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Assessing the explosion effect on rock mass pre-destruction

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Abstract

Introduction. *Theoretical and empirical research into rock blasting proved that detonation wave propagation results in the development of destruction and pre-destruction zones around the explosive cavity. In the destruction zone, rock crushes. In the pre-destruction zone, stresses set up by the detonation wave are concentrated on rock mass structure defects, giving rise to new micro defects and the development of the existing ones. Rock fracturing and cavitation increase, lowering its strength properties; this is called rock pre-destruction. There are works devoted to the qualitative analysis of rock in the pre-destruction zone, but the problem requires elaboration to offer possibilities for practical application.*

Research aims *to quantify rock mass pre-destruction to use the parameters of rock blasting by borehole charges under opencast mining in engineering calculations.*

Methods of research. *To assess the degree of rock mass pre-destruction at a distance from the charge axis, a pre-destruction intensity coefficient is used. The destruction zone radius is determined by a well-known method. In the destruction zone, the value of the pre-destruction intensity coefficient is higher than one, i. e. there is discontinuity of the rock mass. Beyond the destruction zone, there is a pre-destruction zone where the value of the pre-destruction intensity coefficient is less than one. The pre-destruction zone boundary is at distances of the order of 200–250 charge radii. The pre-destruction intensity coefficient of a particular zone attained after all charges have been fired is determined by summing the pre-destruction intensity coefficient from every charge. According to the energy approach, rock strength can be assessed by the value of the specific drilling energy intensity. In order to determine the reduction value of the specific drilling energy intensity in a particular zone, it is essential to know the drilling specific energy capacity of this zone in the natural state, the pre-destruction intensity coefficient attained after a large-scale blast of borehole charges, and specific drilling energy intensity of completely disintegrated rock. The effect made by another borehole charge explosion on the rock mass is weaker due to its pre-destruction by previous blasts. So we propose the impact multiplicity coefficient that reflects the accumulation of pre-destruction in a particular zone under the sequence blasting of borehole charges.*

Results. *The expected value of the specific drilling energy intensity has been calculated for the individual arbitrarily spaced wells within the pre-destruction zone of a particular rock mass zone. The calculation results were compared with the practical values measured during blasting preparation in the preset rock mass zone.*

Conclusions. *The findings of this study have made it possible to quantify the impact of explosions on rock mass pre-destruction. The developed technique makes it possible to predict the value of drilling energy intensity in the pre-destruction zone and, as a result, establish the required specific energy intensity of detonation and hence the consumption of explosives. Thus, it becomes possible to reduce the consumption of explosives under the existing blasting scheme at the enterprise and model other charge initiation types to select the least expensive one.*

Keywords: *rock; large-scale blasting; pre-destruction intensity coefficient; impact multiplicity coefficient; specific drilling energy intensity; explosive consumption.*

Introduction. There are a lot of works on the qualitative analysis of rock state in the pre-destruction zone created as a result of the effect of the blast loads on the rock mass [1–6]. However, the pre-destruction problem hasn't been studied closely, and the results obtained are of little practical value. This work attempts to quantify rock pre-destruction degree to use the parameters of rock blasting by borehole charges in the conditions of opencast mining in engineering calculations.

The existing perception of the pre-destruction mechanism is as follows. The stresses from the detonation waves concentrate on structural defects that are always abundant in the rock mass (microcracks, pores, defects in mineral grains, etc.), giving rise to new dispersed micro defects and the growth of the existing ones [7]. Rock fracturing and cavitation increase, lowering its strength properties; this is called rock pre-destruction [8]. So, today pre-destruction means the process of micro defects appearance and development.

The pre-destruction is henceforth understood as the change in the relative strength of the rock mass without visible discontinuity, associated only with impact from previous blasts. Rock softening as a result of natural fracturing is not considered.

Methods of research. A quantitative measure is required to assess the degree of rock mass pre-destruction. Regarding the effect, the blast has on rock, as quasi-brittle fracture influenced by the stress wave, the following ratio can be written for the radial relative deformation ε at a distance r from the charge axis [9]:

$$\varepsilon(r) = \varepsilon_0 \left(\frac{R_0}{r} \right)^2, \tag{1}$$

where R_0 is the charge radius, m; ε_0 is a dimensionless coefficient reflecting the intensity of explosive energy release and the degree of the energy transfer to the rock,

$$\varepsilon_0 = \sqrt{\frac{\gamma D^2}{E\left(K^2 - 1\right)\left(1 + \frac{2\pi^2}{1+\nu}\right)}},$$

where γ is the initial density of the explosive, kg/m^3; D is the detonation velocity, m/s; K is the polytropic index of the detonation products; E is Young's modulus of the confining material, Pa; ν is the Poisson's ratio of the confining material.

For all points of the rock mass within the destruction zone with radius r^* confining the charge, the following condition is fulfilled according to the maximum strain energy theory:

$$\varepsilon(r) \geq \varepsilon^* = \frac{\sigma_{\text{tens}}}{E},$$

where ε* is the ultimate relative radial strain; σ_{tens} is the tensile strength of the confining material, N/m^2.

At the border of the indicated zone, the limit relation is fulfilled

$$\varepsilon(r^*) = \varepsilon_0 \left(\frac{R_0}{r^*} \right)^2 = \varepsilon^*. \tag{2}$$

Taking (2) into account, relation (1) becomes

$$\varepsilon(r) = \varepsilon^* \left(\frac{r^*}{r} \right)^2. \tag{3}$$

For rock beyond the destruction zone, i.e. if $r > r^*$, then $(r^*/r)^2$ can formally be considered a measure characterizing strength properties reduction caused by the charge detonation effect. Let us call it the pre-destruction intensity coefficient:

$$\overline{K} = \left(\frac{r^*}{r}\right)^2.$$

Then (3) becomes

$$\varepsilon(r) = \varepsilon^* \overline{K}.$$

In this interpretation, rock is regarded as destroyed if the pre-destruction intensity coefficient reaches a value equal to one. This condition is fulfilled within the destruction zone, i.e. under $r \le r^*$. Under $\overline{K} < 1$, which is typical under $r > r^*$, the effect made by a blast is not enough for rock destruction. However, the stress wave, concentrating on rock mass structural defects, gives rise to new and enlarges existing discontinuities, which reduces rock strength properties. This effect subsides with distance from the charge center, the pre-destruction intensity coefficient decreases converging to zero. Rock mass pre-destruction can be neglected at distances of the order of (200–250) R_0 [10].

So, the rock mass zone surrounding the charge we shall refer to as the pre-fracture zone; for this zone the following condition is fulfilled:

$$r^* < r < (200 - 250) R_0.$$

It should be clarified that the pre-destruction intensity coefficient is not an absolute characteristic of rock mass strength properties. It only reflects the degree of rock strength relative change in a particular zone of the rock mass. Rock strength properties in this zone of the rock mass in the natural state are taken as a reference point, i.e. with no explosion load on this area of the rock mass. This means that rock mass zones with completely different strength properties can correspond to coefficient $\overline{K} = 0$, provided that the rock in these zones is in natural state, porosity, fracturing and other defects considered. Rock destruction in this rock mass zone with discontinuity and fragmentation from the explosion load corresponds to $\overline{K} = 1$.

The radius of the destruction zone r^* under borehole charges detonation can be calculated using the procedure described in [11]. The following equation therefore should be solved for $\overline{r}^*_{\text{ref}}$

$$\frac{c_1 + c_2 \overline{r}^*_{\text{ref}}}{\left(\overline{r}^*_{\text{ref}}\right)^{1,1}} = \frac{\sigma^{\text{dyn}}_{\text{tens}}}{0.545 \rho C_{\text{p}}},$$

where $\overline{r}^*_{\text{ref}}$ is the reduced radius of the destruction zone under the reference explosive detonation, m; ρ is the rock density, kg/m^3; C_{p} is the velocity of the longitudinal wave in the rock mass, m/s; c_1 and c_2 are coefficients that depend on rock acoustic impedance, $c_1 = 0.09 + 0.228 \cdot 10^{-7} \rho C_{\text{p}}$, $c_2 = \left(0.07 - 0.224 \cdot 10^{-7} \rho C_{\text{p}}\right) 10^{-2}$; $\sigma^{\text{dyn}}_{\text{tens}}$ is dynamic tensile strength, kPa; $\sigma_{\text{tens}}^{\text{dyn}} = K_{\text{tens}}^{\text{dyn}} \sigma_{\text{tens}}^{\text{st}}$; $K_{\text{tens}}^{\text{dyn}}$ is the dynamic coefficient, $K_{\text{tens}}^{\text{dyn}} = 4.81 - 0.97 \cdot 10^{-1} \rho C_{\text{p}}$; $\sigma_{\text{tens}}^{\text{st}}$ is the static tensile strength, kPa.

The destruction zone radius for the explosive applied is

$$r^* = R_0 \overline{r}^*_{\text{ref}} \left(\frac{\gamma Q}{\gamma_{\text{ref}} Q_{\text{ref}}} \right)^2,$$

where γ_{ref}, γ and Q_{ref}, Q are the charge density and explosion heat of the reference and applied explosive respectively, kg/m^3 and kJ/kg.

When doing calculations, it is necessary to take the PETN as a reference explosive, for which $\gamma_{\text{ref}} = 1500$ kg/m^3, $Q_{\text{ref}} = 5860$ kJ/kg.

Under a large-scale blast of a group of borehole charges, the pre-destruction intensity coefficient of the rock mass zone in question as a result of a separate *i*-th charge detonation is as follows

$$\overline{K}_i = \left(\frac{r^*}{r_i} \right)^2, \tag{4}$$

where r_i is the distance between the i-th charge center and the selected zone of the rock mass, m, $i = \overline{1,n}$, and n is the number of charges in the group.

The pre-destruction intensity coefficient of the indicated zone of the rock mass, attained after the charges have been fired, is determined by summing the pre-destruction intensity coefficient from every charge [9]:

$$\overline{K}^{\Sigma} = \sum_{i=1}^{n} \overline{K}_i. \tag{5}$$

Let us consider a small area of the rock mass. Rock within this area is naturally disturbed, considering fracturing, porosity and other defects. Let us estimate rock strength by the specific drilling energy intensity according to the energy approach [12–14]. Let the specific drilling energy intensity of rock in natural state be equal to e^0, and in this case the pre-destruction intensity coefficient, as indicated above, is equal to zero: $\overline{K}^0 = 0$. Completely destroyed rock in the considered rock mass zone corresponds to the specific drilling energy intensity e^* and coefficient $K^* = 1$. Any intermediate state of rock as a result of blast effect is characterized by a well-defined value of the specific drilling energy intensity e, and some value of the pre-destruction intensity coefficient $\overline{K}^{\Sigma}$ corresponds to it. Naturally, the following conditions are fulfilled: $e^* < e < e^0$; $\overline{K}^0 < \overline{K}^{\Sigma} < \overline{K}^*$ or $0 < \overline{K}^{\Sigma} < 1$.

Assuming that the specific drilling energy intensity as a result of blast effect, is equal to the relative change in the pre-destruction intensity coefficient, we get

$$\frac{\Delta e}{e^0 - e^*} = \frac{\Delta \overline{K}}{K^0 - K^*},$$

where

$$\Delta e = e^0 - e;$$
$$\Delta \overline{K} = \overline{K}^0 - \overline{K}^\Sigma.$$

After rearrangement we get

$$\Delta e = \left(e^0 - e*\right)\overline{K}^\Sigma. \tag{6}$$

So, the specific drilling energy intensity of rock in the selected area, after the blast impacted on it at an intensity corresponding to $\overline{K}^\Sigma$, will be

$$e = e^0 - \left(e^0 - e*\right)\overline{K}^\Sigma. \tag{7}$$

Note that, upon reaching $\overline{K}^\Sigma = 1$, $e = e*$, which corresponds to complete destruction of rock. On the contrary, at $\overline{K}^\Sigma = 0$ (no impact), $e = e^0$, which corresponds to the natural state of rock.

To determine the value of the specific drilling energy intensity reduction Δe in a particular rock mass zone, it is therefore necessary to know the specific drilling energy intensity of this zone in its natural state e^0, the pre-destruction intensity coefficient $\overline{K}^\Sigma$ resulting from the large-scale blast of borehole charges, and the specific drilling energy intensity of completely destroyed rock $e*$.

A set of measurements and calculations was performed to check ratio (6).

A polymorphic rock mass, which is a conglomerate of rocks, such as argillite, siltstone, tuffite, sandstones, etc., was studied by experiment. Fine-grained sandstone whose share is 56% of total rock mass, was accepted as a rock mass-building rock for calculations.

Large-scale blasts of Emulast AS-30FP-90 charges in 250 mm diameter holes, 13±0,5 m deep were monitored, located on a 5 x 5 m grid on 12±0,5 m high benches in the rocks of medium blastability category. Sludge of natural moisture from drilling wells with Atlas Copco DML LP 1200 rigs was used for stemming.

Within an open pit, we selected two adjacent, sequentially developed technological blocks with a shared horizon and evaluated the impact made by the large-scale blasting of block 1 charges grid on the rock mass zone directly adjacent to the exploded block (Figure 1).

Rock within the zone of well line no. 1 of control technological block 2 corresponds to this area. Measurements and calculations were carried out for each well in the line by the following procedure.

When preparing for blasting at the technological block, the drilling energy intensity of a well in line 1 was measured, let it be the well p. The attained value corresponds to the specific drilling energy intensity of rock weakened by the preceding explosion in the adjacent block 1, i.e. $e_{(p)} = e$.

For the selected well, the value of the specific drilling energy intensity of the nearest well q of technological block 1 measured before the explosion, was taken as the specific drilling energy intensity of rock in natural state, i.e. $e^0_{(p)} \approx e^0_{(q)} = e^0$. This assumption is valid because wells p and q are side by side.

The average value of specific energy intensity of drilling wells to a depth of 1.5–2 m of all wells in technological block 2 was taken as the value of specific energy intensity of drilling destroyed rock *e**, which corresponds to the upper part of the horizon, which is actively destroyed by previous blasts in the subdrilling and by heavy equipment [13].

The value of the pre-destruction intensity coefficient $\overline{K}^{\Sigma}$ attained due to the explosion load, was calculated using specially designed software (*Shishkin E. A., Leshchinskii A. V., Shevkun E. B. RF software registration certificate no. 2017617987. Detecting pre-destruction near wells when carrying out large-scale blasts in quarries. Pacific National University; 2017*). This program is designed to calculate the rock pre-destruction intensity coefficient by simulating a real explosion of a borehole charge grid considering the location of charges on the surface of the technological block, the sequence of initiation, the explosive type and characteristics of charging, the strength of rock building up the rock mass, and the distance between the detonated charge and the rock mass zone under consideration.

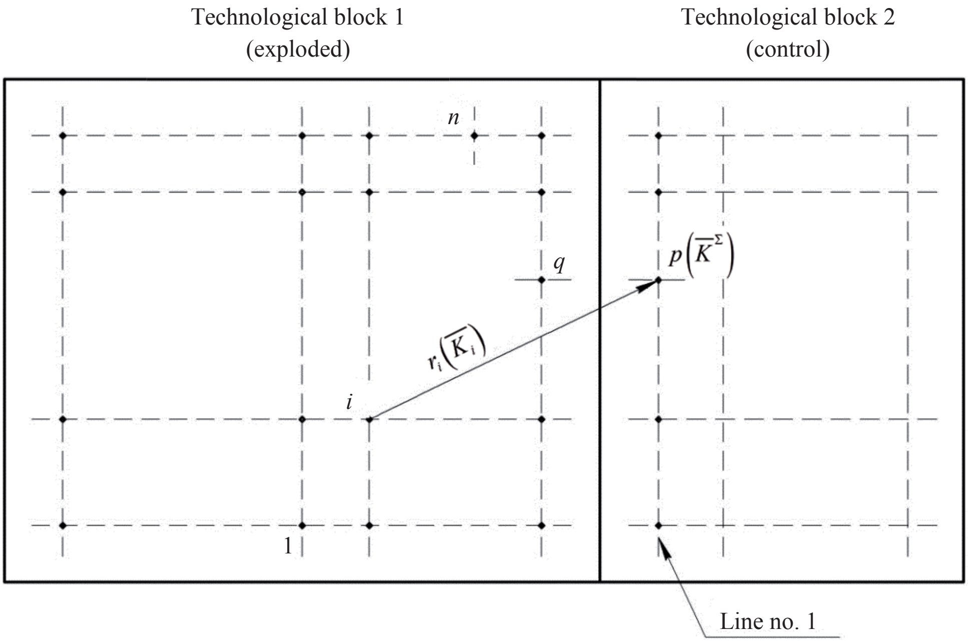

Figure 1. Scheme of adjacent technological blocks
Рисунок 1. Схема смежных технологических блоков

The values of parameters in question for all wells in line 1 of technological block 2 were obtained in the described way to be used in formula (6). Analysis revealed quantitative and qualitative discrepancy between the values. The values of pre-destruction intensity coefficient were found overestimated and exceeded one for some wells, which indicates complete destruction of rock near these wells. However, the energy intensity measured when drilling the wells was found much higher than the drilling energy intensity of the destroyed rock.

The discrepancy appears to be explained by the fact that in the millisecond-delay blasting, the sequence of impacts made by stress waves from individual charges on rock should be considered. Defects number and size as well as rock mass cavitation grow with each blast, which results in more intense attenuation of explosion waves [15, 16]. The effect made by another borehole charge explosion on the rock mass is therefore weaker due to its pre-destruction by previous blasts.

A correction coefficient seems indispensable which includes the accumulation of pre-destruction in the preset zone under borehole charges sequence blasting. Let us denote the coefficient α and call it impact multiplicity coefficient. In a millisecond-delay blasting method we multiply the pre-destruction intensity coefficient calculated according to (4) by the impact multiplicity coefficient. Then (4), (5), (6), and (7) become

$$K_i = \bar{K}_i \alpha_i; \quad K^{\Sigma} = \sum_{i=1}^{n} K_i; \quad \Delta e = \left(e^0 - e^*\right) K^{\Sigma}; \quad e = e^0 - \left(e^0 - e^*\right) K^{\Sigma}. \tag{8}$$

The impact multiplicity coefficient for the i-th charge blasting will be introduced as follows

$$\alpha_1 = 1; \qquad \alpha_i = \left(1 - \sum_{1}^{i-1} \bar{K}_i \alpha_i\right)^{\beta}, \qquad i = \overline{2,n}, \tag{9}$$

where β is an index that depends on the properties of rock building up the rock mass.

For i = 1, α_1 = 1 because rock is in its natural state before the first blast, the pre-destruction intensity coefficient is zero, and, the effect from the first blast is therefore transferred to rock without weakening.

It is necessary to point out that in formula (9) the numbering of wells i precisely corresponds to the sequence of borehole charges blasting. The expression in parentheses calculates rock softening by all preceding blasts.

To calculate the value of index β for each well of the first line of technological block 2, the equation was built according to (8):

$$\frac{\Delta e}{e^0 - e^*} = K^{\Sigma}.$$

Or in an expanded form:

$$\frac{\Delta e}{e^0 - e^*} = K_1 + K_2 + \ldots + K_i + \ldots + K_n, \tag{10}$$

where:

$$K_1 = \overline{K_1} \alpha_1, \qquad \alpha_1 = 1;$$

$$K_2 = \overline{K_2} \alpha_2, \qquad \alpha_2 = \left(1 - K_1\right)^{\beta};$$

$$K_3 = \overline{K_3} \alpha_3, \qquad \alpha_3 = \left[1 - \left(K_1 + K_2\right)\right]^{\beta};$$

$$\ldots$$

$$K_i = \overline{K_1} \alpha_i, \qquad \alpha_i = \left(1 - \sum_{1}^{i-1} K_i\right)^{\beta}, \qquad i = \overline{2,n};$$

$$\ldots$$

$$K_n = \overline{K_n} \alpha_n, \qquad \alpha_n = \left[1 - \left(K_1 + K_2 + K_3 + \ldots + K_i + \ldots + K_{n-1}\right)\right]^{\beta}.$$

We get one value of the index by solving equation (10) for the unknown β. The value of β for each well of line 1 of technological block 2 was calculated in a similar way. After that the result was averaged over all wells in the line.

Similar calculations were done for some pairs of adjacent technological blocks within the open pit.

Results. With the obtained value of index β, the expected value of specific drilling energy intensity was calculated for particular wells arbitrarily located in the pre-destruction zone of technological block 2. After that, calculation results were compared with practical values measured during preparation of blasting at technological block 2. The value of e^0 of the nearest well of the first line was taken as e^0 for the indicated wells. Such an assumption should not introduce a major error in the expressions because only 5 lines of the technological block fall into the pre-destruction zone under the drilling and blasting parameters in the coal mine.

Conclusions. The survey has made it possible to quantify the blasting effect on rock pre-destruction. The developed method allows to predict the value of drilling energy intensity in the pre-destruction zone and establish the necessary blasting specific energy intensity, and, consequently, the consumption of explosives [12, 13]. So, it is possible to reduce the consumption of explosives under the blasting scheme that exists at the enterprise and model other ways of charge initiation to find the least expensive.

However, it is necessary to point out that the application of the method is complicated by the fact that it is necessary to pre-determine the value of index β for a particular mine working.

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Оценка влияния взрывов на предразрушение массива горной породы

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Реферат

Введение. *Теоретическими и эмпирическими исследованиями процесса разрушения горных пород взрывом доказано, что после распространения детонационной волны вокруг взрывной полости формируются зоны разрушения и предразрушения. В зоне разрушения происходит дробление породы. В зоне предразрушения напряжения, вызванные детонационной волной, концентрируются на дефектах структуры породного массива, что приводит к зарождению новых и развитию существующих микродефектов. Нарушенность и пустотность породы возрастает и, следовательно, снижаются ее прочностные свойства, что и характеризуется как предразрушение породы. Существуют работы, посвященные качественному анализу состояния горных пород в зоне предразрушения, однако тема требует разработки для практического применения.*

Цель работы. *Количественная оценка степени предразрушения породы массива для использования в инженерных расчетах параметров взрывной отбойки горных пород скважинными зарядами при открытой разработке месторождения.*

Методология. *Для оценки степени предразрушения массива горной породы на расстоянии от оси заряда используется коэффициент интенсивности предразрушения. Радиус зоны разрушения определяется по известной методике. В зоне разрушения значение коэффициента интенсивности предразрушения больше единицы, т. е. имеет место потеря сплошности массива. За зоной разрушения расположена зона предразрушения, в которой значение коэффициента интенсивности предразрушения меньше единицы. Граница зоны предразрушения расположена на расстоянии примерно 200–250 радиусов заряда. Коэффициент интенсивности предразрушения заданной области массива, достигнутый после взрывания всех зарядов, определяется суммированием коэффициентов интенсивности предразрушения от каждого из зарядов. В соответствии с энергетическим подходом прочностные свойства горной породы можно оценить величиной удельной энергоемкости ее бурения. Для определения величины снижения удельной энергоемкости бурения породы в заданной области массива необходимо знать удельную энергоемкость бурения этой области массива в естественном состоянии, коэффициент интенсивности предразрушения, достигнутый в результате массового взрыва скважинных зарядов, а также удельную энергоемкость бурения полностью разрушенной породы. Влияние очередного взрыва скважинного заряда на породу массива оказывается ослабленным в результате ее предразрушения*

предшествующими взрывами. Поэтому предложен коэффициент кратности воздействия, учитывающий накопление предразрушений в заданной области массива при последовательном взрывании скважинных зарядов.
Результаты. *Выполнен расчет ожидаемой величины удельной энергоемкости бурения отдельных скважин, произвольно расположенных в границах зоны предразрушения заданной области массива. После этого результаты расчета сравнивались с практическими значениями, измеренными при подготовке взрывных работ в заданной области массива.*
Выводы. *Получена возможность количественной оценки влияния взрывов на предразрушение массива горной породы. Разработанная методика позволяет спрогнозировать величину энергоемкости бурения породы в зоне предразрушения и исходя из этого установить необходимую удельную энергоемкость ее взрывания, а следовательно и расход взрывчатого вещества. Таким образом, появляется возможность уменьшения расхода взрывчатого вещества при существующей на предприятии схеме взрывания, а также возможность моделирования других вариантов инициирования зарядов с целью выбора наименее затратного.*

Ключевые слова: *горная порода; массовый взрыв; коэффициент интенсивности предразрушения; коэффициент кратности воздействия; удельная энергоемкость бурения; расход взрывчатого вещества.*

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