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DETERMINATION OF OPTIMUM TRUCK NUMBER AT OPEN COAL QUARRY

Optimum truck numbers of an enterprise can be found by dividing the period of time passed between a departing truck after loading, the arrival at the dumping location, the arrival at the point of loading again and the average loading time parameters of a truck. The average loading time of the truck is directly associated with the bucket fill factor and cycle time of the excavator. While the bucket fill factor depends on the mechanical strength and the discontinuity characteristics of the rock, the cycle time is related to bucket volume, the strength and the discontinuity characteristics of the rock. In this study, two relations predicting the average cycle time of the bucket fill factor for both hydraulic and electric excavators is done by seven excavators with different bucket volumes, and mass characteristics of eight different rocks from a coal open pit mine. According to the above, the optimum truck number was developed.

Keywords: Optimum truck number, excavator, rock mass characteristics

1. Introduction

Overburden and ore excavation-loading are intensively carried out in open quarry mining. The rocks of rigid formation are loosened through blasting, and then excavation-loading processes are carried out. However, for the rocks that have a soft characteristic, the excavation-loading operation is applied directly. The cost from the excavators and trucks at open quarry enterprises is approximately 50% of the open quarry operating cost [1,8]. The most important factor affecting the cost of excavation-loading is the waiting durations of the excavators and trucks during the operations. If the waiting period is short, not only will the production of the enterprise increase, but the production cost will also be reduced [1]. Researchers have carried out certain studies for being able to minimise these waiting times [3-7,9,10,12,17]. A transportation network can be

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established so that the available excavators and trucks will be automatically directed to each other. This will eliminate unnecessary waiting times during excavation-loading, resulting in a decrease in the number of trucks required at the enterprises [2,13]. The research carried out related to this subject are determined depending on simulation techniques.

In an open quarry enterprise, the trucks loaded by the excavators unload the material either to the overburden area or the ore dumping area, according to the type of material. The period of time passed from the departure of a truck after the loading to the dumping area and the arrival to the point of loading again, plus the average loading time of a truck, are very important parameters. Optimum truck number ensures that the excavators and the trucks will not wait. This can be obtained by dividing these durations by each other. The optimum truck number can be expressed by the following equation.

$$N_{t\,opt} = 1.2 * \frac{T_{d-a}}{T_1} \tag{1}$$

$N_{t\,opt}$ — the optimum number of truck (piece),
1.2 — safety factor,
T_{d-a} — the time between departure and arrival (sec.),
T_1 — loading time (sec.).

T_{d-a} value can be expressed by the following relation.

$$T_{d-a} = \frac{D}{St} * 3600 \tag{2}$$

D — dump distance (km.),
St — the average speed of truck (km./hour).

The zones for excavation, overburden or ore dumping areas are known beforehand in the production planning. Dump distance (*D*) is fixed at an open quarry enterprise and can be determined easily by the distance measuring technique. The average speed of the truck can be almost the same, provided that route (road slope, road condition, etc.), truck operator and truck type parameters are the same. This duration is the same unless the route and the types of trucks used are not changed. If the working experiences of the truck operators are the same, it can be ensured that the truck operator factor is fixed. Accordingly, if the average loading time of the truck is known, the optimum truck number can be determined for the overburden or the ore production.

The average loading time of the truck is an effective parameter when sending the trucks to the excavators automatically so that there is no waiting at loading. This is directly associated with the bucket fill factor and cycle time of the excavator. These parameters depend on the mechanical strength and the discontinuity characteristics of the rock being excavated [1,11,13-16]. The research is related to only rock mass characteristics of the excavation area. However, excavator bucket volume and truck chassis volume values also affect the loading time of a truck. While the value of mechanical strength of the rock and truck chassis volume are high, the loading time of a truck increase, they will decrease in cases with high excavator bucket volume and rock discontinuity characteristics. Therefore, the average loading time of a truck will vary depending on the mass characteristics of the rock being excavated, the excavator bucket volume, and the truck chassis volume accordingly.

$$T_1 = \frac{Vc * tc}{Vb * k} \tag{3}$$

Vc — truck chassis volume (m^3),
tc — cycle time of the excavator (sec.),
Vb — excavator bucket volume (m^3),
k — bucket fill factor of excavator.

The cycle time (tc) value can be written by the following relation:

$$tc = td + tf + tdu + te \tag{4}$$

td — digging time of excavator,
tf — filled swing time of excavator,
tdu — dumping time of excavator,
te — empty swing time of excavator.

During the excavating, the filled swing time, dumping time and empty swing time of the excavator will have the same value as the average. Here, the average swing angle parameter has to be provided with the same value. However, the digging time of the excavator varies depending on the bucket volume of the excavator, mechanical strength of the rock and rock discontinuity characteristics. Thus, the cycle time of the excavator will also depend on the bucket volume of the excavator, mechanical strength of the rock and rock discontinuity characteristics. Besides this, the bucket fill factor (k) is directly related to the mechanical strength of the rock and rock discontinuity characteristics.

In this study, two relations predicting the average cycle time of the bucket fill factor for excavators is done by seven excavators with different bucket volumes, and mass characteristics of eight different rocks from a coal open pit mine. According to the above, the optimum truck number was developed for hydraulic and electrically operated excavators. Through this, the optimum truck number will ensure that the excavators and the trucks do not wait at the open quarry enterprises that are carrying out direct excavation operations. In previous studies on the subject, the minimisation of the excavators and trucks waiting times were provided with the transportation network. These studies have been based on theoretical data only. However, with this study, the waiting times aforementioned were considerably reduced by using real data.

2. The information about the working area and the trucks – the excavators used in the tests

Tests were carried out at G.E.L.İ. (Southern Aegean Lignite Enterprises) located in Yatağan District, Muğla Province, Turkey. Study tests were conducted at eight different sites. Since these sites have a soft formation, direct excavation processes have been carried out in all of them. Four of them do not include any discontinuity characteristics, and one of them contains neither discontinuity nor rock strength characteristic because the tests in this site have been conducted in the coal stocking zone. However, in the remaining three other sites, both discontinuity and rock strength characteristics exist. The sites were numbered so that they are not confused with each other (Table 1).

TABLE 1

The properties of study sites

The number of study sites	The properties of study sites
1	It has not any discontinuities but has rock strength
2	It has not any discontinuities but has rock strength
3	It has not any discontinuities but has rock strength
4	It has not any discontinuities but has rock strength
5	It has both discontinuities and also rock strength
6	It has both discontinuities and also rock strength
7	It has both discontinuities and also rock strength
8	It has neither discontinuities nor rock strength

Seven excavators with different bucket volumes have been used in the study. Two of them are electric excavators with a flat bucket, and five of them are backhoe hydraulic excavators. Truck chassis volume values are 36 and 88.88 m^3. Each of them was named according to either the bucket or truck chassis volumetric values. This prevents the excavators and the trucks from being confused with each other (Table 2).

TABLE 2

The properties of excavator and truck used in the tests

Excavator type	Excavator bucket volume (m^3)
Flat bucket electric excavator	11.48
Flat bucket electric excavator	7.65
Backhoe type hydraulic excavator	3.98
Backhoe type hydraulic excavator	6.80
Backhoe type hydraulic excavator	5.00
Backhoe type hydraulic excavator	6.00
Backhoe type hydraulic excavator	2.90

3. Field and laboratory studies

Information in Table 3 shows excavator type, study site and truck type that correlate to one another. While the average number of bucket cycles required to fill a truck was recorded by observation, the average cycle times of the excavator during the digging were determined by a chronometer in a sensitive manner in the study areas. Table 4 shows this information.

TABLE 3

The information of study sites place of excavators and trucks

The number of study site	Excavator bucket voume (m^3)	The truck chassis volume (m^3)
1	**2**	**3**
1	11.48	36.00
2	11.48	36.00

1	2	3
3	11.48 / 7.65 / 3.98 / 6.80 / 6 11.48 / 7.65 / 3.98 / 6.80 / 6	36.00
4	11.48 / 7.65 / 3.98 / 6.80 / 2.9	36.00
5	5 / 6	36.00
6	5 / 6 / 2.9	36.00
7	6 / 2.9	36.00
8	11.48 / 7.65 / 5 / 6	88.88

TABLE 4

The information of the average data measured

The number of study site	**The average number of bucket cycle required to fill a truck measured (piece)**	**The average cycle time of an excavator (sec.)**	**The average loading time of a truck, (sec./truck)**	**The volume of truck chassis, (m^3/truck)**
For 11.48 m^3 excavator				
1	3.34	30.74	102.55	36
2	4.42	30.44	134.44	36
3	3.56	32.53	115.92	36
4	3.45	31.21	107.55	36
8	7.74	31.05	240.42	88.88
For 7.65 m^3 excavator				
3	5.35	25.40	135.85	36
4	5.17	24.68	127.65	36
8	11.62	25.41	295.22	88.88
For 3.98 m^3 excavator				
3	11.17	18.28	204.15	36
4	10.90	17.02	185.44	36
For 6.80 m^3 excavator				
3	6.62	23.90	158.18	36
4	6.38	23.55	150.22	36
For 5 m^3 excavator				
5	7.27	21.39	155.55	36
6	7.58	22.09	167.44	36
8	17.78	20.95	372.48	88.88
For 6 m^3 excavator				
3	7.41	22.09	163.66	36
5	6.00	23.81	142.86	36
6	6.32	25.05	158.22	36
7	6.98	25.30	176.54	36
8	14.81	23.12	342.45	88.88
For 2.9 m^3 excavator				
4	14.96	15.75	235.58	36
6	13.07	17.00	222.12	36
7	14.27	17.23	245.78	36

The important parameters here are filling ratios of a truck, experience of excavator operator, and manufacture year of the excavators. The parameters in the realised tests were provided with the same conditions. Besides this, the average swing angle parameter has to be a 90 degree of value.

The discontinuity characteristics exist only in the sites numbered 5, 6, and 7 among the investigation areas. The discontinuities there become apparent as cracks. Therefore, the line survey method has been used for determining the discontinuity characteristics. The mm-division measuring tape has been utilised for being able to perform the line measurement. The line survey is a method where statistically most satisfactory results are obtained in the collection of the data related to the characteristics of the discontinuities and the rock masses. Distance values per crack have been calculated for each site being excavated by measuring the crack distance values of the sites using a measuring tape (Table 5).

TABLE 5

The properties of the average discontinuities interval belong to the study sites

The number of study site	**The average distance measurement (cm)**	**The average number of cracks (piece)**	**The average discontinuities interval of digging surface (cm/crack)**
5	1000	45	22
6	1000	23	43
7	1000	14	68

Samples were taken from each study site where the tests are carried out, and uniaxial compressive strength values were determined by carrying out many tests in the rock mechanics laboratory. Table 6 gives average, standard deviation, and test numbers belonging to the said test.

TABLE 6

Average uniaxial compression strength of the studied material

Study site	**The average uniaxial compressive strength, (MPa)**	**Number of tests (piece)**
1	2.70±0.3	16
2	6.80±0.4	13
3	4.81±0.3	18
4	3.60±0.2	11
5	5.30±0.2	12
6	6.90±0.2	15
7	8.30±0.2	11
8	—	—

4. Evaluation

The average bucket fill factor was calculated for each test. We can obtain the number of bucket cycles required to fill a truck when the chassis volume and the bucket volume parameters are divided by each other. In this situation, the bucket fill factor will be 100%. When we divide this value by the average number of bucket cycles required to fill a truck, we will provide the average bucket fill factor (Table 7).

TABLE 7

The data used to calculate the bucket fill factor

The number of study site	The truck chassis volume, (m^3/truck)	The bucket volume, (m^3)	The number of bucket cycles required to fill a truck when the bucket fill factor 100% (piece)	The average number of bucket cycles required to fill a truck measured (piece)	The average bucket fill factor (%)
For 11.48 m^3 excavator					
1	36	11.48	3.14	3.34	94
2	36	11.48	3.14	4.42	71
3	36	11.48	3.14	3.56	88
4	36	11.48	3.14	3.45	91
8	88.88	11.48	7.74	7.74	100
For 7.65 m^3 excavator					
3	36	7.65	4.71	5.35	88
4	36	7.65	4.71	5.17	91
8	88.88	7.65	11.62	11.62	100
For 3.98 m^3 excavator					
3	36	3.98	9.05	11.17	81
4	36	3.98	9.05	10.90	83
For 6.80 m^3 excavator					
3	36	6.80	5.29	6.62	80
4	36	6.80	5.29	6.38	83
For 5 m^3 excavator					
5	36	5.00	7.20	7.27	99
6	36	5.00	7.20	7.58	95
8	88.88	5.00	17.78	17.78	100
For 6 m^3 excavator					
3	36	6.00	6.00	7.41	81
5	36	6.00	6.00	6.00	100
6	36	6.00	6.00	6.32	95
7	36	6.00	6.00	6.98	86
8	88.88	6.00	14.81	14.81	100
For 2.9 m^3 excavator					
4	36	2.9	12.41	14.96	83
6	36	2.9	12.41	13.07	95
7	36	2.9	12.41	14.27	87

As it is known from the literature, the rock strength and the discontinuity properties of the excavation surface and bucket volume of the excavator affect the cycle time of the excavator considerably. The relation predicting the average cycle time has been formed by using the uniaxial compressive strength, the discontinuity interval (cm/crack), bucket volume values (Eq. (5)). Here, while uniaxial compressive strength is used to represent the rock strength, the discontinuity interval is used to represent the discontinuity properties. Besides this, the relation prediction of the bucket fill factor has been provided by using the uniaxial compressive strength and the discontinuity interval (cm/crack) values (Eq. (6)). These relations have been calculated primarily for backhoe hydraulic excavators. The data used in the formation of the relation are in Table 8. Then the equations established have been interpreted for flat bucket electrically operated excavators. Since the tests at the 8th study site have been carried out at the coal stocking area, the uniaxial compressive strength and the discontinuity interval values of this site is taken as zero. Only the study sites numbered 5, 6, and 7 contain the discontinuity interval (cm/crack) among the study sites. Therefore, the discontinuity interval values of other study sites have been determined to be approximately 1000 cm/crack.

$$tc = (9.47) + (2.26 * Vb) + (0.206 * \sigma) - (0.00172 * j) \tag{5}$$

$$k = (102) - (1.18 * \sigma) - (0.0153 * j) \tag{6}$$

tc — the average cycle time (sec.),
Vb — excavator bucket volume (m^3),
σ — the average uniaxial compressive strength (MPa),
j — discontinuity interval of digging surface (cm/crack),
k — the bucket fill factor.

9.47 value in Eq. (5) represents filled swing time (*tf*), dumping time (*tdu*) and empty swing time of the excavator (*te*)'s total values are determined in Eq. (4). This relation is seen in Eq. (7).

$$9.47 = tf + tdu + te \tag{7}$$

When we examine the relation for predicting the cycle time of the excavator in Eq. (5), we see that cycle time and discontinuity interval of the digging surface parameters are inversely proportional to the coefficient of 0.00172. However, they should be directly proportional, and the cycle time and bucket fill factor depend on each other. Furthermore, the discontinuity interval parameter is not only related to the cycle time but to the bucket fill factor. Thus, we see that the relation for predicting the bucket fill factor in Eq. (6) is that the effect of the discontinuity interval parameter is a very high coefficient of 0.0153.

TABLE 8

The data used for equation 5 and 6

The number of study site	**The average cycle time of the excavator, (sec.)**	**The bucket fill factor (%)**	**The bucket volume, (m^3)**	**Average uniaxial compressive strength, (MPa)**	**Discontinuities interval of the digging surface (cm/crack)**
1	**2**	**3**	**4**	**5**	**6**
For 3.98 m^3 excavator					
3	18.28	81	3.98	4.81	1000
4	17.02	83	3.98	3.60	1000
For 6.80 m^3 excavator					
3	23.90	80	6.80	4.81	1000
4	23.55	83	6.80	3.60	1000
For 5 m^3 excavator					
5	21.39	99	5.00	5.30	22
6	22.09	95	5.00	6.90	43
8	20.95	100	5.00	0	0

1	2	3	4	5	6
For 6 m^3 excavator					
3	22.09	81	6.00	4.81	1000
5	23.81	100	6.00	5.30	22
6	25.05	95	6.00	6.90	43
7	25.30	86	6.00	8.30	68
8	23.12	100	6.00	0	0
For 2.9 m^3 excavator					
4	15.75	83	2.9	3.60	1000
6	17.00	95	2.9	6.90	43
7	17.23	87	2.9	8.30	68

The average cycle time and the bucket fill factor values for the hydraulic excavators with different bucket volumes were estimated using Eqs (5), (6) and compared with the real values (Table 9, 10). Also, from Table 9 and 10, the margins of error are limited between the estimated values and the real values.

It is considered that the equation determined would not be suitable for the excavator of a different type. As the electrically operated excavators are heavier than the hydraulic excavators, it is expected to excavate more rapidly than the hydraulic excavators under the same conditions. This is because the heavy excavator will excavate in a shorter time period and has a higher bucket fill factor. From this point of view, the cycle times of these excavators are assumed to be shorter. Thus, the relations for predicting the cycle time and the bucket fill factor for electric excavators were developed as shown in Eqs (8) and (9).

$$tc = 0.92*\left[(9.47)+(2.26*Vb)+(0.206*\sigma)-(0.00172*j)\right] \quad (8)$$

$$k = 1.1*\left[(102)-(1.18*\sigma)-(0.0153*j)\right] \quad (9)$$

TABLE 9

Comparison of cycle time of the hydraulic excavator during excavating measured and calculated

The number of study site	The average cycle time of the excavator, measured (sec.)	The average cycle time of the excavator calculated according to Eq. (5) (sec.)	Error, %
1	2	3	4
For 3.98 m^3 excavator			
3	18.28	17.74	2.99
4	17.02	17.49	2.76
For 6.80 m^3 excavator			
3	23.90	24.11	0.86
4	23.55	23.86	1.31
For 5 m^3 excavator			
5	21.39	21.82	2.04
6	22.09	22.12	0.11
8	20.95	20.77	0.88

1	2	3	4
For 6 m^3 excavator			
3	22.09	22.30	0.94
5	23.81	24.08	1.15
6	25.05	24.38	2.69
7	25.30	24.62	2.69
8	23.12	23.03	0.38
For 2.9 m^3 excavator			
4	15.75	15.05	4.48
6	17.00	17.37	2.19
7	17.23	17.62	2.27

TABLE 10

Comparison of bucket fill factor of hydraulic excavator during excavating measured and calculated

The number of study site	**The average bucket fill factor of the excavator, measured (%)**	**The average bucket fill factor of the excavator calculated according to Eq. (6) (%)**	**Error, %**
For 3.98 m^3 excavator			
3	81	81.0	0.03
4	83	82.5	0.66
For 6.80 m^3 excavator			
3	80	81.0	1.28
4	83	82.5	0.66
For 5 m^3 excavator			
5	99	95.4	3.63
6	95	93.2	1.89
8	100	102.0	2.00
For 6 m^3 excavator			
3	81	81.0	0.03
5	100	95.4	4.59
6	95	93.2	1.89
7	86	91.2	6.01
8	100	102.0	2.00
For 2.9 m^3 excavator			
4	83	82.5	0.66
6	95	93.2	1.89
7	87	91.2	4.79

Average cycle times of excavation are estimated for electrically operated excavators by using Eq. (8) are given in Table 11. Examining Table 11, the values estimated for the excavators are very close to the real values. The average bucket fill factor values for the electric excavators were estimated by using Eq. (9) and compared with the real values (Table 12). Examining Table 12, the values estimated for the excavators are very close to the real values except for the second test with a 21.89% error. It is thought that this situation is caused due to the data collection conditions.

TABLE 11

Comparison of cycle time of electric excavator measured and calculated

The number of study site	The average cycle time of the excavator, measured (sec.)	The average cycle time of the excavator calculated according to Eq. (8) (sec.)	Error, %
For 11.48 m^3 excavator			
1	30.74	31.51	2.51
2	30.44	32.29	6.08
3	32.53	31.91	1.90
4	31.21	31.68	1.51
8	31.05	32.58	4.92
For 7.65 m^3 excavator			
3	25.40	23.95	5.73
4	24.68	23.72	3.91
8	25.41	24.62	3.12

TABLE 12

Comparison of bucket fill factor of electric excavator during excavating measured and calculated

The number of study site	The average bucket fill factor of the excavator, measured (%)	The average bucket fill factor of the excavator calculated according to Eq. (9) (%)	Error, %
For 11.48 m^3 excavator			
1	94	91.9	2.27
2	71	86.5	21.89
3	88	89.1	1.28
4	91	90.7	0.33
8	100	102.0	2.00
For 7.65 m^3 excavator			
3	88	89.1	1.28
4	91	90.7	0.33
8	100	102.0	2.00

When we combine Eqs (2), (3), (5) and (6) with Eq. (1), the optimum truck number for the hydraulic excavator will ensure that the excavators and the trucks do not wait and can be calculated using Eq. (10).

$$N_{t\ opt} = 1.2 * \frac{\frac{D}{St} * 3600}{\frac{Vc * \left[(9.47) + (2.26 * Vb) + (0.206 * \sigma) - (0.00172 * j) \right]}{Vb * \left[(102) - (1.18 * \sigma) - (0.0153 * j) \right]}} \tag{10}$$

When we combine Eqs (2), (3), (8) and (9) with Eq. (1), the optimum truck number for the electric excavator will ensure that the excavators and the trucks do no wait and can be calculated by Eq. (11).

$$N_{t\,opt} = 1.2 * \frac{\frac{D}{St} * 3600}{\frac{Vc * 0.92 * \left[(9.47) + (2.26 * Vb) + (0.206 * \sigma) - (0.00172 * j)\right]}{Vb * 1.1 * \left[(102) - (1.18 * \sigma) - (0.0153 * j)\right]}} \tag{11}$$

Mining enterprises that carry out the overburden and the ore excavation can determine the required optimum truck number using the equations obtained by the bucket and truck chassis volume, the uniaxial compressive strength, and the discontinuity characteristics of the rock. Thus, ensuring a reduction in production costs.

5. Results

In this study, a relation has been developed for determining the optimum truck number that will ensure that the excavators and the trucks do not wait at open quarry enterprises, allowing them to carry out direct excavation operations. In determining the relation, the period of time passed from the departure of a truck after loading, to the dumping area, to the arrival point, back to loading again, and the average loading time of a truck have all been used as parameters. The first parameter can be easily calculated by the enterprise. However, the second parameter depends on the bucket fill factor and cycle time of the excavator. The bucket fill factor depends on the mechanical strength and the discontinuity characteristics of the rock and the cycle time is related to the bucket volume, the strength and the discontinuity characteristics of the rock. Two relations predicting the average cycle time of an excavator and bucket fill factor is done by using seven excavators with different bucket volumes and mass characteristics of eight different rocks from a coal open pit mine. Thus, allowing for the optimum truck number to be developed. The said relation was developed for hydraulic excavators and then was applied for electrically operated excavators. A result of the study showed that the discontinuity interval of the rock is also effective. Considering the equations developed for the hydraulic excavator, the largest margin of error in calculating the average cycle time of the excavator was 4.48%, the largest margin of error in calculating the average bucket filling factor of the excavator was 6.01%. When we consider the same situation for electric excavator, the largest margin of error in calculating the average cycle time of the excavator was 6.08%. Finally, the largest margin of error in calculating the average bucket filling factor of the excavator was 21.89%.

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