Mitigation Effects of a Water Barrier on Dynamic Loads on the Human Body at Explosions in Tunnels

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Abstract. According to the standards ISO 6184/4 and EN 14373, the efficacy of explosion suppression systems is estimated by maximum reduced (suppressed) shock wave overpressure, recorded in a suppressed explosion event. In addition to this, a significant interest is the capability of explosion protection systems to reduce the dynamic loads on the human body. This task is not considered in standards. The G. Tsulukidze Mining Institute has been studied mitigation of dynamic loads on human by water barrier, generated using the protective system. The system composed of a blast detector, a wireless device for activation and an absorber. During an accidental explosion, the proposed system immediately forms a protective water barrier in the zone to be protected to reduce the overpressure generated by a shock wave. A prototype model has been manufactured, installed and tested under real explosion conditions in the underground experimental base of the G. Tsulukidze Mining Institute. An anthropomorphic test device Hybrid III 50th was used during testing. To register dynamic load generated during an explosion, 7 sensors were installed in different zones of the dummy. Tests were conducted both with the use of the protective system and without it, in conditions when the charge weight was 2 kg, and the distance from the charge to the dummy was 8,5 m. Comparative analysis showed that the protective system, which contains one absorber (may contain several absorbers), reduces the dynamic loads generated in different zones of a human body by 30-50%.

1. Introduction
The development of systems of protection from explosions has become particularly relevant in recent years. The emphasis is on terrorist and accidental explosions, as well as methane or dust-air mixture explosion in coalmines and at other industrial sites. The principle of the operation of protective systems presupposes the creation of blast mitigating barriers on the path of blast wave propagation in the protection zone. At present, mines in different countries use immovable or moveable passive water trough barrier to protect from methane explosion. The requirements to the passive water trough barriers are provided in the Standard EN-1459-2 (2007). The protective water barrier is created in the process of the spill of water from 40-90 litre volume troughs. The protective system activates and water disperses exclusively at the expense of blast pressure. According to the Standard, the distance between the barriers should not exceed 75m for concentrated water trough barrier and 30m for distributed water trough barrier. Water concentration at barrier location should be at least 5 l/m³ and 1 l/m³ respectively. [1]

An automatic explosion extinguishing system activated by means of a blast or flame detector has advantages over passive water trough barrier. An automatic system enables for the use of dispersed
water as an extinguishing agent and enables an immediate formation of a water mist barrier. Studies have shown that water mist is characterized by attenuation properties of shock wave overpressures and fires. The influence of droplet size, density, spray velocity and other characteristics of dispersed water flow on explosion mitigation and in controlling fires have been established [2-6]. O. Igra et al have provided a review of the methods used for the attenuation of shock/blast waves [7].

Contemporary automatic protective systems are composed of three main sub-systems, those of: i) threat detection and alarm signal generation; ii) control action and iii) blast absorbing agent discharge.

Such blast protection systems are now available in a variety of designs [8-12]. The systems differ in terms of blast detection (optical, thermo, pressure sensors or their combination), an extinguishing agent (dispersed water, stone dust or another blast absorbing agent), discharging mechanism (pressurised gas, pyrotechnical device or detonating cord) and agent container capacity. Systems of this kind have been developed and applied in various mines; e.g., in Ukraine (AVP-1), Germany (BVS), UK (“Graviner”), Russia (ACVP-LV), US, etc. Research has been conducted to develop a system for protection from dust explosion in industrial sites and plants producing chemicals, plastics, textiles, pulp and paper, pharmaceuticals, as well as mills [12]. However, related scientific papers published so far do not provide comprehensive information on the working capacity of such absorbers. This paper presents the results of the determination of efficacy explosion suppression system by dynamic loads on the human body.

2. Testing methodology
Testing methodology entailed the measurement of dynamic load on a human’s body with mist generated by the system and without mist, under the same blast conditions. The test plan and the location of the protective system in the tunnel are shown in Figure 1.
The following sensors were installed in the dummy model - Hybrid III (Figure 2, 3):

1. Pressure sensor PCB in the front part of the head;
2. Pressure sensor PCB in the chest;
3. Pressure sensor PCB in the lower tibia;
4. Accelerator END7264B-2000-300 in the lower part of the spine,
5. Three-channel force sensor 2564 JLN2 in the neck.

The system was tested under the following conditions: charge weight: $W=1 \text{ kg}, 2 \text{ kg}$, type of explosive – ammonite 6JB; distance from the charge to the sensors: - 8.5 m; distance from the charge to mist: 3.0 m. Nozzles BETE P120 were used in the suppression section and the flow rate was 30.3 l/s.

![Figure 2. Location of sensors on Hybrid III](image1)

![Figure 3. Photo of the dummy model Hybrid III in the underground opening](image2)

The signal generated at sensors was transferred to the signal amplifier, and then to the digital oscilloscope Tektronix 420. The experiments were conducted in the underground experimental base of the G. Tsulukidze Mining Institute Figure 4, 5.

![Figure 4. Chart of a measuring device](image3)

![Figure 5. Signal recording devices in the observation module](image4)
3. Test results

3.1. Impact of water mist on shock wave overpressure on the human body

Overpressure histories on a human for the explosion at charge weight W=1kg without mist and with mist are shown in Figure 6.

![Figure 6. Overpressure histories on the human body W=1 kg; A - without water, B - with water](image)

Table 1 shows the highest values of shock wave overpressures and impulses on the human at W=1kg.

| №  | Overpressure, kPa | Duration of the positive phase, ms | Impulse, kPa·ms | Overpressure reduction coefficient, Kp= ΔPa/ΔPm | Impulse reduction coefficient, Ki=Ia/Im |
|----|-----------------|---------------------------------|-----------------|---------------------------------|---------------------------------|
|    | Without mist    | With mist                       | Without mist    | With mist                       | Without mist    | With mist                       | Without mist    | With mist                       | Without mist    | With mist                       |
| 1-1| 65              | 40                             | 7               | 4                              | 280              | 160                            | 1.25            | 1.75                            |
| 2-1| 48              | 27                             | 4               | 3                              | 108              | 81                             | 1.78            | 3.33                            |
| 3-1| 99              | 37                             | 7               | 6                              | 693              | 192                            | 2.67            | 3.60                            |
| Av.| 71              | 35                             | 6               | 4.3                            | 426              | 150                            | 2.02            | 2.84                            |

3.2. Impact of water mist on the reduction of dynamic loads on the human body at W=1kg and W=2kg

Histories of dynamic load on the human body for the explosion at charge weight W=1kg without mist and with mist are shown in Figure 7.
Figure 7. Histories of dynamic load on the human body $W=1$ kg, a - without water, b - with water
1 - Shear force $F_x$ in the neck, 2 - Axial compression force $F_z$ in the neck, 3 - Flexion bending moment $M_y$ in the neck, 5 - Pelvis vertical acceleration $A_g$

Histories of dynamic load on the human body for the explosion at charge weight $W=2$kg without mist and with mist are shown in Figure 8.

Figure 8. Histories of dynamic load on the human body $W=2$kg, a - without water, b - with water
1 - Shear force $F_x$ in the neck, 2 - Axial compression force $F_z$ in the neck, 3 - Flexion bending moment $M_y$ in the neck, 5 - Pelvis vertical acceleration $A_g$

Tables 2 and 3 show the dynamic loads on a Hybrid III at $W=1$kg and $W=2$kg

### Table 2. Dynamic loads on a Hybrid III at $W=1$kg

| Part of body | Dimensional quantity | Without mist | With mist |
|--------------|----------------------|--------------|-----------|
| Upper neck load cell | Shear force $F_x$ | 160 N | 110 N |
| | Axial compression force $F_z$ | 360 N | 240 N |
| | Flexion bending moment $M_y$ | 1 N·m | 0.7 N·m |
| Pelvis acceleration | Vertical acceleration $A_g$ | 9 g | 6 g |

### Table 3. Dynamic loads on a Hybrid III at $W=2$kg

| Part of body | Dimensional quantity | Without mist | With mist |
|--------------|----------------------|--------------|-----------|
| Upper neck load cell | Shear force, $F_x$ | 280 N | 200 N |
| | Axial compression force, $F_z$ | 400 N | 310 N |
| | Flexion bending moment, $M_y$ | 2 N·m | 1.2 N·m |
| Pelvis acceleration | Vertical acceleration, $A_g$ | 14 g | 11 g |

### 4. Conclusions

The proposed methodology for assessing the water barrier mitigation effect, based on a comparison of the dynamic loads on the human body, makes it possible to reasonably evaluate the effectiveness of explosion protective systems.

The results of the protective system testing in the underground opening:

1. Shock wave overpressure on the human body are reduced by 1.25-2.67 times, on average – by 2.02 times; pressure impulses are reduced by 1.75-3.60 times, on average – by 2.84 times.
2. Shear force $F_x$, Axial compression force $F_z$ and Flexion bending moment $M_y$ are reduced by 22-33%.

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