Strategies to assess the hazards presented by abandoned room and pillar mines

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Abstract Abandoned mines present problems of surface instability which form a major handicap to the development of areas underlain by them. In theory the stability of pillars and roofs of the mine openings can be calculated providing the parameters describing rock mass strength and structure are available. In practice, flooding and collapse make it impossible to obtain the data necessary for analysis and even if access is possible certain necessary information is almost always unobtainable. In consequence reliance is mostly placed on "rule of thumb" experience. The author argues for the institution of an internationally organized experience database which might lead to the quantification of hazard via a form of rock mass classification.

THE PROBLEM

Early mines were mostly located outside the towns in which the miners lived. The mining methods used in such mining were often variants of room and pillar techniques and left openings abandoned on withdrawal from the mine. Subsequently town limits expanded over these mines which, in time, collapsed. The time between abandonment and collapse may be of the order of hundreds of years so that generations of structures may function in apparent safety before collapse occurs.

Instability of the mine roof brings about local collapses of limited extent by migration of the mining void to surface, while if one pillar collapses this may, by a domino effect, cause other pillars to fail and result in a more widespread subsidence (Fig. 1). If support platforms to partially infilled shafts fail surface soil may flow into the shaft. The stability of any mine opening depends on the location of the water table and the degree of saturation of overlying strata; groundwater movements and rainfall contribute significantly to mine stability.

THEORY

To determine the stability of an abandoned mine it is necessary to calculate the stability of the mine roofs between pillars and of the pillars themselves. It seems to be generally accepted that the strength of the mine roof depends, in the most simple case, on the thickness of the roof beam of rock, the elasticity of the rock and the tensile strength of the beam rock. Equations presented by Obert & Duvall (1967) are given in Fig. 2 to illustrate the data required to solve these equations. Stability of the roof also depends upon the horizontal stresses acting.
Many different formulae exist to calculate pillar strength; most are of the form indicated in Fig. 2 and include pillar dimensions and rock strength as their measurable parameters. While the stresses that may bring about roof failure are, in theory, due to the self weight of the roof beam, those that bring about pillar crushing come from the weight of the strata supported by the pillar. Stresses on the pillar may be conveniently, but only approximately, calculated by the tributary area method, assuming that the distribution of the strata above and the unit weights of the various strata types are known.
Most modern pillar strength formulae have been devised to aid design of mine pillars to give the most profitable extraction. Any uncertainties regarding strata load and pillar strength may be accommodated by increased safety factors and thence modified by experience. In the same way gallery span may be calculated and modified by experience as mining progresses, so that eventually a uniform logical mine design is achieved. In the case of the long abandoned ancient mine, mine design, if ever undertaken, was based on experience alone. Mining may have been intermittent so that the mine layout was not uniform.

The roof

Roof collapse leads to upward void migration (Fig. 1) to some limiting height determined by rock mass characteristics. The main characteristics are the thicknesses of beds which will serve as beams (Fig. 2), their strength and, not shown in Fig. 2, the frequency, orientation and strength of any joints traversing the beds. It may be assumed that the miners had, by experience, determined the span dimensions for a reasonably safe tunnel for their particular conditions. This span may have been increased by pillar robbing on withdrawal from the mine but later roof collapse has been caused by agencies acting through time to weaken the roof beam. Once the initial failure has taken place this may be repeated with successive beams until either a stratum of high mass strength is encountered or the fallen material, occupying a greater volume fallen than in situ, bulks sufficiently to support the roof. It is essential for surface construction to estimate how far the mining void may rise above the workings. This will depend upon mine height and span, local rock mass characteristics and the bulking properties of the roof rock. It is generally considered that migration up to 3 to 5 times the height of the mining void is usual (Bell, 1988) but may extend far above this in particular circumstances.

In bedded and jointed relatively strong rocks it is usually assumed that roof collapse is mostly related to the properties of the roof rock mass. However, Bekendam & Price (1993), observing the collapse of mines in the more-or-less unjointed calcarenites of the Maastrichtian of The Netherlands, noted that roof collapse was sometimes associated with the stress cracks, developed in the pillars, passing upwards into the roof beam.

Pillars

At the time of abandonment the mine pillars are sufficiently strong to support the load of the overburden, but may thence then deteriorate and weaken until they fail. Bekendam & Price (1993) in their specific study, attributed decay in calcarenite pillars to creep; other authors reviewing the topic, such as Bell (1988), recognize that pillar strength deterioration may have many causes.

The factor of safety of a system of pillars in a mine will depend upon the contrast between strength of the pillars and the stresses upon them, which must be calculated to make this comparison. Most pillar design formulae assume rectangular pillars; many very old mines show pillars of very irregular form, to which the mine design formulae have limited applicability. A formula for irregular pillars has been produced by Bekendam & Price (1993) but this may not be appropriate for jointed rocks. In the West Midlands of England it has been observed (Anon, 1983) that mining voids in the Upper
Wenlock Limestone may migrate upward into the overlying weaker Ludlow Shales, which then form the pillars which, being weaker, may crush under the overburden load.

LIMITATIONS

Abandoned mines, particularly coal mines, are often flooded and cannot be entered. Roof collapse, or a general collapse due to pillar crushing, may also prohibit entry to every part of the mine. As a consequence of this it is commonly not possible to obtain data on mine dimensions, which are essential parameters to both roof and pillar stability formulae. In some cases it may be possible to assess horizontal dimensions from old mine plans, but these, if they exist, are seldom sufficiently accurate for stability calculations, and very seldom include any indications of pillar height. They usually also lack indications of the depth of the workings below surface and the inclination of the mine floor.

For certain mines, particularly coal mines, geological studies aided by boreholes may establish the depth and orientation of the seam within which the mine is to be found, but for other mines, such as those in chalk, the mined horizon is not easily distinguished and, in any case, the mine may not be confined to a single stratigraphic layer. In the latter case it is exceedingly difficult to determine the location of the mine by any means other than directly encountering it via a shaft, pit or borehole. It is not often possible to enter a mine to produce a detailed plan showing all the dimensions necessary for calculation. It is equally difficult to obtain the geological data required, particularly regarding roof conditions. Most investigations are undertaken in mines, already in a distressed condition, to assess their collapse potential; extracting rock samples for testing from sagging mine roofs and deteriorating mine pillars is not a pastime to be recommended to the reader.

Thus, while the theory to determine stability is, to a certain degree, available, the necessary data is seldom present.

STRATEGY

While research into mining and rock mass mechanics must continue to find ways to calculate the stability of abandoned room and pillar mines, much is to be gained from the assembly and analysis of experience. Subsidence from the collapse of old mines and their associated shafts threatens the property and the life of the citizen, who has at least the moral, if not the legal, right to be informed of these hazards. Accordingly the citizen dwelling in areas affected by this problem must be made aware that it exists, where it is to be found and the hazards it poses. To do this catalogues of mine locations and explanations of the hazards they present, written for the non-specialist, should be published.

The development of awareness

The first stage in developing a strategy to deal with the problems presented by abandoned mines is to define and describe these problems in the particular areas in
which they are found. Such a description (Anon, 1993) has been produced with regard to the subsidence problems faced by the city of Norwich in Norfolk, Great Britain.

Norwich, a city of some 125 000 inhabitants, lies in the valley of the River Wensum. Upper Cretaceous chalk is exposed in the lower valley sides which are capped by Pleistocene and younger deposits. Open pit and underground mines have won chalk and flint, the former being used as source for lime and the latter as construction stone. Mining may have begun as long ago as the Neolithic and was certainly well established in the thirteenth century. The last mine closed in 1945. The mine galleries were of the order of 2 to 3 m wide and typically 2 to 2.5 m high, although more recent workings range up to 6 m high. In profile some are horseshoe shaped and others have a flat roof connecting at a sharp angle to vertical or steeply outwardly inclined side walls. Such plans of the workings as exist indicate that the galleries were excavated parallel to the shallow dip and strike of the beds, giving right-angled intersections which occasionally formed pillars although it appears that no regular room and pillar mining system was developed. The chalk/overburden surface is marked by infilled solution pipes which may have been encountered in the workings. The mines contain some inscriptions suggesting their age and there are many descriptions of the tunnels in the literature, such as those by Woodward (1831) and Atkins (1983). These descriptions are of historical interest but contain little information regarding the mining methods used and the reasons for the selection of mine locations.

There have been numerous subsidences, mostly as the result of void migration following roof collapse, causing building damage and, in one case, two fatalities. Norwich has, of course, other examples of subsidence damage resulting from other causes and the report "Subsidence in Norwich" deals with these as well as those resulting from past mining. While the most severe subsidence events are associated with past mining, the number of these events is relatively small in comparison with those connected with other causes such as leaking pipes, sewer collapse and solution features in the Chalk. The report is intended to make developers, planners and the general public aware of the subsidence problems in Norwich so that future works may be undertaken with proper regard to such potential hazards.

The description and correlation of experience

National mining agencies usually have a duty to inspect accessible mines and they, and local authorities, have the duty to describe and catalogue subsidence events. To gain from the experience of others it is necessary to establish the basic parameters which are necessary to describe the situation, with the hope of perhaps being able eventually to devise techniques of stability analysis similar to those incorporated in the rock mass classifications developed for tunnel design (Bieniawski, 1989). The rock mass classification approach has been used in one case, that of the calcarenite mines in South Limburg, The Netherlands, where "stand-up times" to collapse calculated using a rock mass classification system showed a quite good correlation with the recorded ages of collapsed mines (Hack & Price, 1990).

The parameters to be included in such a system would include the following:

(a) **Mine geometry**
Dimensions of rooms and pillars, height of pillars, elevations and slopes of floor and roof;
(b) **Collapse geometry** Dimensions of collapse features relative to the mine geometry and the landscape;

(c) **Rock mass** Thickness of beds, rock types, strength of the rock types, joint characteristics spacing and orientation, mass and material weathering;

(d) **Soil overburden** Types, grading and strengths of soils involved in the collapse characteristics;

(e) **Groundwater** Mine flooded or dry, position of the water table;

(f) **Age of the mine** The dates of opening and abandonment of the mine and any indications of mine progress;

(g) **Collapse event details** Associations with heavy rainfall, blasting, earthquakes etc.

It is unlikely that accurate values for the data mentioned above could be provided for every site with collapse problems, but some estimates could be given. Thus mine geometry could be perhaps assessed from a combination of seam thickness and knowledge of mining practice at the time of mining, while geological details could be estimated from nearby boreholes or exposures. At present accounts of collapses at one location usually lack some element of data vital to the use of this experience at some other site. The systematic collection of data including the parameters (a) to (g) would provide a data base which, when manipulated, might lead to empirical assessment of collapse hazard. The rock mass classification systems for tunnel design successfully applied today are empirical, based on much information. To develop a similar system appropriate to subsidence problems arising from collapsing room and pillar mines would require much data, derived from experiences in many different geological and mining situations. The collection of such an extensive data base requires co-operation at international rather than regional or national level. Within Europe such an endeavour could be sponsored by the European Union.

**REFERENCES**


