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BLASTING CONTROL AND MONITORING SYSTEM FOR SAFETY IMPROVEMENT DURING BLASTING OPERATION. A CASE STUDY IN GUILAIZHUANG GOLD MINE

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Abstract: The design of a blasting monitoring and control system and its practical application in a blind gallery named Dongguabang in Guilaizhuang gold mine in China was presented in the paper. Based on reason analysis of blasting accidents occurring in metal mines, a blasting accident model is established in order to explain the process of the accident and its direct reasons. Also, effective approaches for preventing blasting accidents and avoiding casualties are achieved by controlling unsafe behaviour of workers and elimination of the critical "touch". Combined with analysis of safety ergonomics of blasting devices, all these make a joint contribution to providing theoretical instruction and references to establishment and design of blocking functions of blasting monitoring system. A set of blasting monitoring and control system is implemented, and equipped with blocking functions when unsafe behaviour and conditions appear. Tests of the monitoring system are carried out in the Donguabang heading of Guilaizhuang gold mine. It is documented that the blocking functions and the central computer platform run well during the tests. Test results reveal that blasting monitoring and control system and its functions are able to ensure safety and fulfil work requirements in Guilaizhuang gold mine.

Keywords: *Model of blasting accident; Unsafe behavior; Safety ergonomics; Blocking function; Monitoring system*

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1. INTRODUCTION

Currently, blasting is one of the most popular methods used in various engineering applications and can been seen commonly applied during mining, tunnelling and underground excavations. In particular, in more than 90% of the cases, it is utilized in gold mines in China, which stems mostly from economic factors. As a consequence, blasting-related accidents appear frequently along with the widespread application of the blasting operations in gold mines. Blasting accidents not only cause financial losses to gold mine-operating companies, but more importantly, result in casualties. From this viewpoint, it is of a great significance to prevent happening of the blasting accidents.

Considering prevention of the blasting accidents, Bajpayee et al. (2003a; 2003b) have done some statistical research in American open pit mines, which happened during the 1978–1998 period and found that fly rock hazard and no warning boundary present during the blasting operation contribute mainly to the blasting accidents. Kecojevic V. et al. (2005) also did research on the fly rock phenomena and area security in blasting-related accidents. Stojadinović S. et al. (2011) also did some prediction of fly rock trajectories for forensic applications using ballistic flight equations. Nefis M. et al. (2016) applied photo-analytical method to measure the size of fragments by using FragScan system which help to monitor blasting and optimize blast design. Grześkowiak A. et al. (2016) carried out research on blast affected zones in opencast mines. In other published research, Zhu et al. (2015) summarized unsafe behaviour observed during blasting operations in years 1950–2009 and found that the critical drawbacks in procedures related to the site management, charging and first methane check trigger directly 88% of the accidents related to the blasting operation. Kricak L. et al. (2012) did some studies on the topic of environmental and safety accidents related to blasting operation and tried to find the relationship between environment and accidents. Some blasting accident cases occurring in the open pit metal mines have been analysed via fault tree method (Wang and Chen, 2010a; Wang et al., 2010b). The authors concluded that the main reason of the blasting accidents is related to the inadequate site management. For instance, the particular cases comprise: no warning lines being present, improper warning being issued, irresponsible staff, insufficient safety protection, no warning signals given, as well as unsafe treatment of the blasting materials. Also, Guo et al. (2009) had studied the blasting accidents in marble mine by using the fault tree approach and calculated minimal cut sets and minimal radius sets, as well as analysed structural importance. In order to control happening of the blasting accident in a daily management, it is necessary to find characteristics or laws of occurrence of the accident and to undertake specific prevention measures.

In this paper, research on design of a blasting control and monitoring system is discussed from both, theoretical aspect and also using a case study of the Guilaizhuang China) gold mine. Analysis of the blasting accidents, which happened in metal mines in China during the last 20 years allowed to make a proper classification, summarizing the reasons of different accidents. At the same time, it was possible to present a blasting model for interpretation of the blasting accidents, as well as to propose an approach to prevent them. Finally, the designed control system installed in the Dongguabang blind gallery of the Guilaixzhuang gold mine is discussed. The conducted tests showed functionality of the system, which is ensuring safety of operation and fulfils work requirements in the gold mine.

2. THEORETICAL ANALYSIS OF A BLASTING ACCIDENT

2.1. STATISTICAL ANALYSIS OF CHINESE METAL MINE DATA FROM THE LAST 20 YEARS

Blasting accident can be considered as a common type of an incident occurring in mines, especially in metal mines, because of a widespread usage of blasting agents. Statistical analysis of available data reveals that a number of blasting accidents, which occurred in years 2001–2012 accounts for ca. 30% of the total accidents in non-coal mines, and is in the sixth place of all of the accidents in mines (Wang et al., 2007a; Liu et al., 2012). Similarly, due to a commonly used blasting operation in gold mines, such types of accidents are also relatively frequent. Recordings from the last 20 years about typical blasting accidents, which occurred in Chinese metal mines, are collected from available data (Wang and Jiang, 2010c) and listed in Table 1.

Table 1. Statistics of blasting accidents in Chinese gold mines
(available data from last 20 years)

No.	Type/Reason	Number of accident	Rate [%]
1	Fly rock	4	2.69
2	Blasting vibration	26	17.45
3	Blasting wave	24	16.11
4	Blasting fume and dust	26	17.45
5	Misfire	13	8.72
6	Safety guard, signal and distance	10	6.71
7	Quality of blasting materials and wrong operations	34	22.82
8	Improper disposal of blasting materials	4	2.69
9	Gas explosion	2	1.34
10	Blasting network	1	0.67
11	Sulfur spontaneous combustion	2	1.34
12	Other types	3	2.01
Total		149	100

As demonstrated in Table 1, it can be concluded that there are four main types of blasting accidents, related respectively to the quality of used blasting materials and wrong handling/operations (ca. 22.8%), blasting-related fume and dust (ca. 17.5%), blasting-caused vibrations (ca. 17.5%) and also blasting wave (ca. 16.1%). The root reason for the first three types of accidents can be linked mainly with human error. As their total ratio is close to 60%, they constitute the main part of all of the blasting accidents. Therefore, avoiding the human errors in blasting operations can be regarded as a critical method to decrease number of the blasting accidents. Besides, checking the quality of the blasting material before the actual blasting is a necessity for prevention of blasting accidents, because on one hand, it eliminates the possible faults which may cause an accident, and on the other hand, it decreases a possibility of bringing about human errors. Based on the above presented analysis of the accidents, it can be also determined that it is crucial to carry out accident prevention in advance considering two aspects, one, which is related to the elimination of unsafe conditions regarding blasting materials, the other one is linked with removal of unsafe behaviour of the blasting workers. Dangerous blasting-caused effects, such as fly rock, blasting wave or vibrations, toxic gases, are generated after ignition and are inevitable. Also, isolation of the working staff and the dangerous zone should be effective in prevention of the blasting accidents.

The available statistical data on occurrence of the gold mine blasting accidents was a basis for further considerations of the blasting accident model, as well as a case study related to the development of the blasting control and monitoring system, which was installed in the Guilaizhuang Gold Mine in Shandong Province of China.

2.2. MODEL OF A BLASTING ACCIDENT

Blasting accidents cannot be treated exclusively as independent events in the blasting operation. Actually, there are many potential factors contributing to the occurrence of the accident. For example, in general, miners need to drill boreholes and charge explosive agent before blasting operations. In this time-consuming process, workers are affected considerably from confined working space, which is characterized by high temperature, high moisture level and low air flow speed, causing thermal imbalance in human body. At the same time, after bearing substantial workload, negative influences of vibration and noise, bodies of miners show mental and physical fatigue, which results in declines of physical conditions, attentions and perceptions. This is followed by conscious or unconscious human errors and unsafe behaviour. In consequence, it may bring about incorrect operations or even unpermitted practices in the blasting work. Sometimes unqualified detonators or blasting caps are hidden in the explosive materials and increase the possibility of accident occurrence. In some cases, human error or unsafe behaviour brings about unsafe conditions regarding equipment, tools and materials, but also this probably happens vice versa. One point is definitely undoubted that the occurrence of accident should be related to a visible or invisible "touch" between the unsafe human behaviour and the unsafe condition of the things.

A descriptive model of blasting accident is presented below in Fig. 1. In a schematic map of a blasting model, the root reasons of the blasting accident can be listed as related to four aspects: personal conditions of a miner, features of the blasting work, working environment and management regulations in the mine company. These root factors contribute a combined impact to miners' bad physical and psychological condition. Character tendency and individual characteristics may significantly intensify these negative physical and psychological conditions further into the overall unsafe psychological condition of a worker. Unsafe psychological conditions can easily appear during the blasting operation and commonly are manifested in actions that can be described as: skipping mind, fluking mind, rebellious mind, group mind, flaunting mind, perfunctory mind and impatience. In this case, miners are easy to perform intentional and unintentional unsafe behaviour during the blasting operation, especially during the last part of the blasting work. These unsafe activities are commonly seen in forms of a lack of warning reminders or blasting signals before blasting, non-programmed blocking operations, unfixed blasting site, entering the blasting area or blasting fume and changeable blasting time. Such behaviour, performed by miners or other workers, are putting them into dangerous area or situation, and increasing a possibility for occurrence of the blasting accident at the same time. It is the blasting itself that creates dangerous objects or areas, such as fly rocks, blasting waves, toxic gases, blasting fume region, unstable rock surrounding, water-rich zone, etc. The unsafe behaviour of miners can be divided into two main branches related to human errors and actions against the regulations. When the unsafe behaviour is conducted in the dangerous regions or is encountered with dangerous objects in a fixed time and space, blasting accident is very likely to happen.

The results of the blasting accident can be concluded to two situations: accident which occurs with or without casualties. Currently, it is difficult to avoid all the four discussed above negative factors. Especially, it is hard to eliminate the unsafe physical and psychological condition of workers at the level of current technology and productivity. Actually, unsafe behaviour consists of a series of erroneous actions. The erroneous actions in a blasting operation can be corrected, modified or blocked via properly programmed blasting devices. For example, the blasting machine can be automatically blocked when erroneous actions are performed during the blasting operation. Therefore, recognition of erroneous action matters very much, and prevention of the erroneous actions is an effective way to prevent an accident and cut the "touch" between the unsafe behaviour and the dangerous regions or dangerous objects. It could be realized by introducing programmable of the blasting device. For instance, if miners are conducting the unsafe behaviour or tending to interact with (touch) the dangerous regions or objects, the blasting machine will be blocked or won't trigger the blasting operation. Then, the dangerous zones or objects won't be generated, because of the failed trigger of blasting machine.

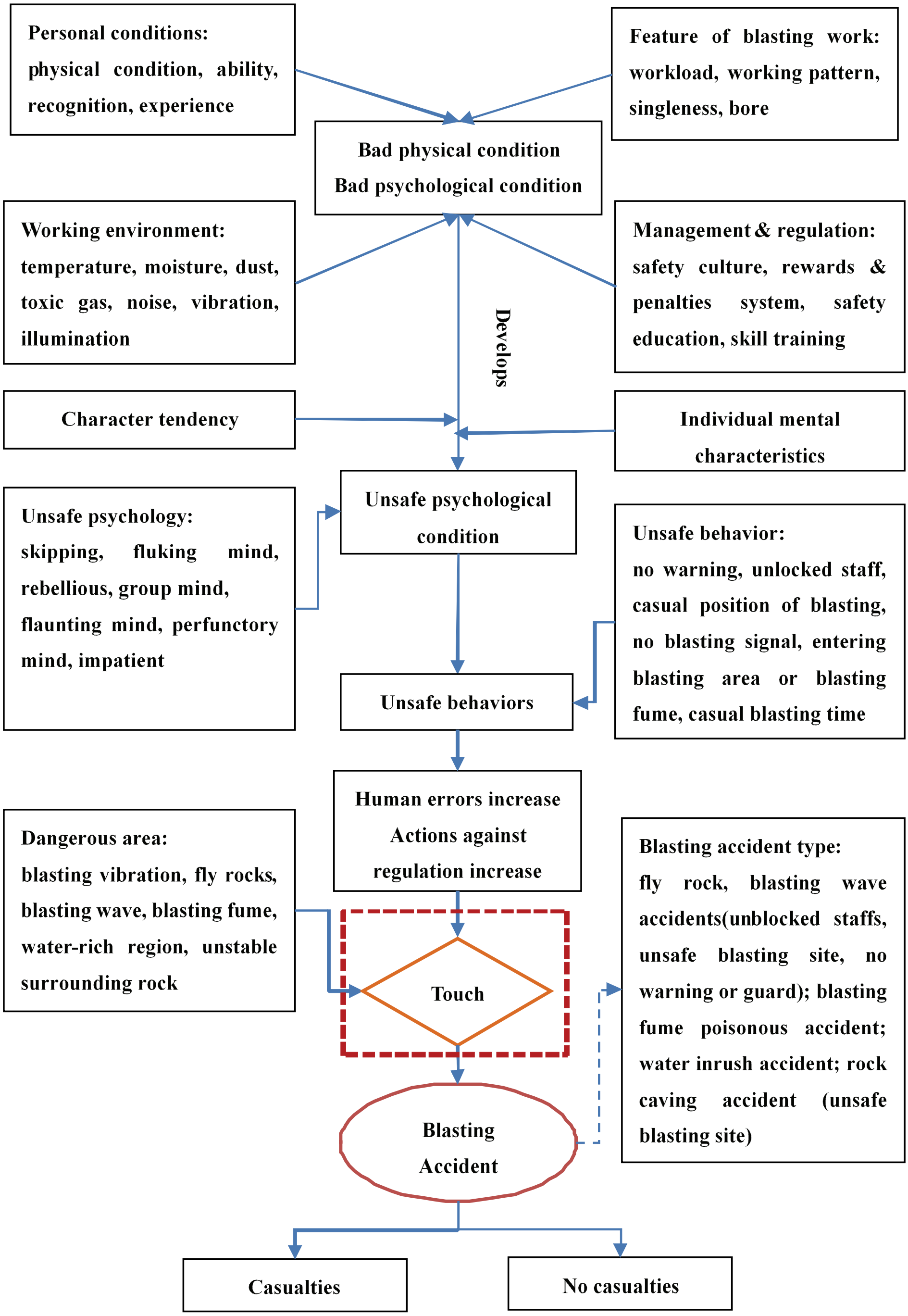


Fig. 1. Schematic map of a model of blasting accident

Theoretically, the discussed blasting accident model provides a good approach for prevention of the accidents. It can be implemented as the specially programmed design supplementing the blasting apparatus, which role is, on one hand, to recognize and revise the incorrect operative acts in the blasting and, on the other hand, to stop the successive blasting operative actions, but also to continue the blasting under safe conditions.

The developed and discussed below blasting monitoring and control system is designed on the basis of the blasting accident model and consists of functional designs aiming not only at reduction of the appearance of unsafe psychological and physical conditions triggering successive erroneous actions, but also at avoidance of the "touch" between the unsafe behaviour and dangerous zones or objects. This functional design can be seen as the principle of prevention of the blasting accidents, and results directly from the blasting accident model.

3. ERGONOMIC DESIGN OF BLASTING MONITORING SYSTEM

Ergonomic design is one of the most significant aspects for the system design, especially for prevention of the accidents. In fact, the process of the blasting operation can be considered as the process of processing information. Effective design to human-machine interaction should be taken into consideration and should be adopted to the working environment. The design concerns mainly a display design and an operative design. Display device is used to transmit running information or signals to workers via visual or aural transmission. Visual transmission, for instance, should include visualization of the blasting machine, LED design of a warning alarm, it should coincide with visual features of a human, and it ought to be designed taking into account principles of accuracy, simplification and reasonable layout. Aural information generally is transmitted by alarming device or microphone. An attention should be paid when designing aural apparatus, especially in respect to the following:

(1) aural signal should be in an accepted range for miners to be responded effectively;
(2) aural information should be easily recognized, for example, being in a frequency range from 500 to 600 Hz (Yang et al., 2009);
(3) aural information, especially an important signal, should be easily captured by the miners and even better, accompanied with a light signal.

Audio transmission also requires special design, for example:

(1) effective audio transmission requires up to 75% (Chen et al., 2002);
(2) it should be considered that human subjective cognition reaches maximum when sound intensity is in 60–80 dB range;
(3) noise will have a covering impact on the audio transmission when noise pressure level exceeds 40 dB (Wang et al., 2007 a).

It is also important for the system operators to have a safe, simple and convenient operation experience and to meet the miner's operation habits. For example, settings concerning charging of a blasting machine and a switch to blasting would be adequate and reasonable; anti-clockwise should better be selected as a directive operation; driving force of a switch should take into consideration of precision, rotatory speed, operation mode and smoothness (Wang et al., 2007b). Besides, human errors should be also considered.

Mutual adaptation between the blasting apparatus and working environment is another critical part for design of the blasting monitoring and control system. The set of equipment should be characterized by stability, environmental-adaption and intrinsic safety. Mining faces are commonly characterized by high moisture and heat, ineffective ventilation, bad illumination, hazardous noise and frequent vibrations. Blasting devices should be shielded sufficiently and be able to run in harsh atmosphere and environment. Moreover, intrinsic safety design should be added to the apparatus counteracting an appearance of dangerous situation when the device is in failed run or out of order.

4. BLASTING MONITORING AND CONTROL SYSTEM

4.1. ELEMENTS OF A SYSTEM

The discussed blasting monitoring and control system consists of software and hardware. The software section comprises programming and information management system platform, like online monitoring system, gun monitoring and analysis system,

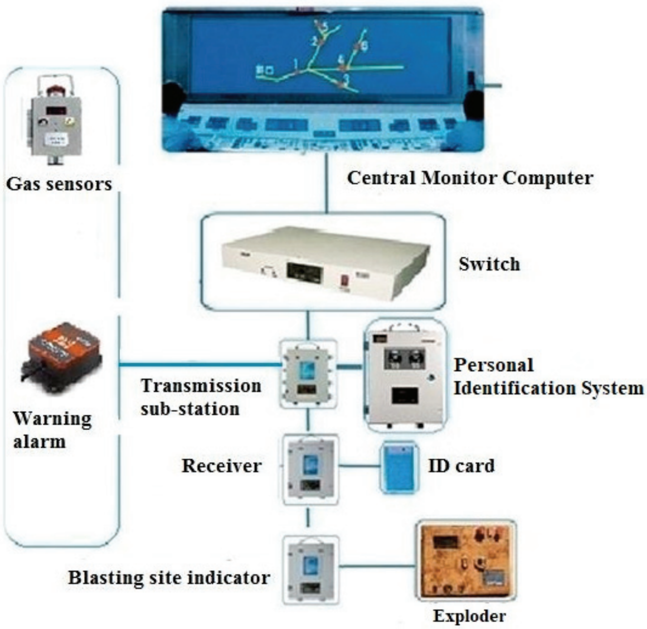


Fig. 2. The diagram of components of the blasting monitoring and control system

blasting data management system and SQL database, which provide technological support for the system. The hardware part includes many module components, such as central monitor computer, switches, transmission substations, personal identification system based on iris pattern recognition, receivers, blasting machine, gas sensors, warning alarm, etc. The software is programmed with C++ language by the customer staff. The diagram of components of the blasting monitoring and control system is demonstrated in the following Fig. 2.

4.2. PRINCIPLES OF OPERATION OF THE SYSTEM

The blasting monitoring and control system can be also divided into two parts according to their placement (depth). The ground part is the core of the blasting monitoring and control, where it provides an overview of the underground blasting works. The blasting

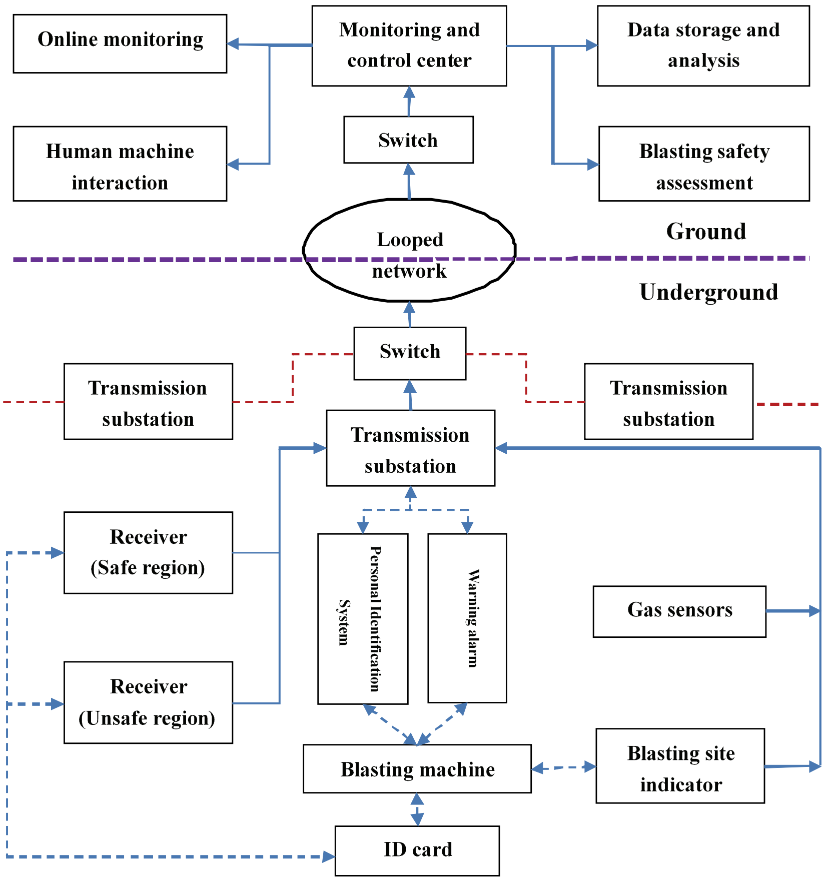


Fig. 3. Schematic diagram of connections of the designed blasting monitoring and control system

system platform can perform a series of functions, for instance, online monitoring, human-machine interactive operation, blasting data storage and analysis, safety assessment of blasting operations, etc. Underground information is transmitted via wired looped network and has a further transformation via switch. The underground part is a critical section for blasting system, because most of the blasting operations are completed underground. Transmission substation is indispensable hub module of information transmission, which collects and transmits signals and data to ground section through the looped network. The receivers placed in safe and dangerous regions, gas sensors and blasting site indicators not only have wired connections to transmission substation, but also supply reliable data and help complete the executive commands. The personal identification system, warning alarm and blasting machine have wireless and indirect connections to transmission substation and provide a direct feedback from the working space to the transmission substation. ID card is an important device for working staff for supplying the positon and identification information to the system. The connections between the discussed modules are illustrated in Fig. 3.

4.3. BLOCKING FUNCTIONS

The blasting machine is equipped with blocking functions, which are in fact the core of the blasting monitoring and control system. Design of these functions originates from the blasting accident model before and is aimed at automatic recognition of unsafe behaviour or actions against regulations, and also at modification or stopping of the incorrect acts via blocking of the blasting machine. It offers good approaches for elimination of erroneous behaviour in blasting operations and allows to avoid generation of dangerous zones or objects, which effectively cuts the "touch" between the unsafe behaviour and dangerous factors. In details, the blocking function of the blasting machine will be executed if: (1) workers are present in potentially dangerous zones; (2) blasting workers are not bound; (3) the blasting site is not in compliance with regulations; (4) blasting time is incorrect; (5) the detonator is in abnormal condition (concerning its resistance, code, quality, etc.); (6) ground monitoring is not well-run.

In the following text, the listed above case (1) is taken as an example to explain the running procedure and the working principle. After completion of the charging, workers will re-check quality of the charging and connections of detonators, tube, and explosive agents. Then, the system will check whether there are workers present in the potentially dangerous zone. There are two receivers installed in the blind gallery. One is placed in the heading, and it is used to detect the numbers of worker in the heading. The other one is installed in the warning line to detect the number of workers in the dangerous zone, which is regarded as a volume space from the warning line to the heading. The position information of a worker is recorded via ID card, which has wireless connection between receivers. The receivers transmit workers' position information to the transmission substation, and then it is further transferred to the blasting monitoring central station. The system will process and operate the data, and send a command to the transmission substation and then to the terminal modules. If there are workers present in the potentially dangerous area, the system will execute a negative command. Then, the blasting machine will be automatically blocked and corresponding signal of the blocked condition will be displayed on the screen. The warning alarm will flash and present a signal of "blasting is prohibited" on the screen. If there is no worker in the dangerous zone, then the information will be transmitted to the transmission substation and the other terminal modules. The blasting machine will be set in a pre-blasting mode, and can be charged for blasting. Following, the warning alarm will present a signal of "blasting is ready". Other blocking functions

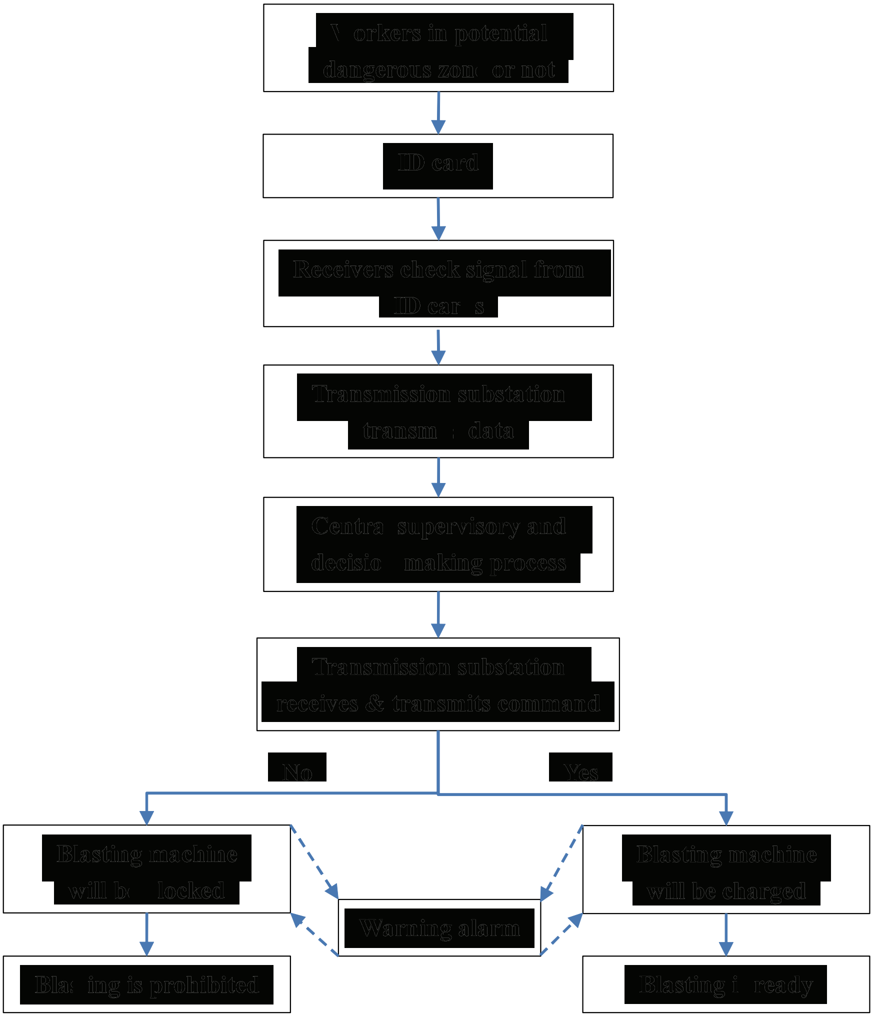


Fig. 4. Flow diagram of the working principle of the blasting blocking function

work alike in terms of the information processing, feedback and sending commands. The discussed process of the blocking function (1) can be demonstrated as a flow diagram in Fig. 4.

5. THE APPLICATION CASE STUDY

5.1. INTRODUCTION TO THE CASE STUDY

Guilaizhuang Gold Mine is located in Shangdong Province of China. Mining activities in this gold mine have begun more than 40 years. In the beginning, the exploitation method was open-pit mining, and it was changed to the underground mining excavation later. Dongguabang is a new gallery used for underground excavation, which is utilized for both prospecting and mining. This gallery is approximately 200 m long. The cross-section shape of the blind gallery is semi-circular arch with a width of ca. 3.0 m and a height of 3.0 m. Blasting method is adopted during the excavation in this gallery. The designed blasting monitoring and control system was successfully installed in the gallery to monitor the blasting operation and to help avoiding the occurrence of the blasting accidents.

5.2. INSTALLATION OF THE SYSTEM

Terminal devices of the blasting system were installed in the Dongguabang blind gallery showed in Fig. 5. The blasting site is located at the sub-branch of the main gallery (marked with a green rectangle in Fig. 6 and it is around 100 m away from the heading. And also, this is the warning line and the border of the safe zone and the dangerous zone. Some devices were also installed there, like the transmission substation, receiver, blasting site indicator, programmed iris identification, and the warning alarm. After completion of

Fig. 5. Installation of modules in Dongguabang gallery

charging and checking, workers related to blasting are obliged to gather in the blasting site and ignite the detonators. Certainly, safety work needs to be performed before ignition to help to eliminate the intentional or unintentional human errors as showed in Fig. 1.

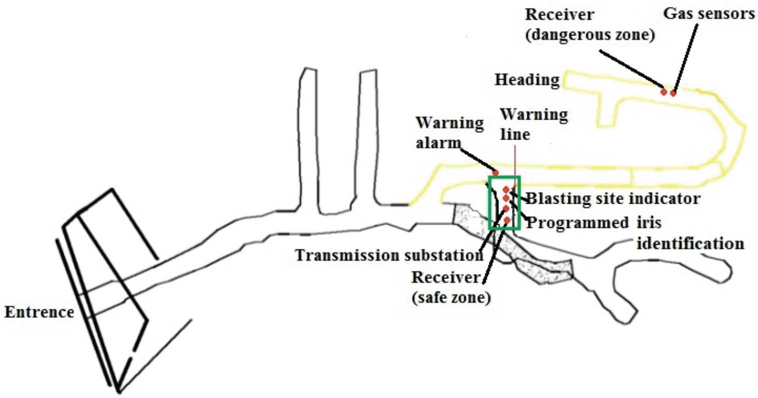
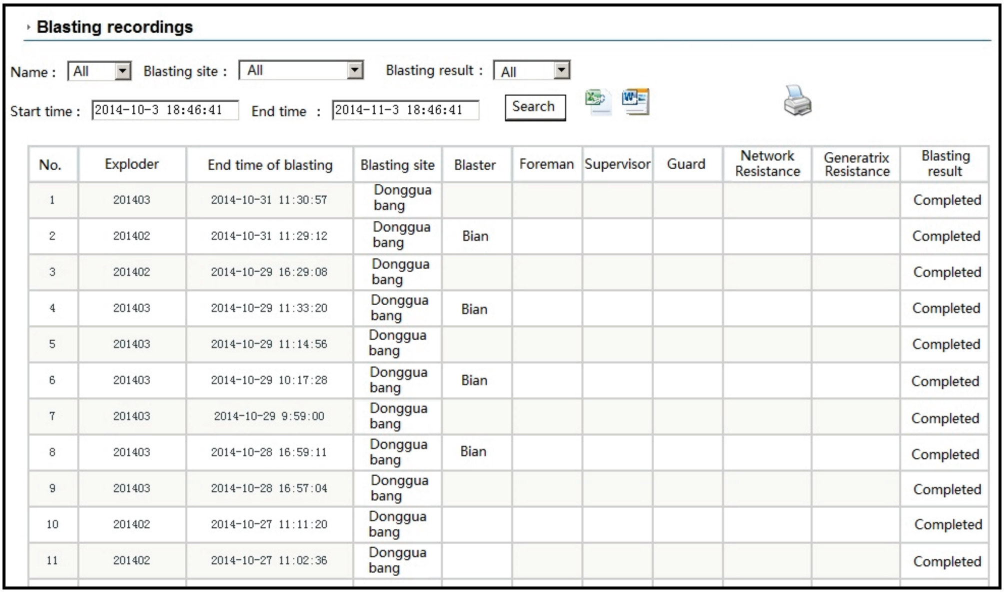


Fig. 6. Schematic map of modules distribution in sub-branch gallery

The whole installation of system was completed on October 25th, 2014 and tested to run successfully on 27th. Afterwards, blasting operations in the blind gallery in Dongguabang was safely conducted at least 10 times according to the blasting re-cordings demonstrated in Fig. 7.



Blasting recordings

Name : All Blasting site : All Blasting result : All

Start time : 2014-10-3 18:46:41 End time : 2014-11-3 18:46:41 Search

No.	Exploder	End time of blasting	Blasting site	Blaster	Foreman	Supervisor	Guard	Network Resistance	Generatrix Resistance	Blasting result
1	201403	2014-10-31 11:30:57	Donggua bang							Completed
2	201402	2014-10-31 11:29:12	Donggua bang	Bian						Completed
3	201402	2014-10-29 16:29:08	Donggua bang							Completed
4	201403	2014-10-29 11:33:20	Donggua bang	Bian						Completed
5	201403	2014-10-29 11:14:56	Donggua bang							Completed
6	201403	2014-10-29 10:17:28	Donggua bang	Bian						Completed
7	201403	2014-10-29 9:59:00	Donggua bang							Completed
8	201403	2014-10-28 16:59:11	Donggua bang	Bian						Completed
9	201403	2014-10-28 16:57:04	Donggua bang							Completed
10	201402	2014-10-27 11:11:20	Donggua bang							Completed
11	201402	2014-10-27 11:02:36	Donggua bang							Completed

Fig. 7. Screenshot of custom software managing database with blasting recordings

Fig. 8. Operations of the blasting management and control platform

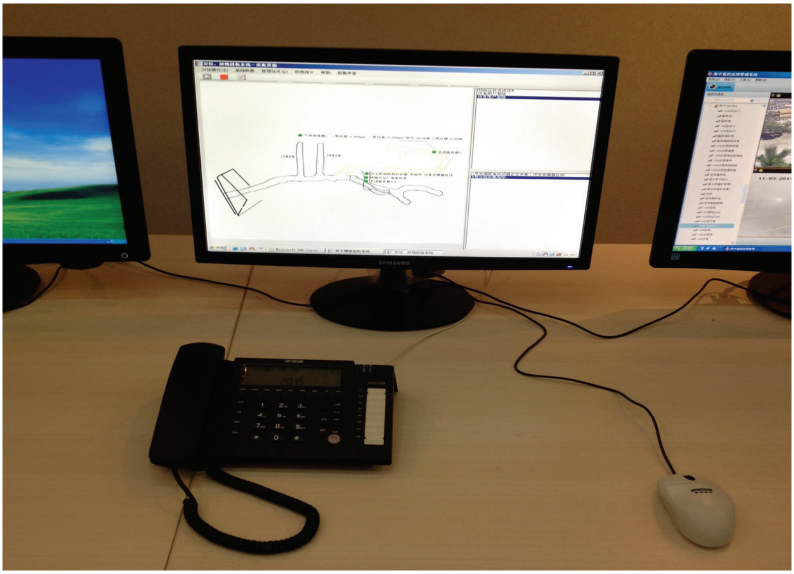


Fig. 9. Running of the blasting management and control platform

In the blasting management and control system, it is possible to monitor the state of the terminal devices. It is also possible to observe which operative step is currently going on. When an emergency appears, stopping of the blasting operation can be done as well. After the blasting, the system platform will automatically collect and store the blasting information, such as name and ID of blasting workers, blasting time, codes of detonators and explosive agents, blasting result, etc. Gas sensors have a 24-hour monitoring function, which can transmit data of concentration of the toxic gas to the ground computer central station. When potential dangerous factors arise, the system can automatically recognize them and remove them, guaranteeing safety during the blasting operation. Photos of the blasting system platform can be seen in Figs. 8 and 9.

6 CONCLUSIONS

A successful application example of the blasting monitoring and management system in the blind gallery of Guilaizhuang gold mine was presented in the paper. The system aims at preventing the occurrence of the blasting accidents. The custom-designed system is based on systematic studies and comprehensive analysis of the available accident data, which allowed to develop a model of a blasting accident. The authors analysed data of the accident cases, which happened in metal mines in China in the last 20 years, and then classified the accidents into different types, summarizing their main reasons. Based on this, it was possible to put forward a blasting model interpreting the process of the blasting accident, and further, to propose the approach to stop the occurrence of the blasting accident effectively. Ergonomic knowledge related to the effective visual and aural transmissions was introduced into the design of the developed blasting monitoring and management system. The obtained results show that the installed system achieves requirements of the blasting operations effectively and performs very well in terms of prevention of the occurrence of the blasting accident.

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