Mining Science, vol. 30, 2023, 171–181

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe Instytutu Gornictwa Politechniki Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received February 12, 2023; Reviewed; Accepted September 26, 2023

EFFECT OF CUMULATION ON DETONATION VELOCITY OF LOW SENSITIVITY EXPLOSIVES

Zdravka MOLLOVA*

University of Mining and Geology "St. Ivan Rilski", Department of Underground Construction, 1000, Sofia, Bulgaria

Abstract: In an effort to improve the parameters of the blasting works carried out with low-sensitivity explosives, bearing in mind the studies of the cumulation phenomenon and the modern knowledge of the concentration of energy in a certain direction or place, studies of the detonation speed at different diameters of the charge of the coarse explosives were carried out – Anfo type with intermediate detonator 900 g cast booster with and without cumulative funnel (CF). Tests carried out in landfills and industrial conditions have shown that the type of intermediate detonator significantly affects the detonation speed, and therefore also affects the other explosive characteristics of the explosives. The highest detonation velocity was achieved when the explosives were initiated with cast boosters with cumulative funnels. Tests have shown that when initiating coarse explosives with boosters with CF, stable detonation of the charges is obtained with optimal fragmentation of the material, and the mass of the used explosives is reduced by 14%. Their use in carrying out blasting works with low-sensitivity explosives of the emulsion and coarse-disperse type leads to an increase in the blasting efficiency, achieving better crushing of the rocks and reducing the costs of additional crushing of the non-gauge.

Keywords: *velocity of detonation, cast boosters, conical shaped charge, explosives*

1. INTRODUCTION

The modern stage of development of geotechnologies is characterized by a slowing down of the pace of qualitative development, which, in turn, is related to a slowing

* Corresponding author: z.mollova@mgu.bg (Z. Mollova)

doi: 10.37190/msc233011

down of the processes of improvement of drilling-explosive works, as the basis of most applied mining technologies. Traditional ore extraction through the use of blast holes or boreholes has largely exhausted its capabilities.

The search for ways to improve the efficiency of drilling and blasting works is carried out mainly in the direction of improvement, automation and robotization of drilling processes, i.e., the methods of creating charging chambers. As for the construction of the blast holes or boreholes, there have been no fundamental changes for quite some time. In all cases, knockdown is performed by monocharges using burst expansion models, when a significant portion of the burst energy concentration is dissipated in all directions and deep into the array.

Approximately 50–70% (according to various estimates) of the total energy of the charge is spent technologically unnecessarily and most often – harmfully, changing the state of the array outside the weaned volume.

This appears as the result of the action of two internal contradictions of the existing system, which cannot be overcome within this model of action of the explosion.

The first contradiction is the one between the energetic expediency of the increasing diameter (and hence mass) of a unit charge and the technical limitations in the field of creating tools for drilling wells of an ever-increasing diameter (Belin and Mitkov 2015).

The second is the contradiction between the technologically necessary asymmetry of the distribution of the energy of the explosion in the array and the absolute symmetry of the energy transfer process of each charge in this array, resulting from the very essence of the detonation phenomenon. The possibility of overcoming the first contradiction is related to the realization of the idea of managing the energy of the explosion by deconcentrated charges, such that single charges of large diameter are replaced by a group of their equivalents in terms of total energy and simultaneously detonated charges of a small diameter (Mitkov 2007; 2014).

In such case, under certain conditions, increasing the number of charges in the group is possible to ensure the formation of a charge equivalent to a single charge of practically any diameter without increasing the capacity of the drilling machine.

Overcoming the second contradiction requires a purposeful and radical intervention in the energy transfer processes in the probed array. Partially, such possibilities also appear in the implementation of the idea of charge deconcentration.

Replacing single charges of large diameter and power with a group of smaller charges equivalent in total energy opens completely new possibilities for controlling the processes of transmission and distribution of the blast energy in the blast array by changing the parameters and spatial position of each single charge in the group.

The preservation of the generally accepted model of a multidirectional explosion, within which the level of dissipative energy losses in different directions is changed through a purposeful change of the shape of the integral front of the shock wave. This creates additional opportunities for increasing the drill and blast work indicators, but due to the general symmetry of the development of energy transfer processes to the array, the phenomenon of useless energy consumption deep in the array, outside the design contours of the demolished blocks, remains (Mitkov 2009).

A great and quite interesting geotechnological perspective is the creation of methods for the destruction of rock formations with a sharp asymmetry in the distribution of the energy of the explosion in space and its maximum concentration in the direction of the destroyed massif. An opportunity to realize this idea is connected with the use of the long-known principle of accumulation of the energy of the explosion depending on the shape of the charge.

2. MATERIALS AND METHODS

It is known, that during the detonation of an explosive charge without a cumulative depression, the energy of the explosive is dispersed in all directions, and the presence of a cumulative depression in the charge leads to a concentration of the energy density in a certain direction. The directional axial cumulation has the greatest importance in practice. This type of cumulation can be realized when initiating axisymmetric charges having a different type of depression – cone, hemisphere, parabola, hyperbola, etc.

The process of formation of a cumulative stream of axisymmetric charges with conical and hemispherical depressions is best studied. The results obtained during X-ray examination of cumulative jets from conical depressions show that the speed in the front part of the jet reaches 9–10 km/s, and in the tail 2–2.5 km/s. The speed of the jet of the same material and hemispherical recess is two times smaller. When a liner is used this difference is compensated by the fact that the mass of the cumulative jet from the hemispherical liner is three to four times greater, so that the total energy of the jet from the hemispherical liner is comparable to the energy of the jet from a cone of the same mass. But due to the fact that in our research there is no need for a cumulative lining, we chose a design with a conical recess and a cone dissolution angle of $2a = 50°$.

In an effort to improve the parameters of the blasting works carried out with low--sensitivity explosives, bearing in mind the above, the studies of the cumulation phenomenon made by Prof. Suharevski M.Ya. and modern knowledge about the concentration of energy in a certain direction or place, research was carried out on the speed of detonation at different diameters of the charge of coarse explosives – type Anfo with an intermediate detonator 900 g cast booster without and with a cumulative funnel. A scheme of a cast booster type cumulative charge is given in Fig. 1. The material for the production of the products comp.B, has the following characteristics: composition:

hexogen – 59.5%, TNT – 39.5%, ceresin or wax –1%, detonation speed D = 7920 m/s at density p_0 = l.7 g/sm^3 and heat of explosion Q = 5.02 MJ/kg.

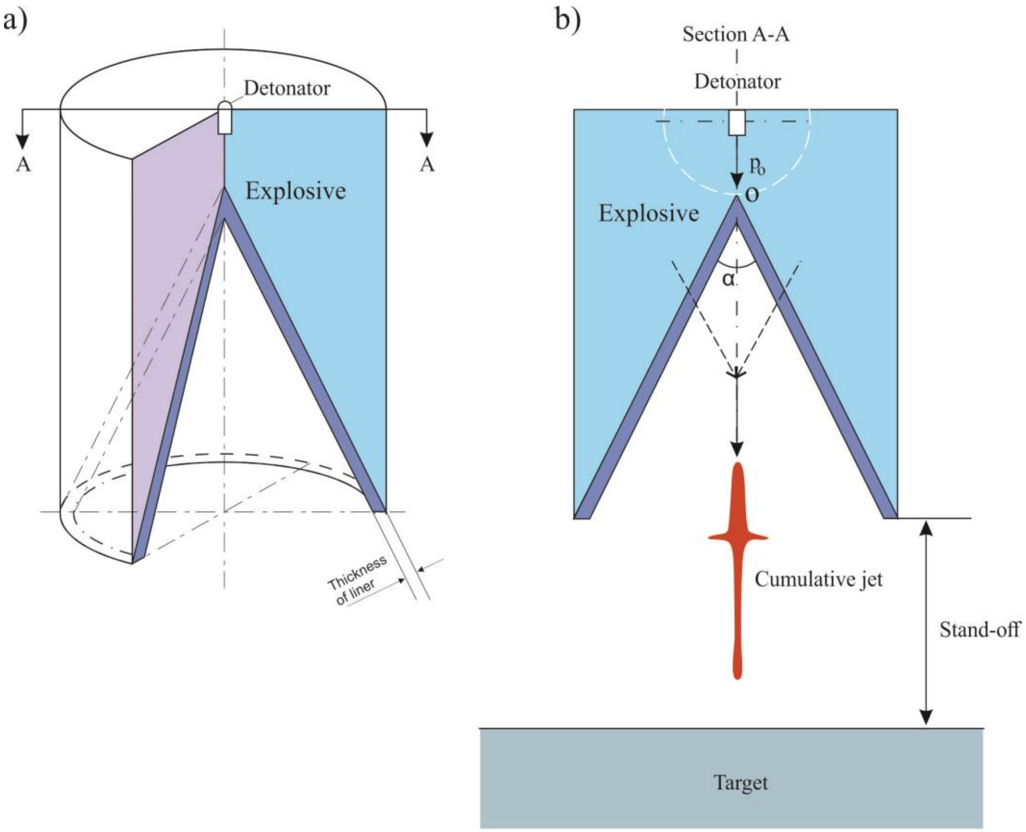

Fig. 1. Scheme of a conical shaped charge (CSC)

The speed of the cumulative jet depends on: the dimensions and shape of the short circuit; the shape, geometry and material of the cumulative opening; the quality, energy content, density and detonation rate of the explosive; the presence of a “lens”; the accuracy of manufacturing the various parts of the circuit breaker and the accuracy of their assembly. Figure 2 shows successive stages of the formation of the cumulative jet captured with a speed camera.

The cross-sectional shape of the cutting shaped charge is shown in Fig. 3. When constructing a physical and mathematical model of the charge operation process, the following conditions were accepted:

– detonation of the explosive charge occurs simultaneously over the entire cross section of the cutting charge, which corresponds to the flat shape of the front of the detonation wave propagating along the charge;

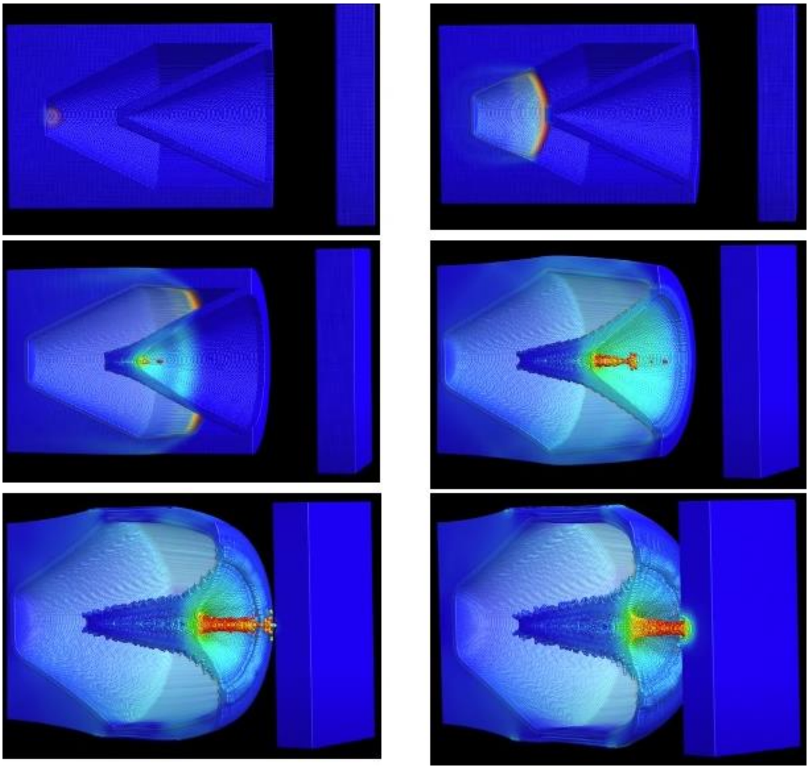

Fig. 2. Successive stages of formation of the cumulative jet

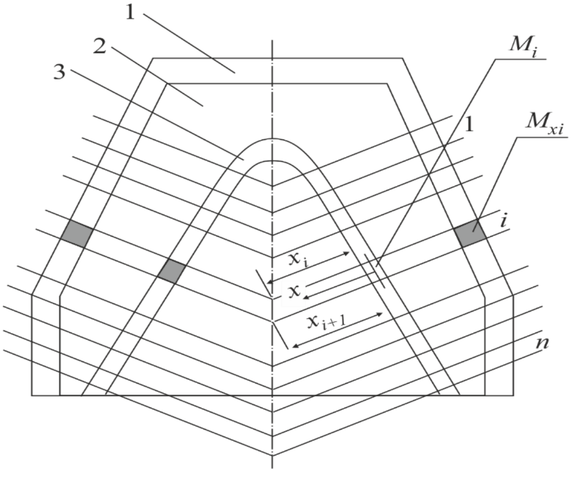

Fig. 3. Scheme of the cross-section of the separation of the calculated sections 1, ..., *n* to determine the kinematic parameters of the cumulative knife:
1 – outer shell of the CSC, 2 – explosive, 3 – cumulative shell

– the movement of each element of the cumulative shell (CS) is carried out in Fig. 3. Successive stages of formation of the cumulus jet in the direction of the normal to its middle part in the undeformed state;
– the speed of movement of each element of the shell is carried out according to the exponential dependence;
– the process of forming a "cumulative knife" during the assembly of lining elements in the plane of symmetry of the cutting shaped charge (CSC) is described by the hydrodynamic theory of cumulation.

To carry out the necessary calculations, the cross section of the cutting charge is divided by planes perpendicular to the average surface of the shell into *n*-parts. For each cross section obtained in this way, the masses of the included elements of the body M_{ki}, the lining M_i and the explosive charge m_i are determined. The final throwing velocity of an arbitrarily taken *i*-th element can be determined from the energy balance equation for a single unilateral leakage products of detonation (PD) and is calculated by the formula:

$$V_i = 0.353D\sqrt{\frac{3\beta i}{3+\beta i}}\ , \tag{1}$$

where $\beta i = m_{ai}/M_i$ – load factor, m_{ai} – active mass of explosives in the *i*-th section, calculated by the formula:

$$m_{ai} = m_i\ /\ 2(1+M_{ki} - M_i\ /\ M_i + M_{ki} + m_i)\ , \tag{2}$$

where m_i, M_{ki} – the mass of the explosive and the outer shell of the charge in the *i*-th section, if the charge does not have an outer shell (M_{ki} = 0), then

$$m_{ai} = m_i 2/2(M_i + m_i).$$

If the charge does not have an outer shell, then the value M_{ki} = 0 and at a certain value of V_i can be used in the definitions:

$$V_i = 1.2D\frac{\sqrt{1+(32/27)\eta i - 1}}{\sqrt{1+(32/27)\eta i + 1}}\ , \tag{3}$$

where $\eta i = (\delta_{ei}\rho_e/\delta_i\rho_o)$, δ_i, δ_{ei}, and δ_i, δ_{ei} and ρ_o, ρ_e are the thickness and density of the shell and explosive, respectively, in the *i*-th charge cross section (Mitkov 2007).

It is important to note that the shell element develops the speed V_i, determined by formulas (1) and (3), not instantly, but in the process of acceleration, overcoming a certain distance. This circumstance can be significant for the upper elements of the shell, the path of movement of which from the initial position to the separation point in the plane of symmetry RZ x_i (see Fig. 3) is small. Therefore, in the case of the above elements, a situation may arise when they will not be able to gain full speed until the moment of liftoff. In this case, it is possible to form a cumulative knife with a negative value of the axial velocity gradient in its front part (the first elements of the knife move more slowly than the subsequent ones). This was experimentally proven in Orlenko (2002).

To take into account the influence of the dynamics of acceleration of shell elements from detonation products, the approach used in describing the process of acceleration of cylindrical fragmenting shells (Zaid et al. 1971) is used. In accordance with this approach, the law of motion of shell elements is written as:

$$V_{oi} = V_i (1 - \exp\{-t / \tau_i\}), \qquad (4)$$

where V_{oi}, τ_i and V_i, respectively: the separation velocity, the characteristic acceleration time and the asymptotic velocity of the *i*-th element of the shell, determined by (1) or (3).

Differentiating expression (4) with respect to time, we find the acceleration of the shell element $a_{oi} = dV_{oi}/dt = (V_i/\tau_i) \exp(-t/\tau_i\}$, from which the characteristic acceleration time under the initial condition $t = 0$ can be defined:

$$(dV_{oi} / dt)0 = V_i / \tau_i = p\max S_i / M_i , \qquad (5)$$

where $p$max – maximum pressure PD, equal to $p\max = p_e D^2/4$, S_i – surface of the *i*-th element of the shell. Then, considering that $M_i = \rho_0 \delta_i S_i$ we get the formula:

$$\tau_i = 4V_i \delta_i \rho_0 / \rho_e D^2 . \qquad (6)$$

By integrating expression (4) with respect to time, we can obtain the distance traveled by the *i*-th element of the shell for a randomly selected moment of time:

$$X_i(t) = V_{it} + V_i \tau_i (\exp\{-t | \tau_i\} - 1) . \qquad (7)$$

The acceleration rate of the shell elements according to (4) depending on the time relative to the characteristic acceleration time is illustrated by the data in Table 1. It follows from the given data that 95% of the final throwing velocity of the shell elements is achieved during the passage time $t = \tau_i$ in accordance with formula (7), the distance $X_i = 2.05 V_i \tau_i$.

Table 1. The dependence of the acceleration rate of shell elements on time

t/τ_i	1	2	3	4	5
V_{oi}/V_i	0.63	0.86	0.95	0.98	0.99

If we substitute in formula (7) the current value of the distance X_i (see Fig. 3), which must be passed from the corresponding shell element to the moment of addition in the CSC symmetry plane, we will obtain a transcendental equation for determining the current time of its movement τ_i. Taking this time into account, according to Eq. (4), the speed of each *i*-th element at the moment of shell assembly is calculated. Taking into account this time, according to Eq. (4), the velocity V_{oi} of each *i*-th element at the time of assembly of the shell is calculated.

The parameters of the cumulative knife formed during the operation of the CSC are determined on the basis of the hydrodynamic theory of cumulation, taking into account the influence of the mechanical properties of the shell material. In accordance with this theory, the speed of the elements of the cumulative knife can be determined by the formula:

$$V_{ji} = V_{oi} \frac{\cos(\varphi i)}{\mathrm{tg}\left(\frac{ai}{2}\right)} - \sin(\varphi_1)\ , \tag{8}$$

where φ_1 – angle deviations vector velocities eject the element through shells from normals to its surfaces at the time of addition, ai – dynamic collection angle (Fig. 4).

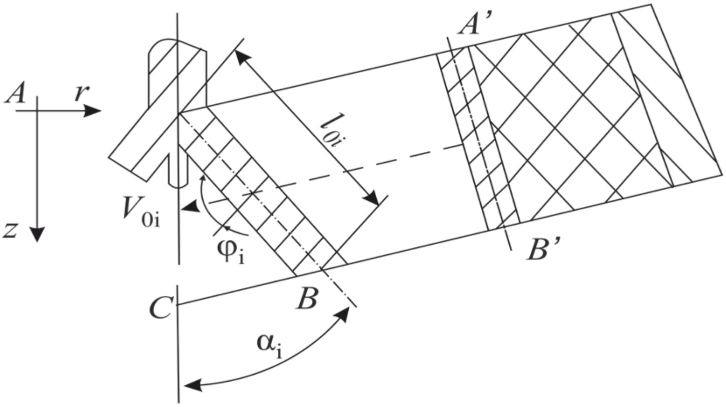

Fig. 4. Scheme of the formation of elements of a cumulative knife

To determine the shear depth under the action of cutting shaped charge on partitions made of various materials based on the calculated parameters of the formed cumulative jet, additional data are needed that characterize the processes of its deformation and destruction of individual fragments. Approximately, we assume that the length l_i of the element of the cumulative jet at the moment of the beginning of the impact on the barrier is equal to its initial length l_{ei} (see Fig. 4), or $l_i = l_{ei}$. Then the depth of penetration of the element of the cumulative jet into the barrier, taking into account the hardness and strength of the latter, can be described by the formula:

$$\frac{L_i}{l_i}=\frac{1-\left(\frac{\rho_T}{\rho_j}\right)\left(\frac{2H_D}{\rho_T V_{ji}^2}\right)}{\sqrt{1+\left(1-\frac{\rho_T}{\rho_j}\right)\left(\frac{\rho_T}{\rho_j}\right)\left(\frac{2H_D}{\rho_T V_{ji}^2}\right)+\sqrt{\frac{\rho_T}{\rho_j}\left(\frac{2H_D}{\rho_T V_{ji}^2}\right)}}}, \qquad (9)$$

where ρ_T, ρ_j – bulk and jet densities, V_{ji} – finite element velocity, H_D – dynamic hardness of the partition material.

To determine the detonation speed of the main charge, a “Microtrap” device from the Canadian company “Mrell” was used, respectively with probes for the range tests and a test cable for the industrial tests in the boreholes.

The range tests were conducted with charges of Anfovex explosive placed in PVC pipes with a wall thickness of 2.5 mm and a charge diameter of 110 mm and a length of 900 mm. Initiation was performed with CB-900 cast booster (CB) with and without a cumulative funnel. The obtained results are given in Table. 2.

Table 2. Detonation speed of ANFO charges initiated by CB with and without CF

Try in order №	CB without CF – *D*, m/s	CB with CF – *D*, m/s
1	3608	4735
2	3705	4515
3	3915	4800
4	3850	4720
Average speed	3770	4693

The industrial research was carried out at the quarry “Ognyanovo K” for mining and production of limestone fractions, located in Plovdiv region, Republic of Bulgaria. The drilled field with boreholes 15 m deep and 102 mm in diameter, with a blast grid of 3.5 × 3.5 m was loaded with Anfovex, half of the boreholes were initiated by CB without CF, and the other half from CB with CF. The speed in the boreholes was measured with the same device and the results are given in Table 3.

Table 3. Detonation speed of “Anfovex” in boreholes with a diameter of 102 mm depending on the type of CB

Try in order №	CB without CF – *D*, m/s	CB with CF – *D*, m/s
1	4336	5682
2	4483	5328
3	4625	5712
4	4543	5570
Average speed	4497	5573

3. RESULTS AND DISCUSSION

From the analysis of the obtained results, the following was established: The coarse-dispersed explosive ANFO has a stable detonation speed both when initiated with cast booster with CF and when initiated with CB without CF. It should be noted that the speed of detonation of the charge when initiated by CB with CF exceeds by more than 900 m/s the speed of detonation of the charge initiated by CB without CF. This represents an increase of over 24% in the detonation speed when using a CF DC compared to a regular DC initiation.

The use of cast booster with CF led to obtaining quite satisfactory results in the destruction of the array and the fragmentation of the material, and the mass of the CB with CF was 130 g less than the standard CB without CF.

Industrial tests have shown that when initiating the coarse explosives with CB with CF, a stable detonation of the charges is obtained with optimal fragmentation of the material, and the mass of the used CB is reduced by 14%.

The tests that were carried out in landfills and industrial conditions showed that the type of intermediate detonator significantly affects the detonation speed, and therefore also affects the other explosive characteristics of the explosives. The highest detonation velocity was achieved when the explosives were initiated with molten boosters with cumulative funnels. Tests have shown that when coarse explosives are initiated with CB with CF, a stable detonation of the charges is obtained with optimal fragmentation of the material, and the mass of the used CB is reduced by 14%. Their use in carrying out blasting works with low-sensitivity explosives of the emulsion and coarse-dispersed type leads to an increase in the blasting efficiency. A better crushing of the rocks is achieved and the costs of additional crushing of the non-gauge are reduced. The use of intermediate detonators of this type increases the effectiveness of the low sensitivity explosives used.

4. CONCLUSIONS

The following main conclusions can be drawn from the conducted research:

1. When initiating the charges of coarse explosives with CB with CF, the detonation speed of the charges increases from 4497 to 5573 m/s.
2. When working with CB with CF, optimal destruction of the array and fragmentation of the material is obtained, achieving sustainable detonation of the charges.
3. When working with cast booster with CF, the costs of detonation are reduced due to the reduced amount of explosive used for the production of one CB (for CB-900) by about 130 g.
4. Cumulative funnel boosters have excellent water resistance, do not plow and do not pollute the environment during transportation and use. They are produced

from products obtained during the disposal of unnecessary army ammunition and have a low cost.

All these characteristics of the new boosters with a cumulative funnel suggest their increasingly widespread application in mining practice, in open pits and quarries, as well as their use in underground and underwater conditions for blasting.

ACKNOWLEDGEMENTS

The presented scientific research was carried out thanks to the funding of the research activity of young scientists and postdoctoral students, in implementation of the first stage of the National Program "Young scientists and postdoctoral students – 2", adopted by Decision No. 206/07.04.2022 of the Council of ministers of the Republic of Bulgaria.

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