Rem: Revista Escola de Minas
ISSN: 0370-4467
editor@rem.com.br
Escola de Minas
Brasil

Cardu, Marilena; Giraudi, Alessandro; Oreste, Pierpaolo
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Rem: Revista Escola de Minas, vol. 66, núm. 3, julio-septiembre, 2013, pp. 375-382
Escola de Minas
Ouro Preto, Brasil

A review of the benefits of electronic detonators

Uma revisão das vantagens dos detonadores eletrônicos

Marilena Cardu
Department of Environment,
Land and Infrastructures (DIATI),
Politecnico di Torino, Italy.
IGAG C.N.R., Turin, Italy.
marilena.cardu@polito.it

Alessandro Giraudi
Department of Environment,
Land and Infrastructures (DIATI),
Politecnico di Torino, Italy.
alessandro.giraudi@piniassociati.com

Pierpaolo Oreste
Department of Environment,
Land and Infrastructures (DIATI),
Politecnico di Torino,
Italy. IGAG C.N.R., Turin, Italy.
pierpaolo.oreste@polito.it

Resumo

A perfuração computadorizada e a temporização eletrônica das detonações são dois avanços tecnológicos que têm tido um papel importante na atualização dos métodos de escavação com explosivos. Apesar disso, a temporização eletrônica dos detonadores ainda é uma solução técnica pouco frequente para problemas de detonação de precisão. Com base em uma extensa pesquisa bibliográfica, esse artigo revisa os resultados alcançados e as principais vantagens esperadas dos dispositivos eletrônicos de iniciação. Após descrever as características primárias desses detonadores, alguns elementos são considerados, a fim de que sejam melhor compreendidas as aplicações em diferentes condições, tanto em céu aberto quanto em subterrâneo, a extensão do número de tempos de retardo, a liberdade na escolha dos intervalos de tempo entre as detonações, a precisão da temporização, a redução das vibrações, o controle do overbreak e da fragmentação. Os resultados são comparados com aqueles obtidos por meio de dispositivos pirotécnicos de temporização e discutidos nas considerações finais.

Palavras-chave: Detonador eletrônico, detonador pirotécnico, perfuração e detonação, detonação de precisão, precisão na temporização.

Abstract

Computerized drilling and the electronic timing of detonations are two technological breakthroughs which have had an important role in updating drilling and blasting excavation methods, although the electronic timing of detonators is still a comparatively infrequent technical solution to precision blasting problems. On the basis of an extensive collection of published cases, this paper reviews the successes achieved and the main expected advantages from the electronic ignition devices. After describing the primary characteristics of these detonators, some elements will be considered, in order to better understand their applications in different conditions, both in open pit and underground sites: extension of the time delay number, freedom in the choice of time intervals between detonations, timing accuracy, reduction of vibrations, control of back-break and fragmentation. The results are compared to those obtained by pyrotechnical timing devices, and summarized in the concluding remarks.

Keywords: *Electronic detonator, pyrotechnic detonator, Drill &Blast, precision blasting, timing accuracy.*

1. Introduction

Electronic devices (ED) were developed from an idea originated in the 1990s. Till now, EDs have been developed in Italy during the testing stage. They can fulfil the demand for increased accuracy, but their costly technology has hindered their expected growth.

In an ED, delay is achieved electronically; a computer chip is used to control delay timing. An integrated circuit chip and a capacitor internal to each detonator control the initiation time.

An electronic detonator has a number of advantages, e.g. higher precision, improved blasting result owing to a wide range of delays, reduction of airblast/ground vibration, and safe use in extraneous electric environments, and the possibility of limiting the amount of detonators per shot. It has some disadvantages too, e.g. higher cost per detonator and the need for intensive training for users.

Conventional timing systems, to be compared to electronic timing, are listed in Table 1 and shown in the sketches (Figure 1). Electronic timing, in its turn, comprises electric detonators that include an ignition energy storage device and a programmable electronic timer, wired together with the programming, energy feeding and activation system. This makes it possible to decide freely, and obtain accurately, whatever distribution of detonation times is desired by the blast designer. Moreover, mixed systems (electronic + A_3, electronic + A_4) are possible.

Since the electronic detonators (and other components of the system, including the trained operator) are more expensive than conventional systems, the intrinsic advantages arising from the electronic timing option deserve to be weighted against the higher cost.

In Table 2, some relevant features of electronic systems are compared to

Systems	Components	Scheme
Electric with pyrotechnic delay elements	Blasting machine, wires, ignition pill, delay element, primary or special NP (Non Primary) charge	A_1
Electric with separate circuits powered in sequence	Blasting machine (including a timer), wires, ignition pill, primary or special NP charge	A_2
Non-electric with shock tube and pyrotechnic delay elements	Any source of priming shock, shock tubes, pyrotechnic delay elements, detonating primary or special NP charge (for branching and for main charge detonation).	A_3
Non-electric with detonating cord and pyrotechnic delay elements	Any kind of detonator, detonating cord, pyrotechnic delay elements (relays).	A_4
Safety fuse	Fuse ignition devices, fuse, blasting caps	A_5
Mixed systems	Most common: A_1+ A_2, A_1+ A_3, A_1+ A_4, A_5+ A_3, A_5+ A_4, but more complex system are possible	

Table 1
Commonly used timing systems.

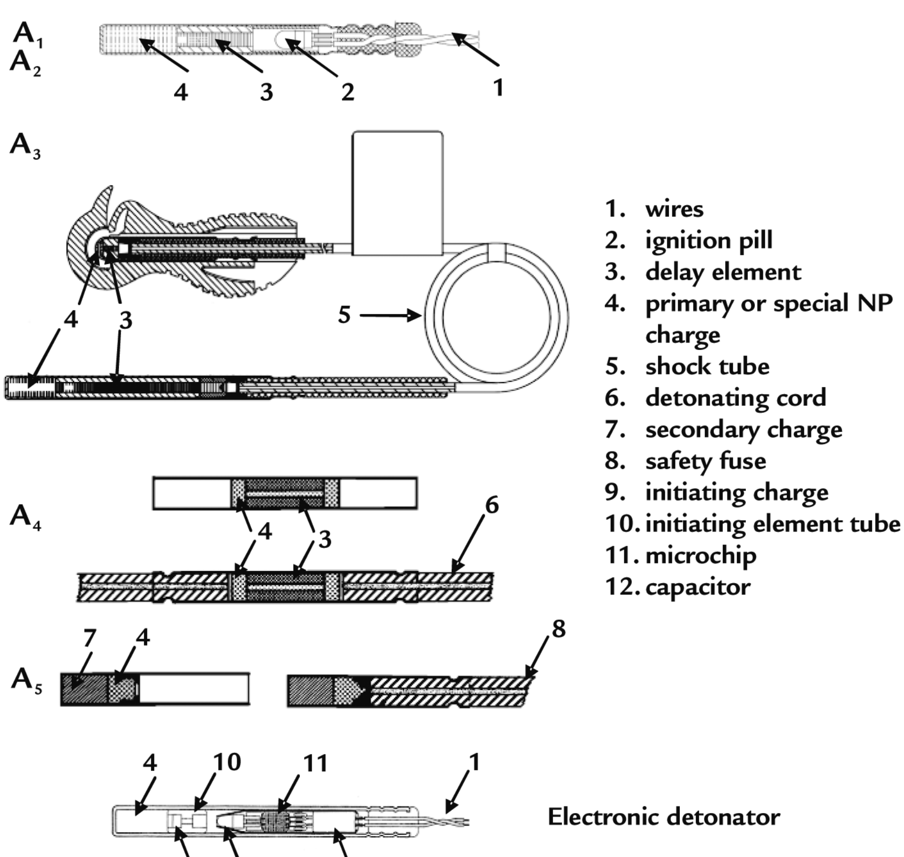

Figure 1
Sketches of conventional timing systems compared to electronic detonators.

	Electronic	A_1	A_2	A_3	A_4
Max number of possible detonation times	up to 3000 (up to 200 per line)	usually 20	up to 800 (up to 80 per line)	ideally unlimited	ideally unlimited
Accuracy in actual detonation time setting	± 0.1 ms	± 10 ÷ 20 % of the nominal interval	± 10 ÷ 20 % of the nominal interval	± 10 ÷ 20 % of the nominal interval	± 10 ÷ 20 % of the nominal interval
Duration of time intervals between explosions	min 1 ms	from 8 to 30 ms (SP) from 250 to 500 ms (LP)	min 1 ms	from 25 ms (SP) from 100 to 500 ms (LP)	
Number of detonators needed for a blast	the same as charges	the same as charges	the same as charges	the same as charges (not considering connecting units)	1 (A_1 or A_3 or A_5); dependent on the number of needed delays (A_4)
Max number of detonators that can be used in a blast	up to 3000	depending on blasting machine, up to 1000	up to 800	depending on connections, up to 200	ideally unlimited
Max duration of the blast	up to 15 s	up to 10 s	up to 16 s	up to 7 s	up to 4 s
Number of kinds of detonators needed for a blast	1 type	the same as detonation times	1 type	the same as detonation time	1 type (A_1 or A_3 or A_5); 1 type (A_4)

Table 2
Comparison of firing systems.

conventional systems. The safety fuse is disregarded, being used practically only in $A_5 + A_3$ and $A_5 + A_4$ mixed systems.

With regard to accuracy, there are some other considerations: flashover (owing mainly to inaccuracy in drilling and charging) is not affected by the timing systems; the detonation of a charge can last some *ms* to some *ms* depending on the explosive and the size of the cartridge; and inaccuracy of *ms* in the detonation starting time definition implies an inaccuracy of some metres in knowing the space travelled by a detonation front in the explosive, by a shock front in a rock, or by the tip of a propagating crack. In practice, in addition to the congenital inaccuracy due to type of explosive and to its geometry, the inaccuracy (even only a few ms) due to the timing sequence must be taken into account.

Moreover, geometrical and geomechanical details of the mean are described forcibly in a statistical way, which adds some uncertainty: absolute accuracy of the results' prediction is not possible, even when laboratory tests on artificial materials are carried out.

More information is available in literature (Reisz et al., 2006). The accuracy of detonation times, however, rules out a great number of random effects, provided that the same care is taken in refining the explosion timing, drilling, charging and stemming.

In general, accurate and flexible timing allows blasters to make small hole-to-hole and row-to-row changes to account for drilling inaccuracies. Adjusting the blast design to actual conditions can improve safety and fragmentation, which can cut costs by optimizing the loading and hauling cycle, increasing crusher throughput, and reducing the amount of oversize handling and secondary breaking.

A great advantage of this type of detonator is its safety in the case of any stray currents, radar radiation or other electromagnetic interference, as well as its safety in the case of misuse. It cannot be fired simply by a battery or by other electric sources.

In addition, precise and variable delay timing organization enhances highwall stability and bench crest preservation, resulting in safer mine operations and in lower blast-induced ground vibrations. These improvements allow for more accurate placement of boreholes for subsequent blasts. Optimization of the blast design to take greater advantage of the electronic detonators' precision expands the blast pattern and reduces the explosive consumption, without negatively affecting production (Sharma, 2009).

Electronic detonators are generally programmable in 1 *ms* increments and have a delay accuracy (scattering) as low as ± 0.1 *ms*.

Main blasting opportunities with electronic detonators are: frequency and peak particle velocity (*ppv*) control; large open pit patterns (long delays); easiness of multiple decking initiation (minimal delay intervals); large stope blasting; fragmentation optimization; and delay period re-evaluation.

Incorrect timing of explosions (too long or too small an interval) affects the blast result according to different mechanisms:

- Seismic effect may be increased because of unwanted cooperation, or because the actual burden of a charge exceeds the ideal planned burden (as the rock to be broken by the previous explosion should be still firmly in place) or because of positive interference effects.
- Fly rock throw can be increased, either because rock removal by the previous explosion is in a too advanced stage, or because it is still insufficient; in the first case, burden is too small, in the second is too high and the ejection of stemming can take place, due to gun-effect.
- A lack of balance of the actual burdens between the charges of the blast gives rise to localized backbreak effects and to irregularities of the residual face and irregular fragmentation, even when the ideally expected burdens are measured accurately.
- In multi-row blasting, when the breaking line of a row is the free (or "almost free") face of the next row, any irregularity causes further irregularity in the fragmentation.

The present work is the result of a detailed analysis of literature: some works refer to underground stopes, while others examine open pit mines and quarries. In order to evaluate the benefits from the use of EDs, the data considered (seismic effects, fragmentation, and overbreak) are defined in the following, in percentage terms, according to the ratio (1):

$$\text{value \%} = \left(\frac{\text{data ED}}{\text{data PD}} - 1\right).100 \tag{1}$$

2. Opencast works

The study by Sharma (2009) examines the structural response to blast-induced ground vibration. He underlines the importance, from an environmental point of view, of minimizing vibrations induced in urban dwellings by blasting. The maximum response of a building to blast-induced ground vibration occurs whenever the frequency of the ground vibration matches the natural resonant frequency of the structure: if there is little or no energy at the resonant frequency of the structure, the structural response to the vibration will be negligible.

By choosing delay times (Δt) that create "destructive interference" at frequencies that are favoured by local geology, the vibration that excites structural elements could be reduced. In this method, accurate delay times are crucial for effective vibration control. Electronic detonators have less than 1 *ms* scatter. In this light, researchers have started to find both limitations and different potential in this new technique of controlling blast vibration.

The computer analysis determines the application of delay timing between holes, rows and decks which would produce the most favourable blast-induced vibrations for buildings and urban dwellings.

In Table 3 and Figure 2, data pertaining to ED and to pyrotechnic detonators (PD) are shown.

A reduction of the *ppv* is noticeable when ED are used: this trend is shown in Figure 2, where scaled distances are plotted against peak particle velocities; data refer to 18 blasts that were fired during testing on site, 9 of them with PD and the rest with ED.

The study by Bartley et al. (1998) refers to the employment of a 60 kg/hole charge per delay (cpd); the events were monitored at a distance varying from 400 m to 822 m. Deacon et al. (1997) refer to another case, in which the cpd were in the 20-46 kg/hole range using PD, and in the 16-20 kg/hole range using ED; the events were monitored at a distance of 140 to 180 m (using PD), and from 130 to 160 m (using ED).

During mining operations in a South African quarry (quartzite and sandstone) McFerren et al. (2004) adopted ED and PD (shock tube). The *cpd* was 230 kg and the powder factor was 0.42 kg/m^3. The *ppv* monitored by Chavez et al. (2003) are the results of the blast with the comparison of ED vs. PD, with interhole delays of 12 ms in a French limestone quarry. In the same paper, the reductions of *ppv* generated by ED in another quarry are reported; 40 to 55 % with respect to the *ppv* obtained by PD.

Few authors evaluate the frequency increase when EDs are employed. In particular, by using the relation F = 1000/delay to get the dominant frequency, the expected value of the frequency can be calculated (Deacon, 1997; Chavez, 2003).

As shown in Table 4, by adopting ED instead of PD an increase of frequency values is observed.

Also, the airblast levels were recorded by Baka Abu (2002) and McFerren et al. (2004) during mining operations. The first author obtained these results: the airblast levels were reduced from 127 dB to 108 dB (-15 %) using ED instead PD. McFerren et al. (2004), during blasts initiated with ED instead of PD, observed a reduction of 3 %.

Another comparison between ED and PD is the rock fragmentation degree obtained from the blast (Table 5).

Grobler (2003) refers to the results obtained in surface mining, particularly on the log-linear plot of muck pile; ED produced a reduction in the upper size and the fines. In contrast, the grain size distributions related to ED, evaluated by König et al. (1994) and Havermann et al. (1995), are systematically higher compared to PD.

The study by Bartley (2001) of the post-blast muck pile excavation indicated a 25% reduction in dig time using *ED*.

Authors:		*ppv* Min			*ppv* Max		
		ED	PD	%	ED	PD	%
Deacon C., Duniam P., Jones M., 1997		8.85 mm/s	12.18 mm/s	**-27**	13.54 mm/s	25.8 mm/s	**-47**
Bartley D. A., Trousselle R., 1998	Rad.	0.25 mm/s	0.51 mm/s	**-51**	5.21 mm/s	5.72 mm/s	**-9**
	Vert.	0.25 mm/s	0.38 mm/s	**-34**	4.06 mm/s	3.94 mm/s	**3**
	Tran.	0.64 mm/s	0.76 mm/s	**-16**	7.49 mm/s	10.7 mm/s	**-30**
Bartley D. A., Winfield B., McClure R., Trousselle R. 2000	Rad.	4.57 mm/s	3.3 mm/s	**38**	8.89 mm/s	5.84 mm/s	**52**
	Vert.	2.54 mm/s	3.3 mm/s	**-23**	6.1 mm/s	4.57 mm/s	**33**
	Tran.	2.79 mm/s	5.08 mm/s	**-45**	14.2 mm/s	7.11 mm/s	**100**
\\ R., Chantry R., 2003		3.0 mm/s	3.8 mm/s	**-21**	5.0 mm/s	9.8 mm/s	**-49**
McFerren W., Moodley P., 2004		0.13 mm/s	0.8 mm/s	**-84**	24.3 mm/s	152.0 mm/s	**-84**

Table 3
Comparison between different *ppv* values, using ED and PD firing systems separately.

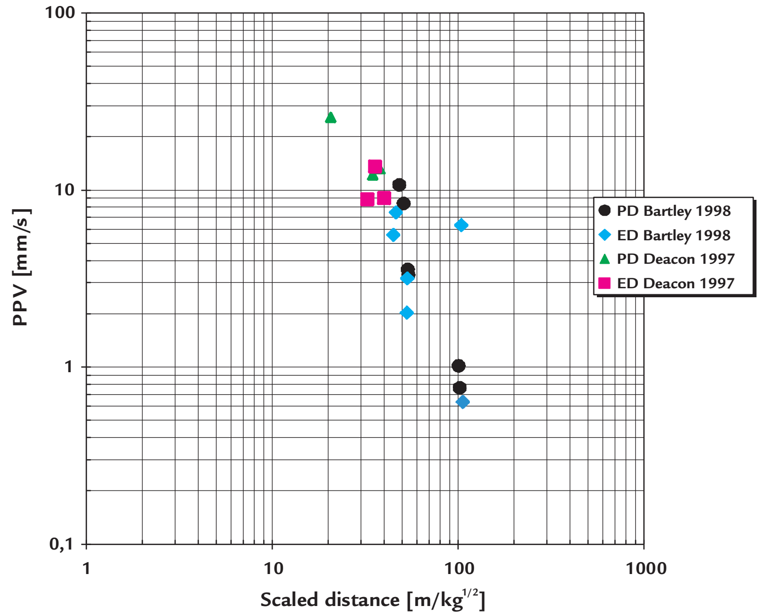

Figure 2
The *ppv* data from Deacon et al. (1997) and Bartley et al. (1998) have been processed to obtain a comparison between ED and PD.

Table 4
Comparison between different frequency values using ED and PD firing systems separately.

Authors	ED	PD	%
Bartley D. A., Trousselle R. 1998	26 ÷ 64 Hz	20 ÷ 47 Hz	30 ÷ 36 %
Carter R. A., 2002	26 ÷ 39 Hz	8 ÷ 20 Hz	> 95 %
Bartley D. A., Winfield B., McClure R., Trousselle R., 2000	13 ÷ 63 Hz	19 ÷ 55 Hz	-31 ÷ 15 %
McFerren W., Moodley P., 2004	30 ÷ 71 Hz	26 ÷ 57 Hz	15 ÷ 25 %

Table 5
Rock fragmentation as a result of a blast, considering ED and PD, respectively.

Authors	Max Size			Mean Size			Min Size		
	ED	PD	%	ED	PD	%	ED	PD	%
Havermann T. et al., 1995	1500mm	1800mm	**-17%**	255mm	410mm	**-38%**	60mm	100mm	**-40%**
Deacon C., Duniam P., Jones M., 1997	680mm	900mm	**-24%**	125mm	200mm	**-37%**	20mm	50mm	**-60%**
Bartley D. A., Trousselle R., 1998	1115mm	1485mm	**-25%**	236mm	291mm	**-19%**	13mm	21mm	**-38%**
König R., Petzold J., 1998	1100mm	1500mm	**-27%**	250mm	400mm	**-37%**	75mm	100mm	**-25%**
Petzold J., Hammelmann F. 2000	812.8mm passing			406.4mm passing			202.3mm passing		
	78.30%	63.20%	**19%**	34.90%	24.10%	**45%**	9.40%	4.80%	**96%**
Bartley D. A. et al., 2000	-						203mm passing		
				214mm	320mm	**-33%**	76.70%	55.90%	**-37%**
Mckinstry R., Floyd J., Bartley D., 2002	90 % passing			50% passing			10% passing		
	3.98 *	7.07 *	**-44%**	2.87 *	2.92 *	**-2%**	1.44 *	0.99 *	**45%**
Grobler H. P., 2003	90% passing			50% passing			10% passing		
	500mm	750mm	**- 33%**	70mm	70mm	**0%**	10mm	3mm	**233%**
McFerren W., Moodley P., 2004	53mm sieve aperture			13.2mm sieve aperture			2mm sieve aperture		
	10%	17%	**-41%**	50%	75%	**-33%**	90%	95%	**-5%**

* (block size, diameter of the equivalent sphere).

Moreover, the crushing operations show a reduction of electric power consumption (kWh/t) of about 6–10 % if EDs are employed.

When EDs are employed, thanks to the improvement of the fragmentation, the block size distribution is upgraded (in comparison with PD) as follows:

- maximum block size: reduction of 24 %.
- mean size: reduction of 25 %.
- minimum size: reduction of 10 %.

3. Underground works

In the last 15 years, some applications of the electronic detonators have been developed, to be employed underground, especially in tunnelling. In some cases, electronic devices can be used even in mixed systems, as shown in Figure 3.

The study by Svärd (1993) refers to the employment of a 3 kg/hole charge per delay (*cpd*), while Thomasson (2000) describes an event in which a 400 g/hole *cpd* was adopted.

Cho (1997) refers to another case, in which the *cpd* were in the 125–500 g/hole range in case of PD, and in the 125–375 g/hole range in case of sequential blasting. The events were monitored at a distance of 20 to 33 m (in the case of PD), and from 21 to 42 m (in the case of sequential blasting). See Table 6.

Some experimental blasts were carried out by Wetherelt (2007) for a comparative study of *ppv* in a tunnel. In the first blast, PDs (non electric detonators) were employed, while in the second EDs (with the same delay times as in the previous case) were used. The results obtained by monitoring ground vibrations are shown in Figure 4; the *cpd* employed for the tests was 1.60 kg.

The comparison of an ED vs PD firing system in underground mining activities is not so relevant in terms of muck-pile fragmentation (see Table 7), as quoted by Tose and Baltus (2002).

The authors, whose works are quoted in Table 8, point out that an improvement of the blast's precision and a reduction of the overbreak is noticeable, thanks to the employment of electronic detonators. In tunnel driving, more advantageous results can be obtained in the quality of the blast: overbreak lowers by more than 40 %, by resorting to the mixed system ED-PD, realized by adopting PD for the cut and for the stoping holes and ED for the contour holes. EDs are employed most of all in the contour holes, if they have to be fired simultaneously.

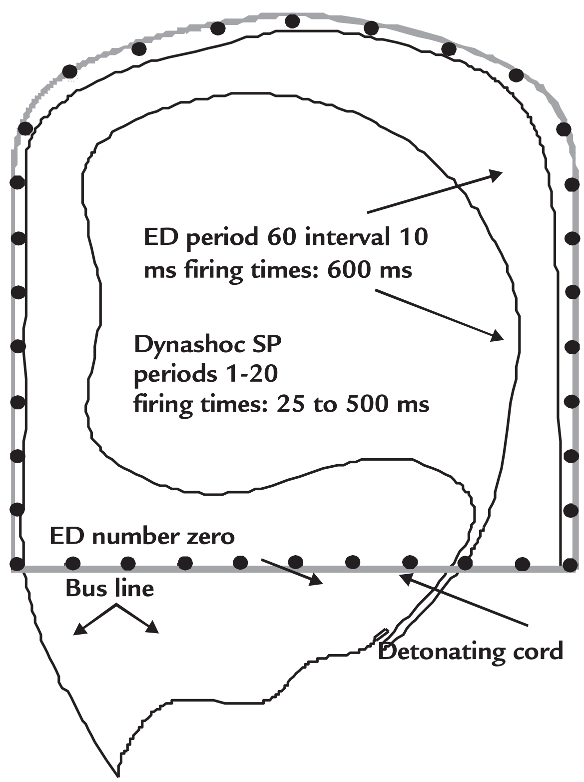

Figure 3
Priming pattern by employing the mixed system ED-PD (König R., 1994, Modified).

Authors		ED (mm/s)	PD (mm/s)	%
Svärd J., 1993	33 caps per round	4	8	**-50**
	44 caps per round	9	16	**-44**
Thomasson C., 2000	-	7	12.1	**-42**
Cho Y. D. et al., 1995		sequential blasting	-	**-14 ÷ 18**
Wetherelt A., 2007		2.25 - 65.02	0.83 – 45.72	**40 ÷ 292**

Table 6
Comparison between different ppv values by using ED and PD firing systems respectively.

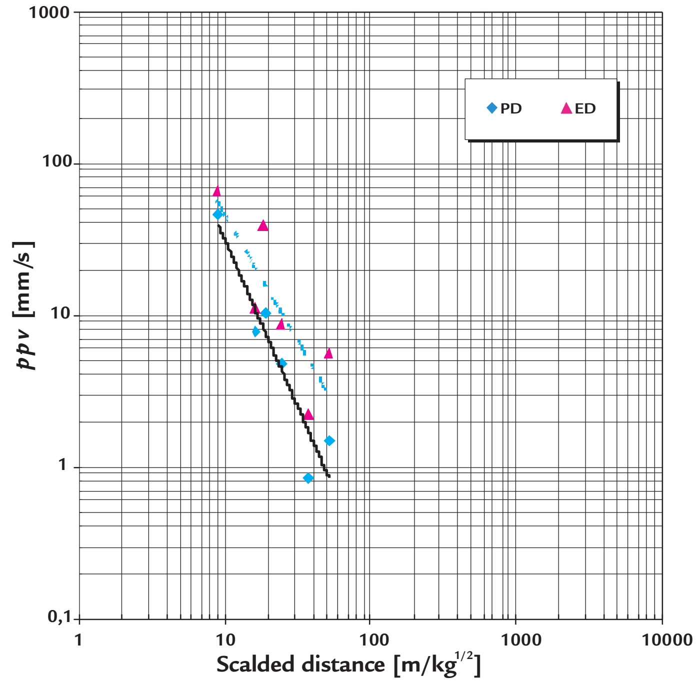

Figure 4
ppv data (taken from Wetherelt A. 2007) have been processed to obtain a comparison between ED and PD.

Table 7
Rock fragmentation as a result of a blast, considering ED and PD, respectively.

Authors	Size	ED	PD	%
Tose S. J., Baltus C., 2002	1000 mm	98.8 %	98.2 %	**1 %**
	300 mm	72.8 %	77.4 %	**- 6 %**
	25 mm	6.3 %	6.1 %	**3 %**

Table 8
Comparison between different profile accuracy values using ED and PD firing systems separately.

Authors	Profil		
	ED	PD	%
Stratmann M. ,1996	10 cm	25 cm	**-60 %**
Fauske A., 1998	-	-	**-60 %**
Bleuzen Y. et al.,2005	-	-	**-30 %**
Yamamoto M. et al., 1995	-	-	**-6 %**

4. Conclusions

The results of this review show that the employment of EDs is advantageous in terms of vibration reduction, increased frequencies, airblast, improved fragmentation in the muck pile, diggability, crushing cost saving (less energy used during the primary and secondary fragmentation), and control of overbreak, which allows greater profile accuracy. Nevertheless, EDs' advantages are satisfied where an accurate design of the blast and an adequate hole's drilling and charging are guaranteed.

As discussed, the electronic detonators provide more accurate timing than the conventional pyrotechnic detonators which rely on the combustion speed of a pyrotechnic composition. The timing accuracy capability of the electronic detonator allows for:

- More efficient application of explosive energy.
- Improved muck size uniformity.
- Increase in excavation productivity.
- Cost saving in excavation operations.
- Improved public acceptance of blasting.
- An additional benefit of electronic detonators. i.e. the improved control of blast-induced vibrations and airblast.

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Artigo recebido em 28 de junho de 2012. Aprovado em 28 de março de 2013.