Reducing Blasting-Induced Ground Vibrations at the Velkolom Čertovy Schody-Západ Quarry

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Abstract. The study discusses the use of the electronic initiation system and software modeling to reduce ground vibrations induced by blasting works. The main part compares non-electric and electronic initiation systems, namely how the system-type affects the peak vector sum (PVS). The study evaluates blasting works conducted between 2011 and 2020 at the Velkolom Čertovy schody quarry. Koněprusy limestone deposit mined from a quarry Velkolom Čertovy schody belongs to one of the most significant mining locations in the Czech Republic. The main mining technology used in breaking rock mass at the Velkolom Čertovy schody quarry is blasting (namely bench blasts and overburden blasts). Blasting generates ground vibrations that affect the surroundings of the quarry. The information on ground vibrations is continuously collected at the predetermined measurement sites through a monitoring network. The network constantly monitors peak particle velocity (PPV), PVS, frequency, and other parameters. The key measurement site appears to be Prošek Dome (M15) in the Koněprusy Caves. At this measurement site, the limit value of the PVS is stipulated at 3.0 mm s^-1. If this value is exceeded, it is necessary to establish measures which lead to blasting restrictions (e. g. decrease in the weight of the deck charge, bench blast rows reduction). To meet the criteria, the Velkolom Čertovy schody-západ quarry started to use the electronic initiation system (E*STAR) along with the specialized software Paradigm for vibration modeling. This study, using data collected at the measurement sites Prošek Dome (M15) and Koněprusy No. 19, compares the PVS generated by the non-electric initiation system (Shock*Star) without modeling and by the electronic initiation system (E*STAR) with modeling. As reference years for non-electric initiation were stipulated years 2011, 2012, 2013, and for electronic initiation years 2018, 2019, and 2020. An analysis of 467 bench blasts executed at the quarry was conducted – or rather, the analysis of the PVS values collected at the pre-selected measurement sites. The analysis shows that the average value of the PVS at the measurement site Prošek Dome (M15) decreased from 2.05 mm s^-1 to 1.64 mm s^-1 when using the electronic initiation system with vibration modeling. The decrease in the PVS value was observed at the measurement site Koněprusy No. 19 as well, namely from 0.48 mm s^-1 to 0.31 mm s^-1. In addition, significantly fewer occasions of exceeding the PVS limit value were reported at the measurement site Prošek Dome (M15), specifically from 6.7 % to 2.7 % of the blasting works conducted within the selected reference years. The study also describes fundamental principles of work with the Paradigm software. Based on the vibration analysis, parameters of the bench blasts need to be adjusted: timing, number of deck charges or rows, etc. Finally, the study summarizes the benefits of the electronic initiation system with modeling.
1. Introduction

The study investigates the reduction of ground vibrations generated by blasting works at the Velkolom Čertovy schody quarry with regard to, in particular, the effect of ground vibrations on the complex Koněprusy Caves. The quarry is the biggest producer of lime and limestone products in the Czech Republic. Annually, the quarry extracts two million metric tons of raw material from the Koněprusy deposit. As regards the chemical composition, this area is known for limestones of the highest quality in the Czech Republic (Devonian limestones) [1, 2]. The Velkolom Čertovy schody quarry is divided into two sections: West and East. The study deals with the section West, which is reflected in the whole name of the quarry, or rather, its section, since West is translated as “západ” in the Czech language. Thus, the name Velkolom Čertovy schody-západ (VČS-Z) quarry. The VČS-Z quarry is located near the Koněprusy Caves and the shortest distance between the Caves and the center of blasting works is less than 300 meters. Since the Koněprusy Caves belong to the biggest karst caves in the Czech Republic and as such are frequently visited [3], it is vital to protect them from adverse effects of blasting works in the nearby quarry. Therefore, ground vibrations are constantly monitored and the blasting work parameters are adjusted in accordance with the collected data. The situation is depicted in figure 1.

Figure 1. Situation overview: Velkolom Čertovy schody-západ quarry and Koněprusy Caves

A part of the explosion energy that is not used up in rock mass breaking is released into the surrounding environment, spreading out from the blast location in all directions in the form of elastic shock waves [5]. Blasting-induced ground vibrations are characterized by three main components: vibration source, transmission medium (rock mass) and vibration receiver. All of these components can be at least partially adjusted. The transmission medium can be modified by drilling a borehole line, which partially influences transmission of the shock waves. The vibration receiver, such as a building, can be adapted to withstand higher strain. However, there is no way of directly influencing the Koněprusy Caves, the main receivers in the present study. It is therefore clear that the component that needs to be adjusted the most is the vibration source, which means modifying the blasting works [4].
In the field of contemporary blasting technology, reduction of ground vibrations is achieved predominantly by appropriate detonator timing.

To reduce ground vibrations, the VČS-Z quarry has traditionally employed deck charges in boreholes. For blast timing, non-electric initiation system (Shock*Star) has been used. However, this method reached its limits since it is impossible to reduce deck charges endlessly. Blasting works become uneconomical and difficult to conduct. The same limitations apply even to the reduction of bench blast rows (which, in certain cases, can lead to the decrease of ground vibrations) and to the reduction of the total charge [6]. Therefore, the quarry sought further ways of reducing the effect of ground vibrations on the surroundings, especially on the Caves. Gradually, an electronic initiation system (E*STAR) was introduced, subsequently also complemented by various software solutions for vibration modeling. Over time, a single modeling software solution started to be used exclusively, namely the program Paradigm. The study compares the two above discussed time periods: the period characterized by the use of the non-electric initiation system (Shock*Star) and the period of the electronic initiation system (E*STAR) with modeling in Paradigm.

The results of the study show decrease in the peak vector sum (PVS), the main parameter, and the number of exceedances of the PVS limit value at the measurement site Prošek Dome (M15), which was stipulated by an authorized body at 3.0 mm s^{-1}. The study included data from years 2011–2013, the years in which the non-electric initiation system was employed, and data from years 2018–2020, in which the quarry already fully used the electronic initiation system with modeling. A frequent use of the electronic initiation system with modeling is rare in the Czech Republic and the VČS-Z quarry is the only quarry where this method is regularly availed.

2. General parameters of blasting works and monitoring of ground vibrations
The typical blasts in the VČS-Z quarry are bench blasts or overburden blasts (i.e. bench blasts with more than 3 rows of boreholes). The general parameters, summarized in table 1, are the same for both studied time periods [6, 7].

| Parameters                  | Unit | Value     |
|-----------------------------|------|-----------|
| Diameter                    | mm   | 92        |
| Slope                       | °    | 15        |
| Borehole length             | m    | 12.5-21.5 |
| Bench height                | m    | 11-20     |
| Burden                      | m    | 2.8       |
| Spacing                     | m    | 2.8       |
| Stemming                    | m    | 2.5       |
| Interdeck stemming          | m    | 0.75      |
| Average deck charge         | kg   | 12.5-17.5 |
| Average total charge        | kg   | 1820      |
| No. of deck charge per hole | -    | 3-5       |
| No. of row                  | -    | 1-3       |

Ground vibrations in the surroundings of the VČS-Z quarry are continuously monitored, that is to say, each individual blast is recorded and evaluated at the following measurement sites: Prošek Dome (M15) – cave, Kukla Dome (M12) – cave, Prošek Dome (M9) – cave, Prošek Dome (M7) – cave, Koněprusy No. 19 – building, and Havlíčkův Mlýn No. 38 – building. The evaluated parameters are, in particular, peak particle velocity (PPV) values, PVS values and frequency distribution.
measurement sites were selected for the analysis in this study: the Prošek Dome (M15) in the Koněprusy Caves and the building Koněprusy No. 19 (The selection is explained in Chapter 4.1).

3. Electronic initiation system and the used modeling software

3.1. Electronic initiation system

The study does not intend to describe properties of the electronic initiation system in depth, it merely emphasizes the major properties that can directly reduce ground vibrations. Since the quarry used initiation systems E*STAR (Austin Powder, USA), these products are discussed in the following paragraphs [8].

Electronic initiation is a modern method of blast initiation. The detonator delay is controlled by a microchip, not regulated by the combustion of the delay element. The ignition is initiated by a built-in capacitor that releases electrical energy directly into a fuse, which ignites the primary charge of the detonator [9]. With the use of this initiation system, it is possible to program (i.e. define the delay time) individual detonators on a large scale and with great precision (see below). This enables the system users to employ the program Paradigm to model individual situations and to design blast timing in such a way that the adverse effects of blasting are minimized. The analysis and subsequent modeling are conditional on the use of the electronic initiation system. Although it is possible to work with the non-electric initiation system in Paradigm, this system does not provide a great timing variability and is not nearly as precise as electronic detonators. The selected parameters are presented in Table 2.

Table 2. Main parameters of timing of an electronic detonator E*STAR.

| Parameters                  | Unit | Value |
|-----------------------------|------|-------|
| Minimum delay               | ms   | 1     |
| Maximum delay               | ms   | 20 000|
| Minimum delay increment     | ms   | 1     |
| Accuracy of nominal delay   | %    | 0.01  |

3.2. Modeling software Paradigm

Paradigm (Igneous Tech, Australia) is a software solution designed for observation and optimization of blasting work parameters, including their effect on the surroundings. Although the program offers a broad spectrum of functions, the study will point out only the main procedures related to modeling of ground vibrations [10].

The program works with different timing of electronic detonators. It identifies suitable time combinations to reduce ground vibrations. In order to achieve that, it uses interference of the tension waves at the location of the receiver to eliminate or at least reduce tension wave amplitudes. The first phase which precedes the vibration modeling consists in blasting of the so-called signature hole at the planned blasting location. The signature hole is a single borehole with a small charge (usually 25.0 kg in the VČS-Z quarry). The initiation is conducted in a single delay interval. This blast elicits response at measurement sites (so called receivers) and the following parameters are collected: PPV (in individual components), PVS, frequency, and development in time. The collected data serve as the basis for determination of the main transmission medium coefficients (K), along with precise coordinates of both the signature hole and the measurement site. Whereas the timing is determined with the help of the program Paradigm, the blast design itself is devised in a standard manner. The timing is set according to the selected intervals and pre-determined transmission medium coefficients (K). Depending on the number of detonators, deck charges, boreholes, and rows, as many as tens of thousands of timing combinations may arise. The combinations can be further filtered out on the bases of various aspects. The main parameter in the VČS-Z quarry is the minimum PVS. After the best combinations are selected and the blast is executed, predicted PVS values (or PPV, frequency) are compared with the actual values.
and the transmission coefficients (K) may be re-adjusted. Thorough work with the coefficients leads to high prediction accuracy of the PVS value (PPV, frequency) at measurement sites.

4. Blast comparison: non-electric versus electronic initiation system with modeling

4.1. Methodology

In order to compare ground vibrations induced by blasting using either the non-electric or the electronic initiation system with modeling, the following criteria were defined: time delimitation, initiation system type, and vibration measurement reference sites (measurement sites).

As regards the selected time periods, years 2011, 2012, 2013 represent the use of the non-electric initiation system (Shock*Star), whereas years 2018, 2019, and 2020 mark the use of the electronic initiation system (E*STAR) with modeling in Paradigm. The period between the selected years was deliberately left out due to the transition between the initiation systems at the VČS-Z quarry. Further, the period did not include modeling in the selected program. It is also important to note that a gradual training of blasters and other specialized workers took place in the transition years. Thus, the results would be difficult to compare. The vibration measurement reference sites were selected based on their comparability (measurement had to take place throughout the whole selected time interval). The following measurement sites were chosen: Prošek Dome (M15) and Koněprusy No. 19. The key site appears to be the Prošek Dome (M15) in the Koněprusy Caves. The limit PVS value at this site was stipulated at 3.0 mm s\(^{-1}\). If this value is exceeded, representatives of mining organizations, blasting work providers and the Cave Administration of the Czech Republic meet and negotiate. The meeting results in proposed and approved measures leading to reduction of ground vibrations. For blasting work providers, the measures are essentially restrictions that decrease economic efficiency of blasting. The typical examples are restrictions regarding the deck charge size, number of bench blast rows and total charge size. The providers therefore aim to reduce the exceedances of the limit value to a minimum, or rather to eliminate them altogether.

A total of 467 bench blasts were executed at the VČS-Z quarry in years 2011–2013 and 2018–2020. Special blasting works and blasting works with a very small total charge were excluded from the analysis to avoid distortion of the results. Blasting work parameters maintained either the same or similar in the studied time periods (technical documentation of individual bench blasts was examined). The executed blasts induced ground vibrations that were recorded by a monitoring network. Since the PVS value is the decisive parameter in the documents that regulate blasting works, it was chosen as a means of comparison in this study.

4.2. Analysis and its results

The analysis presumes that the number of executed blasts is sufficient for basic statistical processing. The most suitable parameter for analysis appears to be the average PVS value collected in the selected years at the both measurement sites. The PVS value illustrates that the employment of the electronic initiation system with modeling lead to a reduction of ground vibrations. Further, the study includes extreme vibration values (exceedances of the PVS limit value 3.0 mm s\(^{-1}\) at the Prošek Dome measurement site). It is assumed that if the electronic initiation system reduces PVS values at the observed measurement sites, the number of exceedances should be lower for the reference period in which the electronic system was used, when compared to the former non-electronic initiation system period. For the sake of comparison, it is necessary to perform a recalculation which takes into account both the number of executed bench blasts and the number of the exceedances of the limit value. The observed values (number of bench blasts, PVS values, exceedances of the limit value) are presented in table 3. The table further includes information on blasted volume to imagine the blast size.
Table 3. Overview of bench blasts and observed values.

| Year | 2011 | 2012 | 2013 | 2018 | 2019 | 2020 |
|------|------|------|------|------|------|------|
| Initiation system | non-electric | electronic | non-electric | electronic | non-electric | electronic |
| Number of blasts | - | 56 | 89 | 71 | 82 | 88 |
| Blasted volume | t | 611 565 | 913 754 | 709 503 | 998 630 | 1 053 018 | 824 585 |
| Prošek Dome (M15) | No. of measurements | - | 56 | 88 | 67 | 78 | 87 | 75 |
| PVS year avg. mm s⁻¹ | 1.921 | 2.263 | 1.953 | 1.580 | 1.644 | 1.690 |
| PVS period avg. mm s⁻¹ | 2.046 | 1.638 |
| Koněprusy No.19 | No. of measurements | - | 54 | 86 | 71 | 81 | 88 | 80 |
| PVS year avg. mm s⁻¹ | 0.557 | 0.515 | 0.372 | 0.325 | 0.305 | 0.304 |
| PVS period avg. mm s⁻¹ | 0.482 | 0.311 |
| Number of exceedances | No. | - | 2 | 6 | 7 | 2 | 4 | 1 |
| Percentage year % | 3.6 | 6.7 | 9.9 | 2.4 | 4.5 | 1.2 |
| Percentage period % | 6.7 | 2.7 |

The situation is represented graphically in figures below. Figure 2 shows the PVS value at the measurement sites Prošek Dome (M15) and Koněprusy No. 19. Black lines represent the period of the non-electronic initiation system, green lines indicate the period of the electronic initiation system. Figure 3 shows the percentage of exceedances of the monitored PVS value at the Prošek Dome (M15) measurement site. The used color code is the same as in figure 2.

Figure 2. PVS values at the measurement sites Prošek Dome (M15) and Koněprusy No. 19
5. Results and discussion

The conducted analysis clearly demonstrates decrease in vibrations achieved through the use of the electronic initiation system (E*STAR) with modeling (Paradigm). Comparison of the total average value in years 2011–2012 (non-electric initiation) with the total average value in years 2018–2021 (electronic initiation with modeling) shows that the average PVS value at the measurement site Prošek Dome (M15) decreased from 2.05 mm s\(^{-1}\) to 1.64 mm s\(^{-1}\). A significant decrease from 0.48 mm s\(^{-1}\) to 0.31 mm s\(^{-1}\) was observed at the measurement site Koněprusy No. 19 as well. Similarly, the number of exceedances of the limit value at the measurement site Prošek Dome (M15) was reduced from 6.7% to 2.7% of the blasts executed in the selected years. As can be seen in table 3, the limit value at the measurement site Prošek Dome (M15) was exceeded merely once in 2020.

Understandably, it we need to recognize that conditions change over time. No blast is comparable with the preceding blast because the rock mass was altered by the preceding blast. The blast that follows is therefore necessarily located elsewhere. For this reason, the study investigates a time period as long as possible to cover as many blasts as possible, and by that as many blast locations as possible.

5.1. Further benefits of the electronic initiation system

If the vibration modeling is done thoroughly and the transmission medium coefficients (K) are adjusted according to the actual observed values collected in the blast execution, the electronic initiation system along with the program Paradigm provide a very precise prediction of ground vibrations. This makes it possible to push the traditional boundaries and execute bigger blasts, blasts with a greater number of rows, blasts with a smaller number of deck charges in boreholes, etc. A smaller amount of deck charges in a borehole means simpler and faster charging of boreholes and detonator saving. A greater number of rows or boreholes ensures a greater blasted volume of the rock mass. These facts can consequently improve the economic efficiency of blasting works. Understandably, it is necessary to adhere to technological procedures and standards in the process of blast execution: precise pre-blast geodetic survey and careful charging. Modeling of ground vibrations takes blasting works to a next level because
the traditional measures to reduce vibrations also lower the economic efficiency of blasting. In our future investigations, we would like to focus on the difference between the prediction and the reality of blasts.

6. Conclusion
A comparison of this kind is quite rare in the Czech Republic. The reason behind this is that the VČS-Z quarry is the only quarry where the electronic initiation system with modeling has been used on a regular basis for a several years now. The study includes data collected over several years; the total of 467 blasts were analyzed. The results reveal both the reduction of ground vibrations and exceedances of the limit value at the measurement site Prošek Dome (M15). Since quarries in the Czech Republic often occur in close proximity of buildings and structures (and caves – in karst areas) [1], it is crucial to pay due attention to ground vibrations. Therefore, we presume that both the electronic initiation system and the selected modeling software solution will gain in importance in the future.

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