MINING-INDUCED SURFACE DAMAGE AND THE STUDY OF COUNTERMEASURES[1]

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Abstract: Coal constitutes China's major energy resource. The majority of the coal is produced from underground mining operations. Surface subsidence may amount to 80% of the thickness of the seam mined, while the subsided volume is around 60% of the mined volume underground. An area of 20 hectares of land will be affected with each 1 million tonnes of coal mined, thereby causing severe surface damage. Following a description of the characteristics of surface damages due to underground mining disturbance, this paper elaborates on the damage prediction method, standards applied for evaluating the damages experienced by surface buildings, land reclamation methods in subsided area, measures for reinforcing and protecting buildings in mining-affected areas, and performance of antideformation buildings.

Additional Key Words: ground strains, land reclamation, antideformation building.

Introduction

Ninety-five percent of the run-of-mine coal is produced by the longwall caving method in China, causing severe ground subsidence. Investigation shows that 20 hectares of land will be affected with the mining of every 1 million mt of coal. This leads to inundation, waste and damage of land, moving of buildings due to damage, and ecological deterioration in mining areas. Great importance has been attached to these problems. Since the early 1950's, research accomplishments together with related policies, codes, and technical specifications that have been implemented have brought about marked economic and social benefits.

Characteristics of Mining-induced Surface Damage

Mining of a large amount of coal underground leads to collapse and movement of overburden and hence surface subsidence. Therefore, the damage is characterized by spoiling and deterioration of land and damage of surface buildings.

Damage and Deterioration of Land

This poses one of the main environmental impacts in mining area, which manifests itself in the following aspects:

(1) Presence of subsidence trough: Owing to the effect of coal mining, the originally flat land will slope and become hilly, reducing the productivity. In areas with high ground water level, the land may be waterlogged or bogged;

(2) Presence of cracks and steps on the surface due to subsidence: This usually occurs at the outer edge of the subsidence trough and fault outcrop, resulting in discontinuity of land as well as reduction of its water and fertilizer-retaining capability;

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(3) Presence of cockpit-formed subsidence trough: This generally occurs in places with karst water or where steeply inclined, shallow thick seams are mined. The land in this case is rendered inoperative, and even the land outside the subsidence trough may be affected;

(4) Loss of land due to dumping of coal refuse: Of the total output of run-of-mine coal produced underground, coal refuse shares about 20%. Though much work has been done on its comprehensive utilization, a large amount of refuse is still stockpiled, consuming land and causing pollution of the environment;

(5) Pollution of land: There are two pollution factors, i.e., use of mine waste water for irrigation and leaching of acidic refuse by rainwater;

(6) Salinization of soil: After intensive evaporation of highly mineralized ground and surface water in large areas of mining-induced low-lying land, the land is salinized due to accumulation of soluble salts.

The substantial reduction of cultivated area for farmers in mining areas has brought about severe social problems. For example, in the mining districts under the Kailuan Coal Mining Administration, the subsided area totals 14,647 ha with 3,284 ha ruined and 9,247 ha affected. Out of the total area affected, 1,151 ha are waterlogged all year round, and about 60,000 farmers are deprived of their cultivated land.

Damage of Surface Buildings

China is populous and has densely distributed villages. In coal-bearing areas, there is a large number of surface buildings. According to incomplete statistics, in the main mining areas in China, a total of 87.6 billion mt of coal is locked up underground, and the locked-up coal deposits under villages total 52.2 billion mt or 60% of the total. This phenomenon is severe, particularly in 10 provinces, such as Hebei, Shandong, Shanxi, and Henan, where a total of more than 1 billion mt of coal is sterilized respectively.

Under the effect of mining operations, the ground surface and hence the buildings will undergo deformation and various degrees of damage.

(1) Uniform surface subsidence is generally less harmful to buildings. However, when the subsidence is great and the ground water level is high, the surface will be waterlogged, thereby reducing the load-bearing capacity and strength of the foundations. Generally, a building undergoing even settlement is under the effect of dynamic deformation of surface. As long as the building is able to stand the dynamic effect and no water hazard is imposed, no damage will be experienced by the building.

(2) The tilt of the foundation of a building is basically similar to that of the ground surface, except that a tall building or a structure with a small base area will experience greater damage.

(3) Generally, tensile and positive curvature deformations occur simultaneously, and the same is true with compressive and negative curvature deformations. In the former case, a building would experience the following damages:

- Presence of vertical cracks at the bottom of a building, which increase in width from top to bottom;

- Presence of increasingly widening cracks in a vertical direction of the upper part of wall sills, on the eaves part above the lintel of doors or windows, in the middle of the wall body, or above the juncture of the walls;

- Presence of inverted splayfoot-formed cracks at corners, or near doors or windows;

- Presence of cracks on the roof slabs;

- Movement or even drawingout of roof trusses, beams, or purlins.

Under the effect of surface compressive and negative curvature deformations, a building would suffer the following damages:

(1) Presence of splayfoot-formed cracks on the wall near the doors or windows;

(2) Presence of horizontal cracks above or below the window openings and at the places were the masonries change in cross section;

(3) Presence of vertical cracks at the juncture of vertical and horizontal walls, and in the middle of wall bodies;

(4) Peeling off of plaster, bulging, and local damage of wall, and deformation of doors or windows;

(5) Bulging of the middle part of the roof.

Prediction and Evaluation of Mining-induced Damages

Study of the Law Governing Ground Movement

Since 1956, more than 2,000 observation lines and two observation networks have been established in the main mining areas across China. With the data obtained, a sound basis has been laid for the study of laws governing ground subsidence in mining areas.

Early in the 1960's, a negative exponent function method was proposed by the Tangshan Branch of the Central Coal Mining Research Institute (CCMRI) for calculating subsidence along the main cross section of a subsidence basin. Later, an equation for determining the subsidence value of other sections and a method for deriving the related parameters were proposed. The negative exponent function method is shown in figure 1 and expressed in equation 1.

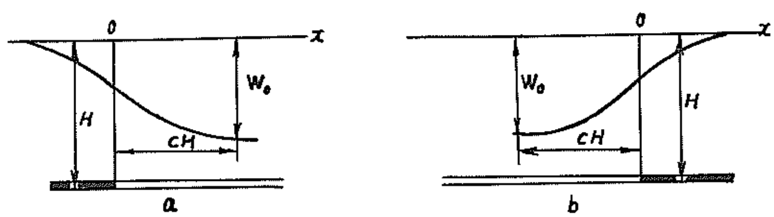

Figure 1. Subsidence curve of main profile along the strike.

$$W(x) = w_0 \exp[-a(c + x/h)^b], \qquad (1)$$

Where W_o = The maximum ground subsidence under supercritical extraction conditions, mm;
H = Depth of boundary of workings, m;
a,n,c = Specific parameters involved in negative exponent function method. a = Development factor in the lateral direction; b = Profile factor; c = Position factor of the point with maximum subsidence value.

The sign "+" denotes that the $\dot{x}$ axis extends in a direction toward the worked-out area, while "-" indicates the direction is towards the coal pillar.

The prediction precision is greatly controlled by the accuracy of ground movement parameters. To reduce errors as much as possible, an accurate determination method has been proposed. Through the use of this method in calculating parameters at nearly 200 observation stations, the variation of ground movement parameters under different lithological conditions is listed in table 1.

From the 1970's on, electronic computers were applied for predicting ground movement in mining gently to steeply inclined coal seams and for plotting sectional and isoline drawings.

Table 1. Main ground movement parameters under different overburden conditions.

Method	Character of overburden	Subsidence factor	Lateral development factor	Profile factor	Position factor
	Hard	0.42-0.64	--	2.9-3.2	--
			a,=4.5~6 a,=3~5		c,=tg31° c,=tg36°
Negative Exponent Function Method	Medium-hard	0.65-0.84	a,=2.28~ 2.21 In α / ß	2.6-2.9	c,=tg(31° -0.5 α)
			a,=0.16~ 2.54 In α / ß		c,=tg(36° +0.5α)
	Soft	0.85-1.15	--	2.4-2.6	--

Evaluation of the Degree of Damages Experienced by Buildings

For safety mining of coal locked up beneath surface buildings, a preevaluation of the degree of damage suffered by buildings should be made. The degree of mining-induced damage of a building is governed by ground deformation and the antideformation capability of the building. Based on the results of a study, the classification of damages of houses of mixed brick-wood is listed in table 2.

Study of Countermeasures and Structural Precautions

Land Reclamation Technique Applied in Subsided Area

The land reclamation in the subsided area is designed to restore the affected land to a usable state for better environmental control.

The methods currently used in China fall into the following categories:

(1) Engineering or biological means in different stages or sequence;

(2) Land reclamation with the use of coal refuse, ash from powerplants, or by applying methods such as shallow refilling after extensive excavation, dewatering, formation of terrace land and comprehensive approach;

(3) Land reclamation for construction, agricultural, forestry, fishery, and recreational purposes or for comprehensive applications.

Table 2. Classification of damages of houses of mixed brick-wood structure as related to ground deformation.

Classification of damage	Ground Tilt (mm/m)	Ground curvature (10^{-5} 1/m)	Deformation horizontal strain (mm/m)	Description of damage	Repair requirements
Class I	<3	<0.2	<2	Small fractures less than 5 mm in width appear on walls	Not necessary
Class II	3-6	0.2-0.4	2-4	Cracks 5-10 mm wide on walls. Doors & windows sloping slightly. Plaster comes off and slight dislocation of beam support.	Minor repair
Class III	6-10	0.4-0.6	4-6	10-30 mm-wide cracks on walls. Slant of doors & windows, tilt of walls, dislocation of beam heads. Cracks or heave observed in floors and walls.	Periodic repair
Class IV	>10	0.6-0.8	>6	30 mm wide cracks accompanined by vertical, horizontal, and oblique fractures in walls. Walls leaning or bulging noticeably. Severe dislocation of beam heads. Bulging of roof.	Overhaul

Engineering Means

The land is backfilled, reclaimed, excavated, and leveled by mechanical means in a manner to suit local conditions and application of the land reclaimed.

(1) With the use of coal refuse as backfill material, additional benefits can be obtained in the reduction of area of land for stockpiling and improvement of environmental control.

In cases where the reclaimed land is intended for use as a construction site, backfilling should be made on a layer-by-layer basis, together with vibration compaction for increasing the load-bearing capacity and stability of the foundations. The thickness of the individual layer is determined by using the following equation:

$$H = 0.5Q + 20 \tag{2}$$

where H = Layer thickness, cm,
Q = Capacity of vibration compactor, kN.

If the refuse is backfilled once to the designed depth, intensive ramming should be applied to the foundation area. The depth to which the intensive ramming should be applied is calculated with the following equation:

$$h = (0.4 \sim 0.7)\sqrt{QH} \quad (3)$$

where h = depth rammed, m,
Q = Weight of hammer, 10kN,
H = Falling height of entire hammer, m.

If the refuse contains a considerable proportion of ferric sulfide, a layer of clay should be placed on each thick layer of refuse as an isolation layer or the topmost refuse layer should be sealed up to avoid spontaneous combustion or release of poisonous matters.

(2) Use of ash from power plant as backfilling material.

- Construction of ash yard with topsoil removed from the subsided area;
- Ash delivered hydraulically from the power plant to ash yard via pipeline;
- The water decanted in the yard is discharged from the drainage ports;
- When the ash yard is filled to the designed elevation, the dam is removed, and soil is placed on top of the ash to form farmland.

(3) Extension of the depth of severely subsided area through mechanical or manual means for raising fish, planting lotus roots, or irrigation purposes. The soil dug out is used to backfill the slightly subsided area to form paddy fields or dry farmland. The method is widely used in subsided areas with accumulated water because of its noticeable economic and ecological benefits.

(4) If the ground surface in the subsided area is still higher than the nearby lake or river water level, drainage channels are dug leading to the lake or river. An area with deep accumulated water is changed into a fish pond. If the waterflow in the river is impeded due to variations of the riverbed, pump stations may be set up in wet seasons to discharge the water into the lower section of the river. In addition to protection of the ecological environment, there is no need to move the villages in the affected area.

(5) In subsided areas with low ground water level or slopes, the land may be leveled and transformed into terrace land.

(6) Reclamation of the subsided area in a well planned way to suit local conditions with an aim to turning the reclaimed area with relatively small input into agricultural, fishery, forestry, construction, or recreational places.

Biological Method

This method is designed to restore the fertility and productive capacity of affected land with organisms, usually a process proceeded in the wake of an engineering approach. It consists mainly of soil improvement and optimal selection of vegetation variety.

The methods used for soil improvement involve:

(1) Biological method (green manuring method): Planting perennial or annual leguminous plants in areas under reclamation to accelerate the curing of soil;

(2) Application of fertilizer for higher content of organic materials in soil in an attempt to ameliorate the soil structure for improved physicochemical property;

(3) Blending method: For soils with excessive clay or sands, a blending method is used to adjust the clay/sand ratio for increased fertility;

(4) Chemical method: Use of lime for acid soil amelioration.

Structural Precautions for Affected Buildings

The structural measures adopted may fall into two categories:

(1) Addition of rigid elements, such as reinforced concrete foundation girths and columns to increase the integrity and antideformation capacity of a building;

(2) Adoption of flexible measures, i.e., provision of sliding layers, expansion joints, and selection of rational length of individual units for better adaptability to ground strain and smaller additional stress.

The structural precautions as described above may be applied on both existing and new buildings.

Existing Buildings

Based on experience gained in protection of buildings in mining-disturbed areas, the following technical measures can be effectively adopted:

(1) For buildings subject to Class II damage (see Tables 2 and 3), expansion joints and reinforced concrete foundation girths can be provided;

(2) For buildings suffering Class III damage, in addition to the above measures, reinforced concrete girths, steel ties, as well as reinforced concrete columns, should be provided;

(3) Buildings suffering Class IV damage should be removed and rebuilt. In particular cases where strengthening measures are required, apart from the measures as described, reinforced concrete anchor slabs should be provided for the foundations;

(4) Provision of trenches for partially absorbing the compressive deformation.

New Antideformation Buildings

Apart from adoption of rigid and flexible structures, one of the key measures for new buildings is provision of a horizontal sliding layer between the superstructure and the foundations for effectively reducing the effect of horizontal ground strains. Use of this new method since the late 1970's has promoted China's structural precaution technique for buildings in mining areas to a new horizon.

The technique for designing new antideformation buildings was first developed by the Tangshan branch, CCMRI in 1978, and the 1,350 m^2 club with this design was first built at the Zhijiang Coal Mine. Later, 36 antideformation buildings with a total area of 24,586 square meters were successively built in mining-disturbed areas. Of these, 11 were residential buildings, 13 were village houses, and 12 were public buildings. The buildings all withstood the test when three coal seams beneath (aggregate mining thickness: 4.1 m) were mined with a longwall method along strike. Since 1983, 300,000 m^2 of different kinds of antideformation buildings have been successfully erected prior to start of operations at mines under Yangquan, Huoxian, Pindingshan, Yima, Chenghe, Datong, Tiefa, Nanpiao, Qitaihe, Hegang, and Kailuan Mining Administrations.

The main considerations involved in designing new antideformation buildings are:

(1) Rational planning and optimal selection of construction sites: In this respect, the long-term development plan and mining activities should be taken into consideration. The axis of a new building should run as parallel or normal to the strike of seam as possible. For a building located at the edge of the subsidence basin, its long axis should run parallel to the subsidence isopleth, while a building at the flat bottom of a subsidence basin should keep its long axis normal to the direction of face advance. Buildings of any kind should not be located in areas subjected to the adverse effects due to mining. For instance, erection of a building at the deflection point of a subsidence basin should be avoided. Likewise, the construction sites should not be located in areas subjected to discontinuous cracks or in areas with water hazards or that are liable to undergo earth slump.

(2) Structural Form: Buildings to be erected in mining-disturbed areas should be designed as simply as possible. A building should preferably be separated into a number of rectangular units of identical height, structural rigidity, and uniform load. With a predicted value of ϵ greater than 6 mm/m, the length of each unit is preferably less than 20 m while at a ϵ value smaller than 6 mm/m, a length in the range of 20-25 mm should be selected. Furthermore, the longitudinal and transverse load--bearing walls should be symmetrically arranged relative to the central axis.

(3) Foundations: The buried depth of the foundations should possibly be reduced to a level just below the frozen depth and enough to meet the load-bearing requirement. On the top of foundations is a horizontal sliding layer on which reinforced concrete girths should be placed. Even in case the foundations are not on the same level, placement of sliding layers is indispensable.

(4) Walls: The partition walls, and door and window openings of equal width and height should be uniformly arranged according to height and length of walls. The distance between the edge of an opening and that of the building should be no less than 1.5 m and no smaller than 0.6 m away from the axis of T-juncture of longitudinal and traverse walls. Moreover, lintels for doors and windows should be of reinforced concrete structure, and tie bars should be provided at corners and the T-juncture of walls. Use of hollow walls should be avoided.

(5) Reinforced Concrete Girths and Columns: Reinforced concrete girths and columns must be provided for new buildings. They should be anchored with each other so as to form a skeleton system. The girths are to be placed on top of sliding layers.

(6) Slabs and Roof: The slabs, roof, and wall girths should be of cast-in-situ structure to form an integral system.

If precast concrete slabs are used, the supporting length on the wall should be no less than 10 cm. The slabs should be tied firmly with girths and walls. The beam or roof truss and walls should be reliably secured. Use of brick arch or concrete arch structures liable to induce lateral thrust force is in no case allowed.

Technoeconomic benefits obtained by applying antideformation techniques at the Zhijiang Coal Mine are as follows:

(1) Movement and deformation of buildings: Based on field observation data, the subsidence and tilt of a building and the ground where the building is erected are closely related to linearity of deflection. The deflection experienced by the building is in inverse proportion to the building's integral rigidity. Because of the provision of sliding layers, noticeably less horizontal strains were observed on walls.

(2) Change of width of expansion joint: The club's two adjacent units isolated by an expansion joint underwent a displacement of 136 mm relative to each other and the gap widened 129 mm in an east-west direction. Eighteen domestic buildings all experienced a relative displacement of 220 mm without showing any cracks in the walls. This has demonstrated the effectiveness of the provision of expansion joints.

Table 3. Maximum movement and strains of buildings and ground.

Bldg.	Obs. Station	Sub. (mm)	Tilt (mm/m)	Pos.Curvature (10^{-4}/m)	Neg.Curvature (10^{-5}/m)	Ext. (mm/m)	Comp. (mm/m)	Structural Design
Guest House	Wall	2823	21.1	1.25	1.34	0.9	1.2	Anti-
	Ground	2834	36.0	6.99	7.51	16.5	5.1	Deformation
Club	Wall	2712	14.0	1.86	1.19	2.5	3.4	Anti-
	Ground	2707	26.3	2.84	9.32	5.0	18.3	Deformation
Kinder garten	Wall	2245	31.4	1.84	1.60	1.2	1.7	Anti-
	Ground	2239	33.1	3.22	3.95	9.8	25.9	Deformation
Police Sub-Station	Wall	2571	18.6	1.82	3.58	1.4	2.0	Anti-
	Ground	2586	22.7	6.20	8.60	13.8	13.1	Deformation

(3) Results of observation with nine groups of stations at the interface of the reinforced concrete foundation girths and foundations revealed that the foundations underwent a displacement of 121 mm relative to the walls, demonstrating the marked performance of horizontal sliding layers.

(4) Based on predicted strains before mining, a greater ground compression was expected. Therefore, trenches were excavated on both the south and north sides of the club with less structural rigidity. Observations made after ground strains were stabilized showed that the south and north trenches experienced maximum compression strains of 229 mm and 578 mm, respectively. The successful performance of trenches in reducing horizontal strains, particularly compression, was fully borne out. For instance, compression strains of 8.3 mm/m and 14.3 mm/m were absorbed between observation stations N2-S2 and N5-S5, respectively.

(5) Conventional buildings versus antideformation buildings: The antideformation performance of village houses has been described above. Only individual houses showed slight fissures on door and windows. Six conventional houses were severely damaged due to mining, affecting their normal use because of the presence of a maximum tilt of 190 mm and 70 mm wide cracks on walls.

(6) Economic analysis: The cost incurred for applying antideformation measures on a building shares on average 14% of the total cost of its civil work.

Concluding Remarks

The research-derived accomplishments obtained over the past 3 decades have made important contributions to the development of China's coal industry and have brought about marked economic, environmental, and social benefits. With regard to land reclamation, apart from further improvement of existing technical measures, efforts will be placed on enhancement of land utilization and economic efficiencies and development of ecological and biological measures for reducing the period required for regaining the productivity of affected land. Regarding structural precautions against damage to buildings, the study will be directed towards the development of technology and processes for applying both flexible and rigid structures, which have been so successfully used on new and existing buildings, as well as the structural pattern and design of buildings offering both deformation and earthquake-resistant performance. All the activities planned are aimed at pushing structural precaution technology to a new level.