Geomechanical processes at closed mines in Donbass coalfield and their potential effects at surface

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Synopsis
One of the prinicpal technical problems that arises in the Donbass coalfield during the closure of mines that are no longer viable is the activation of geomechanical processes and their effect at the surface. The main pre-condition for the initiation of such processes is the presence of voids and foliations underground. It is not possible to predict when the closure of these voids will occur, but the results are repeated slumping of the rock mass, ultimately affecting the surface. The consequences can be surface collapse or deformation.

Collapse cones appear above the collars of vertical shafts, shallow workings, fissures and gaps in thick solid seams. Additional movement and deformation are possible above stopes when the rock mass has been been made wet by flooding of the mine is and also when zones of concentrated deformation become active. The knowledge that can be derived from experience so far and from the monitoring of closed mine sites needs to be collected and applied. The monitoring scheme in Stakhanov District of Donbass is reviewed along with the first observations of surface deformation above closed mines—where anomalous movement was already observed when the mines were operational.

During the closure of non-viable mines in the Donbass region a number of problems have arisen from the impact on the environment. Scientific research to address these issues is at an early stage and experience is being accumulated. The key issue here is 'wet' conservation of mines and rising underground water levels. Issues of activation of geomechanical processes after mine closure and their influence on the surface and surface objects are combined with the problems of territorial flooding. It is impossible to manage the underground processes after the mine is closed.

Coal production in the Donbass has lasted for 200 years and has caused significant changes in the rock mass and at surface: (1) significant subsidence of the surface, of varying dimensions; (2) the fissuring of bearing strata has increased and their physico-mechanical strength properties have decreased; (3) foliations have formed in the rock mass, unsupported strata remain in side workings and voids remain in shallow stopes; (4) many development and permanent workings remain in a pre-caving state; (5) the hydrogeological conductivity and hydrodynamic structure of underground waters have changed and local and general depression craters have appeared; (6) surface structures have been repeatedly underworked and, depending on the provisions for repairing them, have accumulated damage or have endured significant changes in the stress state of the main elements; and (7) there are many vertical and inclined workings that had outlets to the surface which were blocked off at different times and to varying standards of work.

While a mine is operational there are methods of forecasting the extent of surface deformation and its dynamics. In the Donbass the methods of forecasting movement and deformation of surface were developed on the basis of long research and are included in the current 'Rules of Labour Protection'.[1] For conditions of monoclinal bedding in an undisturbed rock mass the accuracy in forecasting movement and deformation is satisfactory (subsidence, 10%; inclination, 30%; horizontal deformation, 40%). It is more difficult when coal seams are being worked in conditions of disturbed bedding (e.g. folding and tectonic faults).

When a mine is operating it is possible to manage the impact on sensitive surface structures by special planning of the mine workings to reduce negative impact, backfilling of the mined void and the preservation of pillars. After mine closure any active management of geomechanical processes is practically impossible.

In the current state of our knowledge of geomechanical process activation it is important to extract as much benefit as possible from experiences hitherto and from the monitoring of closing mine sites. For this reason an attempt is made here to analyse possible modes of activation of geomechanical processes, to explain their origins, to determine what danger they present and to identify ways of reducing their negative impact.

Brief characteristics of Donbass conditions

Mining geological conditions in the Donbass vary enormously. Rock dips vary from 2–3° to 85–87°. The thickness of the seams worked is quite small—0.5 to 2.5 m. The depths of the workings are also very varied: the upper horizons were exploited in the late nineteenth and the first half of the twentieth centuries, but some current workings are at 1400–1500 m.

Disjunctive faults with anticlinal, synclinal or flexural folding characterize the tectonics, and complex combinations of tectonic features are not uncommon. The overburden tends to be shallow, the average thickness being 20–30 m. In some localities chalk deposits 200–300 m thick underlie the carboniferous rocks. The thickness of bearing strata also varies widely. To a first approximation the strength of a rock can be characterized by the degree of metamorphism and the degree of metamorphism is characterized by the coal. Different types of coal are produced in the Donbass: gas and long-flame coals in the west of the coalfield and anthracite in the east.

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In the Donetsk basin the upper horizons were worked out long ago. Accurate, reliable plans are generally absent and no information on the workings or the rock is available. The scale of the problem can be gauged from reports[2] that in 1917 there were 1604 mines in the Donbass; coal was produced mainly from shallow vertical and inclined mines; and two-thirds of the mines were no more than 53 m deep. By the early 1940s there were 200 inclined mines in Donbass, which cut coal at shallow depth. During the period of restoration of the mines flooded during the second world war, to speed up coal production in the basin, more than 600 small, inclined mines were opened. Thus, practically the whole of the basin surface was undermined at different times and at shallow depth.

Fig. 1 Sinkhole above abandoned vertical shaft

Main forms of additional impact at surface

The main precondition for geomechanical process activation is the presence of voids and foliations underground. It is not possible to predict when the closure of these voids will occur, but the results are repeated shifting of the rock mass and movement of these processes up to the surface. The consequences of these processes can be of two types: (1) surface damage and (2) additional movement and deformation of the surface. 'Surface damage' implies collapse cones and the destruction of any objects on the site. Damage is possible in three cases: (1) above vertical shafts and bore pits, i.e. over vertical workings that have outlets to the surface; (2) above extensive workings; and (3) above fissures and cracks in thick, solid strata. Additional movement and deformation can appear above stopes in the event of the rock mass being saturated during mine flooding and also when zones of concentrated deformation become active.

Sinkholes above shafts

Roughly circular craters form above vertical workings. Fig. 1 shows a relatively fresh example. In April, 2001, the ground collapsed above an old shaft, which had been closed off in 1971. Originally, the diameter of the crater was approximately 20 m and it then spread out to 29 m. The depth of the crater was 13–14 m. In general, collapses above vertical workings develop as follows (Fig. 2). Collapse of the platform and shaft entrance (Fig. 3(*a*)) creates a crater of depth H. The upper part of the crater has vertical walls of height H_{90}. A system of concentric cracks (Fig. 3(*b*)) surrounds the crater. It is virtually impossible to forecast the time of collapse. The triggers tend to be heavy rainfall and vibration of machinery and equipment nearby. Current legislation forbids new construction in the Donbass within a 20-m radius of abandoned mine shafts. In many cases the exact location of old vertical workings is unknown, as is the manner in which the shafts were sealed.

It should be noted that mines working steep seams have the greatest number of vertical shafts and bore pits. The Stakhanov District of Donbass, where more than ten mines are being closed, exemplifies this (Table 1).

In the territory of Donetskugol Company, which works mostly flat-lying seams just under Donetsk city itself, there are 352 vertical shafts, 150 driffts, 349 bored shaftts and 27 workings of other types.

The main tasks of scientific research and practical activity in this sphere are: (1) development of methods of pinpointing the location of vertical workings by complex analysis of survey and geophysical data; (2) development of remote techniques for diagnosing the condition of an abandoned mine shaft and forecasting changes in it; and (3) development of

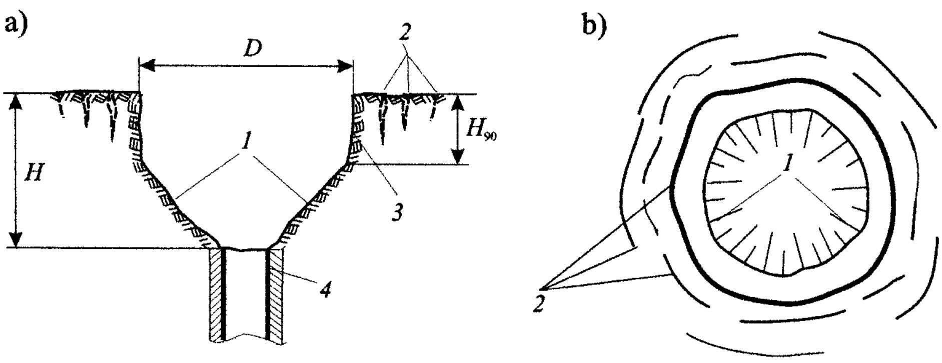

Fig. 2 Mode of collapse above entrance to vertical workings: (*a*) section; (*b*) plan, (1) slopes of crater, (2) cracks, (3) vertical slope, (4) shaft

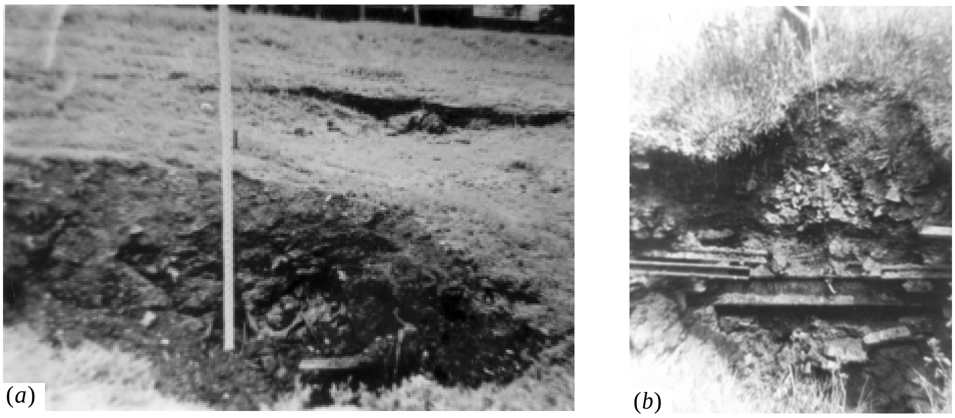

Fig. 3 (*a*) Surface subsidence above entrance to vertical shaft resulting from (*b*) platform collapse

Table 1 Characteristics of closing mines in Stakhanov Region

Mine	Number of worked seams	Dip, °	Number of vertical workings
Bryankovskaya	13	0–55	400
Dzerzhinskogo	6		
Krivorozhskaya	13		
Zamkovskaya	7	0–22	12
Named after Illyich	10	20–45	198
Chesnokova	14	10–70	128
Maximovskaya	5	0–44	76
Central-Irmino	18	22–60	366
Bexhanovskaya	5	0–18	23
Luganskaya	10	5–12	107
Total			1310

Fig. 4 Surface subsidence above ventilation adit

reliable technologies for closing and sealing vertical mine shafts.

Collapses above extensive shallow mine workings

In different areas of Donbass collapses are found above extensive, shallow, old workings (i.e. drifts, inclines, inclined shafts, slopes, crosscuts, etc.). A distinctive feature is the formation of troughs of collapsed ground along the axis of the working. Fig. 4 shows a collapse above a ventilation adit located at a depth of 26 m in one of the anthracite regions of Donbass. Caving craters above extensive workings can reach the surface (*a*) if the depth of the working, H, is less than the height of potential caving, H_k (Fig. 5(*a*)), or (*b*) if there is a route for caved material to escape downdip (Fig. 5(*b*)).

Thirty cases of ground collapse above such workings have been analysed according to the rank of the coal—in effect, the degree of metamorphism. Fig. 6 demonstrates the dependence of the depth of the workings where collapses have appeared on coal rank: the depth decreases with increasing degree of metamorphism. The maximum depths at which subsidence producing surface collapse has been recorded are marked by squares. According to this analysis, surface craters can be formed above anthracite workings at ≤60 m and above long-flame coal workings at up to 100 m. Most of the cases analysed occurred in conditions of increased water content of the rock mass as a result of flooding. Water discharge from flooded mine workings or lowering of its level can also lead to obstructions in the workings, creating conditions for the development of craters. The presence of equipment and machinery must also be regarded as a potential contributing factor. Intersections of workings increase the risk.

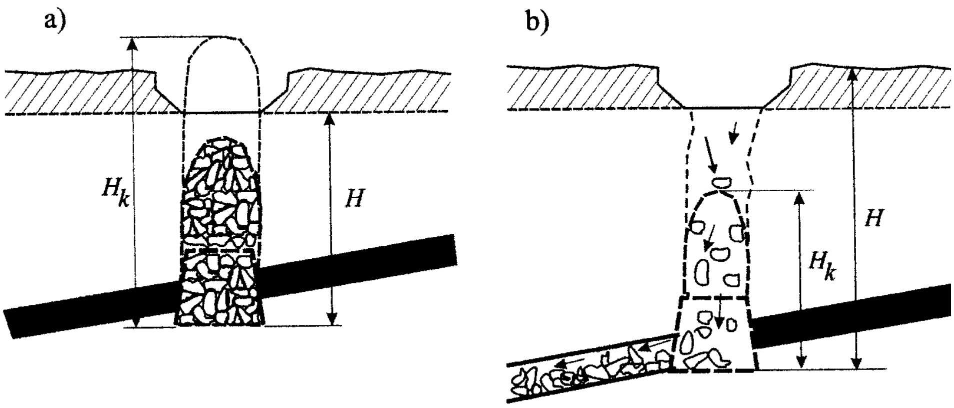

Fig. 5 Modes of collapse above extensive workings

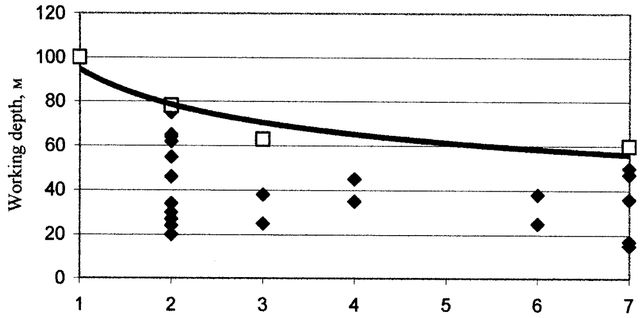

Fig. 6 Dependence of maximum depth of extensive workings that cause collapse on degree of metamorphism/rank of coal—1, long flame; 2, gas; 3, fat; 4, coking; 5, lean–baking; 6, lean; 7, anthracite

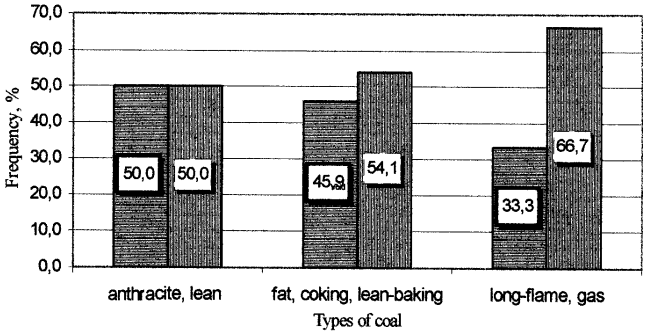

Fig. 7 Frequency of voids (*left*) and cavings (*right*) in shallow extensive workings

To ascertain the probability of voids in those workings 128 boreholes specially drilled to depths of up to 100 m were analysed. Fig. 7 shows the frequency of identification of voids and caved-in workings. The probability of voids persisting in the workings is 40–50% for coking coal or anthracite and about 30% for long-flame and gas coal. Thus, the greater the strength of bearing rock, the higher the probability of voids in extensive workings. Given the considerable extent of such workings and the frequent absence of reliable and accurate plans of old mining works, it can be concluded that the main manageable factor in preventing collapses above extensive workings is the maintenance of a definite level of underground water.

Collapses above fissures and cracks in thick, solid strata

Subsidence or collapse also appears when strong, solid strata (sandstone or limestone) fracture; in this case the depth of the mine makes little difference. Deep cracks or fissures through the whole seam thickness appear at the locations of greatest tension and can open by up to 1 m at the top. Water penetrating the cracks contributes to the formation of long, rift-valley type subsidence at the surface.

One such case occurred in 1985 in the area of Molodogvardeisk town (Lugansk Region). Evidence of subsidence was observed on agricultural land, where perennial grass was planted. The subsidence and collapsed ground formed a general system (Fig. 8), which was connected by

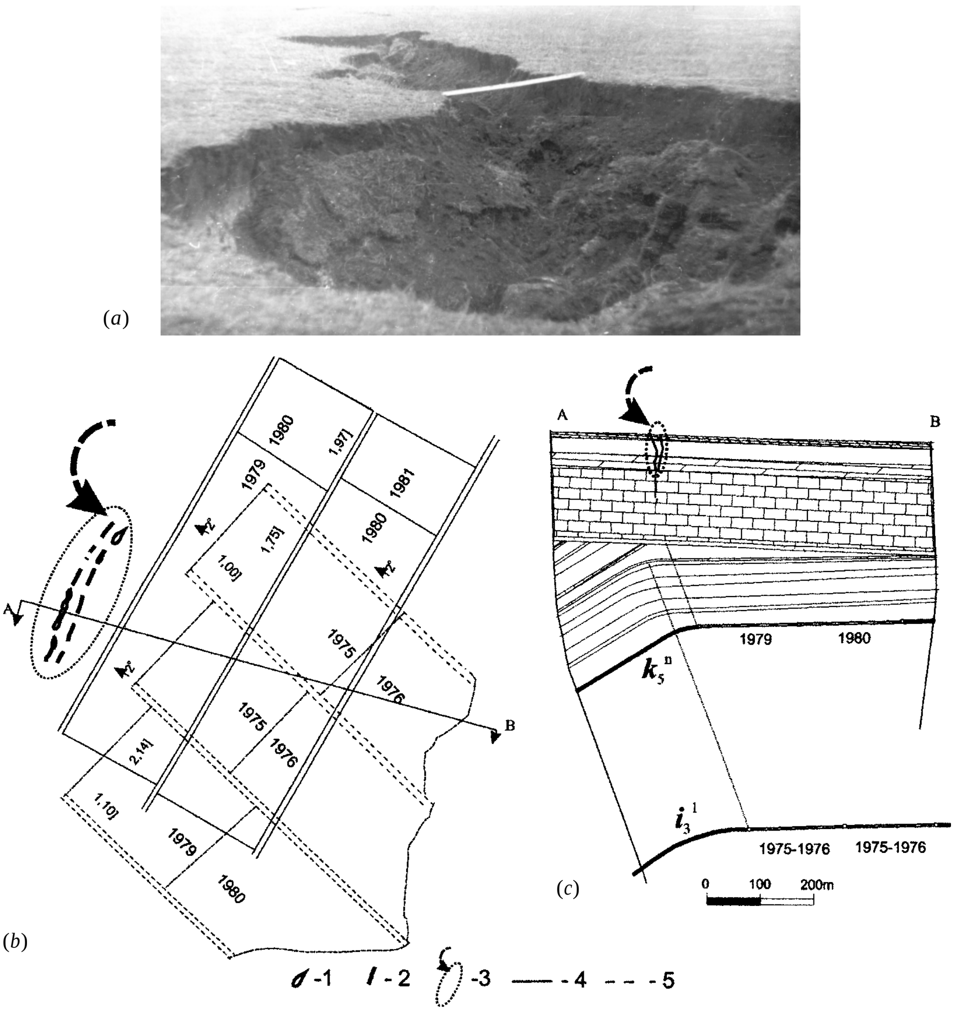

Fig. 8 Subsidence above fissures in thick limestone: (*a*) form of collapse; (*b*) location in relation to mining works; (*c*) geological section along line *A–B*, (1) subsidence, (2) fissures, (3) site of subsidence formation, (4) mining works in seam k^n_5, (5) mining works in the seam i^l_3

joining fissures with vertical displacement of the limbs (benches up to 20–40 cm) or by cracks with openings of up to 40 cm. Three areas of substantial subsidence were noted, the largest of which (Fig. 8(*a*)) was 30 m long, 3–8 m wide and 3–3.5 m deep. The distribution of the cracks and subsidence/collapses coincided with the borders of stopes and change in inclination of the strata (Fig. 8(*b*)). Subsidence was confined to *thalwegs* of the slope. The site had been underworked by mining of two seams: seam i^1_3, approximately 1 m thick, at a depth of 760 m in 1975–79; and seam k^n_5, approximately 2 m thick, at a depth of 360 m in 1979–81. The borders of the zones of influence of the seams coincide (Fig. 8(*c*)). The strata are carboniferous formations and Cretaceous deposits with thicknesses of up to 150 m. Layers of sand, marl, thin sandstones and clays lie above the Cretaceous deposits.

The appearance of subsidence can be explained in the following manner. The coincidence of zones of influence from a total extracted height of 3 m in a single vertical plane led to cracks in the chalk deposits. On the surface the cracks (openings of 10–20 cm) could be traced on both sides of the subsidence, although no cracks were found in the adjacent field (ploughed land). Previous dry years, springs with little flooding, and the fact that the land had not been ploughed for several years contributed to the preservation of the cracks on the surface. The thaw after a snowy winter in 1984–85 resulted in water from the melted snow penetrating the cracks, which had formed during the underworking. The water carried away sand and caused subsidence at the sites of maximum water flow. Thus, subsidence above cracks in thick, solid strata can occur at least five years after mining operations have ceased.

Similar cases have been recorded in anthracite regions in fissures in thick sandstones. Fissures in a thick, solid stratum persist for a long time. Rising underground waters can wash overlying loose material out through such fissures and produce subsidence on the surface. Moreover, the presence of fissures can change the direction of underground water flows significantly when a mine is flooded.

Activation of shifting movement above stopes

No subsidence has been recorded above stopes in the Donbass region, primarily because the seams worked are quite thin, but voids in shallow stopes may remain. Analysis of material from 40 boreholes has shown that the highest probability of remaining voids is in the anthracite regions (Fig. 9).

Rock can cave as a result of inundation, and a shifting trough with steep sides and large deformation can be produced. An example occurred in the town of Zugres in 1984, where sudden surface subsidence was triggered by a burst water main. A trough with 20 mm/m slopes and horizontal deformations more than 10 mm/m was formed above a longwall about 60 m long, which had been worked in 1947 at 40-m depth.

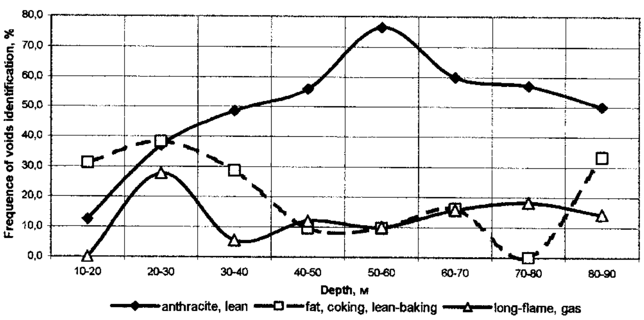

Fig. 9 Frequency of voids identified in shallow abandoned stopes

Unsupported roof spans may remain above relatively small stopes and near pillars (Fig. 10). The size of unsupported spans depends on the rock strength and the area of the mined-out space.

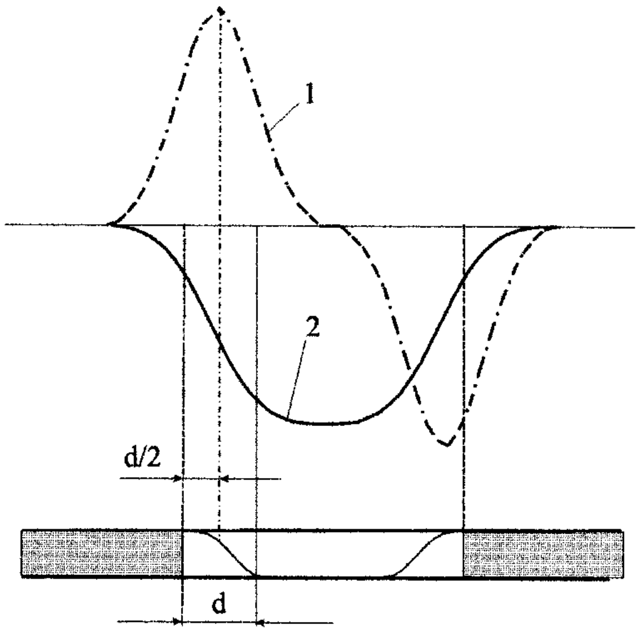

Fig. 10 Defining size of unsupported roof spans near pillars: (1) subsidence; (2) inclines

Table 2 Results of experimental investigations of extent of unsupported roof near sides of stopes

Coal rank	Number of cases	Average depth	*d*/2, m	Maximum span, *d*, m
Anthracite	13	124	26	52
Fat, coking, lean-baking	24	130	22	44
Gas	12	160	16	32
Long-flame	19	123	7	14

On the basis of mathematical modelling it was determined that the span width can be estimated from the position of the point of maximum strain relative to the border of a working (Fig. 10). To exclude any influence of the extent of the workings survey data were analysed only for cases where the surface was completely underworked.

In total, 68 cases were analysed and grouped according to the degree of metamorphism (rank of coal). The analyses reveal that the quantity of hanging roof rock increases with increased metamorphism. Anthracite regions are the most dangerous from the point of view of potential activation. The results indicate that no surface subsidence is likely above stopes in areas of long-flame coal deposits.

Concentrations of surface deformation

Concentrated surface deformations in the Donbass can be observed in three situations: (1) where the steep strata series in the Central Region of Donbass has been worked; (2) where tectonic faults or disturbances have been underworked; and (3) where seams in synclinal and flexure folds have been worked.

In cases of the first type a series of benches appears on the surface, their lateral extent coinciding with the distribution of the strata (Fig. 11). Benches can be observed both in the half-trough to the dip (zone *A*) and in the half-trough to the rise

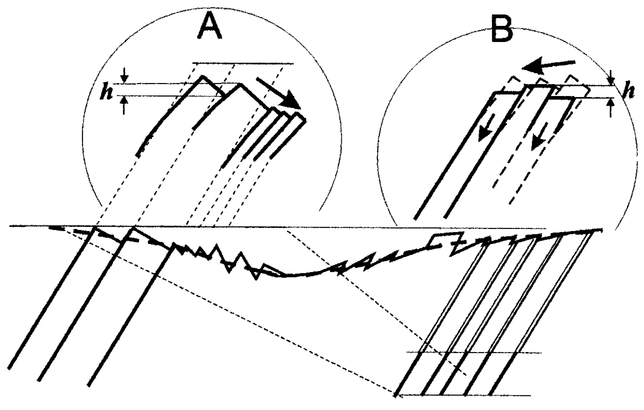

Fig. 11 Bench formation accompanying extraction from series of steep seams

(zone *B*). Strong strata are displaced along weak layers or contacts in the half-trough to the dip as a result of movment into the mined-out space. In the half-trough to the rise strata movement towards the trough centre accompanies shifting on the bedding contacts. Benches in the latter zone are 50–60 cm high, whereas in the half-trough to the dip the tallest are 25 cm. The saturation of weak interlayers during mine flooding leads to additional deterioration of their strength properties and can create benches in the half-trough to the rise; activation of benches in the half-trough to the dip is improbable.

The modes of rock mass displacement and subsidence that occur when tectonic faults are underworked are various and depend on a number of factors. One of the most important is the ratio of the rock mass strength to the disturbed zone strength. A higher saturation of the zone of fractured rocks of the fault can also give rise to concentrations of subsidence and deformation.

Much more complex processes take place during the working of coal seams in folds. Fig. 12 shows one of the modes of dispalcement in a synclinal fold while a steep section is being extracted. Where the strata are cut across cleavage as a result of the change in inclination benches 1 m high can be generated on the surface. The zone of rocks cut is the zone of increased fissuring and it can act as water-saturated zone during mine flooding.

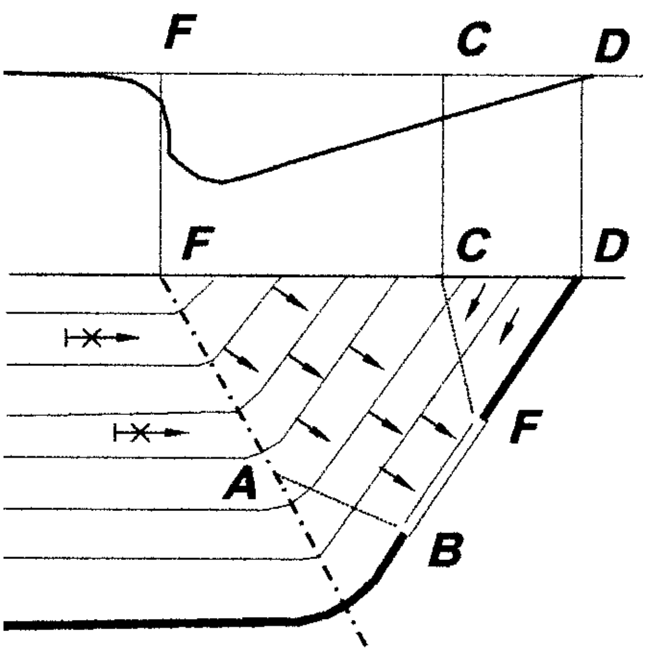

Fig. 12 Subsidence accompanying extraction from steep seam in synclinal fold

Assessment of condition of buildings and other surface structures

Damage resulting from undermining can compromise the future utility of buildings. Research undertaken in the towns and settlements of Stakhanov Region has shown that up to 34% of structures are in an unsatisfactory condition. Secondary damage is being incurred through (*a*) deficient inbuilt strength of load-bearing walls, which have been damaged since they were laid; (*b*) seasonal changes in the foundations, which are subject to a different stress regime since being underworked; and (*c*) seismic influence on the territory as well as vibration from machinery. The significance of the issue is emphasized by the fact that the mine closure process has coincided with changes in Ukrainian approaches to property assessment.

Monitoring of territory of closed mines

Until now in the Donbass there has been no experimental research on subsidence activation during 'wet' conservation of mines. Extensive research is being initiated in the Stakhanov Region (with a high level of underground water) and at some Donetsk mines (low level of underground water). A monitoring system is being established for the territories of closed mines.

Tasks and principles of monitoring

The main aims of monitoring are (1) to acquire experimental data on the presence or absence of surface deformation in the case of flooding of a mine or group of adjacent mines; (2) to establish links between surface deformation during mine closure, the triggers of deformation processes and such factors as level of flooding, depth and age of stopes, dip of the rock mass, presence of rock fractured by tectonic faulting, surface relief and concentrations of surface deformations (benches) formed during earlier underworking of the territories; and (3) to study the behaviour of buildings and structures damaged by repeated underworking.

The foundations have been laid for long-term study of surface deformation and the effects on existing buildings in the Stakhanov region of Donbass, where more than 100 mines were closed simultaneously. There are ten principal profile lines (Table 3 and Fig. 13), which lie across the strike and traverse the zones of underworking completely. The lines are directed as far as possible perpendicular to the strike of the

Table 3 Characteristic of monitoring lines in Stakhanov region

Mine	Profile lines	Benchmarks	Length of lines, km	Special lines
Bryankovskaya Dzerdhinskogo Krivorozhskaya	2	114	11,5	3
Zamkovskaya	1	40	4	
Ilyicha	3	72	7,5	4
Chesnokova	3	62	6,8	
Central-Irmino	1	40	4	
Total	10	330	about 40	7

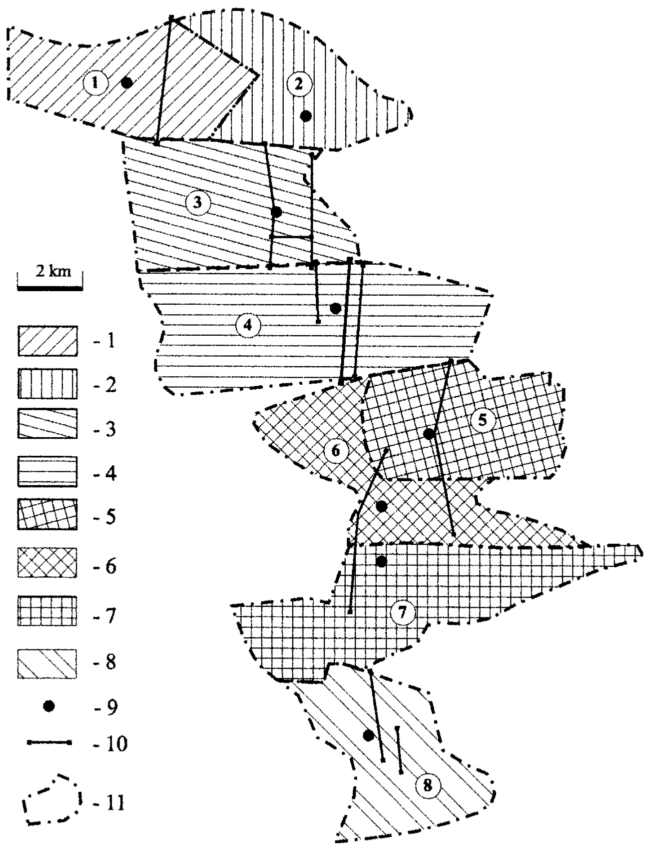

Fig. 13 Distribution of monitoring stations in Stakhanov region: (1) Central-Irmino mine; (2) Maximovskaya mine; (3) Chesnokova mine; (4) Ilyicha mine; (5) Krivorozhskaya mine; (6) Bryankovskaya mine; (7) Dzerzhinskogo mine; (8) Zamkovskaya mine; (9) main shafts of the mines; (10) main profile lines; (11) borders of mine territories

main tectonic faults and the axis of folds. Benchmarks are located about every 100 m. Along these profile lines only height measurements are envisaged in the first stage of the research.

The 'special profile' lines are confined to areas of concentrated (bench-type) deformation. The length of these lines is several hundred metres. Benchmarks are located at 5–10 m intervals. These lines are used for height and linear measurements. More than 30 monitoring stations are being set up to study deformation in buildings that have sustained substantial damage after underworking.

It is planned to take measurements twice each year, in spring and autumn. After the first results have been obtained the monitoring methodology will be refined. Along with the survey observations, monitoring of the hydrological regime is being carried out via a vast net of special boreholes.

First results of subsidence study

Observation already began in 1998 at some sections of three Donetsk mines where working had ceased. At these sites anomalous development of subsidence, connected with the influence of disturbed rock bedding, has been recorded.

During operations at Mushketovskaya mine a large tectonic fault with associated fractured rock, the Mushketovskiy thrust, was noted to have a significant effect on surface deformation (Fig. 14). This effect is registered in the considerable difference between the actual subsidence (curve 2 in Fig. 14(*b*)) and the forecast subsidence (curve 3) and in the concentration of squeezing deformations. The susbsidence has caused serious damage to three five-storey houses.

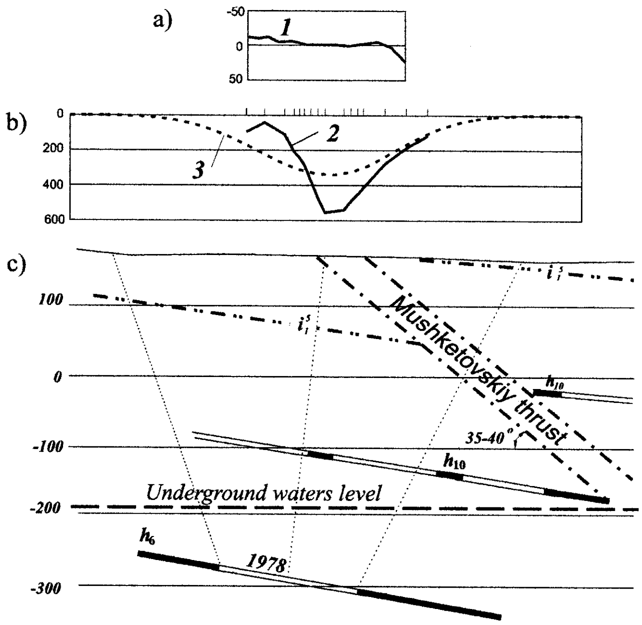

Fig. 14 Monitoring results from Mushketovskaya mine: (*a*) subsidence, mm, after mine closure; (*b*) actual and forecast subsidence due to mining works in seam h_6; (*c*) geological section along line of observations—(1) subsidence during period July 1998–July 2001, (2) measured subsidence for period May 1977–1978 (influence of mining works in seam h_6), (3) forecast ubsidence without taking fault impact into account

Mushketovskaya mine was closed in 1996 and surveying began in July 1998. A hydro-observation borehole, for permanent monitoring of the underground water level, has been drilled near the profile line. During the observation period the underground water level remained almost unchanged at the depth of 355 m (Fig. 14(*c*)). The results of three years of observation prove that fluctuations do not exceed 25 mm.

The influence of another fault was observed at No. 9 Capital mine (Fig. 15). In 1988–94 the monitoring line was underworked by seam h_6, at a depth of 450 m. The seam is inclined at 2°. The thickness extracted reduced from 1.5 to

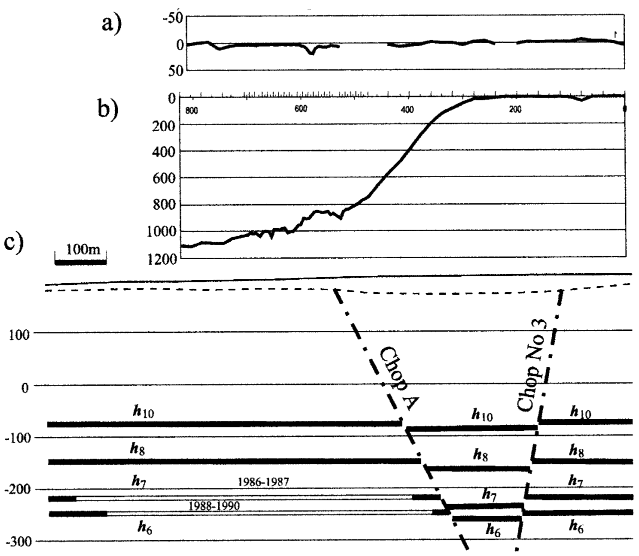

Fig. 15 Monitoring results from No. 9 Capital mine: (*a*) subsidence, mm, after mine closure, July 1998–July 2001; (*b*) subsidence, mm, caused by mining works in seam h_6, June 1988–July 1998; (*c*) geological section along monitoring line

1.1 m as the fault was approached. Irregular subsidence (Fig. 15(*b*)) was observed when working neared the fault—chop A. During the observation period since mine closure (Fig. 15(*a*)) vertical movement has not exceeded 20 mm.

The largest bench in Donbass provides the most graphic illustration of the influence that flexural folds can have on surface deformation. It is visible over more than 4 km. It is so high (in some places exceeding 2.5 m) that it is perceived as part of the topography. The reason for such concentrated deformation is the influence of Vetkovskaya flexure fold (Fig. 16(*c*)). The results of instrumental monitoring demonstrated that working a seam of 1.45–1.6 m thickness at a depth of 1000–1100 m led to an increase in the bench height of about 80 cm (Fig. 16(*b*)).

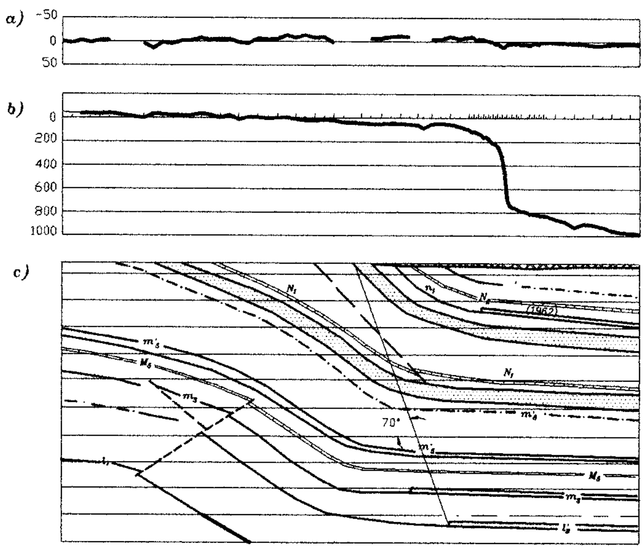

Fig. 16 Monitoring results from October Rudnik mine: (*a*) subsidence, mm, after mine closure, July 1998–July 2001; (*b*) subsidence, mm, June–July 1998; (*c*) geological section along monitoring line

Since 1994 mining works in the area of the monitoring station have ceased. Observations over the past three years demonstrate irregular vertical movements not exceeding ±15 mm (Fig. 16(*a*)) at the same monitoring station. Thus, the first results of research at the closed mines reveal that when the level of underground water is low there is no substantial increase of concentrated deformations.

Conclusions

When coal mines are flooded geomechanical processes may be activated that can manifest themselves as sinkholes or additional subsidence and deformation of the surface. Collapses or subsidence can appear above vertical workings that have outlets to the surface, above extensive workings and over fissures in thick, solid strata. The formation of steep-sided troughs and major deformation is possible above shallow stopes, anthracite-mining regions being the most dangerous from this point of view. Activation of subsidence above old stopes in areas of low-metamorphic coals is unlikely. In the event of water saturation of the rock mass activation of concentrated deformations is possible at the contact points of steep strata, above the tops of faults and in the association with workings in folded strata. If the level of underground water is low, these processes do not cause significant changes at the surface.

Monitoring of the territories of closing mines in the Donbass coalfields should be sustained to provide a more thorough understanding of the processes.

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