Fragmentation Monitoring of Production Blasts at MRICA

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ABSTRACT

In a follow-up of 12 production blasts in a quarry at the Mrica project on Java, tightly spaced porous bands were found to govern fragmentation to the extent that the average fragment size k_{50} was nearly independent of the specific charge within the range 0.30-0.56 kg/m³. This finding resulted in a reduction of the running costs for drilling and blasting by 20-40%.

Our work has given considerable practical benefits and insights into the blasting process, even if the results were of no direct use to check out fragmentation predictions based on models, which was one of our main goals.

DESCRIPTION OF PROJECT

The Swedish Detonic Research Foundation, SveDeFo, has monitored 12 production blasts at Mrica on the island of Java in Indonesia. At Mrica the SABCON consortium, which consists of Skanska AB, Balfour Beatty, ASEA and Boving & Co Ltd, has been building a power and irrigation dam bridging the Serayu river and the adherent power plant.

At Tampomas 3-4·10⁶ m³ of rock were quarried for the dam from mid 1985 till mid 1988. This quarry was chosen as the site to test the correlation between fragmentation and the specific charge as well as structure and strength of the rock. The project is part of SveDeFo's ongoing effort to produce accurate fragmentation prediction models, and it was carried out in cooperation with Skanska AB.

During late October-November 1986, the following work was made on site;

- Overall structural mapping;
 - Core drilling;
 - Blast data collection;
 - Blast monitoring;
 - Fragmentation measurements;
 - Mapping of benches before and after blasting in order to assess blast damage and drill hole deviations.
- It was then supplemented by;
- Core mapping;
 - Laboratory testing (point load strength, tensile strength, fracture toughness, Young's modulus and sonic properties);
 - Digital analysis of fragmentation photos;
 - Analysis of fragmentation results

The results have been reported by Abrahamsson et al. (1987) and Ouchterlony et al. (1988).

THE ROCK AT TAMPOMAS

The quarry at Tampomas was originally the remains of the core of a volcano which rose 150 m above the surroundings. The rock

was mainly a competent andesite with a porosity of a few percent. It was penetrated by both thin porous bands, see below, and larger areas with a porosity of up to 20%. Its density was normally 2.400-2.500 kg/m³. Its Young's modulus was measured as 25-40 GPa, its Poisson's ratio as 0.15-0.25 and its sonic velocities as 3.400- 4.600 m/s (P-wave) and 2.200-2.700 m/s (S- wave). The porous areas consistently had lower values than the intact ones.

Measured strength data show the same tendencies. The point load strength index for the intact rock was typically 5-7 MPa and 20% less for the porous one, the corresponding tensile strengths were 8.1 and 7.4 MPa and the fracture toughness values 1.68 and 1.26 MN/m^{1.5} respectively. The porous bands, which would escape an unexperienced observer, thus form intact weakness planes in the surrounding andesite.

The horizontal scanline mapping of the rock surface displayed 4 independent families of fractures at Tampomas. The northern and southern parts of the quarry have similar structures since a turning of the southern fracture systems by 15-40° westward give a good correlation with the northern ones.

The average fracture spacings lay within 0.4-4.7 m and for the fracture lengths within 2-7 m. These values were analysed and the measurement errors were found to be acceptable. As expected the spacings follow exponential distributions whereas the fracture lengths rather follow lognormal distributions. See table 1.

One fracture family is subhorizontal and it was mapped separately using vertical scanlines. It was then that a subhorizontal structure in the rock was detected. At some places a color banding was observed, at others none. Near remaining half casts these bands were sometimes fractured. The study of a diamond sawn surface later showed this banding to consist of rock with higher porosity.

This observation was supported by the testing of the drill cores through the correlation with the lower strength values and by that

FIG. 1. The Tampomas quarry at elevation 325-340 m. Note the subhorizontal fractures on the bench face which are mainly blast induced.

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TABLE 1.

Results of calculation of mean fracture spacings and mean fracture lengths for the northern (N) and southern (S) parts of the Tampomas quarry.

System	Mapped no.	%	Spacing $\bar{x}$ (m)	x_o (m)	$\bar{l}$ (m)	Length l_o (m)	l_r (m)
Hor. scanlines (N):							
N8OW/85NE	205	37	2.12	2.10 ^e	3.46	3.52	4.08
N5E/85SE	97	18	1.95	1.80 ^e	3.05	3.15 ^e	3.61
N8OW/5NE	100	18	0.42	0.44 ^e	2.72	2.81	2.14
NOE/55NW	50	9	2.85	2.75 ^e	4.50	4.81 ^{el}	5.09
All systems 452 83 (Total mapped 547)							
Hor. scanlines (S):							
N6OW/85NE	79	21	2.40	2.62 ^e	5.91	6.13	14.1
N6OE/60SE	67	17	4.74	4.67 ^e	4.50	4.72 ^{el}	6.62
N4OE/10SE	95	25	0.80	0.73 ^e	3.72	3.86 ^l	2.84
N1OE/55NW	40	10	3.35	3.88 ^e	4.12	4.42 ^{el}	5.03
All systems 281 73 (Total mapped 385)							
Vert. scanlines (S+N):							
N35W/15NE	71	75	0.41	0.44 ^e	3.32	3.47 ^l	5.14
Symbols:							
$\bar{x}, \bar{l}$ = averages, i.e. calculated sample means.							
x_o, l_o = mean values of fitted exponential distributions.							
l_r = fracture mean length obtained from a distribution free determination, see Abrahamsson et al. (1987).							
e, l = passing Kolmogorov-Smirnov goodness-of-fit test at 5% significance level for exponential (e) or lognormal (P) distributions or both (el).							

a moistened core surface dries faster where it is porous. The thickness of these bands is typically 2-10 mm and their spacing 100-200 mm. Fractured porous bands constitute the main part of the subhorizontal fracture system, see figure 1.

The rock mass properties were evaluated according to both Barton's Q-system and Bieniawski's RMR-system (Kirkaldie, 1987). With Q-values of 8-11 and RMR-values values 87-92 the rock mass quality is fair to very good. The southern part of the quarry had somewhat better rock since the block sizes on the average were 4.6 m³ against 1.1 m³ in the northern part and the average uncracked horizontal area of the blocks, were 5.8 m² and 2.7 m² respectively.

DRILLING AND BLASTING

At the time of our monitoring, 10 m high benches were worked in the northern part of the quarry and 15 m high ones in the southern part. The blastholes were nominally Ø 76 mm. The basic drilling pattern used staggered rows with a 2.5x3.0 burden to spacing unit and vertical holes. A typical blast consisted of 4 rows, 40-70 m wide by 8-10 m deep. Every week 2-3 blasts of 3-8000 m³ of rock were fired.

Depending on weather conditions, the blast hole columns were charged with ANFO plus Premix additive or Gelignite HE (an ICI/Atlas Taiwan Corp. Dynamite). The bottom charge was the same in both cases, 6 sticks of Ø 65x400 mm Gelignite. The Gelignite column consisted of Ø 55 mm sticks. The stemming consisted of 1.5 m of cuttings in the 10 m benches and 2.0 m in the 15 m ones.

The ignition system used two Nonel ms delay caps in each hole and a fuse initiated 5 g/m detonating cord as the trunk line. Except for blast no. 6, which was fired row by row, the firing sequence was a shallow V-opening. The number of holes with ANFO in each blast varied between 0% and 72% since usually both types of holes were used. Therefore their blasting effects were estimated.

The weight strength of the Gelignite is 10-15% higher than that of ANFO. A Ø 76 mm ANFO charge has a linear density of 3.7 kg/m while a column charge of Ø 55 mm Gelignite holds 3.3 kg/m, giving the same strength. The common bottom charge consisted of 6 Ø 65x400 mm Gelignite sticks, giving 4.5 kg/m. Considering that the Gelignite is decoupled so that the pressure time history of the gaseous detonation products is more drawn out, like the ANFO one, both hole types were judged to be essentially equal in blasting performance.

The bottom charge is the same in both benches and the stemming is somewhat less in the 10 m bench. These effects counteract each other and the holes of the 10 m and 15 m benches are thus essentially equally heavily loaded.

Blast monitoring of detonation velocities (VOD) and primer action was made in a number of holes. The measured VOD values for ANFO and Gelignite were 3500 and 5500 m/s respectively, the latter comparing well with the 5200 m/s claimed by the manufacturer. The primer test showed that 260 g of Gelignite was sufficient to initiate the ANFO which acquired its terminal VOD already after 0.4 m.

Visual inspection and coring showed blast induced fractures down to 1-2 m below the bottom of the bench. On the bench face

their dip was nearly vertical, striking parallel to existing fractures which had obtained permanent residual openings. Many of the horizontal fractures on the bench face were probably also caused by the blasting, especially near the half casts.

Of the 12 blast monitored at Mrica, 6 came from the northern part of the quarry (10 m benches) and 6 from the southern part (15 m benches). The blast direction was always NE except for blasts no. 3 and 8 where it was SE. Since the fragmentation tended to be on the fine side for use as dam fill, burden and spacing could be increased from 2.5;3.0 m to 3.0;3.5 m during our work while the holes in some blasts were drilled at 70° instead of vertically to improve the diggability of the muck pile. See table 2.

FRAGMENTATION MEASUREMENTS

The fragmentation from blast no. 11 is shown in figure 2. The following measurements were made;

- Visual inspection (muck pile profile, uniformity and average fragmentation);
- Counting of boulders (blocks exceeding 1-2 m³ in volume);
- Sieving (by hand with mesh sizes from 4.75 to 350 mm);
- Photographing for digital analysis

The results are compiled in table 2.

From 7 muck piles, samples weighing 8-12 tons were selected for hand sieving. The trucks were weighed with and without payload. The samples each contain roughly 0.1% of a muck pile. They were taken from the centers of the piles. All resulting fragment size distributions are shown by Abrahamsson et al. (1987).

The muck piles were photographed from an excavator at about 5 m distance and, where possible, perpendicular to a surface with an applied scale. (Figure 3). Each picture covers about 0.2 % of the muck pile. They were subsequently evaluated using semi-automated equipment, requiring manual digitising of every

FIG. 2. The muck pile resulting from blast no. 11.

fragment upon which a computer calculates the size distribution (Nie and Rustan, 1987).

The total error of the method is given as ± 25 %. During our work the following factors were investigated

1. The operator error was found to be ± 5 %.
2. The number of photos. The size distributions from blasts no. 4 and 7 were evaluated with both 5 and 10 photos. For practical purposes 5 photos were found to be sufficient. Figure 4 shows the variability between the different photos of blast no. 6. The values in table 2 are averages from 5 photos.
3. A comparison with manual sieving, by photographing two sieve samples for a digital analysis. In one case the agreement was excellent. In the other the photoanalysis gave a considerably coarser result, probably due to material segregation during the handling of the sieve sample.

TABLE 2

Summary of data relating to the blasting at the Tampomas quarry.

Blast no ¹	Specific charge (kg/m ³)	Fragm. sieve/photo ² (mm)/(mm)	Burden; spacing (m).(m)	Bench height ³ (m)	Fract. freq. (1/m)	Porous bands ⁴	Specific drilling (m/m ³)	Hole incl. (°)	Perc. ANFO ⁵ dir.	Blast dir.	Boulders weight (%)
1-S	0.49	- /170	2.5.3.0	15	0.72	++	0.135	90	72	NE	2.0
2-S	0.51	- /170	2.5.3.0	15	0.64	++	0.141	90	69	NE	>2.0
3-N	0.56	- /175	2.5.3.0	10	1.24	+	0.180	90	58	SE	<0.5
4-S	0.49	100/125	2.5.3.0	15	0.82	++	0.139	90	71	NE	1.0
5-S	0.52	- / 65	2.5.3.0	15	0.76	0	0.147	90	41	NE	1.5
6-S	0.42	310/125	2.5.3.0	15	0.72	0	0.138	90	15	NE	3.0
7-N	0.30	265/190	2.5.3.5	10	1.00	+	0.113	90	0	NE	1.0
8-N	0.35	325/155	2.5.3.5	10	1.17	+	0.137	90	20	SE	<0.5
9-S	0.36	- /150	2.5.3.5	15	0.51	0	0.132	90	0	NE	4.0
10-N	0.48	165/195	2.4.3.0	10	0.96	+	0.146	70	32	NE	<0.5
11-N	0.39	205/165	3.0.3.5	10	0.73	++	0.138	70	27	NE	<0.5
12-N	0.32	165/205	3.0.3.5	10	0.63	++	0.108	70	25	NE	<0.5

Note 1: S and N denote the southern and northern parts of the quarry respectively.

Note 2: Fragmentation measure given is k₅₀ the average fragment size or the mesh size through which 50% of the muck pile passes.

Note 3: The bench height was 15 m in the southern part of the quarry and 10 m in the northern one.

Note 4: Expected influence of porous band on fragmentation; 0 = none, + = moderate, ++ = strong.

Note 5: The total of ANFO + Gelignite in each blast is 100%.

The fragmentation curves from the photo analysis all have more fines than the sieving curves, probably because the computer treats all undigitized voids between the fragments as fines. This may be another source of error.

Table 2 shows that the k_{50} values obtained from the photo analysis both have a lower average and less scatter than the sieving k_{50} values. See also table 3. Both observations may be explained by the sieve sample representing only around 0.1% of the muck pile whereas 5 photos represent 10 times as much. Thus the sieving is more sensitive than the photo analysis to fragments of a given size.

FIG. 3. One of five photos of blast no. 12 used for the fragmentation curve.

As an example the sieve sample from blast no. 6 contained a block of about 1 m^3 which made up about 25% of the sample. Its occurrence totally distorts the sieving result while its influence on the photo analysis results would be minimal since it represents only 2.5 % of the rock covered. Figure 4 shows that if this block is discounted, the sieving k_{50} drops from 310 mm to 170 mm, which we believe to be more representative. Compare it with the photo analysis value of 125 mm.

The difference is large for blast no. 8 as well, a sieving k_{50} value of 325 mm versus a photo analysis one of 155 mm. In this case the whole sieve sample was probably unrepresentative. Thus our conclusion was that we prefer the photo analysis over sieving,

weight passing %

FIG. 4. Fragmentation curves for blast no. 6. Digital analysis results are given both as range for 5 individual photos and averaged (solid line). Lower dashed line shows sieving results.

even if the method is relatively inaccurate and time consuming.

DISCUSSION OF RESULTS

The average fragment size k_{50} from the photo analysis is shown versus specific charge q in $\text{kg}(\text{ANFO})/\text{m}^3$ in figure 5. The scatter is so large that the tendency that is seen for a finer fragmentation (lower k_{50}) with increasing specific charge (higher q) is not statistically significant.

We can thus only state that the fragmentation is independent of the specific charge. A more accurate measurement method, a larger span of q -values or substantially more blasts monitored would perhaps have altered this conclusion but these measures couldn't be effected within our project.

Since the independence of k_{50} on q was unexpected however

FIG. 5. k_{50} plotted versus specific charge for all 12 blasts monitored at Tampomas. The dots denote the results from the 10 m high benches in the northern part of the quarry, the circles those from the southern part. Porous bands were observed on the bench face of all rounds except three. For the latter ones, no. 5, 6 and 9, these bands were at most barely visible.

we looked for other correlations between the parameters in table 2. The following results were obtained:

Part of Quarry or Bench Height:

These parameters coincide. The fragmentation is significantly coarser in the 10 m benches in the northern part of the quarry than in the 15 m benches of the southern part, even excluding blast no. 5 (table 3). A survey of the conditions at Tampomas and in the literature showed that bench height could hardly be the cause.

The other conceivable cause is the rock mass properties. If we compare the average uncracked horizontal area of a block with the area covered by each blast hole, i.e. burdenx spacing, then we have a relevant measure. In the southern part the block area is 5.8 m^2 and the blast hole area $7.5\text{--}8.75 \text{ m}^2$, meaning that 66-75% of all blocks would be drilled through. In the northern part the block area is 2.7 m^2 and the blast hole area $7.5\text{--}10.5 \text{ m}^2$ giving a penetration ratio of 26-38% of all blocks.

TABLE 3

Sample statistics for fragmentation data obtained at the Tampomas quarry, given as mean $\pm$ std.dev. (no. values).

Choice of sample	k ₅₀ in mm
1. Photo results, all 12 blasts	158 $\pm$ 38(12)
2. Sieving results, all 7 blasts	219 $\pm$ 83(7)
3. Photo results, same 7 blasts	166 $\pm$ 33(7)
4. Sieving results, except no.6 and 8	180 $\pm$ 61(5)
5. Photo results, same 5 blasts	178 $\pm$ 32(5)
6. Photo results, northern part	181 $\pm$ 19(6)
7. Photo results, southern part	134 $\pm$ 39(6)
8. Photo results, S except no.5	148 $\pm$ 23(5)
9. Photo results, S no. 1,2 and 4	155 $\pm$ 26(3)

According to work by da Gama (1983), Winzer et al. (1983) and Bouden-Romdhane et al. (1987) this should have given a lower k₅₀ in the northern part of Tampomas than in the southern one, instead of the other way around. It does however refer to rock which was more fractured than that at Tampomas since the penetration ratio was only 2-18%. Our results agree better with earlier Swedish experience in less fractured rock, see Larsson (1974). According to him k₅₀ could possibly be 50% higher in fractured rock for the same specific charge. At Tampomas the difference is 35%.

A fragmentation which is governed by the porous bands mentioned previously is the probable explanation for our results however, see further below.

Fracture Frequency:

For each blast we used the scan line mapping data from the bench, to calculate the fracture frequency. These values are a measure of the local rock structure but no correlation with the fragmentation was found.

Porous Bands:

Along each bench face the visible amount of gently dipping structure, i.e. the blast induced cracks and color banding which we later found to coincide with porous and weak rock, was mapped as being barely visible, visible or clearly visible. These values were then weighed together and the benches rated according to whether one could expect no influence, moderate influence or a strong influence of the porous bands on the fragmentation, see table 2.

As a result there were 3 benches where the porous bands were largely absent, i.e. no. 5, 6 and 9 in the southern part of the quarry. For them the average fragmentation decreases strongly with increasing specific charge.

For the other blasts in the southern part of the quarry, the fragmentation is no longer significantly finer than in the northern part. See table 3. Thus we had an expected moderate or strong influence in the porous bands in nine benches. For them fragmentation is independent of the specific charge and the range of k₅₀ values, 125-205 mm, coincides closely with the average band spacing of 100-200 mm.

These correlations form a strong indication that the

weakness planes formed by the porous bands govern the fragmentation.

Specific Drilling:

Only blasts no. 3, 7 and 12 stand out. For them there is naturally a correlation with the specific charge but none with the fragmentation.

Hole Inclination:

Blasts no. 10, 11 and 12 were drilled with inclined holes. Thus the muck pile was easier to dig but the fragmentation tended to be somewhat coarser than for the blasts with vertical holes. Since the porous bands were visible in all three benches, this fact is the probable cause for any such difference, rather than the hole inclination.

Explosive Type:

The relative amount of ANFO in each blast has an apparent correlation with the specific charge in table 2. The actual cause is however that the time when burden and pacing were increased, i.e. after blast no. 5, coincides with rainier weather during charging and hence with less ANFO in the drill holes. The explosive performance of an ANFO/Gelignite blast hole was previously judged equal to a pure Gelignite hole and there is accordingly no correlation between explosive type and fragmentation.

Blast Direction:

Benches no. 3 and 8 in the northern part of the quarry face SE, all others face NE. There is no correlation between blast direction and fragmentation in our work, nor did a follow up of a large number of previous blasts show such a correlation. Boulders:

The blasts in the southern part of the quarry had 1-4 % boulders, versus 0-1 % for those in the northern part. Since the stemming length is roughly proportional to the bench height, 1.5 m in 10 m and 2.0 m in 15 m, this is hardly the reason for the observed difference in boulder ratio. There is no correlation between boulder ratio and specific charge either.

There may be a correlation between few boulders and coarse fragmentation, but we believe it to be less important. The major correlation is with the rock structure. The boulder ratio in the southern part of the Tampomas quarry is on the average four times larger than in the northern part which coincides with the estimated average in situ block size ratio, 4.6 m³ versus 1.1 m³.

CONCLUSIONS

The most important conclusion of our monitoring of the blasts at Tampomas is that where the porous bands occur they appear to govern the fragmentation to the extent that k₅₀ is independent of the specific charge. Our extensive rock mechanics testing, which proves that these bands are much weaker than the surrounding rock, and the localization of blast induced cracks to these bands support it. The difference in boulder ratio in the blasts in the two parts of the quarry is probably explained by the difference in in-situ block size. The fact that the southern part with coarser blocks gave a finer fragmentation is probably explained by that the porous bands were hardly visible in three of its benches. When these bands are absent the specific charge governs fragmentation, the rock becomes easier to blast and k₅₀

decreases significantly with increasing specific charge.

The possibility of using the fragmentation results from Tampomas in order to verify a prediction model, which contains the rock structure, is very limited. The expected correlation has been reduced chiefly to the statement that a previously unobserved fine structure, the porous bands, are completely dominating. These bands were as far as we know similar wherever they occurred.

That the homogeneous andesite, i.e. the rock without porous bands, would be easier to blast coincides with Swedish experience but not with foreign work. To explain this discrepancy would force us to speculate about a fragmentation mechanism which is hard to confirm. The relatively low accuracy of the photo analysis method of measuring the fragmentation increase the speculative part.

Thus putting aside the rock structure factor leaves us with 3 blasts in the homogeneous andesite. They form an insufficient basis for checking a new model and since they display the traditional relation between fragmentation and specific charge, what remains is largely a comparison with traditional fragmentation formulas. Two well known prediction formulas, the Kuz-Ram one (Cunningham 1983, 1987) and the SveDeFo one (Holmberg, 1974; Holmberg and Ouchterlony, 1982) have been used to estimate k_{50} in Appendix 1. The results are plotted in figure 6.

As can be seen the Kuz-Ram estimates show a relatively good

FIG. 6. Predictions by the SveDeFo and Kuz-Ram fragmentation formulas for conditions at Tampomas quarry. Open circles mark blasts where no porous bands were observed.

agreement with the Tampomas data as a whole. The SveDeFo estimates bracket the Kuz-Ram ones which are perhaps better in that the dependence on specific charge is not as pronounced, but in judging this, the previous conclusion that the fragmentation at Tampomas doesn't depend on the specific charge should be born in mind.

For the blasts where the specific charge was expected to have an influence, blasts no. 5, 6 and 9, the second SveDeFo estimates are good. The exceptionally fine fragmentation in blast no. 9 is not predicted so well however. The low value of the rock constant used, $c = 0.2 \text{ kg/m}^3$, would classify the Tampomas andesite as very easy to blast.

These results show that a well founded fragmentation formula

may be used to predict k_{50} within roughly $\pm 50\%$. Such a prediction will however not pick up the important influence of the porous bands. To make a more detailed prediction model, which could include this, directly meaningful requires first of all a greatly improved accuracy in the fragmentation measurements.

When the blast monitoring of Tampomas started, the drilling pattern was $2.5 \times 3.0 \text{ m}$ and the fragmentation on the fine side for the intended use of the rock as dam fill. During our work the pattern could thus be changed to $3.0 \times 3.5 \text{ m}$ without changing the explosive charges or other conditions. The fragmentation became only slightly from then on coarser and the sparser pattern was used. Hereby the running costs for drilling and blasting at Tampomas were reduced by 20-40%.

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APPENDIX 1

The traditional SveDeFo fragmentation formula reads (Holmberg, 1974)

$$L = \frac{1}{2.27} [V^2 \cdot \sqrt{(1.25/(E/V))}]^{0.29} \cdot (c/sq)^{1.18} \quad (1)$$

where

- L = the average edge length of the average boulder (m)
 V = the burden used (m)
 E = the spacing used (m)
 q = the specific charge (kg/m³)
 s = relative weight strength, breaking capacity of explosive related to Dynamex (kgDx/kg)
 c = the rock constant, which is a blastability index introduced by Langefors and Kihlstrom (1978) (kg/m³). Usually c ≈ 0.4.

From this formula k₅₀ may be obtained as

$$k_{50} = L/2.6, \quad (2)$$

see Holmberg and Ouchterlony (1982). Langefors' original data is better fitted by

$$L = \frac{1}{2.69} [V^2 \cdot \sqrt{(1.25/E/V)}]^{0.29} \cdot (c/sq)^{1.35} \quad (3)$$

however (Ouchterlony, personal communication).

Inserting values for blasts no. 5, 6 and 9 from table 2 and using the relative weight strength of ANFO, s = 0.84, yields the SveDeFo predictions in figure 6. The first one uses the standard rock constant value c = 0.4 kg/m³, the second one c = 0.2 kg/m³, which is low. Values this low have been found for brittle crystalline granite however (Langefors and Kihlstrom, 1978).

The SveDeFo fragmentation curve gives the cumulative weight % y passing a given mesh size x as

$$y = 1 - e^{-(0.76 \cdot x / k_{50})^{1.35}} \quad (4)$$

The Kuz-Ram model (Cunningham, 1983) represents the fragmentation curve by

$$y = 1 - e^{-k_{50} \cdot (x / k_{50})^n} \quad (5)$$

This equation is more general than (4) in that the uniformity index n is dependent on factors like burden/hole diameter, spacing/burden, drilling accuracy and charge length/bench height. The normal range of n is 0.75 to 1.50. The average fragmentation is given by,

$$k_{50} = A \cdot Q^{1/6} / q^{0.8} \quad (6)$$

where k₅₀ turns out in cm:s. Here

- A = rock factor
 Q = total charge weight in TNT equivalents (kg), conversion factor relative to ANFO is 1.15.
 q = specific charge in TNT equivalents (kg/m³).
 Relative to any other explosive used

$$k_{50} = A \cdot (1.15 / s_{ANFO})^{19/30} \cdot Q_e^{1/6} / q_e^{0.8} \quad (7)$$

where subscript e refers to the explosive used and s is its weight strength relative to s_{ANFO}.

Cunningham (1987) gives a formula for calculating the rock factor

$$A = 0.06; (RMD+JF+RDI+HF), \quad (8)$$

where

- RMD = rock mass description; 50 for massive rock
 JF = joint factor; 0 because rock is massive
 RDI = rock density influence; 0.025; ρ-50
 HF = hardness factor; E/3 if E < 50 GPa.

For the Tampomas andesite where ρ = 2.500 kg/m³ and E ≈ 35 GPa, A ≈ 4.45. In our case s_{ANFO} = 1. The linear charge density is about 3.3 kg/m hole which gives Q_e = 33 kg and for the 10 m benches. The Kuz-Ram predictions are also given in figure 6. For the high benches k₅₀ is 1.5^{1.6} ≈ 1.07 times larger.