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Prediction of Vibrations Due to Blast at the Hiré Mine, Côte D'Ivoire

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Abstract: Côte d'Ivoire has, in order to diversify its economic resources, decided to exploit its mineral reserves. Industrial gold mining in Côte d'Ivoire began in 1991 with the opening of the Ity gold mine in the department of Zouan-Hounien, in the west of the country. Several regions of the country have seen mines open. In the Loh-Djiboua region, in the department of Divo, Hiré gold mine opened in 2013. Mine operations consist of mechanical extraction for oxidized ore but also blasting for sulfired ore. Mining operations are then supposed to take place at a minimum distance of five hundred meters from the first dwellings. From the results of the research work, the mining company requests and obtains in 2017, from the State of Côte d'Ivoire, the extension of its operations, in the direction of the city of Hiré, with the possibility of making blast at two hundred and fifty meters from the first dwellings, posing the problem of the proximity of mining blast to the dwellings. The situation appears unprecedented in the mining sector of Côte d'Ivoire. Blast is a source of nuisance, including vibrations. Our study focused on the prediction of vibrations related to shots. Our method of study consisted in first determining, from the formula of Oriard, the constants of the site and to predict from them, the vibrations generated by the explosive blast.

Keywords: Mine, Blast, Habitation, Vibration

1. Introduction

Mining industry plays an important role in the development of many countries around the world and continues to be an important contributor to national and regional economies. It is, for many countries, one of the main drivers of economic development [4]. However, it is one of the activities with a strong environmental impact and is often contested by certain environmentalist civil society organizations and local communities that are directly affected by its nuisances [8]. In Côte d'Ivoire, agriculture has been the mainstay of the Ivorian economy and the main source of employment since the independence of Côte d'Ivoire. However, in order to overcome the fragility of this sector and to diversify economic resources, Côte d'Ivoire has turned to the exploitation of its mineral reserves [22]. Industrial gold mining began in Côte d'Ivoire in 1991 with the opening of the Ity gold mine in the department of Zouan-Hounien, in the west of the country [2]. Gold mining production has continued to grow ever since, rising from two tonnes in 1991 to thirty-eight tonnes in 2020 [9]. Consequently, the contribution of the mining sector has since continued to see its share increase in the Gross Domestic Product. Several regions of the country have seen mines open. In the Sub-Prefecture of Hiré, an operating permit was granted in 2013 to the company LGL Ressources CI SA. In 2017, the mining company requested and obtained from the State of Côte d'Ivoire to carry out explosive attacks up to two hundred and fifty meters from the first dwellings [6]. The situation appears unprecedented in the mining sector of Côte d'Ivoire and poses the problem of the possibility of mining in agglomeration in the Ivorian context. Explosives are sources of nuisance, the main ones being noise, projections, dust and vibrations. Our study focused on the analysis of this last parameter, namely vibration, which appeared to be one of the major nuisances from the point of view of the populations. From any explosion, part of the energy propagates in the form of a solid-state vibration wave both in fluids and in solids [11]. The structure-borne wave train propagates like an earthquake at different speeds depending on the type of wave and the elastic properties of the medium. The rest of the energy developed is used to break down the rock. One of the remarkable effects of the passage of the shock wave is the setting in motion of the ground which is felt by the observer as a vibration. In the field of vibrations, we can measure several data such as displacement, particle velocity, acceleration, frequency. In practice, it is the particle velocity which is the speed of movement of a point on the ground under the influence of vibration that is measured with a simple device [5]. This particular speed, commonly called vibration, is an obvious annoyance for people living near mines and is more likely to cause damage to constructions if it is underestimated or poorly controlled. It is this data that our study plans to predict, before any firing. Good control of the vibration parameter makes it possible to determine with some precision the charge of explosive substances to be used to guarantee the absence of damage. Our method of study consists in predicting, using simple and easily available tools, the vibrations of the shots for the Hiré mine.

2. Materials and Methods

2.1. Materials

The study material consists of explosive substances, distance measuring equipment, data processing software, vibration measuring equipment, shooting equipment, data from previous shots, data of shots to be made. The explosives used for firing are high explosives, subdivided into primary explosives and secondary explosives [5]. The primary explosives used in our study are non-electric detonators and surface fittings. The choice of the non-electric detonator is justified by the fact that it allows, in addition to being economically profitable, greater safety in use compared to electric detonators, and also, greater flexibility in reducing the number of the number of blast holes detonating at once. The secondary explosives used in our study are the booster and the bulk emulsion, a matrix made explosive only in the blasthole. The advantage of its use lies in the safety of use it offers, by reducing the explosive charge available on the firing volley during loading. The equipment for measuring distances was a Global Positioning System (GPS). The GPS receiver, having in its base the position of the satellites at each instant, is capable of giving several pieces of information including the distance between two points [12]. The GPS used in our study is the GARMIN GPSMAP 66st GPS. Computer equipment was used for data processing, the production of regression curves, the establishment of the theoretical vibration prediction model. The software used for this is Microsoft Excel, the statistical functions of Excel having evolved favorably in recent years [18]. The choice of this tool lies in the fact that it is readily available and easy to use. The equipment used during the study for recording vibration data consists of two TEXCEL brand sensors which offer the advantage of giving the vibration measured by direct reading on the screen. The geometric blasting parameters, determined according to the Langefors formulas [17] for blasting, which are the drilling diameter, the depth of the holes, the stuffing height, the foot load, the column load, the load height, the nature of the explosive substances used, the density of the explosive substances used, the quantity of explosive substances used, the connection plan, the value of the vibration measured, allowed the determination of the constants of the site and the prediction of the vibrations. The figures below show the diagram of a blast hole and the typical connection plan used for production of blast.

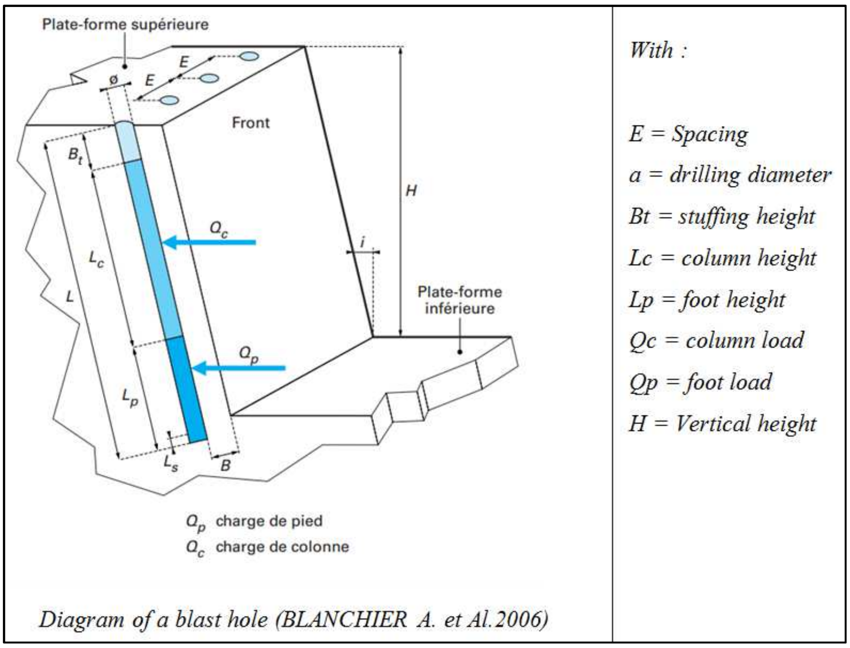

Figure 1. *Diagram of a blast hole.*

The typical connection plan used during the study is shown in the figure below.

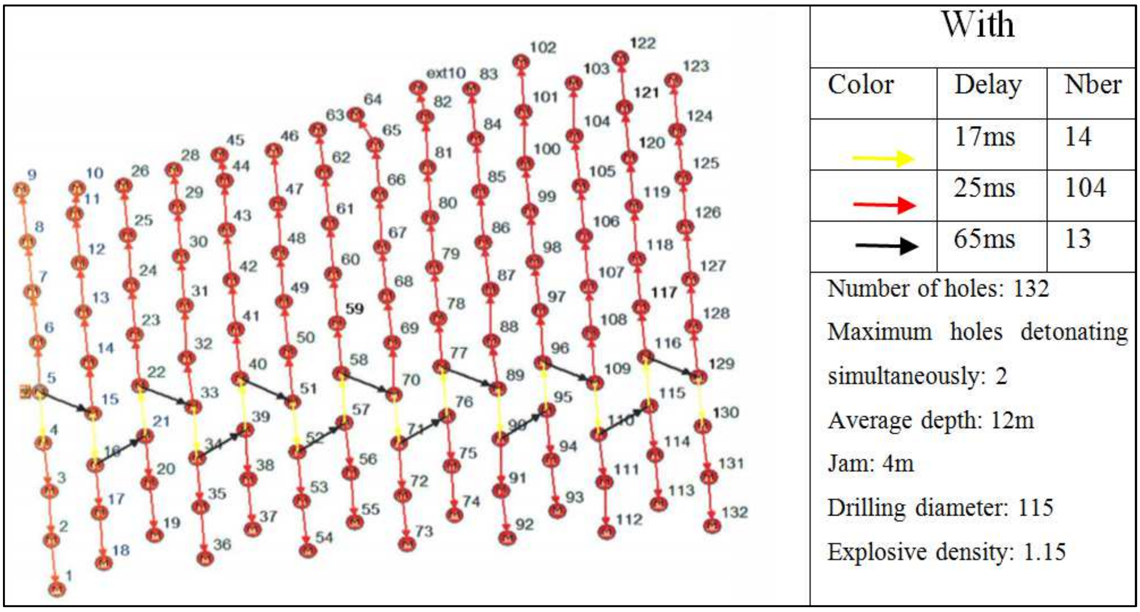

Figure 2. *Typical connection plan.*

2.2. Method

Our method of study consisted initially in determining the distance of the shot (D), then in determining the specific instantaneous charge (Q) of the shot carried out and finally in determining the site constant; Secondly, to predict the vibration V from the determined constant and the parameters of the shots to be carried out. Thus, our method of study consisted in measuring, for each of the shots, from January 01 to June 30 March 2020, the distance and the value of the vibration. Two measurement points are established for each shot, namely the post of the Ivorian Electricity Company (CIE) and the nearest dwelling. Several authors have worked on the question of vibration related to explosive firings and have proposed equations for predicting the vibrations and all these equations estimate the vibration mainly according to two parameters which are the maximum instantaneous load and the distance of measurement [15]. Among these equations, we have among others Ambrasey and Al 1968, Chapot P. 1981 and Oriard 1999 whose formulas are:

$$V = K\,(D/Q^{1/3})^{-b}$$

$$V = K\,(D/Q^{1/2})^{-b}$$

$$\text{and } V = K\,(D/Q^{1/2})^{-1,6}$$

where V = vibration speed, D = the distance between the shot of mines and the point considered, Q = the instantaneous unit charge (quantity of detonating explosive at a given moment), K = coefficient linked to the performance of the shot in the solid mass given, b = the damping coefficient of the seismic waves as a function of the distance, K and b are therefore coefficients linked to the firing methods and the local geology, with b between 1.6 and 1.8 [7].

The Oriard equation was chosen for the rest of our work, presenting a closer experimental model and a greater correlation between the data and also a greater facticity of implementation.

2.3. Determination of Distance D

The determination of the distance (D) is made from the GPS GARMIN GPSMAP 66st. Two measurement points were placed for each shot. The post of the Ivorian Electricity Company (CIE) and the house closest to the firing line.

2.4. Determination of the Maximum Unit Load Q

The determination of the maximum unit charge was carried out taking into account the principle that two charges are considered to be fired at the same time if they have less than eight milliseconds of delay between them [7]. The unit load Q is determined from the blast data, the connection mode used. It is equal to the sum of the charges of the blast holes that explode simultaneously. It is given by the formula

$$Q\,(Kg) = \pi\, d^{2\cdot}\, hc.\, d' / 4000$$

Where Q = maximum instantaneous charge, d = drilling diameter, d' = density of the explosive, hc = height of the explosive charge.

2.5. Vibration Measurement

The vibrations were measured using two sensors, one placed at the Ivoirian Electricity Company (CIE) substation and the other at the nearest dwelling. The vibration is measured by direct reading of the sensor according to the time of the blast.

Figure 3. *Sensor reading.*

2.6. Determination of Constants K and b

From the Oriard equation,

$$V = K\ (D/Q^{1/2})^{-1,6}$$

We have *b,* and

$$K = V / (D/Q^{1/2})^{-1,6} \text{ (Source: [14])}$$

2.7. Frequency Measurement

In addition to vibration, frequency is a very important factor determining the response of structures to explosive blasts. It is important to take into account how the vibration is coupled to the frequency in order to better appreciate the effect of the shot on the structures. The exposed structure will respond very differently to ground motion with a frequency of twenty Hz than with a frequency of one hundred and fifty Hz (14). In this case, the frequencies for each shot are given by sensor reading.

2.8. Vibration Prediction

Once the K and b constants have been determined, we use the Excel spreadsheet to develop a model which, based on the blast parameters provided by the operator, predicts the level of vibration. The model looks like this:

Table 1. *Vibration prediction.*

Site constants		**Hole diameter**	**hole depth**	**Jam**	**Load**	**Explosive**	**Load per**	**Number of Detonating Holes Together**	**Maximum instantaneous load (Kg)**	**Distance**	**Vibration**
K	**b**	**(mm)**	**(m)**	**(m)**	**column (m)**	**density**	**hole (Kg)**			**(m)**	**(mm/s)**
V1	V2	V3	V4	V5	F1	V6	F2	V7	F3	V8	F4

Where: V = Value, F = Formula, specifically, for values:

V1 = Constant K, V2 = Constant b, V3 = Diameter of hole, V4 = Depth of hole, V5 = Height of jam, V6 = Density of explosive, V7 = Number of Holes Detonating Together, V8 = Distance measured.

For formulas:

$$F_1 = V_4 - V_5;\ F_2\ (Kg) = \pi\ V_3^{2.}\ F_1.\ V_6 / 4000,\ F_3 = F_2.V_7;\ F_4 = V_1\ (V_8/F_3^{1/2})^{-V2}$$

3. Results

From the production shots carried out between January 01 and June 30, 2020, we obtain the following results:

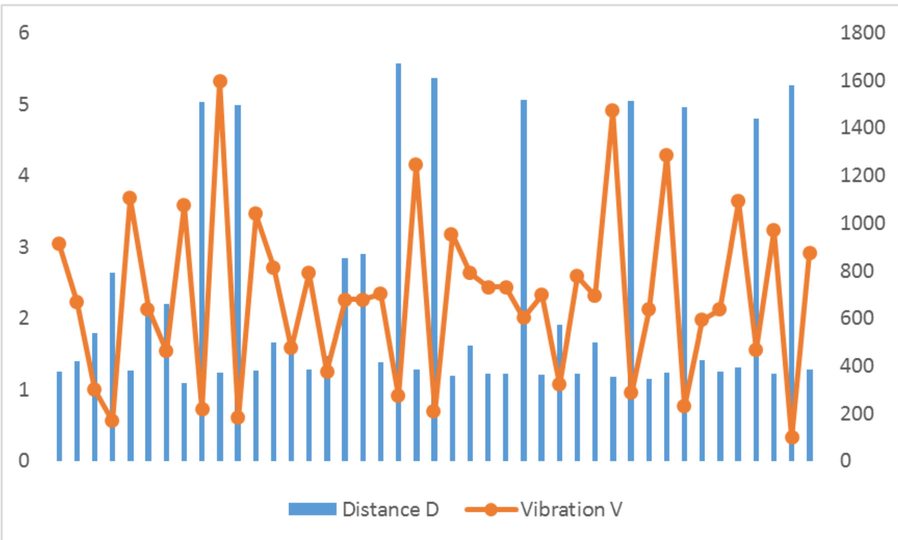

Figure 4. *Vibration as a function of distance of blast.*

Twenty-two production shots were carried out during the first half of 2020 and the vibration measurements are taken from data from the sensors positioned at the CIE substation and at the threshold of the nearest dwelling.

3.1. Value of K and b

From Oriard's equation, we get:

$$b = 1.6 \text{ and } K = 1054$$

3.2. Frequencies Measured

The frequencies measured are between:

Table 2. *Frequency result.*

	Radial	Transversal	Vertical
Frequency	*16.00 et 20.0*	*14.20 et 19.5*	*13.1 et 15.50*

3.3. Prediction of V

From the values of the constants K and b obtained, we predict according to the firing parameters and the connection mode, the value of the vibration for the firings of the second half of the year 2020. We obtain the following values given by the figure below -after:

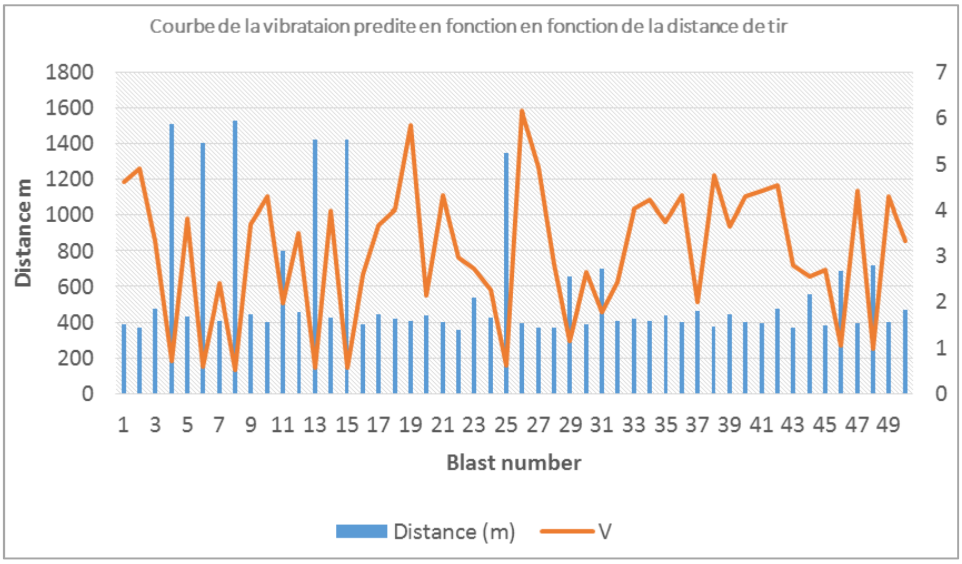

Figure 5. *Predicted vibration based on shooting distance.*

The vibration prediction curve shows that the smaller the distance to the tire, the greater the vibration. The predicted vibrations range from 0.57 mm/s for a distance of 1421.2 m to 6.16 mm/s for a distance of 393.7 m.

3.4. Comparison Between Predicted Vibration and Measured Vibration

The predicted vibration values are compared to the measured vibration values. The figure below gives the comparison between the predicted vibrations and the measured vibrations.

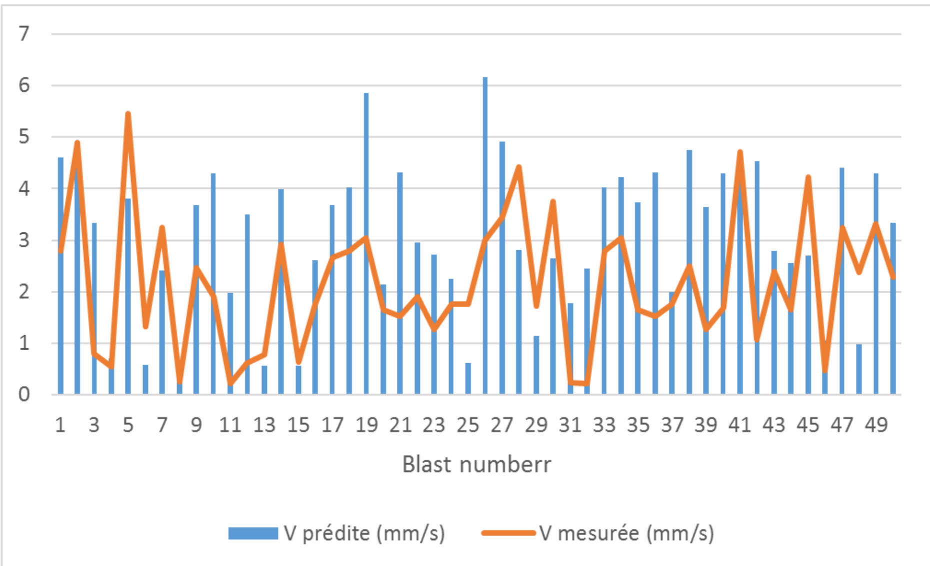

Figure 6. *Predicted vibration / Measured vibration.*

The comparison between predicted vibration and measured vibration gives an average measured vibration/predicted vibration rate of 81.95%

4. Discussion

4.1. Of the Site Constant K

The constant K determined for the Hiré site is 1054. The constant K determined for the Hiré site corresponds to the results obtained in this area by Dyno Nobel [10] which indicates that the values of K are between 500 and 5000, with for an average value of 500 for very hard rocks with a coal face, 1140 for hard rocks with a coal face and 5000 for extremely confined rocks. In the case of the Hiré mine, the formations encountered are micaschists and metagabbros [21], hard rocks with a working face.

4.2. Maximum Instantaneous Load

The maximum instantaneous charge is a function of the number of blast holes that explode within an 8ms interval. The use of a non-electric detonator allows flexibility in order to detonate as few holes as possible simultaneously. The use of electric detonators would not have allowed the same flexibility. For a round of 131 holes, firing the electric detonators (n° 0 to 20), would have given six sequences of detonating holes simultaneously. The maximum unit charge would then be three times that found in the case of non-electric detonator firing.

4.3. From the Vibration Prediction Model

The results obtained with the model show that it offers an average rate of 81.95% of the measured vibrations / predicted vibrations ratio. Requirements of the FEEG (French Explosive Energy Group).

Table 3. *FEEG references.*

GFEE	Sensible	Resistant
Frequency (Hz)	V_{max} (mm/s)	V_{max} (mm/s)
1 à 5	2 à 10	5 à 25
5 à 12	10	25
12 à 45	10 à 40	25 à 100
>45	40	100

In the case of the Hiré mine, the installations of the Ivoirian Electricity Company substation can be assimilated to industrial buildings, while the nearest dwellings are low-rise dwellings.

In the case of Ghana, the Ghanaian regulations set the admissible limit at 2 mm/s [19] thus satisfying the satisfaction of remaining within the limit thresholds, whatever the frequency of the shot. The proposed prediction model could make it possible to predict the vibrations by coupling it with the frequency of the shot. In the case of the Hiré mine, the lowest frequencies are 12, thus setting the vibration limit thresholds at 10 mm/s for sensitive structures and 25 mm/s for industrial structures.

5. Recommendations

The study confirms that vibration is indeed related to distance and instantaneous maximum load. Since the firing distance is imposed by the geological configuration of the site, the mining operator must work as much as possible to reduce the maximum instantaneous load. Minimizing the number of detonating holes at a time appears to be the best option. To this end, we would like to recommend, for blasting operations close to built-up areas, the use of electronic detonators, the programming of the departures of which depends on the operator, offering greater flexibility as regards the prediction of vibrations. A study on the matter could confirm the option.

6. Conclusion

Previous studies relating to the question of vibration of blasting, it appears that the vibration is a function of the distance and the instantaneous explosive charge. The distance remaining in most of the shots to be made difficult to reduce, the only parameter on which the mining company could play in order to minimize the vibrations due to the shots is the instantaneous explosive charge. The instantaneous explosive charge depends on the number of holes detonating at once, the depth of the holes, the height of the stuffing, the nature of the explosives used and the nature of the rock. In the case of the Hiré mine, the reduction of the instantaneous explosive charge, optimal reduction of the instantaneous charge, appears an imperative for a successful harmonious cohabitation. The study shows that vibration control below the indicated thresholds is possible. Firing carried out with non-electric detonators and with bulk emulsion thus allows flexibility in the maximum minimization of the instantaneous explosive charge. The study also shows that by playing on the height of the explosive charge and the arrangement of the detonators, we manage to play on the vibration. However, to take into account errors and all particularities related to the nature of the constructions, it would be desirable for the prediction thresholds to be well below the thresholds set by the FFEG and also take into account the usual frequency of shots.

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