Mining Science and Technology, 10 (1990) 81–91
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Some aspects of mining under aquifers in China

MAO BAI and D. ELSWORTH
Pennsylvania State University, 104 Mineral Sciences Building, University Park, PA 16802 (U.S.A.)
Received January 9, 1989; accepted May 22, 1989

Abstract

Mao Bai and Elsworth, D., 1990. Some aspects of mining under aquifers in China. Min. Sci. Technol., 10: 81–91.

A number of case studies of mining-induced permeability enhancement are documented. The extent of strata failure around active underground mines is determined through use of a borehole discharge test. The test delimits zones and the severity of extraction induced fracturing. From these data, empirical relationships are developed to determine the vertical and horizontal extents of the caving and fracture zones induced by mining. These relationships are developed for a variety of strata types and strengths and give quantitative recommendations applicable to similar mining conditions elsewhere. These recommendations are particularly important for sub-sea or sub-aquifer mining to ensure hazard-free operation.

Introduction

The great complexity and variation of geological and hydrogeological conditions are of critical importance to the mining industry in China. Among other mineral reserves in China, coal is presently claimed to be the most abundant, placing China as the second largest coal producer in the world. There are more than five million Chinese working in the coal mining industry which, coupled with the introduction of advanced technology, quickly exhausts the accessible coal seams and consequently makes the mining environment progressively less desirable. Against this background, coal mining has been carried out since as early as the 1950s in areas which were otherwise understood to be prohibitive. Indeed, mining under these conditions has been instituted so successfully, liberating millions of tons of precious reserves without any disastrous consequences, that current legislation requires extraction of those minable areas which are under surface or interstrata structures secured by necessary safety measures.

Apart from mining under surface buildings, China has developed specific methods of extracting coal seams under aquifers and bodies of water. The objective of this paper is to briefly introduce some of the important aspects of this technique. This is essentially an empirical approach, enriched by almost 30 years experience in China. For clarity, the mining method is confined to longwall extraction.

Mechanisms of strata failure

Longwall mining is a highly efficient method of coal extraction. The method causes subsidence which may result in changes in the

0167-9031/90/$03.50

quality and quantity of groundwater inflow in overlying aquifers, which are potentially hazardous to the mine.

Following longwall extraction, there are three zones formed over the mined area [1,2]: the caving zone, fractured zone and bending zone. The former two are considered to be the result of overlying strata failure while the latter shows few mining-related effects. The three zones can be identified by measuring the changes in the permeability of the overlying strata. To mining engineers, the most interesting region to be looked into, apart from the caving zone, would be the fractured zone that frequently provides access for the water inflow into the mine workings. From experience, the fractured zone may be distinguished from the other two zones by the following criteria:

(1) *Severely fractured zone*. Bed separation appears in most parts of the strata, causing an increase in water conductivity in the region. This zone can be identified by borehole discharge experiments in which the average flow rate is greater than 1.0/s/m.

(2) *Moderately fractured zone*. The strata generally remain intact with only partial bed separation and fracturing. The average flow rates in discharge experiments range from 0.1 to 1.0/s/m.

(3) *Slightly fractured zone*. Only small fractures are induced in the strata. The flow rates in borehole discharge tests are less than 0.1 l/s/m.

Determination of strata failure by *in-situ* flow testing

It is vital that the fractured regions are determined accurately before mining is initiated beneath aquifers, in order to prevent the hazard of tapping the aquifers via mining-induced fractures. One of the most effective methods applied in China is the borehole discharge technique mentioned previously. This method has been employed almost exclusively for this purpose during the past 30 years. The principle of this method is quite simple: A borehole is advanced from either the surface or from the underground roadway to the face. At staged depths, fluid is pumped into the borehole and the flow rate measured at outlet. Since interest is focused in a packed-off section of the borehole, casing may be necessary in conducting the test. The intensity of strata fracturing may be estimated from the test. By completing the flow test under identical pressure heads both before and after the mining cycle, an appraisal of fracturing induced in the overlying strata may be made. By applying a fracturing criterion similar to that mentioned previously, possible zones of strata failure may be determined.

It has been empirically determined that the extent of strata failure depends primarily on the lithology of the overlying strata (lithology is defined macroscopically) as well as on the inclination of the extracted seam.

Strata failure above flat or slightly inclined seams

Flat or slightly inclined seams are those exhibiting a dip magnitude of less than 30°. The extent of strata failure depends primarily on the elastic and fracture characteristics of the surrounding strata. Brittle materials are found to have substantially greater fracturing potential than rocks exhibiting ductile characteristics. Since brittleness may be roughly correlated with rock strength, empirical classifications may be used to divide strata into lithological units. The lithological divisions chosen in the following are weak, medium strong and strong. These results are shown in Table 1.

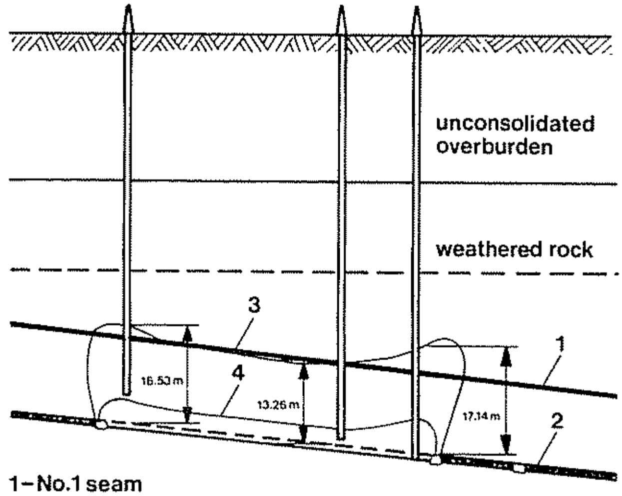
The extent of caving and fracturing has been recorded in a number of lithological types by borehole discharge experiments, as illustrated in Figs. 1–3. The caving zone is

TABLE 1

Strata lithology versus strength of rock

Strata lithology	Uniaxial strength of the rock
Strong	> 40 MPa
Medium strong	20–40 MPa
Weak	< 20 MPa

highest in the most competent strata and rarely penetrates the weaker overlying strata as a result of the lack of competency in these units. The fracture profile is squat in section with extended lobes over the maingate and tailgate.

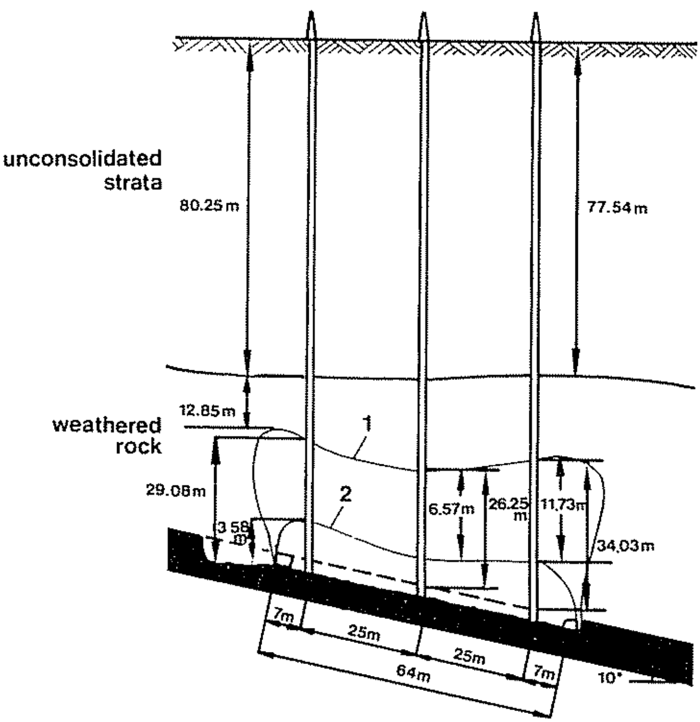


1–No.1 seam
2–No.2 seam
3–fractured zone
4–caving zone

Fig. 1. Strata failure in weak overlying strata.

Strata failure over inclined seams

Inclined seams are those dipping at inclinations between 30° and 60°. Failure zones in these cases propagate upwards in an asymmetric manner in the upseam direction. Rubble originating updip is displaced downseam,



1–fractured zone
2–caving zone

Fig. 2. Strata failure in medium strong strata.

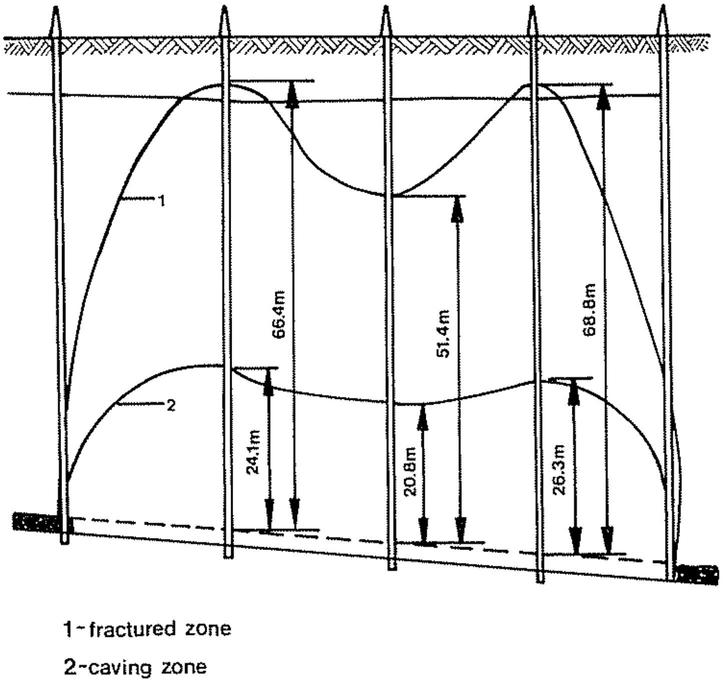


Fig. 3. Strata failure in strong strata.

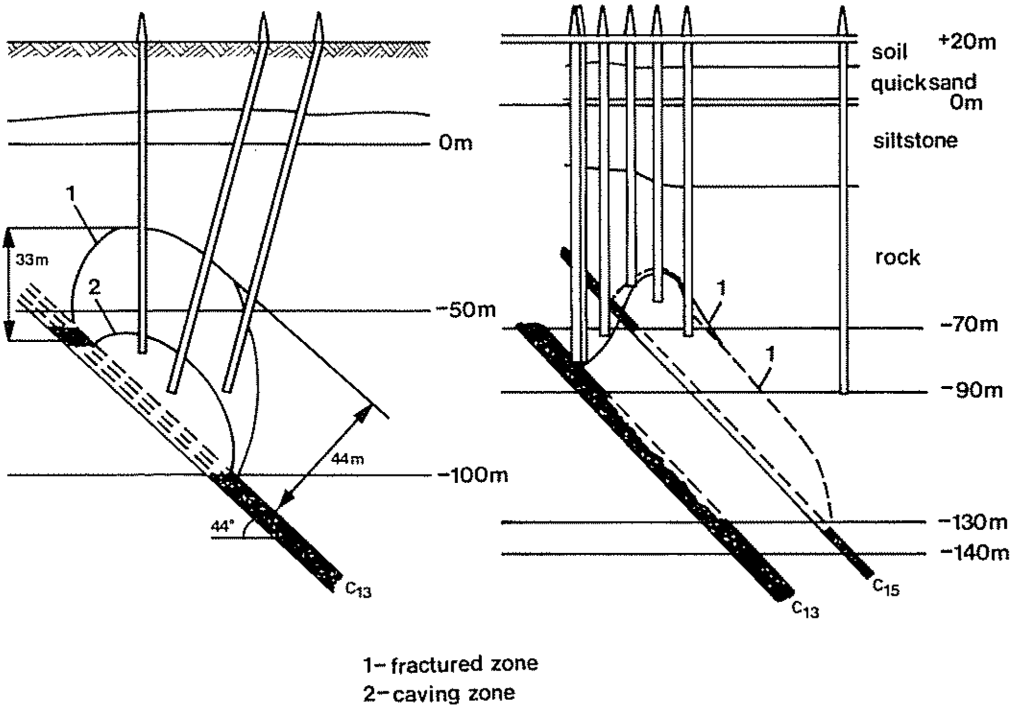


Fig. 4. Strata failure over inclined seam.

removing support from the failing roof. The extent of the failure zone is reduced downdip (see Fig. 4).

Strata failure over steeply inclined seams

Steeply inclined seams are those dipping at angles between 60° and 90°. The failure zones are commonly of irregular shape with caving occurring in the strata directly overlying the steeply inclined seam. Ground movement is commonly subparallel to the seam [3].

Prediction of maximum strata failure height

Study of parameters

A number of parameters affect the development and resulting configuration of fractured and caved zones. Seam thickness is the most important factor influencing the height of the strata failure zone. For different lithological types the failure height asymptotes to a single value for extremely thick seams. Similar to the case of longwall mining the maximum height of a caving zone is reached once the width of the gob exceeds the critical width. This condition is controlled by the bulking of the broken rock comprising the gob area. In addition to the geometric constraints of panel width and seam thickness, strata lithology exercises an important control over fracture development. In strong strata the rocks cave completely with the maximum height of the failure zone reaching between 20 and 30 times the extracted seam thickness. In weaker strata the caving is less well developed with maximum heights of the fracture zone reaching to 9 to 12 times the height of the extracted seam thickness. Clearly, therefore, weaker strata have more desirable characteristics for mining beneath aquifers.

Finally, as mentioned previously, seam inclination primarily affects the geometry of the fracturing and caving pattern. Since the fracture zone moves upwards with the steepening of the seam, this exerts critical control on the possibility of subaquifer mining.

Empirical prediction

Empirical criteria may be developed from the diverse set of data available for mining environments with different lithological and geometric characteristics. The relationship in its most general form is given as:

$$H = \frac{M}{aM + b} + c \text{ (m)}$$

where H = maximum height of strata failure (m), M = extracted seam thickness (m), a and b = coefficients depending upon the strata lithology, and c = mean square deviation.

Prediction of maximum height of caving zone H_c

Strong strata:

$$H_c = \frac{100M}{2.1M + 16.0} + 2.5 \text{ (m)}$$

Medium strong strata:

$$H_c = \frac{100M}{4.7M + 19.0} + 2.2 \text{ (m)}$$

Weak strata:

$$H_c = \frac{100M}{6.2M + 32.0} + 1.5 \text{ (m)}$$

Weathered weak strata:

$$H_c = \frac{100M}{7.0M + 63.0} + 1.2 \text{ (m)}$$

Note that H_c decreases as the strata become increasingly softer.

Prediction of maximum height of fractured zone H_f

The formulation follows a pattern similar to that for the caving zone.

Strong strata:

$$H_f = \frac{100M}{1.2M + 2.0} + 8.9 \text{ (m)}$$

Medium strong strata:

$$H_f = \frac{100M}{1.6M + 3.6} + 5.6\ (m)$$

Weak strata:

$$H_f = \frac{100M}{3.1M + 5.0} + 4.0\ (m)$$

Weathered weak strata:

$$H_f = \frac{100M}{5.0M + 8.0} + 3.0\ (m)$$

Note that H_f also decreases as the strata become increasingly softer.

TABLE 2

Characteristics of aquifers in Quaternary strata

	Aquifer	Flow rate (l/s/m)	Permeability (m/24 h)
Upper	Sand 2	3.1756	116
Quaternary	Sand 3	11.445	
	Sand 4	3.546	99.2
Lower	Sand 1	0.00065	0.071
Quaternary	Sand 2	0.000557	0.034
	Sand 3	0.01233–0.24	0.576–4.13
	Gravel and clay	0.00291	0.1123

Case studies

(1) Mining under thick water-bearing alluvium at the Chaili mine

Regional geological and hydrogeological conditions

The Tengnan coalfield lies in Permian and Carboniferous coal measure strata with seam inclinations varying between 0° and 12°. The thickness of the primary seam is approximately 10 m with the roof consisting of fine- to medium-grained sandstones. The overlying coal measures are 40–60 m in thickness, comprising weak, weathered and fractured strata in the uppermost reaches. The material underlying the weathered cap strata are in the main part, strong and unfractured. The bedrock is overlain by unconsolidated Quaternary alluvium comprising mixed impermeable clay layers with water-bearing sands and gravels. Eight productive aquifers have been identified within the 77 m of unconsolidated overburden. The uppermost of these aquifers are more permeable than the lower beds with the predominant regional groundwater flow orientation being vertically downwards. Flow rates for the various aquifers are identified in Table 2.

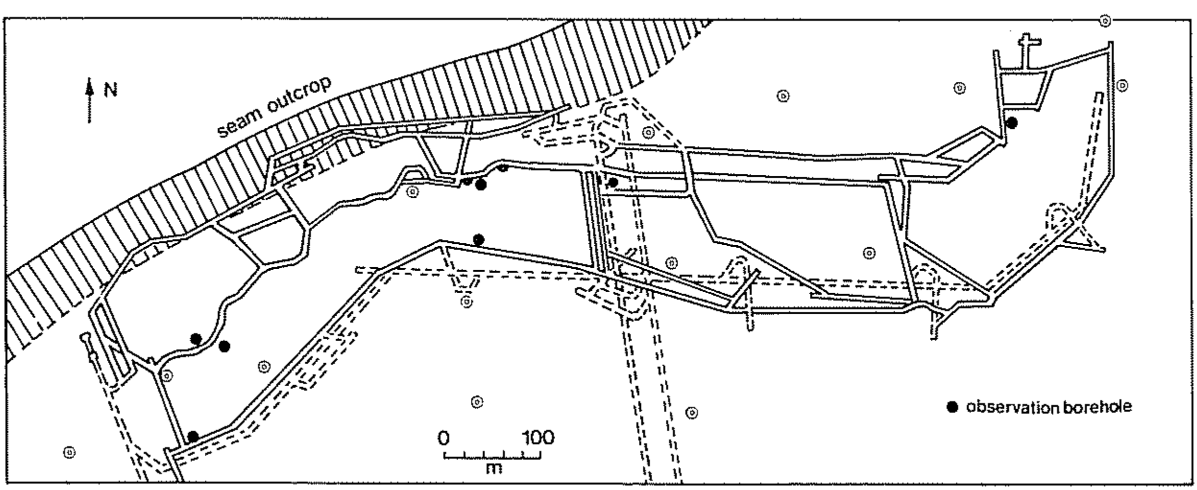


Fig. 5. Layout of measurement boreholes in Chaili coal mine.

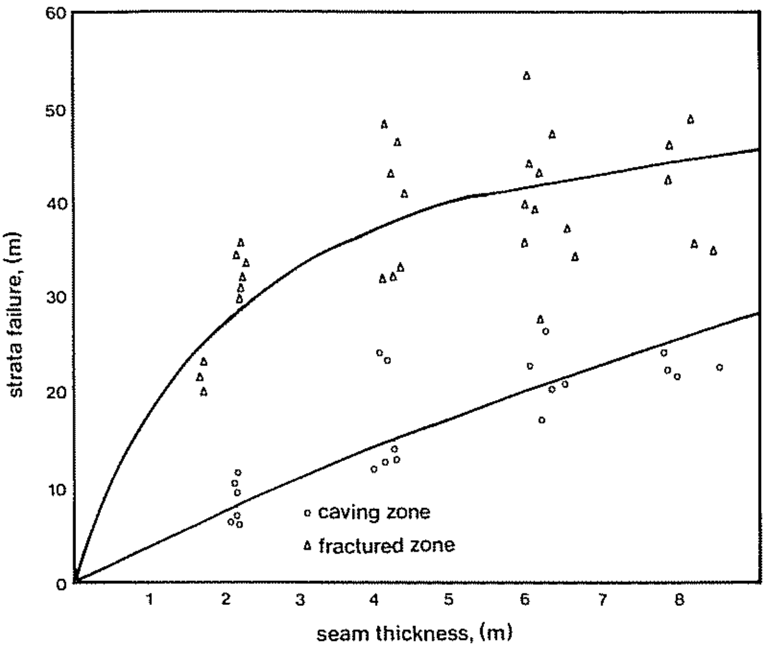


Fig. 6. Correlation between height of strata failure and thickness of extracted seam in Chaili coal mine.

In-situ borehole discharge measurements

The surface borehole discharge method was used to determine the feasibility of completing longwall lift (slicing) mining under the water-bearing and highly permeable overlying strata. A total of ten boreholes was completed for the test procedure as illustrated in Fig. 5. Additional boreholes were located around the periphery of the mine area to determine the regional variation in the fracture-induced permeability. The observed results are illustrated in Fig. 6, identifying correlations between measured heights of the fractured and caving zones and the thickness of the extracted coal seam. For the Chaili mine these results may be fitted to the following specific formulae:

Maximum height of caving zone:

$$H_c = \frac{100M}{0.9M + 24.0} + 3.51 \text{ (m)}$$

Maximum height of fractured zone:

$$H = \frac{100M}{1.8M + 3.6} + 6.01 \text{ (m)}$$

The form of the failure zone induced by mining is illustrated in Fig. 7 for mine excavation in a total of four lifts. Increasing the number of lifts required to remove a certain thickness of seam provides the utility of reducing the magnitude of the caving height above that seam. This is evident in Fig. 7 and is more conclusively illustrated in Fig. 8 where the ratio of failure height to seam thickness is shown to decrease with the increased number of lifts required for excavation. Further economic considerations dictate the feasibility of prescribing the number of lifts for excavation. It is anticipated that when concerns over water in-rush control the feasibility of mining, the utility of this observation is most keenly apparent. In this particular example of the Chaili mine the thick seam was successfully extracted with neither water in-rush nor even excessive groundwater discharge to the mine.

(2) Mining under massive alluvium at the Xingtai coal mine

Regional geological and hydrogeological conditions

The predominant seam is 6.5 m thick, dipping with an angle of between 6° and 8°.

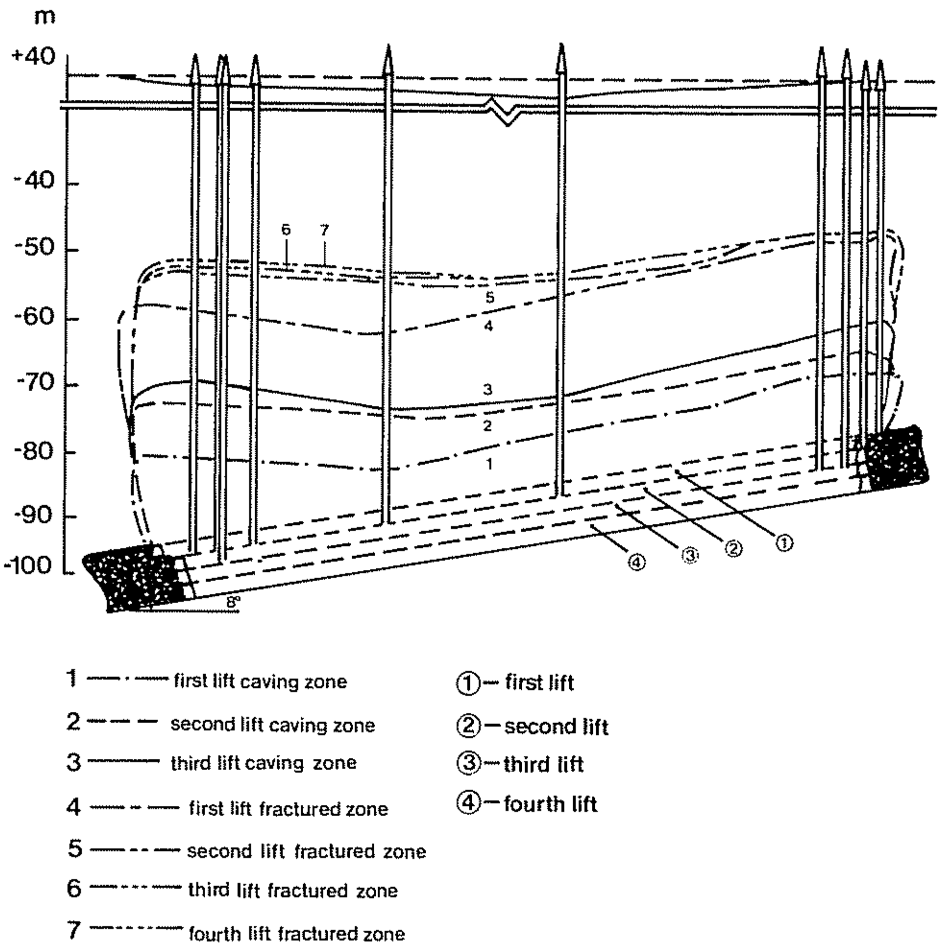


Fig. 7. Observation scheme in Chaili coal mine.

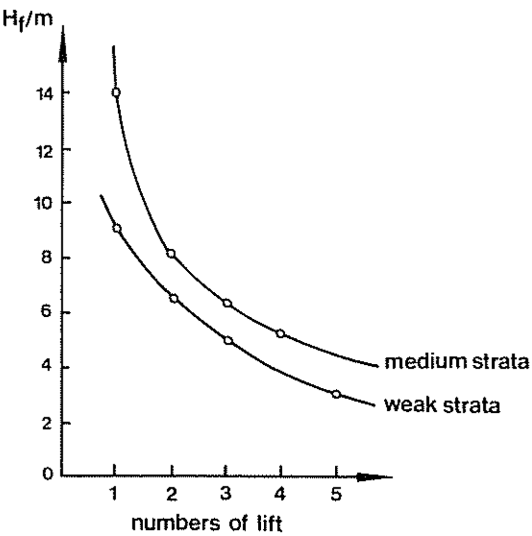


Fig. 8. Ratio of the height of fractured zone to seam thickness against numbers of lift.

The immediate roof consists of medium- to fine-grained sandstone 18 m in thickness with an underlying interbedded sandstone and shale unit of 17 m thickness. The region is overlain by Tertiary and Quarternary alluvium to a thickness of 260 m. The unconsolidated materials comprise clay, sandy clay and mixed sands and gravels. The gravels form the strongest aquifers with individual thicknesses exceeding 19 m in a single unit. Massive interbedded clay layers separate the aquifers, ranging in thicknesses between 70 and 130 m. Flow rates from discharge experiments within the gravel aquifers range between 0.00832 and 0.126 l/s/m corresponding to hydraulic conductivities ranging between 0.0974 and 0.874 m/day. The gravels

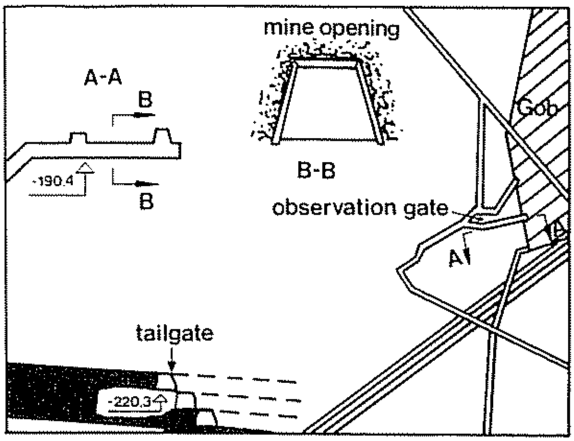


Fig. 9. Layout of observation gate in Xingtai coal mine.

are therefore identified as poor aquifers with no significant hydraulic connection between the Quaternary and Tertiary strata being identified.

In-situ measurements

Measurements were made within a longwall face with a mining width varying between 110 and 170 m and a total length of 460 m. Difficulties encountered in drilling from the surface precluded the use of surface connection for the testing suite. This problem was circumvented by drilling downwards from specially designed underground roadways close to the working face. The special roadway was situated within roof strata overlying the tailgate of the face. The vertical separation between the end of the roadway and the tailgate was 28 m, as illustrated in Fig. 9. This separation was sufficiently close to give ready access to the overlying strata but sufficiently distant to ensure the stability of the roadway once mining was underway.

Observations were conducted independently for each of the lifts. The radiating format of the test holes fanning from the roadway is illustrated in Fig. 10. The progressive development of caving heights is illustrated as a function of seam thickness in Fig. 11.

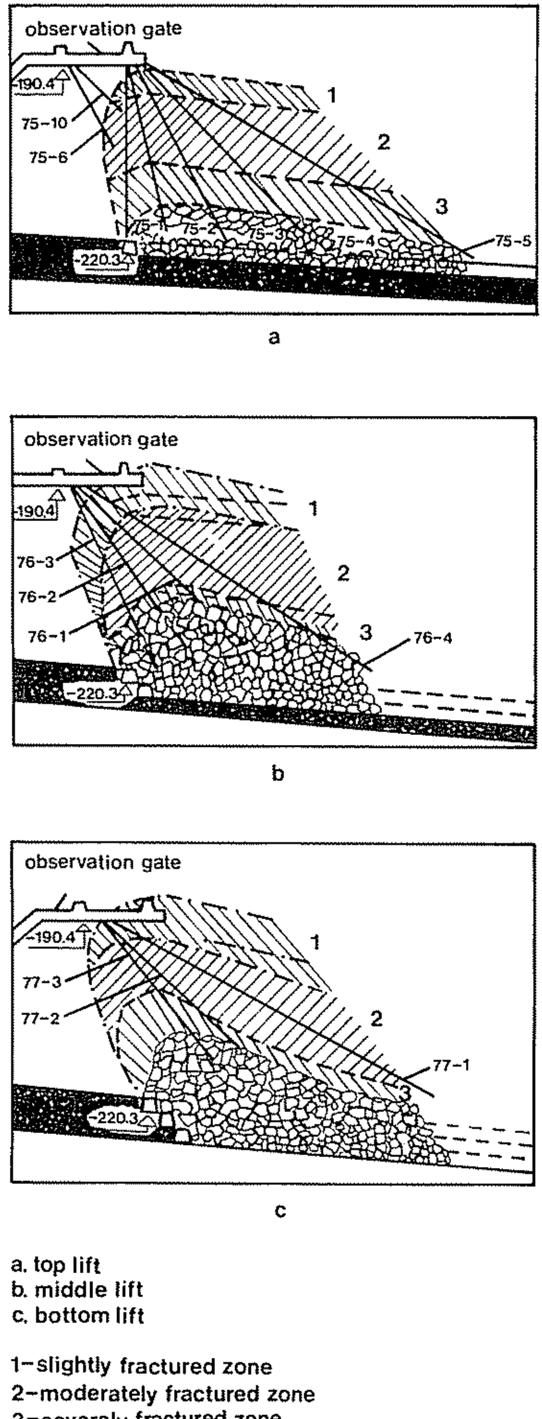


Fig. 10. Boreholes drilled from a special gate road to measure the extent of strata failure. 75–10 = drilling date.

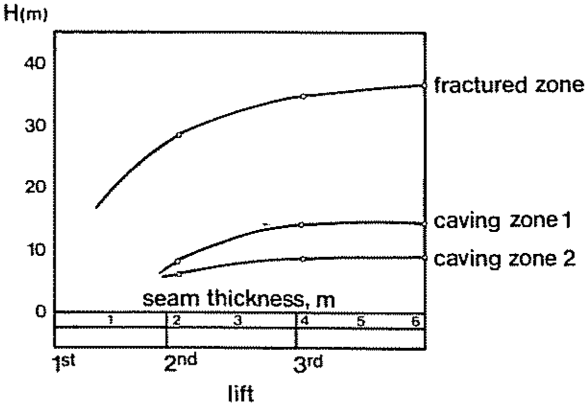


Fig. 11. Height of strata failure against seam thickness in Xingtai coal mine.

Suggested technical measures for sub-aquifer mining

When mining close to overlying aquifers the minimum overburden height that may safely be acceptable may be calculated by applying a suitable factor of safety to the height of the fracture zone calculated from the formulae given previously. Clearly, this height will vary with the lithological type of the surrounding strata but may be characterized for any given region based on some precedent. The broad variability of the coefficients regulating failure height determined within the previous case studies indicates the sensitivity to specific on-site behavior. However, some guidelines may be obtained from examining the worst-case scenarios predicted from the previous equations.

It is most desirable to mine without the added expense of strata dewatering. This is only possible if there is assurance that the fracture zone will not penetrate upwards into the overlying aquifers. It may be necessary to limit penetration below the aquifer if the unit either provides a substantial water resource to surrounding communities or if substantial hazard in mining would ensue. If the major aquifers are present high up within the sedimentary sequence, partial dewatering may be possible to reduce pressures prior to mining.

Grouting may be used as a method to lessen the consequences of penetrating water-bearing strata. Although capable of greatly reducing water inflows, grouts are equally as susceptible as the surrounding rock media to sustaining large permeability increases as a function of ground deformations. The effectiveness of grouting measures must therefore be monitored over time to ensure that no deterioration of the seal occurs.

The mining sequence may be modified to minimize the water hazard. Lift mining offers the substantial benefit of reducing water inflows by minimizing total heights of the fracture zone resulting from extraction. It appears from the empirical results that reducing the thickness of extraction within the first or second lifts is extremely beneficial in minimizing water incursion. Techniques of advance probing during the mining process are also of great value in determining the form of the water hazard prior to the main mining cycle reaching the area in question. The form and magnitude of the potential hazard can be diagnosed early and appropriate remedial measures taken or mining diverted into less fractured areas of strata.

Conclusions

Since considerable danger is involved in mining beneath aquifers, methods devised to determine the reliability of mined structures are of crucial importance. The results presented for the two case studies in China may be of considerable use in determining the potential hazard under similar mining conditions in other parts of the world. A prerequisite in determining the magnitude of the potential hazard is to delineate the sources of the water as controlled by the existing geological and hydrological conditions in the area. Accurate prediction of the effects of mining based on earlier results is crucial to the success of any operation. This prediction should include knowledge of the anticipated maximum heights of fracture zones and caving zones, safe separations between the working face and aquifer bases, and the potential lateral extent of fractured and caving zones. Some data relevant to the determination of each of these parameters based on the normal measured parameters of seam thickness and the lithological nature of the surrounding strata were given in the foregoing. These data may have some applicability in the design of sub-aquifer mining operations worldwide.

Acknowledgement

Access to data provided by Professor Tianquan Liu is most gratefully acknowledged.

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