DIGITAL TUNNEL BLASTING IN A SENSITIVE ENVIRONMENT: N1 PORTO TUNNEL PROJECT, PORTUGAL

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ABSTRACT

The N1 Porto tunnel project is a 650m segment of large-scale civil engineering plan to improve traffic flow between Porto's downtown district, the Santo Antonio hospital district and the highway access. The tunnel is being excavated into a massive "Granito do Porto" granite structure, 4 – 20m below a highly urbanized environment of Porto, Portugal.

The project was originally started in 2000 and was stopped due to the inability to mechanically excavate the granite rock. The city of Porto engineers then turned to traditional drilling and blasting techniques. The use of pyrotechnical delay detonators did not easily comply with the specified environmental and safety requirements concerning blast charging, firing and vibration control resulting in the process taking far too much time. The introduction of digital blasting was proposed to overcome these concerns.

The tunneling operations started again on January 2004 with 50Kg and 1.0m (3.3 ft) blasts 4.5m (15ft) below Porto building foundations. The use of the Daveytronic digital blasting system improved the tunnel advance rate, +190% in sound granite. An overall reduction of 60 operating days in the duration of the excavation of the upper section of the project was reached, while maintaining all specified environmental standards. This timesaving will permit the contractor to complete the tunnel construction in the City of Porto specified period of one year.

INTRODUCTION

The city of Porto required a large-scale civil engineering plan to improve transportation in both downtown and the surrounding districts. This ambitious plan includes both underground railways lines and four road tunnels projects.

As part of this plan, the tunnel N°1 Project, located downtown in a high-density urbanized area was scheduled to be excavated in one of the numerous granite hills in the city. The tunnel is designed as a by-pass through the top of the hill, establishing a one way road to improve the traffic in the Hospital Santo Antonio's district.

DIMENSIONS OF THE PROJECT, GEOLOGY AND ENVIRONMENTAL REQUIREMENTS

The tunnel is a 650 m (2080 ft) overall length project, including a 400m (1280 ft) underground drill and blast excavation of a 100 m2 (10 240 sqft) section. The figure 1 below shows the tunnel layout in its highly urbanized environment.

Fig 1 : Aerial view of the tunnel layout in its urban environment

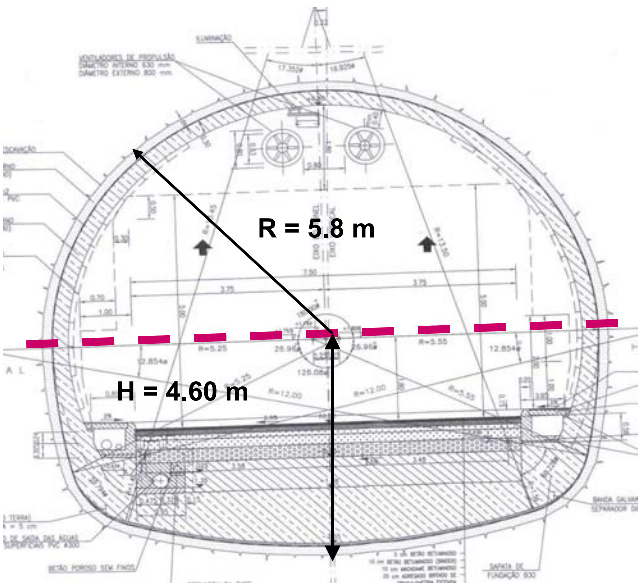


Fig 2: Tunnel cross section

The top part of the section is half cylinder shaped with an external radius of 5.8m downward continued by a multiple radius section. The average top half section is 55 m2 (563 sq ft) and the average bottom section is 45 m2 (461 sq ft, see Fig 2). The technical definition of the project assumes an excavation in two steps, upper half section first followed by the bottom excavation. The dash line in the section drawing defines the limit between both top and bottom sections.

The excavation was performed in a granite intrusion rockmass, the general shape of the geological cross section shown below (fig 3), shows the main geotechnical units. Six different units were defined from 100% sand and clay, to over 90% of sound granite.

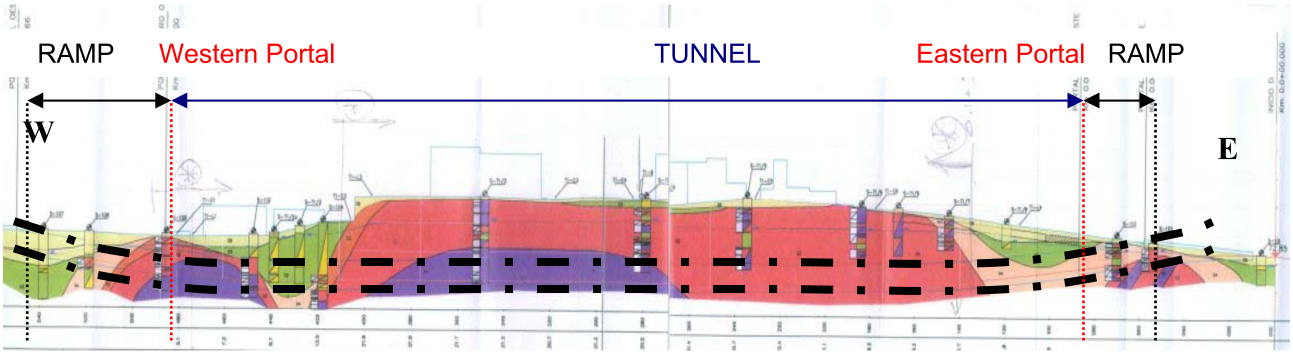


Fig 3: Tunnel geological cross section. Color scale varies from yellow for 100% sand and clay up to purple for over 90% of sound granite.

Despite exploratory research, using geophysics and drilling, the local geology remained fluctuating at the local/blast scale. This affected the basting conditions especially in the first 100m (300ft) on the west front and the first 60m (180ft) on the east front. The local geology defined the excavating method between drilling and blasting for partial or complete section in sound rock and mechanical excavation in clay, sand or highly weathered granite. This led to very different excavating rates from the West front, where the lithology is mainly sand clay and weathered granite, and the East Front where the sound granite was encountered faster.

The tunnel overburden varied throughout all over the excavation layout with a lower value of 4.5m/13.5ft at PK 487, western portal, and a maximum value of 23m/69ft. The graph below (fig 4) shows the overburden versus PK. It also clearly appears that the low overburden is associated with the weathered lithology.

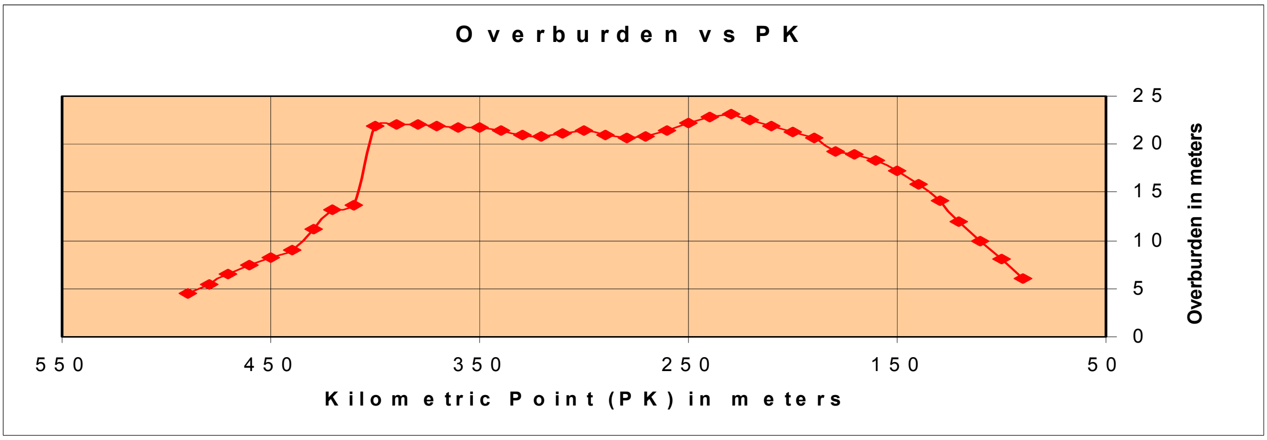


Fig 4 : Tunnel overburden

This environment, both regarding geology, topography and high density urban area, led the project managers to require high degree of pre reinforcements and vibrations control. The vibration limitation was settled by the Portuguese regulation NP 2072 and set at 20mm/s (0.78 in/s), without any frequency specification. Seismic measurements will also be complemented by extensometers and ground level monitoring.

DIGITAL BLASTING SOLUTION

Looking for the appropriate excavation method in this particular environment, the City of Porto project designers ordered a complete study to define the maximum explosive charge per delay and blast size in the drilling and blasting option (Carvalho & al, EFEE, 2003). The resulting technical definition based on pyrotechnic delay detonators and required blasting the upper part section in 4 steps. Blast holes had to be drilled at 1.5 m length maximum using 38 to 42 mm diameter. This method, illustrated by the cross-section below, would result in over 1000 blasts for the excavation of the upper section. This implied a low excavating rate of 1.5 m (4.5ft) per day maximum in the best rockmass and worksite conditions (fig 5).

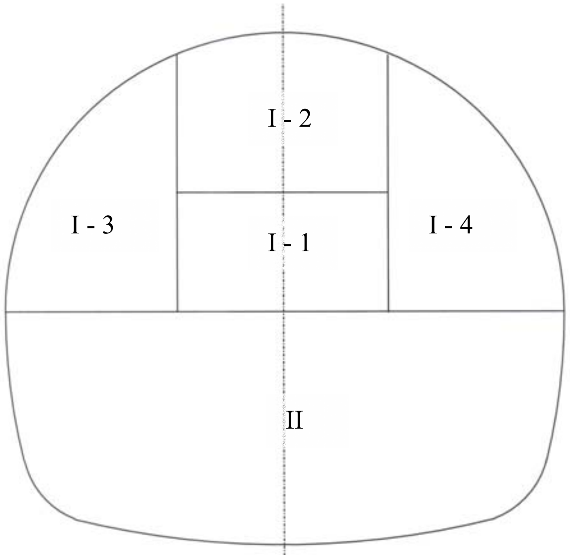


Fig 5 : Pyrotechnical delay detonators blast process

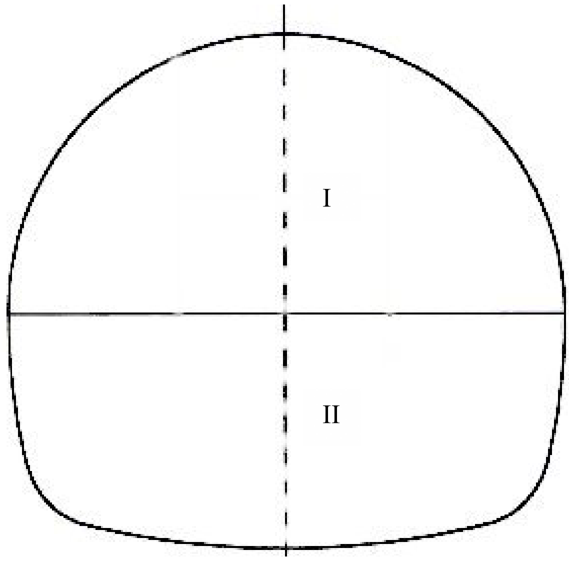


Fig 6 : Digital detonators blast process

At this stage, the digital blasting solution was not taken in account because it was considered as a very new technology with a lack of feedback regarding implementation in this type of civil engineering worksite. Overcoming this, one of the contractors decided to propose a solution based on digital blasting supported by the proper technical assistance of the supplier. Digital blasting capabilities promoted the four following points:

- Proper separation of each single blast hole detonation to reduce at its minimum the charge per delay in the most sensitive areas and on the other hand to optimize productivity in sound rock.
- Flexibility of digital system enabled the blast pattern design for every site condition (frequency control, rock mass reaction …)
- Possibility to provide day to day pattern design evolutions without creating any worksite delivery and storage problems
- Blasting the entire upper section in a single blast, to increase productivity (fig 6).

The aim of the design proposed by Nitro-Bickford after a technical study led to a solution fulfilling the contractor's needs to perform two blasts per day. According to an 1.5 m (4.8 ft) drill length minimum in good rock mass conditions so an excavating rate of 3.0 m (10 ft) per day on each front, a decrease of 75% of the number of blasts and an excavating rate increase by 100 % was expected. This solution allowed building the tunnel in the one year time limit planned by the City of Porto to realize this project. This contractor, Spie Batignolles Europe / FCC Construccion, was finally chosen by the City of Porto to conduct this project, using the digital blasting technology with the dedicated blast design engineering at each stage of the project and the appropriate contractor's crew training.

FROM TRIAL BLASTS TO FULL SECTION ROUNDS

In order to refine the blasting pattern design with respect to the site conditions, a series of tests blasts were organized early December 2003. This operation allowed us to establish the site wave propagation law in the very the short range of 0 to 30 m (0 to 90 ft) using single charge configuration and followed by a burncut blast. All these blasts were extensively instrumented while implementing 6 single point 3D seismic recorders. The figure 7 below shows an example of location and coupling of the seismographs.

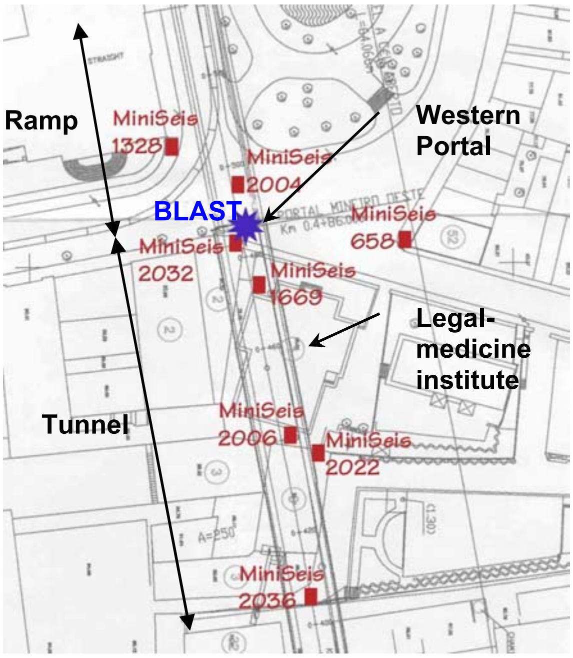


Fig 7 : Trial blasts and seismographs location

Seismograph coupling at the LMI building

The equipment (Miniseis from Larcor / White) was adjusted to 2048 Hz sampling rate, 4 seconds recording duration and equipped with 8 Hz geophones electronically corrected at 1 Hz. Six blasts were monitored and their seismic recording results allowed us to statistically define the seismic law for this zone, based on the international standards for vibration prediction, primarily Langerfors (Sweden) and Chapot (France) theories :

$V = 3380\left(\frac{D}{\sqrt{Q}}\right)^{-1.90}$ (0.92 correlation), where D is the distance in meters and Q the blasted charge in Kg

This formula permitted to calculate the maximum charge per delay allowed with respect to the distance, burncut blast was done utilizing these results.

Fig 8 : Burncut trial blast *Tunnel crew at the shot firing point*

The seismograph trace below (fig 9) shows the recording at the Legal Medicine Institute, on the external part of the building foundations, corresponding to the burncut trial blast (fig 8), with a maximum PPV value of 11,8mm/s 0.46in/s at 15m distance on vertical direction.

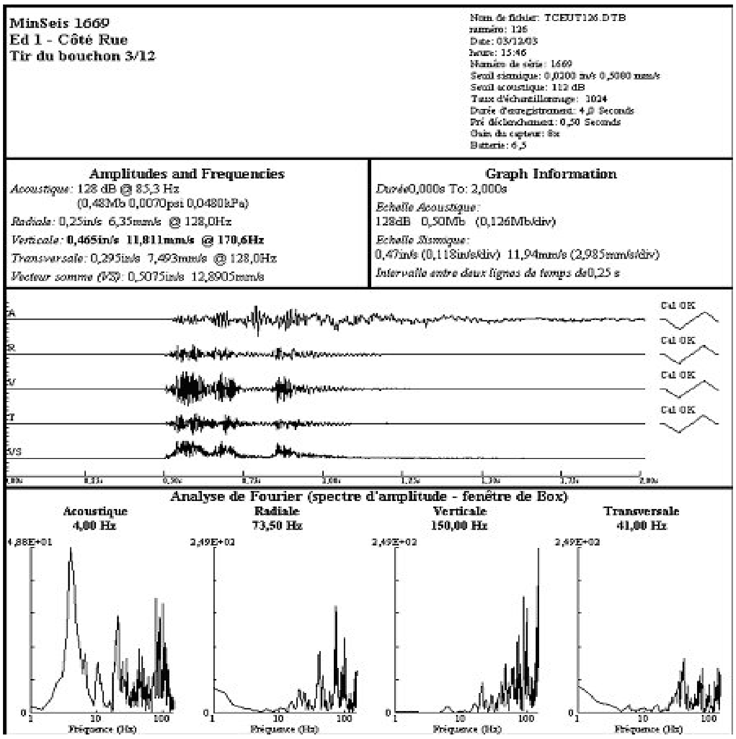


Fig 9 : Seismic record of the burncut trial blast

The results of the trial blasts were:

- A lower than 20 mm/s (0.8 in/s) PPV for a 250g charge per delay at 7 m distance from the blast.
- Seismic traces showed high frequency contain allowing for the shorter distances higher PPVs without potential damage on the existing structures due to the low displacement.
- The signal at the burncut showed a separation between every hole that confirmed there was no pyrotechnic scatter and energy cumulating due to the precision of digital blasting system.
- The result of the burncut blast confirmed the design geometry and the loading of the burncut.

After these test blasts, the next step to reach was the realization of an entire upper section blast. This was conducted gradually in order to confirm the first results in vibration and the mechanical resistance of the roof. Four blasts were organized to reach the first entire section round:

1. Lower part of the section without burncut (previoulsy blasted)
2. Upper part of the section
3. Lower part including burncut
4. Upper part
5. Full section

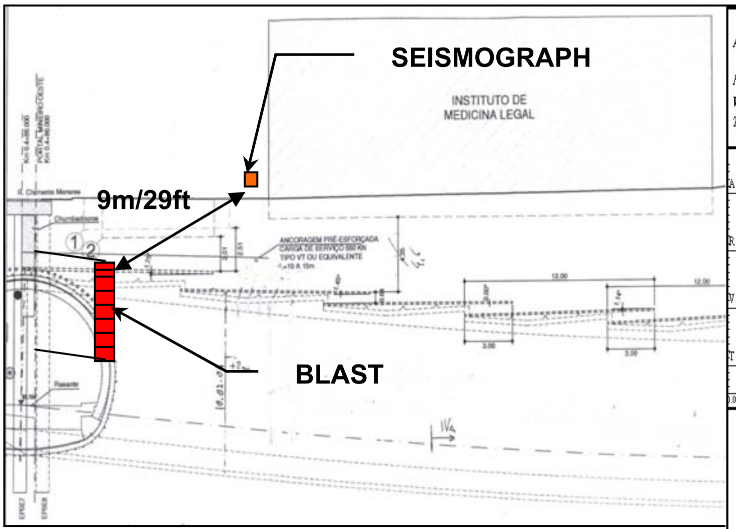
Each of these blasts where monitored and analyzed for the test blasts that allowed us to determine precisely the blast regarding the PPV, frequency contain of the signal and induced displacement. The White 2003 software was used to check precisely the time of the PPV peaks.

Due to the accuracy of the digital detonators used, the time of each peak was easily correlated to the related hole and design evolutions were made step by step up to the final blasting pattern. The main improvements involved changes in the sequence in the upper part of the section to avoid energy cumulating close to building foundations and adjustments to the explosive loading in the same area. We also increased the explosive charge in the floor row and the burncut to improve the blast result as no peak was recognized from these holes. Once these evolutions were completed the blasting pattern gave satisfactory and constant vibration results well correlated to the prediction formula determined during the trial blasts. No damage occurred to the buildings under crossed, especially the LMI building whose foundations where located 4.5 m above the tunnel roof.

The final blasting pattern was defined after about 10 blasts with the following characteristics:

- 160 boreholes
- Drilling length 1.0 m
- Unit charge :
    - Burncut and lower rows : 375 g
    - Upper part : 250 g
    - Contour hole : 125 g and detonating cord
- Total charge : 62 kg
- Overburden in the west front : 4 to 5 m
- Vibration measured (fig 10 & 11):
    - PPV at 6 m : 30 mm/s (1.18 in/s)
    - PPV at 15 m : 10 mm/s (0.40 in/s)

On February 13th, 3 weeks after the 1st blast, 2 blasts were performed the same day. The digital blasting solution reached its goal in doubling productivity.



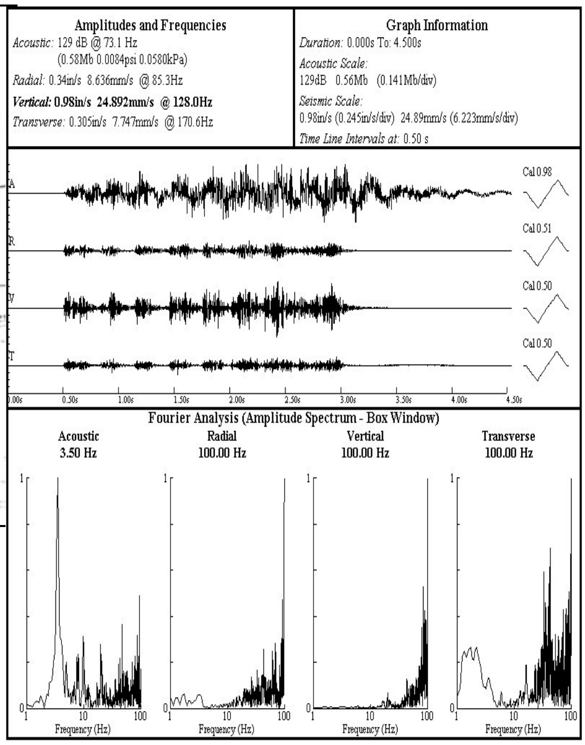
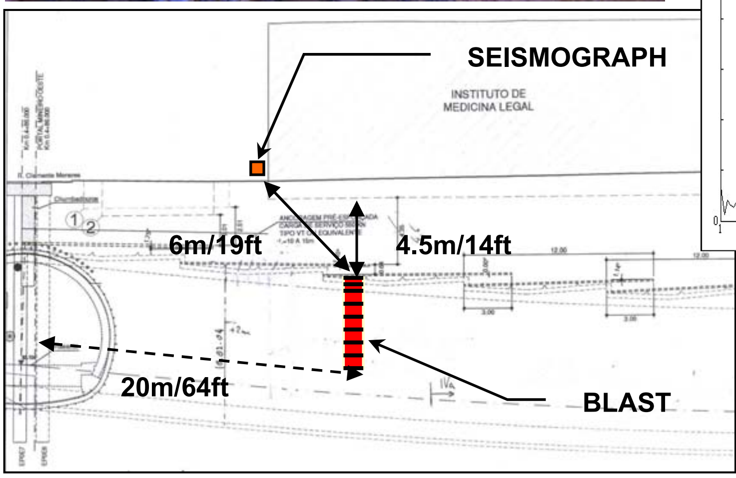


Fig 10 : Above, an example of full section round approaching the LMI building.

Right the corresponding seismic recording.



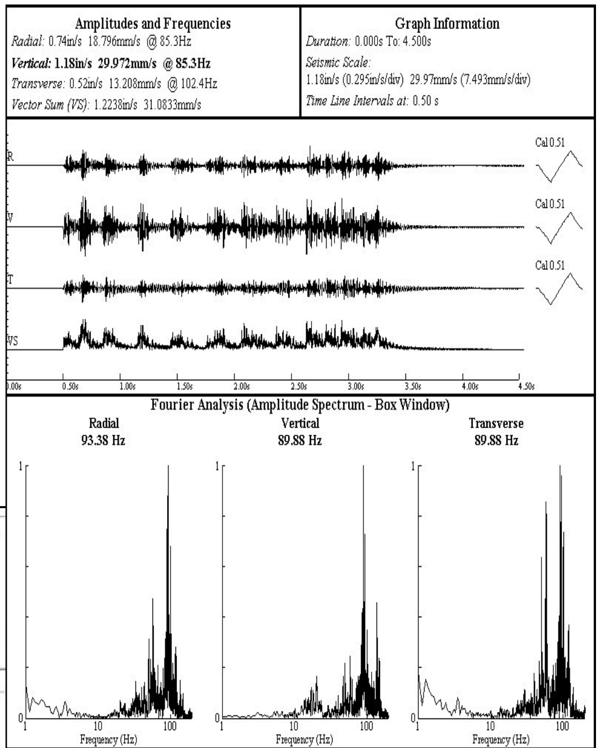


Fig 11 : Blast below the LMI Building
Left high: blast result
Left: Location
Above: corresponding seismic recording

EXCAVATION PROGRESSION

Drilling and blasting were dependent of the local geology which influenced the excavation technique and rate. At the western portal, after 30 m (90ft) of sound granite, the geology turned into weathered granite with an increasing content of sand and clay, both with increased water infiltration. This terminated the drilling and blasting excavation in this front from end of March to July, for mechanical earthmoving. Necessary pre-reinforcements were executed in order to prevent any potential collapse of the gallery roof. These very difficult conditions explained the minor gain realized on this side of the tunnel. On the other hand, the eastern front first encountered 80 m (240ft) of a mix of highly weathered granite sand and clay in the upper part of the section both with hard rock at the bottom. Then a quick and definitive transition into the sound rock allowed an increasing excavation rate, which permitted to make up for the difficulties faced by the western excavation.

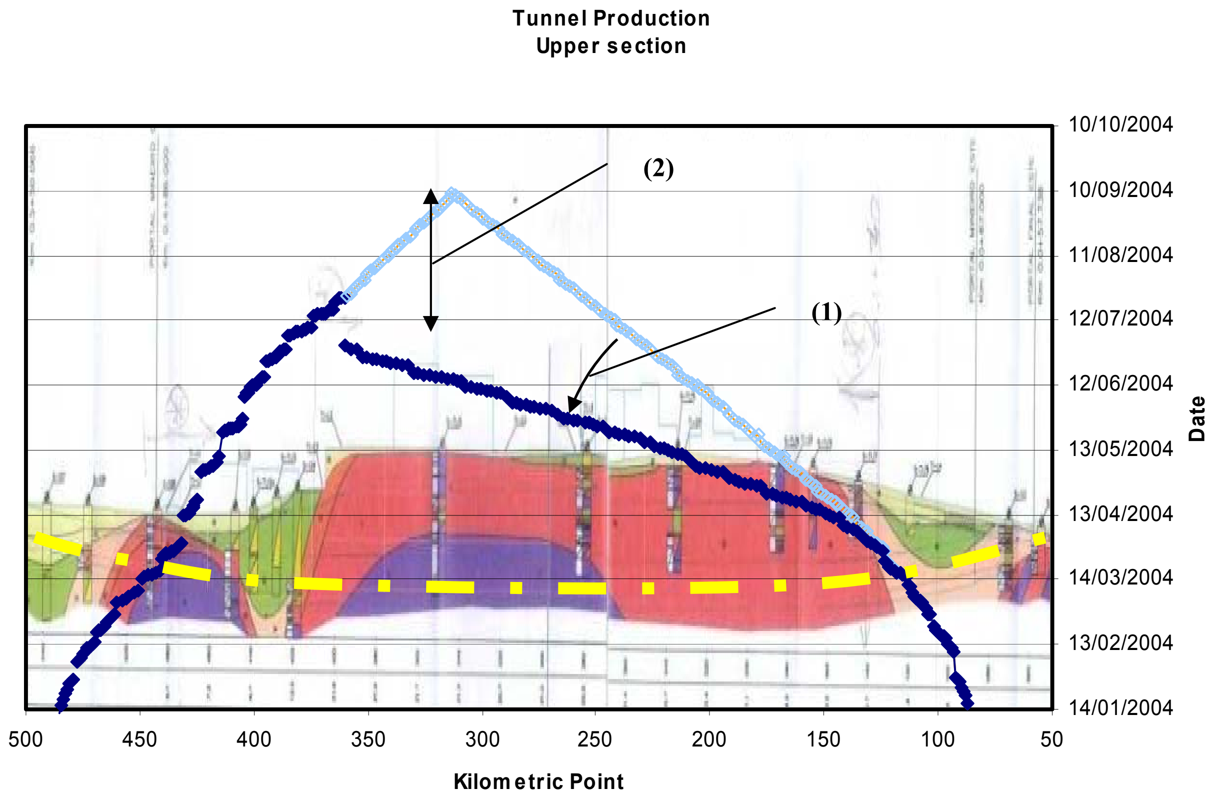


Fig 12 : The graph above shows this production increase with a comparison of the initial project excavation (light line) rate and the realized rate (dark line). The yellow dash line figures the tunnel layout. The geological conditions that slowed the excavation on the west front and at the early stages on the east front were re-introduced in this model to calculate geology-corrected data for the initial project.

It clearly appears that the productivity gain was created in the central sound granite (red and purple) zone from kilometric point 130 to 360, with the following results:
(1)An increased productivity of +190% in sound rock.
(2) An expected global excavation time saving of 60 days.

On the east front, from January 14th to March 30th, the average advance per round was 1.0m (3.2ft). Then from April 1rst to June 30th , corresponding with the kilometric point 110-120 to 360, the tunnel entered into the main sound granite rockmass both with an increased overburden over 10m (32ft). The advance per round increased to an average value of 2.2m (7 ft), this meant a production rate of 4.4m (14 ft) per day. In this particular zone of the excavation, compared to the initial project the production (1.5m/5ft) rate grew + 190%, while maintaining all environmental standards. In order to establish this calculation, we assumed that no significant difference in excavation rate occurred in the highly weathered zones. And that the main production gain was recorded in the central sound zone of the tunnel excavated from the eastern portal. This is illustrated by the graph (fig 12, previous page), where data are displayed over the geological cross-section.

The conjunction of sound granite and increased overburden allowed the growth of the blasts parameters up to the following maxima:

- Drilling length: 2.5 m (8 ft).
- Unit charge: 1.5 kg.
- Total charge per round: 190 kg.
- PPV: 15 to 20 mm/s (0.6 to 0.8 in/s) on the building located at 20 m up the blast.
- Peak excavating rate: 2 blasts per day, 5.0 m (16ft) advance per day, 27.5 m (88 ft) per week.

On June 30th the upper section excavation was stopped on the east front and the junction was conducted from the west front on July 22nd. With respect to the hypothesis mentioned above for the graph data processing, we assume that a minimum of two months have been saved without taking into account the potential benefit on the bottom section excavation this means a global reduction of 30% in the upper section excavation leading to the related cost savings for the contractors.

The excavation of the tunnel was completed end of September 2004. The bottom section was blasted using 3.5m (11ft) advance per round instead of 2.0m (6.5 ft) planed in the initial project.

ENVIRONMENTAL MONITORING

The urbanized environment of this worksite required continuous environmental monitoring. The implemented measurements were related to vibration monitoring, ground topography surveys, ground extensometers. Each blast seismic vibrations were monitored at 4 points. Seismograph locations were following the tunnel advance and dedicated to the most sensitive building surrounding the underground blasts. The seismic signal is analyzed when the PPV value was exceeding 15 mm/s (0.6 in/s). The graphic (fig 13) shows the PPV recorded versus excavation. Except for the values related to the early stage of the excavation on the western portal, Kilometric Points from 430 to 490, the PPV value maintained the limitations of the Portuguese regulation, with very consistent values once in the sound granite from kilometric point 120 to 360. The precision of digital detonators ensured suppressing the inaccuracy due to pyrotechnical delays and led to this regularity. Combined with an accurate drilling, the only parameter that remained fluctuating was the local geology.

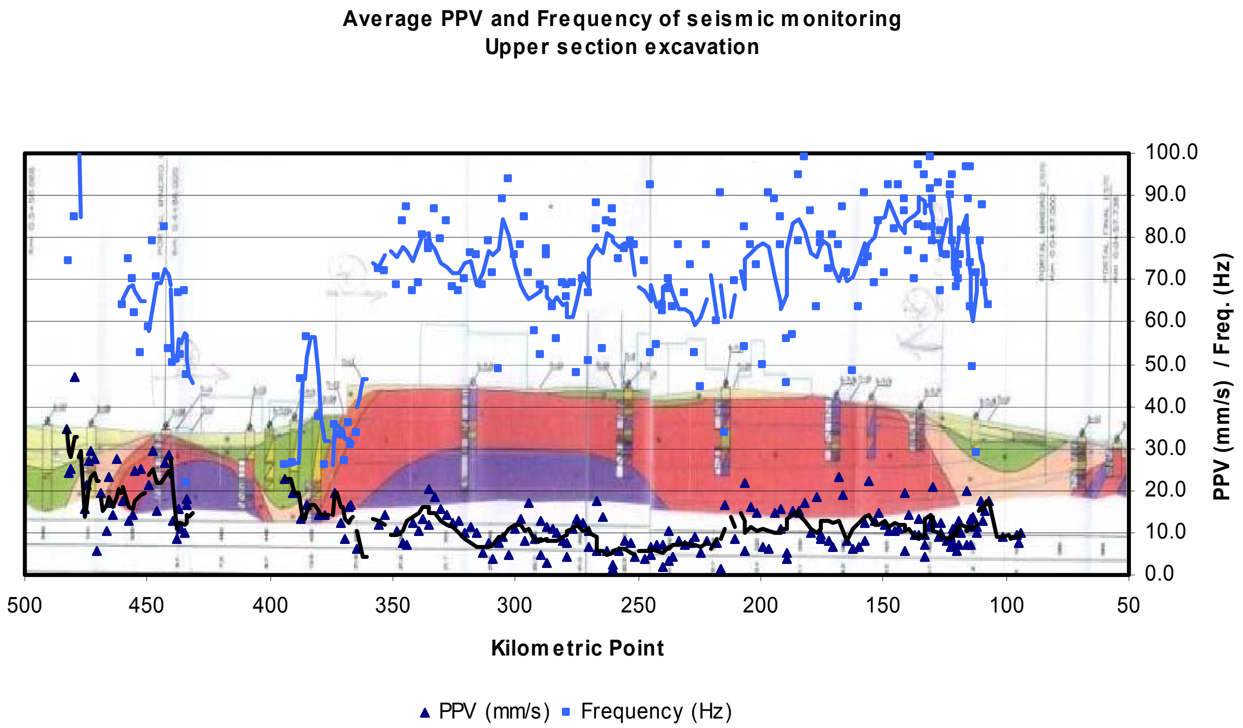


Fig 13 : Average PPV and frequencies versus Kilometric point of the seismic monitoring.

The high frequencies dues to proper charge separation induced low displacements. For example, at an average frequency value of 70 Hz, a PPV of 20 mm/s (0.8 in/s) generate a 45µm (1.8 10^{-3} in) displacement. No environmental damage was related to the blasting activity.

CONCLUSION

The excavation of the N°1 tunnel project in Porto was entirely performed in an environment where concerns were expressed regarding the implementation of drilling and blasting technique. A combination of both geological and economical requirements led the contractors to propose the digital blasting solution. This technology was fully integrated into daily working organization due to its flexibility and both with associated engineering, permitted to accomplish the excavation while maintaining the environmental standards. The high frequency and controlled PPV open the way to increase the advance per round. The digital blasting then generated important cost savings in terms of productivity per round, up to +190% in sound granite. The global duration of the excavation operations could be reduced by 60 days which means 30%, this also generated related costs savings.

We expect this case study to contribute to the widening application of the digital drilling and blasting technique to previously restricted environments. As the drilling and blasting technique remains the cheapest way for rock fragmentation, the aim in implementing the digital blasting is to generate increased productivity and global cost savings for all underground applications.

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