent variables with the largest influence on productivity are shown in equations from (7) to (10), and in Table 7 together with the influence of the slew angle and coefficient of uniformity considered above.

$$Q_{vm} = 354.3595 - 0.8297\ A_T + 52.6848\ n, \tag{7}$$

$$Q_{vm} = -1.0764\ A_T - 4.0188\ A_r + 62.2419\ n + 513.5846, \tag{8}$$

$$Q_{vm} = -\ 0.9973\ A_T - 6.8447\ A_r - 0.2520\ d_{80} + 62.7602\ n + 649.3469, \tag{9}$$

$$Q_{vm} = 6.44\ A_T - 223.01\ A_r - 31.72\ d_{80} + 22.45\ X_c + 127.99\ n + 10574.19, \tag{10}$$

Table 7. Multiple regression analysis of dependence of the excavator productivity Q_{vm} on analyzed determinants.

Mark Equation	Regression Summary for Dependent Variable: Excavator Productivity in Loose State of Material Q_{vm} (m^3/h)	Mean abs. Deviation (m^3/h)
(7)	R = 0.886284; R^2 = 0.785499; Adjusted R^2 = 0.678249; F (2,4) = 7.324; $p < 0.04601$; Std. Error of estimate: 81.529	54.75
(8)	R=0.909546; R^2=0.8272741; Adjusted R^2= 0.6545482; F (3,3) = 4.7895; $p < 0.11534$; Std. Error of estimate: 84.479	44.98
(9)	R = 0.910839; R^2 = 0.829628; Adjusted R^2 = 0.488884; F (4,2) = 2.4348; $p < 0.31172$; Std. error of estimate: 102.76	47.19
(10)	R = 0.999665; R^2 = 0.999331; Adjusted R^2 = 0.995984; F (5,1) = 298.63; $p < 0.0439$; Std. error of estimate: 9.1082	2.82

Considering regression equations from Table 7, Equation (10) gives the smallest mean absolute deviation from productivity calculated by measured characteristics. It appears from the indicators of reliability of multiple regression analysis that for the excavator productivity, the largest common effect is provided by five tested properties. However, due to the extremely large values of performance parameters, e.g., Adj. R^2 is 0.995984, there is a reasonable suspicion that overfitting occurred in this model. Therefore, the estimation equation will very well approximate the initial data on which it is based. It is likely that it would not be as good as the general model by which Q_{vm} could be estimated. Besides, the cross-correlation of the independent variables shown in Table 5 allows the rejection of independent variables. Testing the dependence of the productivity on the combination of the two studied properties already yielded a significantly small mean absolute deviation of the productivity calculated by the measured values. The smallest mean absolute deviation of productivity calculated using the two studied properties was obtained using the equation on the dependence of the productivity on the slew angle A_T and coefficient of uniformity of the heap particle size distribution n. The obtained results indicate that excavator productivity is highly dependent on the material granulometric properties. It can be assumed that equation (7) is the best model for estimating Q_{vm}.

5. Limitations and Future Directions

The limitations of this research are reflected primarily in the relatively small number of data based on which regression analyses were performed. Therefore, the reliability of the performed analyses is limited to the locations and conditions that prevailed at the quarry locations where the measurements were performed. However, despite the relatively low reliability, the analyses showed trends that should be confirmed by future research at more quarry sites. Future research should be improved by more precise measurement of the operating parameters of the excavator, which especially refers to the angle of rotation and the trajectory of the bucket. In addition, when calculating excavator productivity, bucket fill factors taken from excavator manufacturer tables were used. In future research, this should be tested by weighing the mass of material in the excavator bucket using suitable real-time sensors.

6. Conclusions

The primary factors that influence excavator's performance and productivity are the volume of the bucket load and duration of the excavator loading cycle. The excavator cycle time is mainly affected by the bucket fill time and swing angle. A larger swing angle causes a longer cycle time and thus lower productivity.

According to the conducted analyses, the granulometric composition of the material has a major influence on the productivity of the excavator. Materials with larger angles of repose result in an increase in the bucket fill factor. Calculation of the production rate according to ISO standards is more accurate for materials with higher angles of repose while the CECE standard is more appropriate for materials with lower values of the angle of repose. Furthermore, it was found that the swell factor and bucket fill factor are inversely proportional.

Larger amounts of fine particles in granular materials with higher coefficients of uniformity result in an increase in the volume of the bucket load and greater excavator productivity. Therefore, rock blasting fragmentation is directly related to the performance of the loading equipment in open pit mining applications.

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