Economic evaluation of optimum bench height in quarries

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Synopsis

In this research, a model quarry with an annual production capacity of 1 000 000 tonnes has been studied for both pit and hillside quarry cases with constant overall slope angle and variable bench slope angle, considering road grades of 8 per cent and 10 per cent. First, technical requirements have been determined and then the effect of production parameters, such as hole diameter, type of quarrying (pit or hillside) and road grade, on the cost has been investigated to determine bench height.

Based on the results, it has been concluded that hole diameter has to be kept large in both pit and hillside quarrying to reduce drilling unit costs. In addition, in order to take advantage of gravity and reduce transportation cost, it has been suggested that bench height and road grade have to be kept high and low respectively in the case of hillside quarrying (downhill transportation) while, in the case of pit quarrying (uphill transportation), bench height and road grade have to be kept low and high respectively, in order to transport the blasted material to a lower height and distance, to save energy, thus decreasing the transport cost.

Keywords: Quarry, pit, hillside, road grade, bench height

Introduction

Ballast (fine crushed stone) is known as a significant input in the building and construction businesses. Worldwide annual ballast production is 2.15 billion tons. The majority of this has been produced by quarrying. In Turkey, annual production of 35 million tonnes, which amounts to 1.62 per cent of total world ballast production, has been extracted in quarries. In order to reduce the cost in this sector, quarry bench height and other related production parameters must be assessed carefully.

The determination of economical bench height may vary with the types of machinery and equipment being used, topography, environmental conditions, operation plans, etc. Moreover, bench height is closely related to the unit cost of the product. To maintain the cost at an optimum level, determining an economical bench height has to be based on individual economic assessments of quarrying operations followed by the consolidation of individual assessments. Basic quarrying operations consist of blast hole drilling, blasting, loading and transportation. However, other parameters besides bench height, such as rock properties, blast hole diameter, bench geometry, type of explosives being used, size of fragmented rock, loading and transportation equipment, road grades and road stability, etc. directly or indirectly influence the determination of the unit cost of the product.

Previous study

Based on the studies conducted in 1970s, an economical bench height has been suggested to be 12 m (Lechner, 1971). Today, bench height can be designed up to 15 m in large quarries, while it can be 12 m in small ones. Moreover, in small open pit gold mines it is feasible to design bench heights up to 7.5 m since it requires selective mining and the achievement of less dilution (Hustrulid and Kuchta, 1998).

When planning an economical bench height, it has been underlined that drilling speed and penetration rate influence drilling cost. Therefore, blasting operation, which amounts to 20–25 per cent of total unit cost, is considered to be one of the important parameters.

Parameters that have an effect on a safe and successful blast from an economical standpoint can be listed as follows (Atlas Powder, 1986; Bilgin and Pasamehmetoglu, 1993; Dick, 1983; Hock and Bray, 1991; Konya and Walter, 1990; Olofsson, 1988):

- ➤ Mass and material properties of rocks
- ➤ Type, properties and distribution of the explosives being used
- ➤ Overall blast geometry.

The effect of degree of fragmentation after

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detonation on the unit cost is illustrated in Figure 1 (Hustrulid, 1999).

A common concept among researchers reveals that in a blasting operation, other design parameters can be calculated as a function of powder factor and burden thickness based on admissible assumptions (Arioglu, 1990; Langefors and Kihlstrom, 1978; Olofsson, 1988;). Researchers agree that other parameters can be expressed as a function of overburden thickness when determined (Atlas Powder Company, 1986; Gustaffson, 1973; Konya and Walter, 1990; Olofsson, 1988). In this model study, the following relationship in defining overburden thickness has been used:

$$B(m) = d(inch)$$

where, B is burden and d is hole diameter.

Some researchers assume the distance between the blast holes to be a simple spacing between the two holes aligned in the same row, while some researchers define the distance as a delay gap between two adjacent blast holes (Atlas Powder Comp, 1986; Dick, 1983; Langefors and Kihlstrom, 1978). Researchers have suggested certain tolerance values for blast hole error margins (Gustafsson, 1973; Langefors and Kihlstrom, 1978; Naapuri, 1988). In this model study, Olofsson's relationship (Olofsson, 1988) has been employed to determine the spacing between the blast holes and blast hole error margins.

$$E = (d/1000) + 0.03 \times H$$

where E is tolerance value for blast hole error, d is hole diameter and H is bench height.

According to this relationship, an increase in blast hole error margins in long blast holes causes a reduction in practical overburden thickness.

Researchers have assumed, as a result of the studies on charge length and its effects, that charge length varies as a function of burden thickness (Hoek and Bray,1990; Konya and Walter, 1990; Langefors and Kihlstrom, 1978; Gustafsson, 1973; Olofsson, 1988). In this model study, since the powder factor has been varied between 0.24 and 0.66 kg/m^3 for various bench height and hole diameters and because the increasing uncharged part of the hole and bench heights charge lengths have been determined between 0.5 H and 0.91 H depending on increasing blast hole lengths.

For a successful detonation, it is suggested that primer diameter should be equal to charge diameter and primer length should be 2–4 times of the charge diameter (Olofsson, 1988; Hustrulid, 1999). When determining the length of subdrill, researchers have considered subdrill length as a function of burden thickness (Dick, 1983; Hoek and Bray, 1991; Konya, 1990; Naapuri, 1988; Olofsson, 1988; Langefors and Gustafsson, 1973).

In general, bench height depends on the boom length and the bucket capacity of the loader (Hustrulid and Kutcha, 1998). In the process of loading, size of fragmented material and loading cycle-time become essential to the cost (Doktan, 2001). Selecting the most suitable equipment for transportation becomes an important factor that affects the cost (Erçelebi and Engin, 1999; Morgan, 2000; Peterson and Ozdogan, 2001). The process of transportation consists of dynamic variables such as condition and grade of the roads, performance of the trucks, etc. Condition of the road implies constantly changing parameters such as transportation distance, maximum allowed speed, stability and rolling resistance of the road. Each of these parameters influences the transportation cycle-time for a truck (loaded and unloaded trips) and indirectly causes effects on the consumption of fuel, oil, hydraulics and furthermore on the economical life of equipment being used (Kose *et al.*, 2000). In general, the distribution of unit cost in a surface mine is demonstrated in Figure 2 (Goergen, 1987), which was used for checking the model study.

Model study

In this model study, a quarry designed for an annual production capacity of 1 000 000 tons has been studied separately for both pit and hillside cases. In both cases, unit cost analyses were carried out for bench heights of 10, 12.5, 15, 20 and 25 metres and for each bench height, blast hole diameters of 89, 102, 115, 127 and 152 millimetres, as well as for road grades of 8 per cent and 10 per cent. Models for both quarries are shown in Figures 3 and 4.

Overall slope angle of the model quarry has been fixed at 36° for each bench height and a suitable slope angle for each bench in accordance with bench height has been determined.

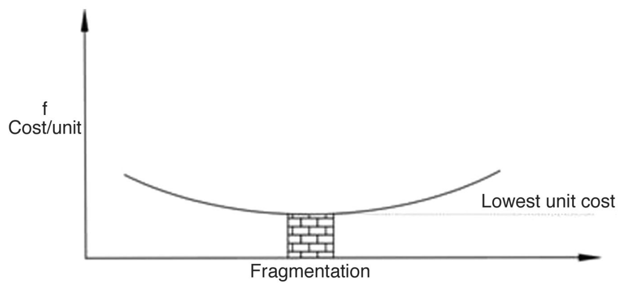

Figure 1—Effect of degree of fragmentation after detonation on the unit cost

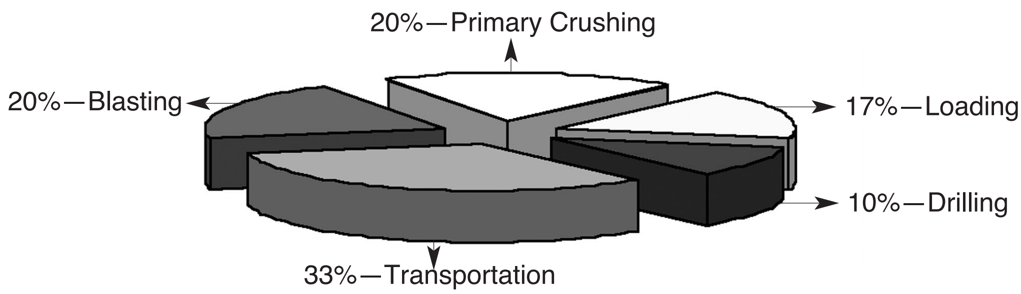

Figure 2—Distribution of the cost in a surface mine (%) (Georgen, 1987)

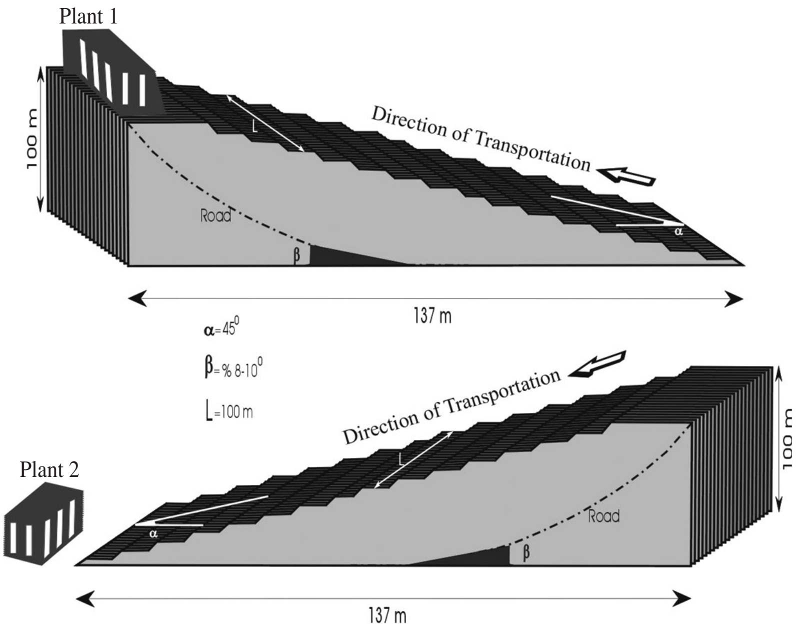

Figure 3—Model geometries for pit and hillside quarries

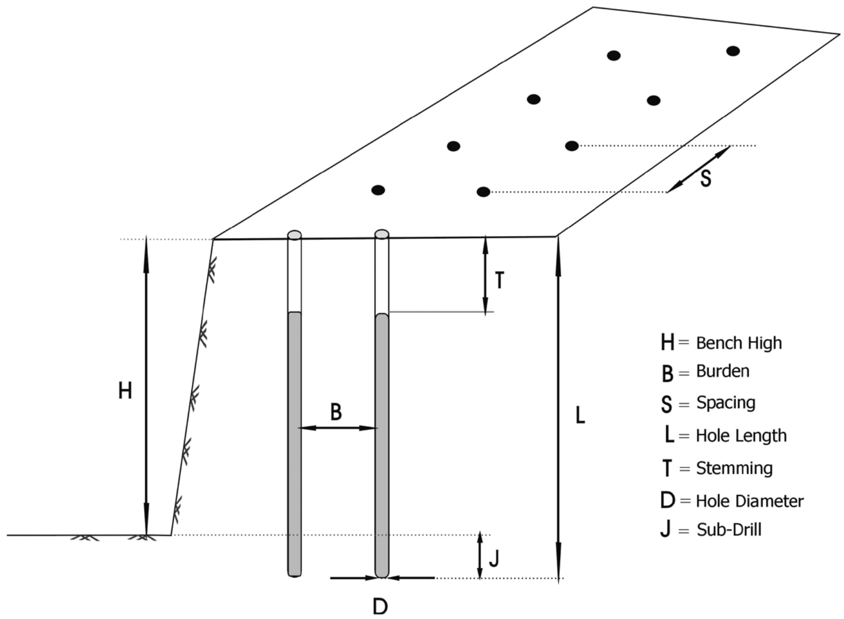

Figure 4—Blast hole geometry on a bench

Bench length and width have been chosen to be 100 m and 10 m respectively. In modeling, the number of benches varies with bench height and bench slope angle. In addition, the crusher facility has been situated at a distance of 100 m from the last bench for both quarry cases.

Drilling

A blast hole drill unit, which can drill holes in diameters of 89–152 mm with hourly drilling capacity of 30 m and productivity rate of 70 per cent, has been employed (Naapuri, 1988). The results of unit cost analyses for various bench heights and hole diameters are illustrated in Figure 5. As seen in Figure 5, the drilling unit cost is reduced as the hole diameter is increased and drilling unit cost increases with growing bench height.

Blasting

For the explosive material, 5 per cent Al added ANFO with a density of 0.9 kg/dm^3 has been proposed, assuming that all the blast holes are dry. The amount of primer has been considered to be 2 per cent of ANFO being used (Kose *et al.*, 2000). Electrical capsules with a delay time of 25 msec have been employed as initiators. In calculations, lengths of detonating cords have been kept 5 m longer than the depth of each blast hole (Kahriman, 2001). Unit prices for explosives elements are illustrated in Table I.

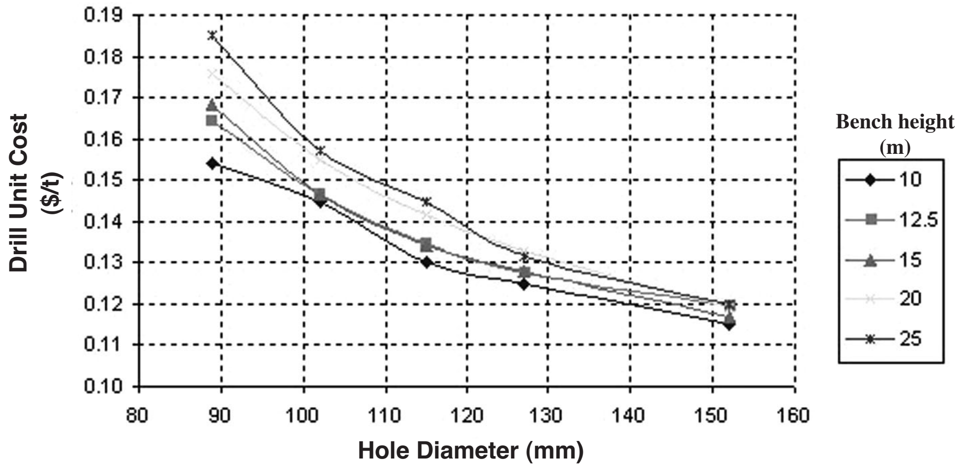

Figure 5—Variation of unit cost with hole diameter–bench height

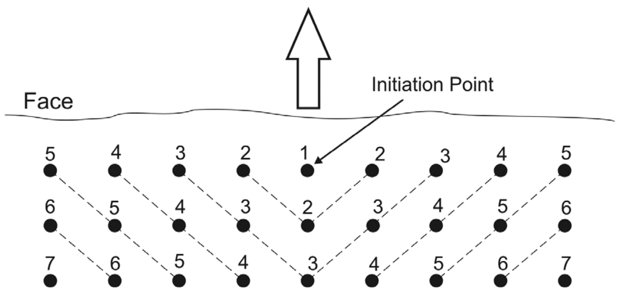

Figure 6—Drilling pattern and detonation sequence

Table I

Unit prices for explosives elements

Explosives elements	Unit price ($)
Anfo	0.55 $/kg
Dynamite	2 $/kg
Electrical capsule	1 $/unit
Connection cables	0.1 $/kg

Table II

Design parameters for various bench heights and hole diameters

Bench height (m)	Hole depth (m)	89 mm			102 mm			115 mm			127 mm			152 mm		
		Burden thickness (m)	Spacing between holes (m)	Powder factor (kg/m³)	Burden thickness (m)	Spacing between holes (m)	Powder factor (kg/m³)	Burden thickness (m)	Spacing between holes (m)	Powder factor (kg/m³)	Burden thickness (m)	Spacing between holes (m)	Powder factor (kg/m³)	Burden thickness (m)	Spacing between (m)	Powder factor (kg/m³)
10	11	3.10	3.88	0.3680	3.60	4.50	0.3358	4.05	5.06	0.3167	4.55	5.69	0.2840	5.50	6.88	0.2374
12.5	13.75	3.00	3.75	0.4278	3.50	4.38	0.3936	4.00	5.00	0.3644	4.45	5.56	0.3425	5.40	6.75	0.2991
15	16.50	2.90	3.63	0.4827	3.40	4.25	0.4442	3.90	4.88	0.4128	4.40	5.48	0.3839	5.35	6.69	0.3391
20	22	2.75	3.44	0.5698	3.20	4.00	0.5398	3.73	4.66	0.4922	4.20	5.25	0.4599	5.20	6.50	0.4057
25	27.5	2.60	3.25	0.6596	3.07	3.84	0.6097	3.60	4.50	0.5514	4.05	5.06	0.5213	5.00	6.25	0.4701

Important design parameters obtained in the result of calculations for hole diameters of 89, 102, 115, 127 and 152 millimetres are given in Table II. The hole pattern and detonation sequence used in the model study are given in Figure 6. As seen in Figure 6, a right-angled V pattern has been utilized on the benches so as to be blasted in 3 rows. For a better fragmentation, a separate delay time (25 m) was considered for each of the holes to create ample free surface for the material that is behind.

The decrease in burden thickness as the hole depth and bench height increases, as seen in Table II, can be explained by the hole error margin in the relationship developed by Olafsson (1988). The powder factor also increases with the hole depth as the uncharged part of the hole (stemming) is compared to the bench height in lower benches.

Blast unit cost values resulting from the cost calculations for various hole diameters for a quarry with an annual production capacity of 1 000 000 tons are demonstrated in Figure 7. In the result of cost analyses, the most economical bench height has been found to be 15 m. At the same time, the blast unit cost has been seen to diminish as the hole diameter grows. As the bench height goes up, unit cost appears to drop; however, for 20 m of bench height, because of the increase in priming, the unit cost tends to build up increase.

Loading and transportation

For the loading process, a front-end wheel loader with 2 m³ bucket capacity has been selected by taking the cost and capacity analyses and previous studies into account. For transportation processes, trucks of 25-tons capacity have been preferred because of their low initial investment and high employment in quarries (Aksoy, 1999; Aksoy, 2000). In order to determine operational expenses that influence the transportation unit cost, condition and grade of the road, truck-road interactions (road resistance, rolling resistance

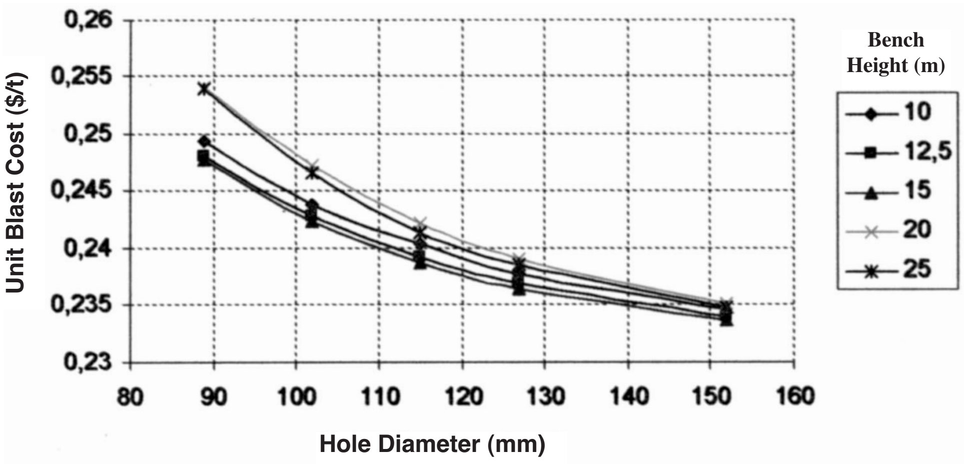

Figure 7—Unit blast cost analysis for bench height-hole diameter

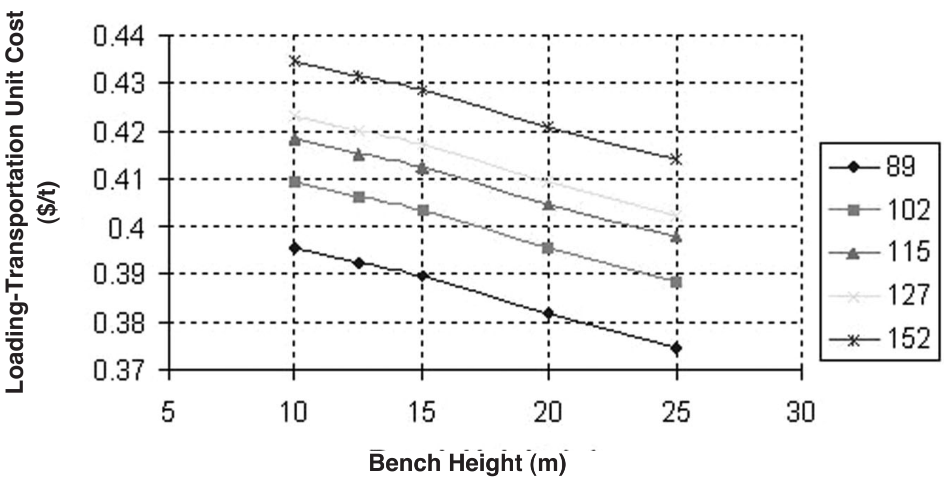

Figure 8—Results of loading-transportation unit cost analysis for a hillside quarry case with an annual production capacity of 1.000.000 tonnes and a road grade of 10 per cent

etc.), and loaded-unloaded trip durations for both pit and cast quarry cases have been included in the cost analyses. In Figures 8 through 11, results of loading-transportation unit cost analyses are illustrated for hillside and pit quarry cases with an annual production capacity of 1 000 000 tons for road grades of 8 per cent and 10 per cent.

In the case of hillside quarrying, the trend resulted in a decrease in loading-transportation unit cost as the bench height and hole diameter increased and an increase in unit cost as the road grade increased, while, in the case of pit quarrying, the trend resulted in an increase in unit cost as the bench height and hole diameter increased and loading-transportation unit cost grew as the road grade decreased.

Results and discussion

In a model quarry designed for 1 000 000 tonnes of annual production, total unit cost curves, which have been formed from various parameters, have been obtained by separately evaluating unit cost analyses for the various activities. According to the results, in the drilling process, drill unit cost has been found to decrease as the hole diameter and bench height increased. When unit blast cost is considered, the most economical bench height arrived at has been 15 m. Furthermore, it has been found that blast unit cost decreased as hole diameter grew larger.

In the process of loading and transportation, unit cost analyses have been performed for both hillside and pit quarry cases with road grades of 8 per cent and 10 per cent. It has been concluded from the results that bench height has to be kept high in the case of a hillside quarry and, on the contrary, bench height has to be kept low in the case of pit a quarry. It is well known that an increase in the size of fragmented material increases the work of loading-transporting. The process hole diameters in both hillside and pit quarry cases have been determined to be large, in a range of 127–152 millimetres. Road grade has been found to be a parameter in reducing the unit cost of loading-transportation work, so road grade has to be designed high in the case of a hillside quarry and low in the case of a pit quarry.

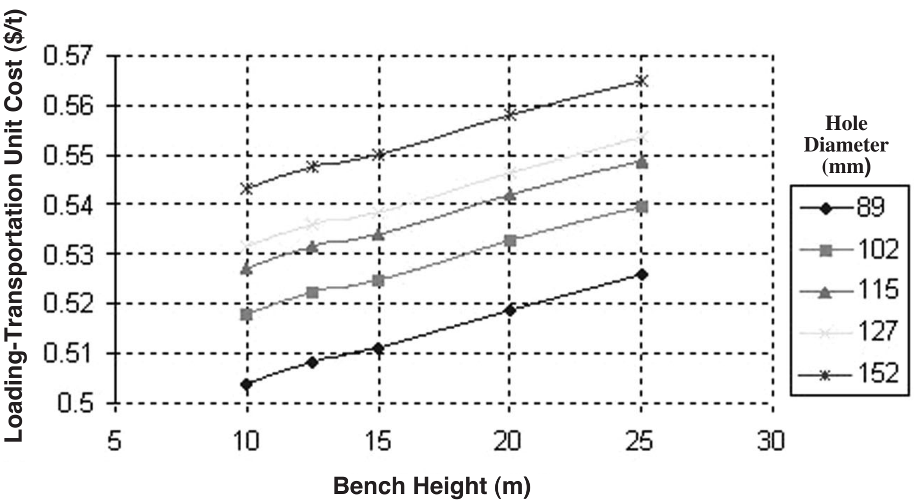

Figure 9—Results of loading–transportation unit cost analysis for a pit quarry case with an annual production capacity of 1 000 000 tons and a road grade of 10 per cent

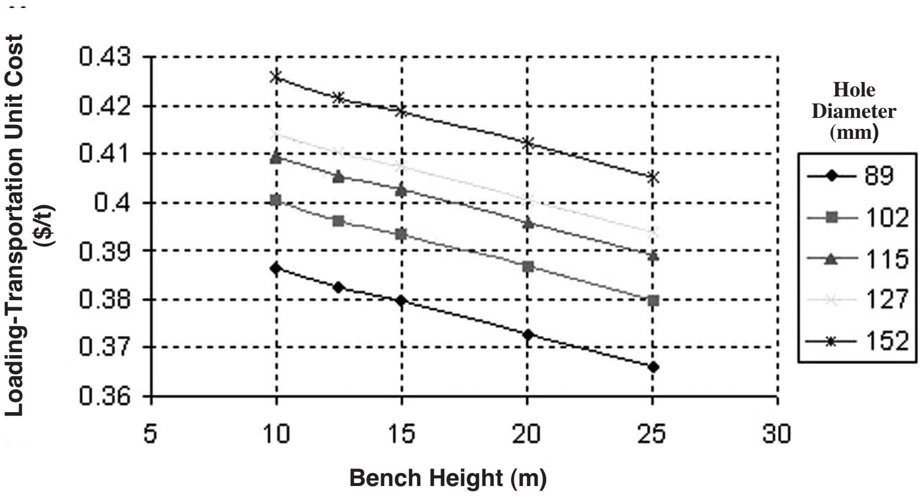

Figure 10—Results of loading–transportation unit cost analysis for a hillside quarry case with an annual production capacity of 1 000 000 tons and a road grade of 8 per cent

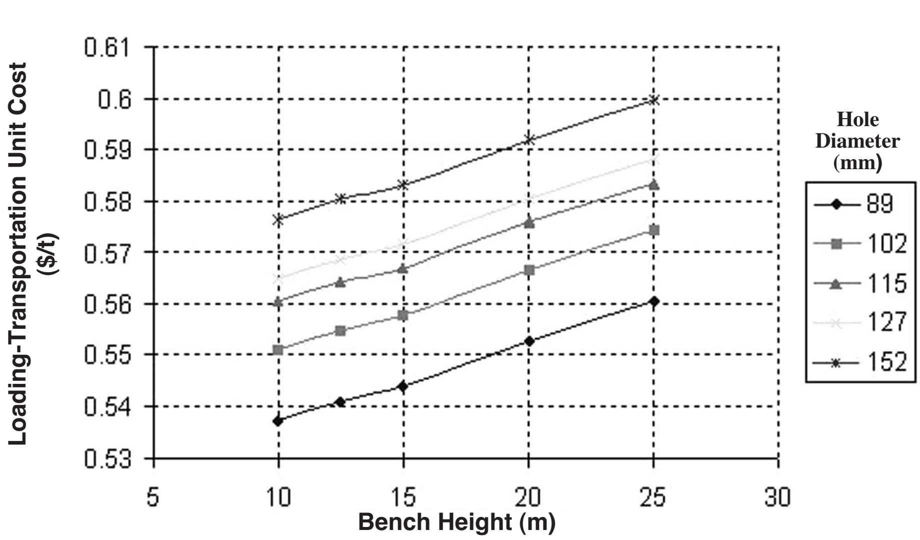

Figure 11—Results of loading–transportation unit cost analysis for a pit quarry case with an annual production capacity of 1 000 000 tonnes and a road grade of 8 per cent

Figures 12 through 15 demonstrate the values of total unit cost analyses attained by separate performances of unit cost analyses for a quarry model designed for 1 000 000 tons of annual production. The cost details obtained according to the model study are given in Table III. Since loading and transporting activities are simultaneous activities, they are considered as a whole. In Figure 16, the effect of each mining activity in terms of percentage over total unit cost for both pit and hillside quarrying is given for the most economical and least economical conditions. As seen from the Figure, the per cent effect of the loading and transporting unit cost in the total unit cost is lower in hillside quarrying than pit quarrying. The per cent influence of the drilling and blasting unit cost over total unit cost seems less in pit quarrying.

Conclusion

Unit cost analyses have been carried out in order to determine the most economical bench height in a model quarry designed for an annual production of 1 000 000 tons. The results pointed out that total unit cost has been discovered to decrease when the bench height is kept low and limited to 10 m in the case of pit quarry and, in contrast, a bench height is designed for higher values (up to 25 m), in the case of hillside quarry.

Also, hole diameter has been found to be an important parameter in determining the bench height. Results indicate that unit cost is reduced for shallow benches when the bench depth chosen is 10–12.5 m and hole diameter is 127 mm and, for higher benches when the bench depth chosen is 15-25 m and hole diameter is 152 m. In addition, unit cost has been found to decrease as long as the road grade is kept high in the case of a pit quarry and low in the case of a hillside quarry.

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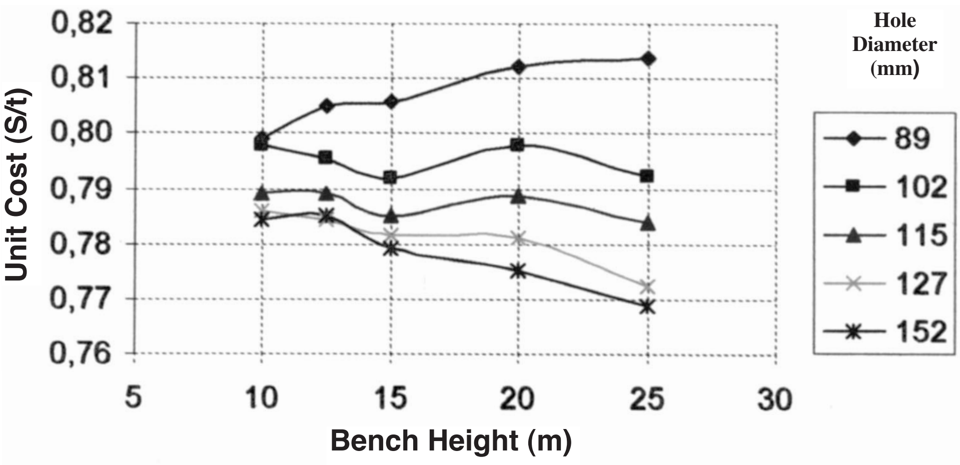

Figure 12—Results of total unit cost analyses for a hillside quarry case with a road grade of 10 per cent

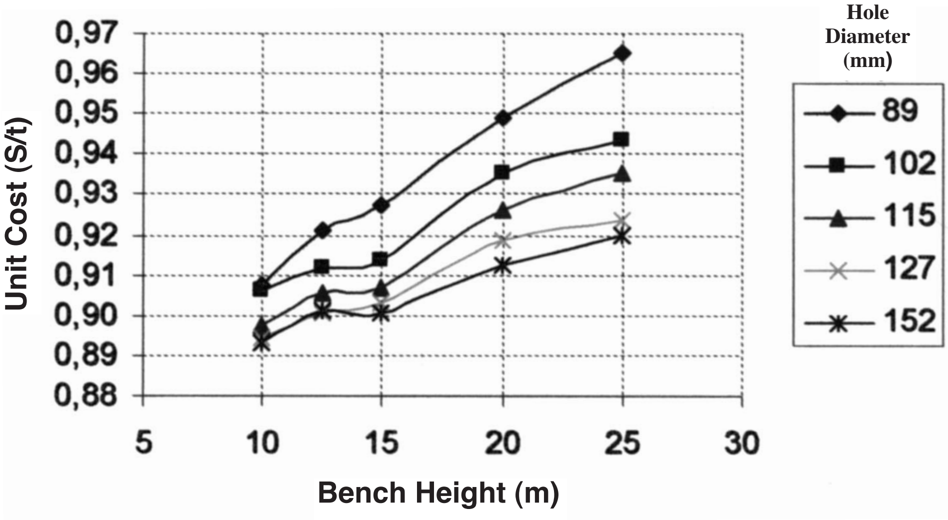

Figure 13—Results of total unit cost analyses for a pit quarry case with a road grade of 10 per cent

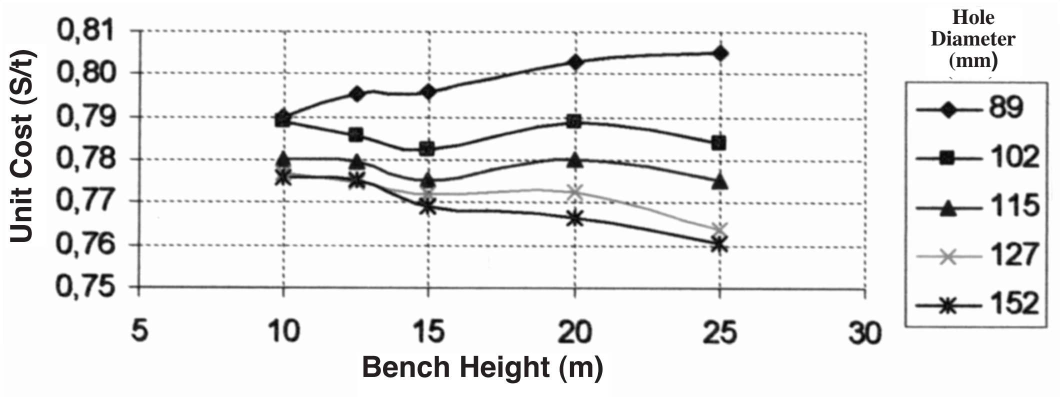

Figure 14—Results of total unit cost analyses for a hillside quarry case with a road grade of 8 per cent

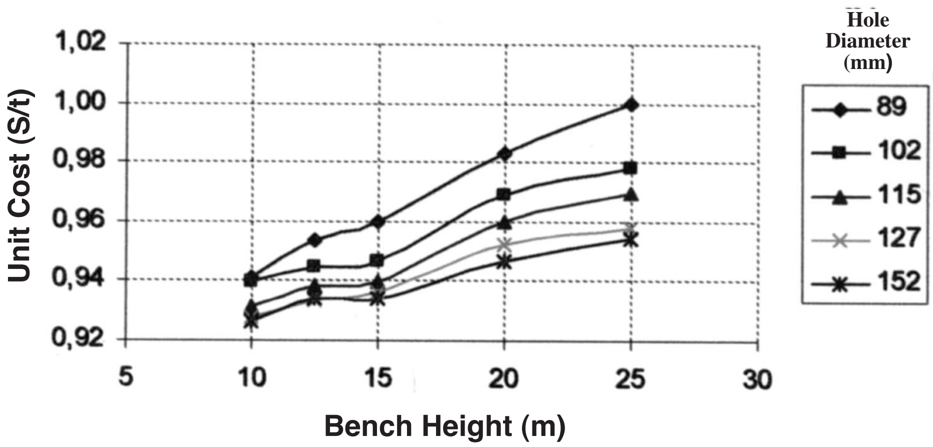

Figure 15—Results of total unit cost analyses for a pit quarry case with a road grade of 8 per cent

Table III

Annual and overall unit cost details

Material		Drilling		Blasting		Loading-transportation			
						Pit		Hillside	
		Min ($)	Max ($)	Min ($)	Max ($)	Min ($)	Max ($)	Min ($)	Max($)
Disposable materials	Shank rod	4356	18732	-		-		-	
	Extension rod	2783	11968			-		-	
	Bit	3068	13192			-		-	
	Extension bush	720	3097			-		-	
	Wheel	-	-			9846			
Repair and service cost	Engine	3236		-		114048			
	Hydraulic equipment	2261							
	Drifter	4379							
	Dust catcher	2889							
	Other	4771							
Operating cost	Fuel	8640	37152	-		315193	354591	228020	259410
	Lubricant	18838	20911	-		20390			
	Anfo	-		183154	183197	-			
	Dynamite	-		14665	14657	-			
	Cap	-		1865	10580	-			
	Cable	-		4009	15870	-			
Labour		7552		29847		51730	53133	44287	49145
Capital cost	Depreciation	30000		-		72485	72540	69460	70835
	Interest	16500		-		22667	23697	22003	22759
	Insurance	300		-		409	410	380	393
	Accident Insurance	6000		-		8197	8208	7592	7867
Unit cost ($/t)		0.116	0.183	0.233	0.254	0.615	0.657	0.516	0.554

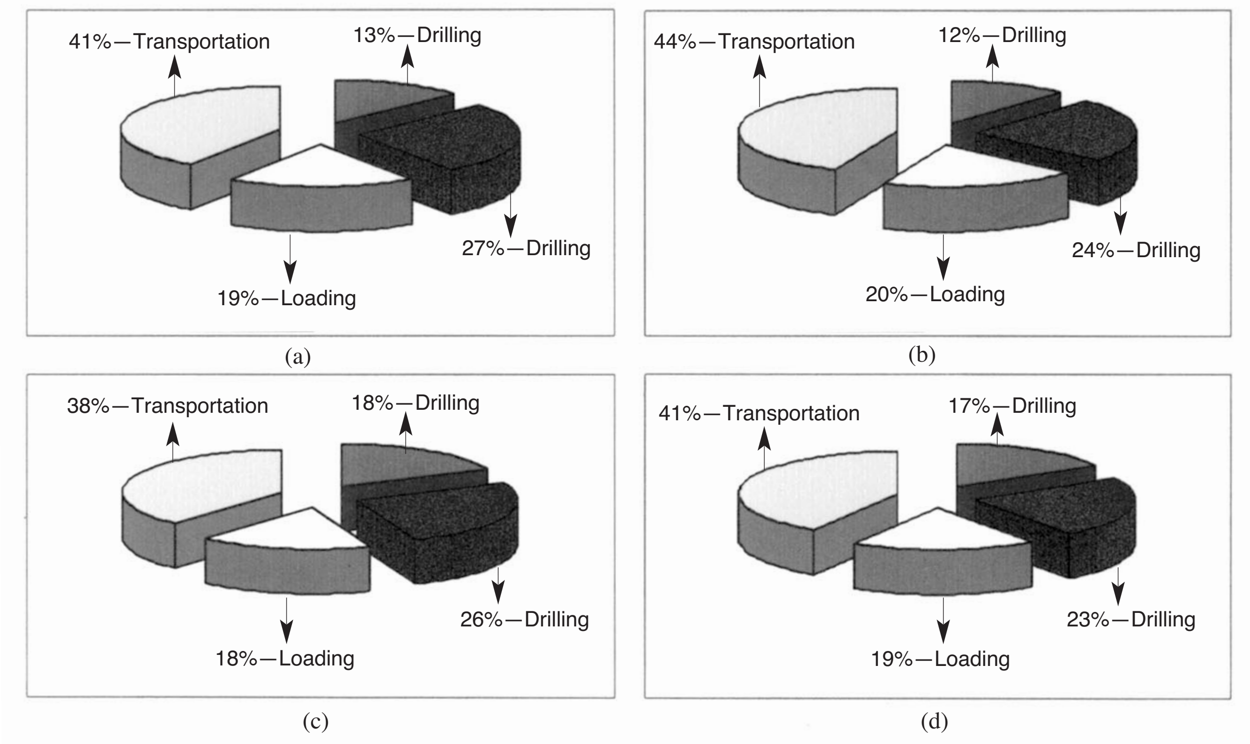

Figure16—per cent effect of all mining activities cost on the overall unit cost. (a) Hillside quarry minimum unit cost,(b) Pit quarry minimum unit cost, (c) Hillside quarry maximum unit cost, (d) Pit quarry maximum unit cost

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