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ROCK FAILURE

SUDDEN ROCK FAILURES IN MINING COAL SEAMS OF THE KIZEL BASIN

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An analysis is performed for the conditions of mining the Kizel Coal Basin at depths greater than 600 m. It is shown that sudden failures of strong rocks occur in the mine-working floor sections, where the underlying layers possess low deformation properties.

Coal seams, mine workings, sudden failure, strong rocks of roof and floor

The Kizel Basin is a complex folded region of the West Ural; its geological structure contains Palaeozoic deposits as a system of submeridionally extended folds representing the basic structural-tectonic elements. The Basin tectonics is in the form of plicate and disjunctive disturbances whose edges displace within the range from 100 to 1000 m. The great disjunctives are accompanied by shear zones characterized by the development of small as well as medium plicated and disjunctive disturbances with amplitudes varying from shares to tens of meters. The number of the disturbances with edge displacements exceeding the seam thickness by a factor of 2 – 3 averages to 4.2 per 1 km of mine field on dip and strike and reaches 2 – 2.5 per 150 m in some sections on the seam dip.

The coal-bearing thickness of 150 – 200 m is represented by Low Carboniferous deposits and mainly consists of 50 – 75 % of quartz sandstone layers, 10 – 25 % of siltstones, 10 – 25 % of argillites, as well as from 3 to 5 % of carbonic rocks and coal. The wall rocks and coal are characterized by high elastic and strength properties. The ultimate uniaxial compression strength makes up from 100 to 300 MPa for quartz sandstones, from 30 to 150 MPa for siltstones, from 22 to 60 MPa for argillites, and from 10 to 50 MPa for black coal. Quartz sandstones are the monomineral rocks composed of quartz grains (65 – 99 %). The grains vary from 0.1 to 0.2 mm in size and have sub-angular and seldom round form. Quartz, clayey, and carbonate cement is regeneration and porous in type. The average porosity of sandstones is 6 %. Siltstones are the psammitic siltsone rocks with grain size from 0.01 to 0.1 mm. Thinly laminated and banded siltstones with clayey cement are most spread. In the main, argillites consist of clayey material (57 – 65 %) with steady inclusions of an organic substance 0.005 – 0.1 mm in size.

The majority of rockburst-hazardous coal seams are thin and medium in thickness (0.6 – 2.5 m); their contiguity varies from 2.5 to 10 and seldom to 30 m. The sequence of strata includes 2 – 3 seams, but there are sections with a single seam. The inclination angles range from flat to steep ones. In intact rock mass, the stress field is inhomogeneous and oriented in sub-latitudinal direction.

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In the Kizel Basin mines, more than 400 rock bursts took place, which makes up almost 70 % of the total number of rock bursts in all mines of the Commonwealth of Independent States. Almost all rock bursts (96 %) occurred when mining coal reserves of the Kizel Principal Anticline. The Anticline is the largest structural-tectonic element of the region; it is complicated by three great faults: the Kosogorsk and Kos'vinsk thrusts both approximately 300 m in magnitude in the west and east, respectively, as well as the Lun'evsk overthrust with the magnitude of 1000 – 1200 m in the north-east.

Under certain conditions combined, sudden failures of rocks containing coal seams began manifesting themselves in the development and stoping faces at a depth of 600 – 700 m. All dynamic manifestations recorded can be divided into three groups:

— sudden failure of rocks in the floor of mine workings;

— sudden rock failures in the roof of the development and stoping faces;

— sudden rock failures including rock bursts in the lateral mine workings.

The first group failures are characterized by the fact that in the coal seam floor, strong rocks are underlaid by those ones with lower strength properties. In the early 1960s, this phenomenon occurred for the first time in the "Klyuchevskaya" mine at a depth of 840 – 870 m from the surface when developing the stoping front in the most failed section of Level VII. In this case, the number of small tectonic disturbances reached 2 – 2.5 per 150 m of length on the seam dip or strike. The mine worked out the sequence of contiguous steeply dipping seams Nos. 9, 11, and 13 thin and medium in thickness. When driving a chute 2 m in width in seam No. 9 which is the lowest in the sequence, a sudden failure of the floor rock took place (March 3, 1963). A crack and a rock upheaval 15 – 20 cm high formed in the mine working along the length of 15 m from the face. In another chute of the same seam, the mine-working floor instantly failed at a length of 42 m. When widening the ore chute driven in safety pillar above the lower haulage entry of stoping face No. 733 (seam No. 9), a sudden rock failure took place in the floor (October 4, 1962). The above-entry pillars were 10 – 12 m in height, the distance between the ore chutes — 12 – 15 m on strike. The ore chutes 2.2 m in width in the upper section were thirled by diagonal crosscuts. The floor failed over the area of 2.5 m^2. Rockburst-hazardous seam No. 9 (0.8 – 0.9 m in thickness) is overlaid by siltstone plate (1 – 1.5 m thick); a siltstone band (1.8 – 2 m) is located immediately in the seam floor, and clay slates occur lower (Fig. 1*a*).

The sudden failures of floor took place in permanent mine workings. In the Uritsky Mine, a section 92 m in length of the north flank incline was put out of operation by sudden failure on July 12, 1963. The mine workings 10 m^2 in cross-section are driven in medium rockburst-hazardous seam No. 11 whose roof and floor are represented by quartz sandstone layer 17 and 2.5 m thick, respectively, followed by interbedding argillites and sitlstones. The cracks and a rock upheaval 0.8 – 1 m high formed in quartz sand of the floor. The operation depth in the failure zone made up 770 – 800 m. On August 26, 1962, a sudden fault of the floor was observed in the same mine in entry No. 202 driven in seam No. 11 at a depth of 875 m. As a result, a crack 10 – 15 cm in width and 40 m in length arose. The mine-working support was not failed (Fig. 1*d*), and the track was uplifted by 10 – 15 cm. It is important that a normal fault approximately 30 m in magnitude occurred at 100 – 130 m away from the entry. In mine No. 4 at a depth of 850 m, two rows of cracks 18 – 20 m long and a rock upheaval by 30 – 40 cm appeared in the mine-working floor due to the rock fault in haulage incline from Level VI to VII. The incline is driven in rockburst-hazardous seam No. 11 with explosive damage of the roof rock composed of quartz sandstones; the floor is sandstone and siltstone interbedding.

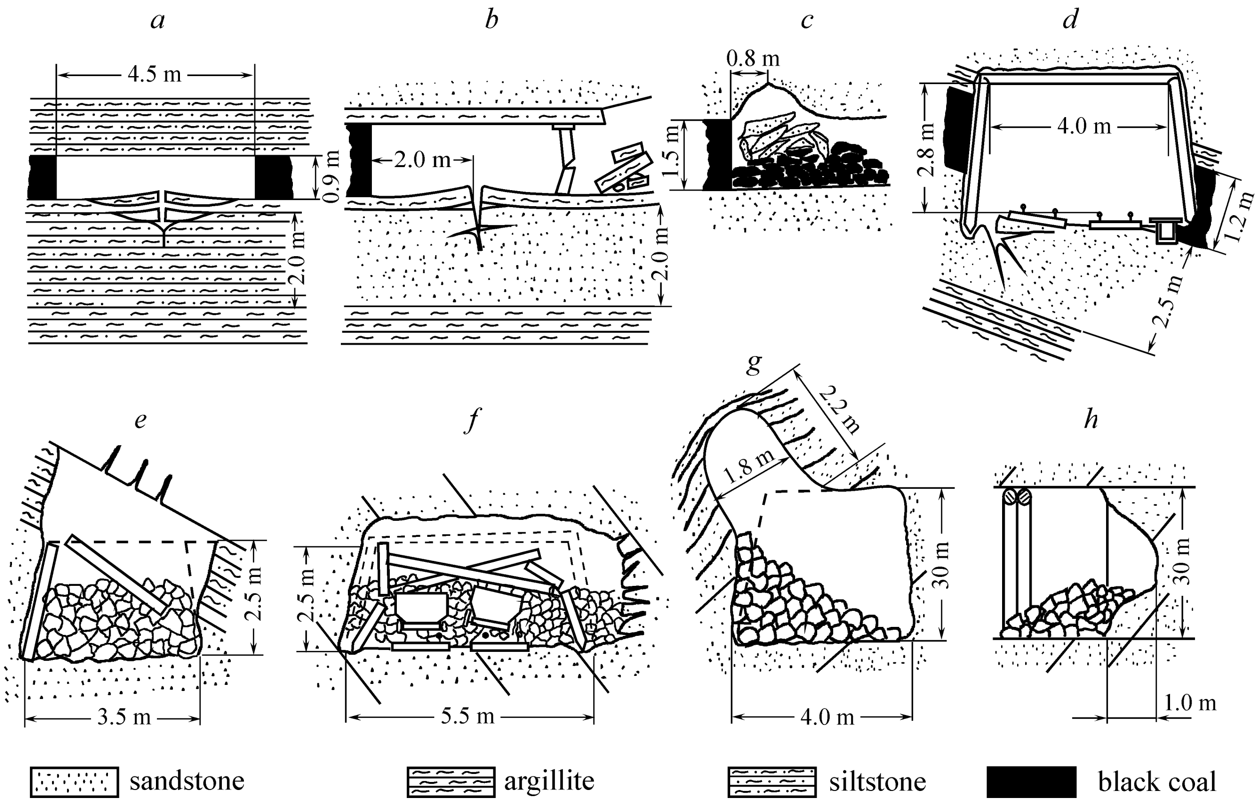

Fig. 1. Characteristic cases of sudden failure of wall rocks in mine workings: *a* — in ore-chute widening; *b* — in active stoping face; *c* — in coal mining in pack-hole; *d* — in haulage entry; *e* — in lateral drift; *f* — rock burst in lateral mine working; *g* — in driving the lateral drift; *h* — in driving the cross-entry

When stoping face No. 292 (“Tsentralnaya” mine) in seam No. 11 was 8 m away from holing chute, a sudden failure of the floor rock occurred (August 8, 1962). A crack 5 m in length on strike and opening of 4 – 5 cm, as well as a rock upheaval by 15 – 25 cm formed. The average seam thickness made up 1.5 – 1.7 m, the dip angle was 15 – 25°. The seam roof and floor were represented by siltstones 0.1 – 0.2 m thick over- and underlaid by 2 m layer of quartz sandstones and argillites lower (Fig 1*b*). In the region considered, the face line of underworking seam No. 13 was at a distance of 66 m. Later, four cases of sudden failure of the floor took place when mining single seam No. 11 in the “Tsentralnaya” mine. The first two of them were recorded in the lower part of stoping face No. 921 (September 3 and 17, 1970, respectively), the seam was 1.1 m thick, and the dip angle equalled 35°. The roof was represented by quartz sandstones, the floor — by argillites 0.5 m in thickness underlaid by 2.5 m layer of quartz sandstones and siltstones lower. Another two failures were observed in upper part of the stoping face on September 21 and October 1, 1973, respectively. The seam thickness was 1.5 m, the dip angle — 25°. The roof and floor were composed of siltstones 0.5 m thick over- and underlaid by quartz sandstones (2 – 3 m) and siltstone layer lower. The roof was controlled by keeping it in packs on strike. In all four cases, the sudden failures with floor detachment and upheaval were within the area between the pack and the face at a distance of 2 – 2.5 m from the latter. The distance between the pack and the stoping face was less than 5 m. In addition, the floor of mine workings driven in coal seam was mostly composed of quartz sandstone or sandy-clayey shales underlaid by argillites, siltstones or coal-bearing rocks.

If the mine-working floor in the seam is represented by a layer of strong rock underlaid by a weaker one, then in the boundary sections of the seam in the rock mass, the underlying rocks are squeezed into the zone under the mine working due to lateral thrust. The squeezed rocks, which decompact and increase in volume, affect the first floor layer and facilitate its deflection inby. This leads to the appearance of tensile and compressive stresses on internal and external surfaces of the deflected layer, respectively. The rock deflection until failure is accompanied by accumulation of the potential energy of the elastic strains; therefore, the layer failure has a dynamic character. The energy released during dynamic failure of the layer consists of the energies of the failed material and the surrounding rock mass. The potential energy stored by rocks before the failure is readily determined by the elasticity theory. According to [1], the loss of stability by rocks of the mine-working roof or floor takes place when the change in their potential energy ΔW outside the post-limiting deformation zone of the surface section ΔS separating the pre- and post-limiting deformation regions is greater than the energy loss g_0 corresponding to the complete failure of the material, i.e., $\Delta W/\Delta S > g_0$. The energy entering from enclosing rocks is the basic component in the failure energy balance. By [1], when the underlying layer stiffness is lower than that one of the failed section, the energy inflow ΔW per the unit of length of the mine working $2x_0$ in width is $\Delta W = 0.5\pi\sigma_0^2[(1-\nu^2)/E]x_0^2$, where ν and E are Poisson's ratio and Young's modulus of the underlying layer rocks, respectively; σ_0 is the stress acting normally to the surface of bedding in the rock mass.

By [2], when carrying out mining operations in coal seams with enclosing rocks prone to sudden failures, the width of mine working driven in the seam is to be less than $1.5n$ or greater than $4n$, where n is the thickness of rock layer. The width of mine working is not limited if the boundary section of the seam is loosened at a depth no less than $1.5n$ from both sides of the working.

In driving an exploration incline to Level XI of the Uritsky Mine, the sudden failures of the roof rocks of seam No. 11 (Fig. 1*c*) occurred differently. The seam was $1.4-1.5$ m in thickness, the dip angle made up $15-18°$. The boundary seam section was characterized by the increased stresses of coal. The floor and roof of the seam were represented by quartz sand and fine-grained light-gray quartz sand $2.5-3$ and $10-12$m thick, respectively. The operation depth was 1000 m. The incline was driven by wide heading with explosive damage of the floor rocks arranged later in the pack-hole along the mine-working edges. The sudden failure began in $10-15$ min after blasting. The failure proceeded non-intensively first, the dimensions of separate sandstone plates did not exceed $0.5\times0.2\times0.1$ m. Further, the failure intensity increased, and the coarseness of separate rock lumps grew and reached $1\times1\times0.2$ m. The failure was accompanied with acoustic and seismic effects damping and recommencing within $1.5-2$ h. During failure, a dome-shaped recess formed in the roof; it was $0.8-1$ m in size along the normal to bedding and from 1.5 to 3 m in length parallel to the face.

When driving lateral mine workings in zones of influence exerted by geological disturbances and coal seam pillars remained, the bursts and sudden failures were recorded in the Lenin, "Klyuchevskaya", "Tsentralnaya", Uritsky Mines, and mine No. 4. First, bursting of small sandstone jointings inconsiderably complicated the mine-working driving. However, as the stresses increased in rocks, this phenomenon reached the intensity dangerous for people. For example, in driving lateral mine working No. 501 in the Lenin Mine, the rock jointings $0.1\times0.1\times0.05$ m in dimension burst from the mine-working face at a distance up to $3-5$ m. The rock failure could be caused by tapping and barring-down the face. In some cases, barring-down led to sudden caving of up to $2-3$ t of rock. The mine observance established that in the first $3-5$ min after blasting, approximately 50 % of seismic energy released. In driving the pit-bottom working over coarse laminated sandstones of Level VI in mine No. 4, the lumps of rock $0.2\times0.2\times0.1$ m in dimension burst from the face at a distance up to 3 m. The total duration of failure reached 50 – 60 min.

In the Uritsky Mine, the lateral drift of Level VI failed along the length of 10 m (Fig. 1*e*) as a result of sudden caving of the roof rocks (October 4, 1961). The drift was driven in the floor rocks of sequence of contiguous steep-dipping seams Nos. 9, 11, and 13 in the coal pillar influence zone. The drift failure was accompanied with strong seismic effect.

Combined with other factors, the rock-mass irregularity can be the reason of sudden rock failure both in driving and operating the mine working. Thus, in the "Klyuchevskaya" mine (September 11, 1962), a rock burst occurred in lateral pit-bottom working of Level VII at a depth of 880 m from the surface (Fig. 1). The pit-bottom working 16 m^2 in cross-section was driven in seam over coarse laminated quartz sandstones in the meridian direction. A water sump and a roundabout were driven parallel to the lateral pit-bottom working at a distance of 10 m from both sides of it. In seam No. 9, the stoping face 40 m distant from the place of rock burst advanced towards it. In consequence of rock burst, the working failed along the length of 10 m. The rock outburst took place at the east edge side at a depth of 1 – 1.2 m. The rock burst was caused by the high mass stresses governed by the great mining depth, the effect of stoping operations in seam No. 9, and the rock-mass irregularity due to mine workings. The conclusion was therefore drawn that at depths greater than 800 m, the distance between workings driven in strong sandstones should be greater than the fourfold width of the largest mine working cross-section [2].

When driving lateral drift No. 901 in quartz sandstones at a depth of 800 m in the "Tsentralnaya" mine, sudden rock failures of another type were noted. An entry 11 m^2 in cross-section was driven in coal seam floor and penetrated gradually the median part of thick quartz sandstone band. As the mine working was completely in the layer of sandstone, the signs of high stresses (bursting, sudden failures) began manifesting themselves in its face. Within the first 10 min after blasting, only acoustic effects (rustles, crashes) were noted. Then, the maximum of seismic and acoustic activity set in; it was accompanied by an intensive rock failure resulting in formation of cavity 1.5 – 1.8 m in diameter and up to 2 m high (Fig. 1*h*). The analysis established that the mine-working section, which was in contact with geological disturbance represented by thin folding with disconformable cleavage, underwent failure. The sudden rock failures terminated as the entry was driven out of geological disturbance zone.

The most hazardous sudden rock failures took place in the "Klyuchevskaya" mine when driving cross-entry No. 54 in quartz sandstones at a depth of 880 m from the surface. The cross-entry 12 m^2 in cross-section was driven from the hanging side towards the sequence of seams Nos. 9, 11, and 13. The sudden rock failures with bursting of lumps $0.3\times0.3\times0.05$ in dimension by 1.5 – 2 m began in the mine-working face when it was 10 – 12 m distant from the first seam in the sequence. After blasting terminated, the failure began; it damped and recommenced within 2 – 3 h, as a result of which a cavity with truncated pyramid shape formed in the mine-working face (Fig. 1*h*). The face tapping and barring-down led, as a rule, to bursting of rock lumps. The reason of the increased stress state of rocks was the tectonic disturbance, i.e., the overthrust 3 m in magnitude. The attempts of decreasing the stresses of rocks in mine-working face by creating the vertical or horizontal unloading slot were unsuccessful.

The analysis of reasons and conditions of sudden rock damages in driving and operating the mine workings shows that in the regions of tectonic disturbances and zones of coal pillar influence, the instantaneous failure takes place in the floor of sandstone layer underlaid by less strong rocks. The feature of geomechanical state of rock mass is the presence of anomalous stress fields, where the stresses can be considerably greater than the lithostatic ones. The most hazardous are the sections adjacent to great tectonic disturbances. Starting from a certain depth, the nonuniformity of the stress state of rock mass is governed by the residual internal stresses which did not relax completely and remained in rocks from the time of their formation or were acquired by rocks under action of temperature, pressure, and other factors. The value of the residual internal stresses can also exceed much the value of the lithostatic ones. When mining operations are carried out under such conditions, natural field of the stresses acting in rock mass is overlapped by the stresses caused by the mine-working driving. Fast transition of blasting operations into the zone with high stresses can bring a rock section to the critical state with further failure due to overlapping of both stress fields. As the experience shows, the self-failure of rocks sets on in 5 – 6 min after the blasting operation completion. Within this time interval, seismic-acoustic events insignificant in force and low in frequency can be observed in rock mass. The self-failure is a mechanism of rock unloading from the anomalous high stresses. Under unloading, the rate of material deformation depends on the level of energy accumulated. If the energy reserves are great, the material omits the stage of microfailures and changes quickly from the critical stress state to the failed one by origination and propagation of the main crack. If the complete unloading is not reached in this case provided the energy reserves are replenished due to “overflow” from its concentration region, then new main cracks nucleate in rock mass until equilibrium sets in. The typical example of rock-mass unloading from the residual internal stresses is sudden failure of rocks in the roof when extracting coal in pack-hole in driving the mine working at a depth of 1000 m (Fig. 1*c*). By this reason, the roof rocks represented by quartz sandstones failed at a depth of 1000 m when drilling relief boreholes over seam No. 11 in the Krupskaya Mine. Cracks up to 20 cm in length originated along the borehole axis, which complicated stoping operations. To avoid failure of enclosing rocks when drilling the relief boreholes under anomalous high stresses, the following conditions were further satisfied: $d < 0.15 - 0.2h$, where d is the borehole diameter, mm; and h is the seam thickness, m.

Thus, an analysis performed for the mining conditions in the Kizel Coal Basin indicates that sudden failures in the roof and floor of mine workings took place at the interfaces of strong and weak rocks.

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