Computational Models for Reduction of Quarry Waste for Breakwater Construction Projects

Venkateswara Rao Surati[1], Koshy Varghese[2] and K. Senthilnathan[3]

[1]M.Tech Student, Construction Technology & Management, Indian Institute of Technology Madras
[2]Professor, Department of Civil Engineering, Indian Institute of Technology Madras
[3]Head, Engineering Technology (Infrastructure), Larsen and Toubro Limited, ECC Division, Chennai

Abstract

Construction of Breakwater requires large volumes of appropriately graded rock. Geological characteristics and blasting practices at the quarry determine the gradation of the quarried rock. If the gradation of quarried rock does not meet design requirements, there is wastage of quarried rock or additional cost to reprocess it to meet requirements. This work utilizes mathematical models to forecast the gradation of rock from primary blasting. These models are programmed in the form of a spreadsheet to be used for decision support. By varying the blasting parameters the best fit between requirements and quarry yield can be found. In addition, a genetic algorithm based optimization model to determine the optimal values is also developed and illustrated with an example.

Keywords: Breakwater rock demand, Quarry yield, Blasting parameters, Spreadsheet, Genetic Algorithms.

Introduction

Breakwater construction involves quarrying, transportation and placing large volumes of appropriately graded rock. The large volumes of rock required and the gradation specified usually necessitates dedicated quarries for the project. Ideally, based on the geology of the quarry and blasting methods, the blasting pattern can be designed to ensure that the rock yield from primary blasting is close to the specified gradation. However, common practice is to produce large size rocks through primary blasting and then break these down to required specifications using secondary blasting. (Carlos, et. al. 1995) This process adds to the cost of the operation and results in considerable wastage of materials.

One of the key reasons for the current practice is that there are no standardized methods and decision support tools available to assist in forecasting the quarry yield for quarry characteristics and alternate blasting patterns (Clarke et. al. 2005). The objective of this work is to propose a decision support methodology based on available models and develop a tool to implement the methodology. The work utilizes the Rosin Rammler model (Vrijling et. al. 1990) to forecast quarry yield. A spreadsheet is used to encode the workflow of the methodology. In addition, the optimization features of the spreadsheet are used to automate the selection of the blasting parameters to minimize excess material. The utility of the tool is illustrated using an example.

Proposed Methodology

Figure 1 shows an overview of the proposed methodology. The design specifications for a particular section of the breakwater are considered as the initial input to the process. It is assumed that the design of the breakwater is frozen and the blasting parameters can be varied to ensure quarry yield obtained matches with the given design requirements.

The design requirement is based on the coastal parameters and properties of rock available in the quarry. The requirements will specify the various sections of the break water and the required gradation of rock for each section. Figure 2 shows typical sections of a breakwater and Figure 3 shows the rock demand requirements for the sections. The yield of the quarry must match with the demand to ensure adequate supply of materials with minimum wastage.

As shown in Figure 1, the yield of the quarry is based on geological characteristics (Rock Intact properties) of the quarry and blasting pattern utilized. Detailed mathematical models have been formulated to estimate the quarry yield.

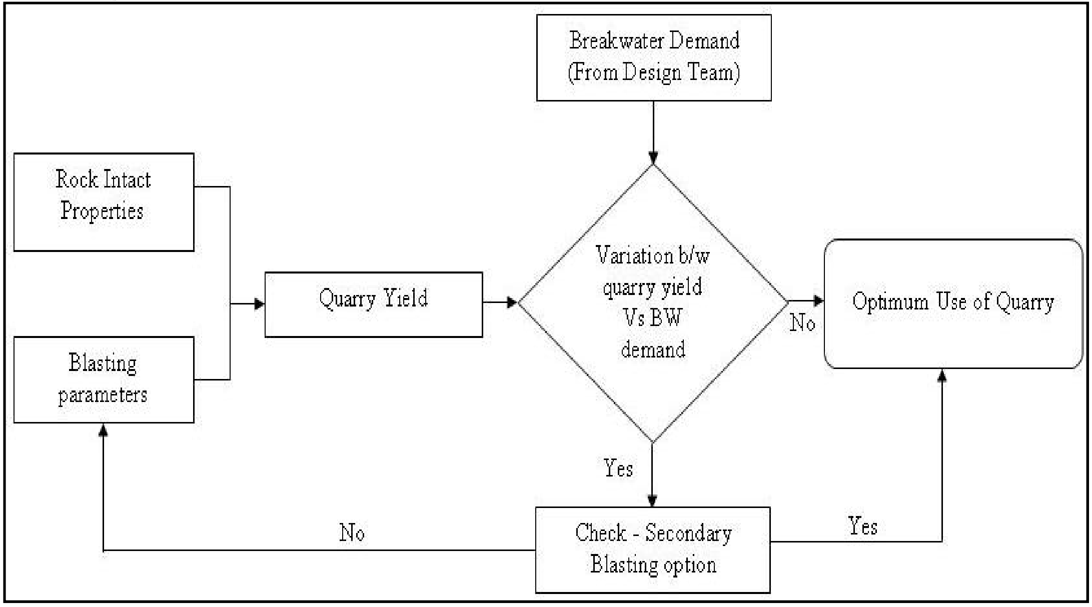


Figure 1 Proposed Methodology – Optimal use of Quarry

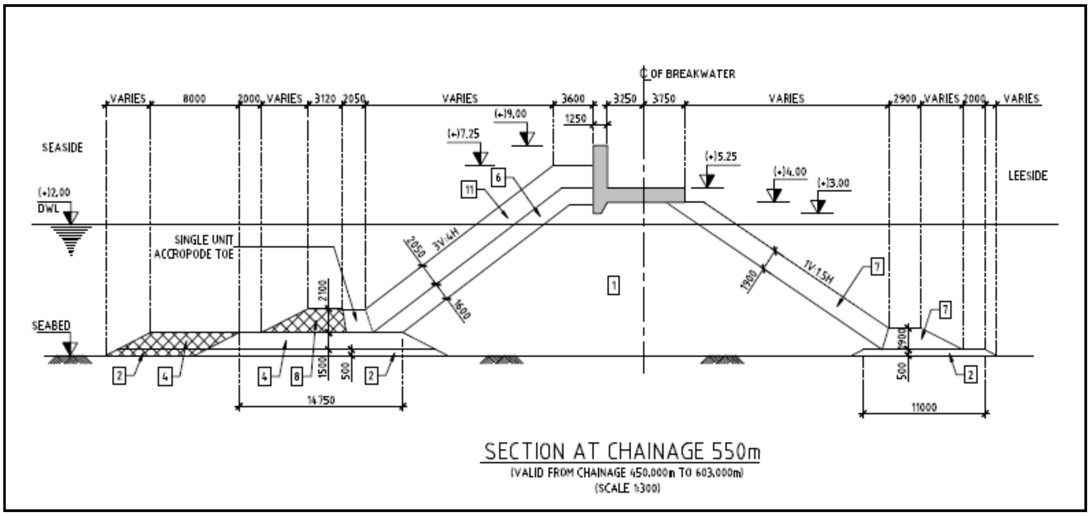


Figure 2 Typical Section of Rubble Mound Breakwater

Model for Quarry Yield:

The quarry yield for this work is calculated using the equation specified by equation (1): (Latham, et. al. 2006a) (Latham, et. al. 2006b)

$$Y = 1 - \exp\{-0.693(D_y/D_{b50})^{n_{RRD}}\} \qquad (1)$$

Where:

D_y - *Specific particle size*

D_{b50} - *50% passing sieve size in the blast pile*

n_{RRD} - *Rosin–Rammler uniformity index for sizes*

D_{b50} is given by Kuznetsov equation; this suggests that average size is controlled by specific charge.

$$D_{b50} = 0.01. A . (V/Q)^{0.8} . Q^{0.167} . (E/115)^{0.633} \qquad (2)$$

Where:

A = rock factor – calculated by equation (3)

Q = charge concentration per blast hole (kg)

V =volume of rock broken per blast hole (m^3)

E =relative weight strength of explosive (ANFO= 100, TNT=115);

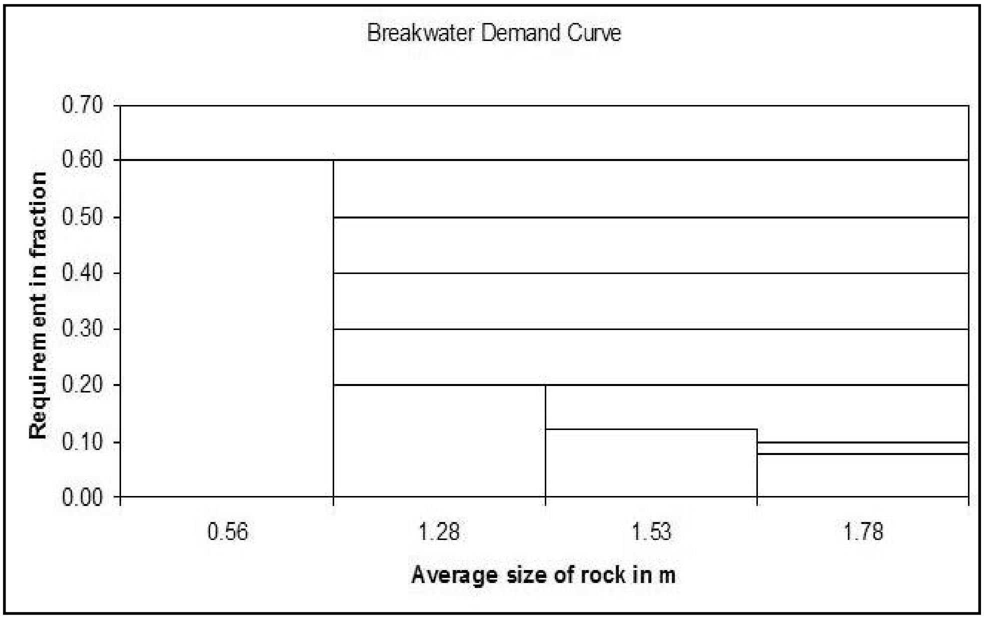


Figure 3 Demand Chart - Breakwater

Rock factor A:

$$A = 0.06(RMD + JF + RDI + HF) \qquad (3)$$

Where

RMD (Rock mass description): 10 if powdery or friable, = JF if vertically jointed, 50 if massive rock

JF (Joint Factor): Joint Plane Spacing term (JPS) +Joint Plane Angle term (JPA)

JPS = 10 if average Principal Mean Spacing (PMS) <0.1 m; 20 if 0.1 < average PMS < to 1 m; 50 if average PMS>1 m.

JPA = 20 if dipping out of face, 30 if striking perpendicular to face, 40 if dipping into face

RDI = Rock Density Influence=$0.025\varrho r$ (kg/m^3) −50

HF = Hardness factor=E/3 if E<50, or UCS/5 if>50, depending on uniaxial compressive strength UCS (MPa) or Young's Modulus E (GPa).

ϱr = Rock Density

n_{RRD} in equation (1) is determined using Cunningham's uniformity index formula

$$n_{RRD} = X\ (2.2 - 14B/d)\{0.5(1+S/B)\}^{0.5}(1-W/B) \\ ((|(BCL-CCL)|\ /L)+0.1)^{0.1}L/H \qquad (4)$$

Where

d = borehole diameter (mm)

B = burden (m)

S = spacing (m)

BCL = bottom charge length (m)

CCL = column charge length (m)

L = total charge length above grade (m)

H = bench height or hole depth (m)

W = standard deviation of drilling error (m)

X = Design Pattern (Square pattern=1, Staggered pattern= 1.1)

Using the above models the yield of the quarry can be calculated. The yield of the quarry is expressed as the % of each rock grade range. The yield can be varied based on the following 4 key blasting parameters Charge Length, Burden, Spacing and Bench height. These are illustrated in Figure 4.

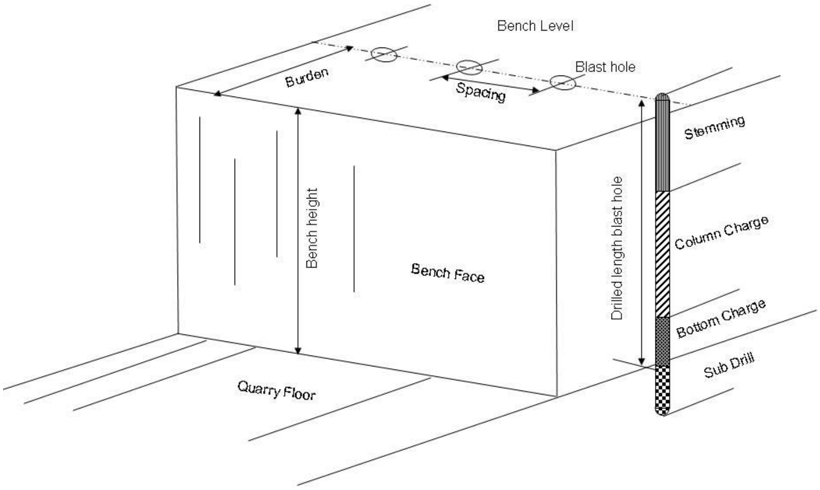


Figure 4 Quarry Blasting Parameters

The % of rock yield from the quarry in each fraction can be varied by altering the blasting patterns. Figure 5 shows three alternate yield curves and a comparison to the demand.

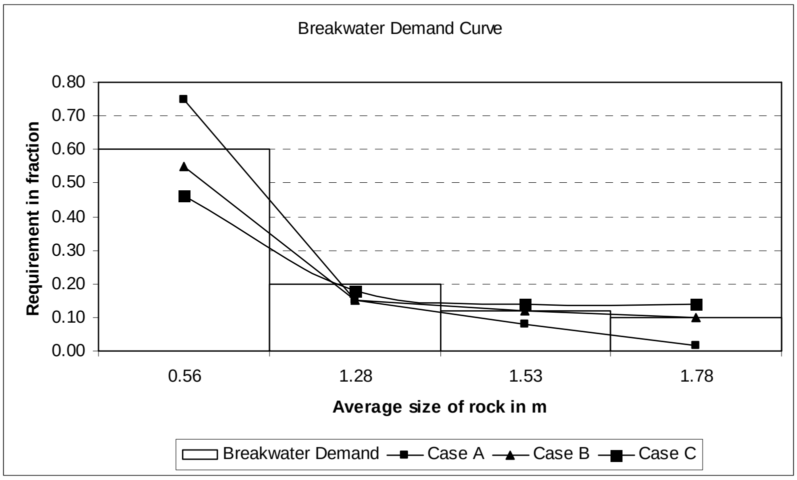
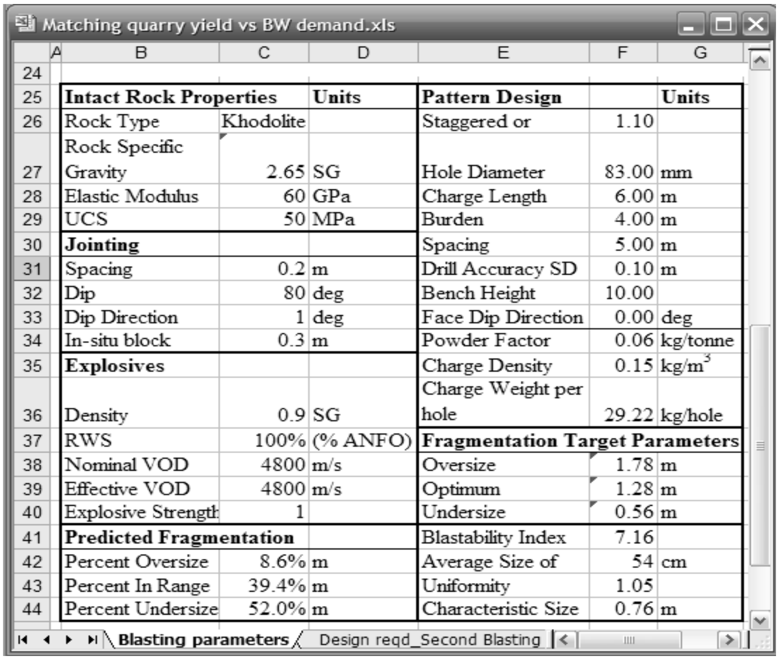


Figure 5 Alternate Quarry Yield vs Demand

In comparing the alternatives it can be seen that (i) For Case A, the yield of smaller size rock is more than the demand and larger rock is less than demand. This leads to wastage as the excess smaller rock cannot be used and additional quarrying has to be done to get adequate large size rock. (ii) For case B the yield of smaller size rock is less than demand and the yield of some fractions of larger rock are more than demand, in this case the larger rock can be broken up using secondary blasting to meet the requirements of the smaller rock. (iii) For case C, the yield of smaller rock, is much less than the demand and the yield of large rock is much higher, in such a case, extensive secondary blasting is required to break the excess large rock to meet the secondary rock requirements and this will be at a significant additional cost. Of the three cases presented, Case B is the preferred alternative as the primary yield is close to the demand and a minimal amount of secondary blasting is needed to meet the final demand requirements.

Using the models and methodology presented above a spreadsheet was developed to assist with the selection of the blasting parameters which can result in minimizing the wastage as well as cost of secondary blasting operation.



	A	B	C	D	E	F	G
24							
25		**Intact Rock Properties**		**Units**	**Pattern Design**		**Units**
26		Rock Type	Khodolite		Staggered or	1.10	
27		Rock Specific Gravity	2.65	SG	Hole Diameter	83.00	mm
28		Elastic Modulus	60	GPa	Charge Length	6.00	m
29		UCS	50	MPa	Burden	4.00	m
30		**Jointing**			Spacing	5.00	m
31		Spacing	0.2	m	Drill Accuracy SD	0.10	m
32		Dip	80	deg	Bench Height	10.00	
33		Dip Direction	1	deg	Face Dip Direction	0.00	deg
34		In-situ block	0.3	m	Powder Factor	0.06	kg/tonne
35		**Explosives**			Charge Density	0.15	kg/m^3
36		Density	0.9	SG	Charge Weight per hole	29.22	kg/hole
37		RWS	100%	(% ANFO)	**Fragmentation Target Parameters**		
38		Nominal VOD	4800	m/s	Oversize	1.78	m
39		Effective VOD	4800	m/s	Optimum	1.28	m
40		Explosive Strength	1		Undersize	0.56	m
41		**Predicted Fragmentation**			Blastability Index	7.16	
42		Percent Oversize	8.6%	m	Average Size of	54	cm
43		Percent In Range	39.4%	m	Uniformity	1.05	
44		Percent Undersize	52.0%	m	Characteristic Size	0.76	m

Figure 6 Data Input Sheet

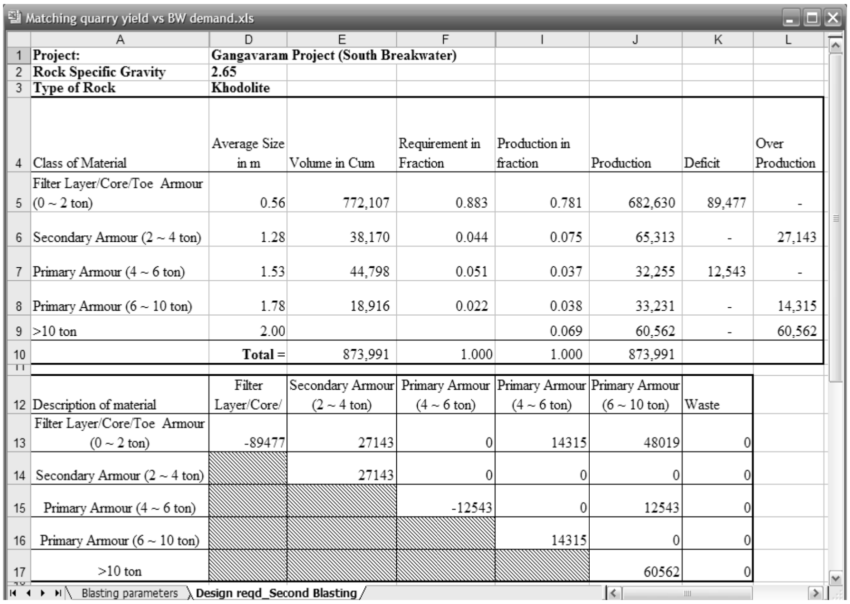
Spreadsheet Development and Usage

The spreadsheets developed to model the process are shown in Figure 6 and Figure 7. Figure 6 shows the sheet in which all the variables related to quarry properties and blasting are entered. The four decision variables are entered in this sheet (Burden, Charge Length, Spacing and Bench Height). Based on these variables the

% retention of each size is calculated and the estimates of quarry yield in % of each size are computed- this is displayed in Figure 7. The totally volume of rock has to be estimated based on the topography of the quarry and blasting pattern. The volume of rock yield for each size is calculated using the total volume and volume in each fraction. A comparison between the design rock requirement and the quarry yield gives the excess rock for that section.

The lower part of the second spreadsheet represents the secondary blasting in the form of a matrix. The rows & columns represent that size of rock. As smaller rock can be obtained from larger rock (but not vice versa) the cells above the diagonal represent the quantity of smaller rock which can be obtained from a particular row representing the larger size through secondary blasting.

To use the tool in a decision support mode the values of the decision parameters can be entered in the first sheet and based on the wastage obtained the decision maker can adjust the values until minimal wastage is obtained. An alternated usage is to be able to optimize the using an appropriate method.



Project: Gangavaram Project (South Breakwater)
Rock Specific Gravity 2.65
Type of Rock Khodolite

Class of Material	Average Size in m	Volume in Cum	Requirement in Fraction	Production in fraction	Production	Deficit	Over Production
Filter Layer/Core/Toe Armour (0 ~ 2 ton)	0.56	772,107	0.883	0.781	682,630	89,477	-
Secondary Armour (2 ~ 4 ton)	1.28	38,170	0.044	0.075	65,313	-	27,143
Primary Armour (4 ~ 6 ton)	1.53	44,798	0.051	0.037	32,255	12,543	-
Primary Armour (6 ~ 10 ton)	1.78	18,916	0.022	0.038	33,231	-	14,315
>10 ton	2.00			0.069	60,562	-	60,562
	Total =	873,991	1.000	1.000	873,991		

Description of material	Filter Layer/Core/	Secondary Armour (2 ~ 4 ton)	Primary Armour (4 ~ 6 ton)	Primary Armour (4 ~ 6 ton)	Primary Armour (6 ~ 10 ton)	Waste
Filter Layer/Core/Toe Armour (0 ~ 2 ton)	-89477	27143	0	14315	48019	0
Secondary Armour (2 ~ 4 ton)	▨	27143	0	0	0	0
Primary Armour (4 ~ 6 ton)	▨	▨	-12543	0	12543	0
Primary Armour (6 ~ 10 ton)	▨	▨	▨	14315	0	0
>10 ton	▨	▨	▨	▨	60562	0

Figure 7 Results Sheet

Optimization Model

In the manual mode a number of options will have to be explored to arrive at the optimal decision parameters. To automate this process the use of optimization was explored. The initial formulation objective was to minimize the variation between the requirement fraction and the production fraction. The constraints were to limit the fractions within a 5%-7 % range to ensure that primary blasting produced deficit of smaller rock and an excess of larger rock. The objective functions and constraints of the model are as follows:

Objective

$$\text{Minimize} \sum_{EachGrade} (\text{Produced Fraction - Required Fraction})$$

Constraints

% Deficit Production (0-2 Tons) <= 0.05

% Deficit Production (2-4 tons) <= 0.05

% Deficit Production (4-6 tons) <=0.05

% Excess Production (6-10 tons) <=0.07

% Excess Production (> 10 Tons) <=0.07

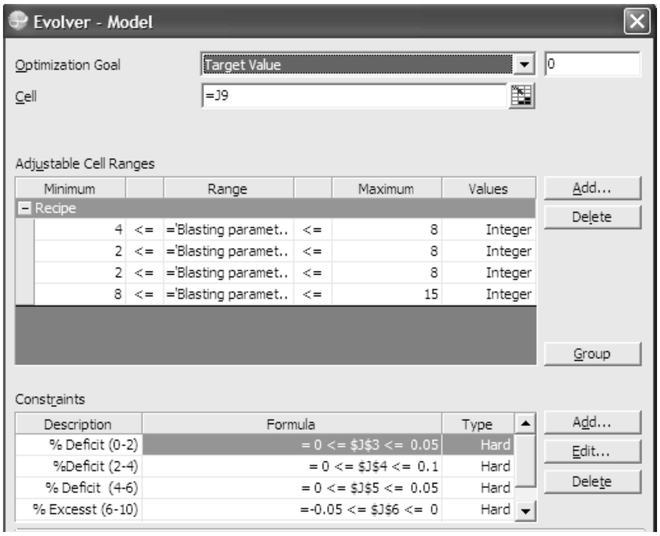
Initially the solution of the model was attempted with solver available in Excel. However, as there were logical statements in the spreadsheet model, the solver was not able to map the input parameters to outputs in continuous space. As a result the solutions obtained from these attempts were not valid.

A Genetic Algorithm (GA) can map input to output without the need for continuous space representation. The spreadsheet based GA - Evolver was used to represent the optimization model and solve it. Figure 8 shows the settings screen in Evolver.

The inputs were restricted to integers and the range of each input parameters was also specified. In addition to the objective of minimizing the excess rock, a model which required the deficit and excess rock to be balanced to archive a target value of 0 was also run. A population size of 50 was specified with the default crossover and mutation parameters. For the constraints specified the solution converged within 10 generations to the target value. Table 1 shows the values obtained for a case study of a recently completed breakwater project. The corresponding demand and yield graphs are shown in Figure 9.

Optimization was also attempted by narrowing the deficit and excess ranges in the constraints. This would provide a theoretically perfect answer; however, after numerous attempts no valid solutions were obtained.

The optimization model was primarily developed to investigate the applicability of modeling the demand yield problem and feasibility of generating results. Based on this preliminary study a more detailed optimization models can be developed. A natural extension is to consider the cost of secondary blasting also in the model and optimize both stages to ensure minimum wastage and cost of the operation.



Optimization Goal: Target Value 0
Cell: =J9

Adjustable Cell Ranges

Minimum		Range		Maximum	Values
Recipe					
4	<=	='Blasting paramet..	<=	8	Integer
2	<=	='Blasting paramet..	<=	8	Integer
2	<=	='Blasting paramet..	<=	8	Integer
8	<=	='Blasting paramet..	<=	15	Integer

Constraints

Description	Formula	Type
% Deficit (0-2)	= 0 <= \$J\$3 <= 0.05	Hard
%Deficit (2-4)	= 0 <= \$J\$4 <= 0.1	Hard
% Deficit (4-6)	= 0 <= \$J\$5 <= 0.05	Hard
% Excesst (6-10)	=-0.05 <= \$J\$6 <= 0	Hard

Figure 8 Genetic Algorithm Based Evolver Model

Summary

This study effectively illustrated how the efficiency of a complex task such as quarry production planning for breakwaters can be improved using appropriate quantitative models implemented in a spreadsheet. The quantitative models used have been validated on numerous quarries; the accuracy of the forecasts will depend on the applicability of these models to quarry under consideration. This field validation can be done during the trial blasting stage of quarry study. Further, the optimization offers potential to automate the decision process in selecting the appropriate blasting parameters. Continuing work in this area is focused on applying the models to live projects and further refining the optimization models.

Table 1. Optimization Results for a Breakwater Project

Class of Material	Required Fraction	Production Volume	Production	Deficit	Over Production
Filter Layer/Core/Toe Armor (0-2)	0.883	0.837	732,192	39,915	-
Secondary Armor (2-4)	0.044	0.042	36,916	1,254	-
Primary Armor (4-6)	0.051	0.021	18,933	25,865	-
Primary Armor (6-10)	0.022	0.024	20,837	-	1,921

>10 ton	0	0.070	65,113	-	65,113
TOTAL	1.000	1.000	873,991	**67,034**	**67,034**

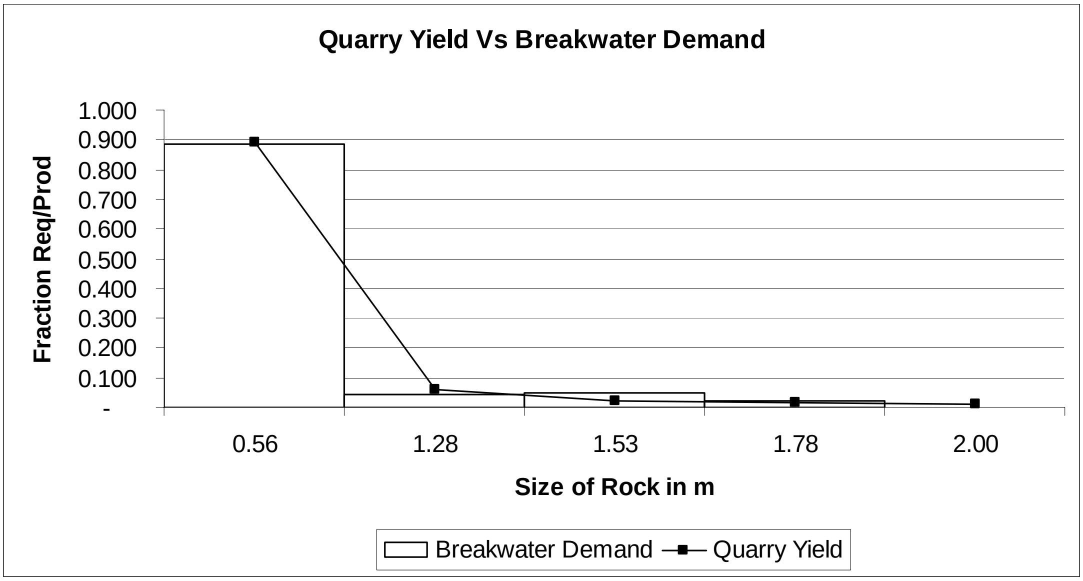


Figure 9 Yield vs. Demand Curve

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