Ground movements over the coal mines of southern Limburg, The Netherlands, and their relation to rising mine waters

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Abstract In southern Limburg coal mining has been undertaken for more than 500 years at depths ranging from 0 to more than 800 m. Extensive subsidence, locally exceeding 10 m, resulted in considerable damage. This damage was generally caused by longwall mining at deeper mining levels and can be referred to as sag or through subsidence. After the abandonment of the mines in the 1970s most mine water pumps were switched off and the deeper mines became flooded. Due to the rising mine waters a small vertical lift occurred at the surface of up to 25 cm, which did not bring about additional damage. At the beginning of 1994 pumping ceased completely and the mine waters will reach the shallow mines in the near future. The presence of water in the shallow mines, which are still open, and its overburden will adversely affect the stability of roof, pillars and shafts. This may result in the formation of sinkholes or subsidence troughs threatening structures at the surface. Also the water-supply might be impeded. This article gives an overview of the consequences of the mining activities which arose in the past and deals with the effects of flooding of the shallow mines and eventual saturation of its overburden which can be expected in the future.

INTRODUCTION

In southern Limburg the first mining was undertaken more than 500 years ago in the southeastern part where coal fields had been discovered close beneath the topographical surface. In the shallow seams, which generally dip about 10 to 30° towards the south-east, the long pillar mining system (in German: Langkammerpfeilerbau) was applied. This resulted in an underground pattern of alternating galleries and pillars of a few hundred metres length, orientated parallel to the strike of the seam and interconnected locally by transverse galleries. The mine workings are considered to be still open.

During the beginning of the twentieth century there was a change over to longwall mining. In the course of time coal was mined down to depths of more than 800 m. Pneumatic stowing of panels occurred when unacceptable damage at the surface was expected. The discovery of the enormous natural gas resources in the 1960s marked the end of coal production. In 1974 the last mine was closed. The total coal production, of the 12 mines within the south Limburg coal fields altogether, from the beginning of this century till 1975 measured 600 * 10^6 tonnes.

The mining of coal brought about a range of ground movements. The longwall mining resulted in extensive subsidence, causing substantial damage at surface structures. After abandonment of the mines the mine water economy was terminated for the greater part. The deeper mines became flooded, which induced a small uplift at the surface. Since the pumping of mine water has ceased now completely the shallow mines will be flooded as well in the near future. Considering subsurface stability the water will have a negative effect not only on the behaviour of the rock masses in the direct vicinity of the still open mine workings, but also on the behaviour of the overlying rock and soil units and eventual support structures. The formation of sinkholes might be the result.

SUBSIDENCE DUE TO LONGWALL MINING

The deformation of the rock mass overlying a mined longwall panel is illustrated in Fig. 1. According to Kratzsch (1983) the overburden can be divided into four zones on the basis of characteristic deformation behaviour. These zones are, from bottom to top:

- the immediate roof layer, which separates from the rock mass above and collapses either on top of the stowing material or, if no stowing has been applied, on the floor filling the mine opening with rock debris
- the main roof, which deflect downwards gradually over the underlying disintegrated rock mass, resulting in movements along discontinuities, predominantly near-vertical joints;
- the intermediate zone, which deflects downwards more or less elastically with only minor movements along some bedding planes;
- the surface zone, consisting of soil which behaves plastically. This zone deflects gradually over the solid bedrock resulting in a subsidence trough at the surface.

The extent of a subsidence area is determined by the angle of draw, which is about 45° for the coal fields of south Limburg. The maximum subsidence at the surface was observed to be nearly equal to the seam thickness. Pneumatic stowing proved to reduce the surface subsidence with about 50%. The subsidence at an arbitrary point is calculated according to the empirical integration-grid method (see e.g. Kratzsch, 1983). For south Limburg the integration grid consists of five concentric rings and is radially subdivided into eight sectors. The radius of the outer ring is equal to the seam depth. The contribution to subsidence within the concentric rings is respectively 40, 28, 16, 12 and 4% of the seam thickness.

The subsidence measured locally more than 10 m and brought about considerable damage in one of the most densely populated areas of The Netherlands. Most damage was the result of the dynamic character of the mining process, i.e. the daily advance of the coal face. Figure 2 shows the subsidence due to coal mining in south Limburg.

UPLIFT DUE TO RISING MINE WATER

The mines of southern Limburg were abandoned in phases and mine water pumps were switched off one by one. To protect the still operating mines against flooding dams were built at various locations which resulted in a repartition of the coal fields into a series

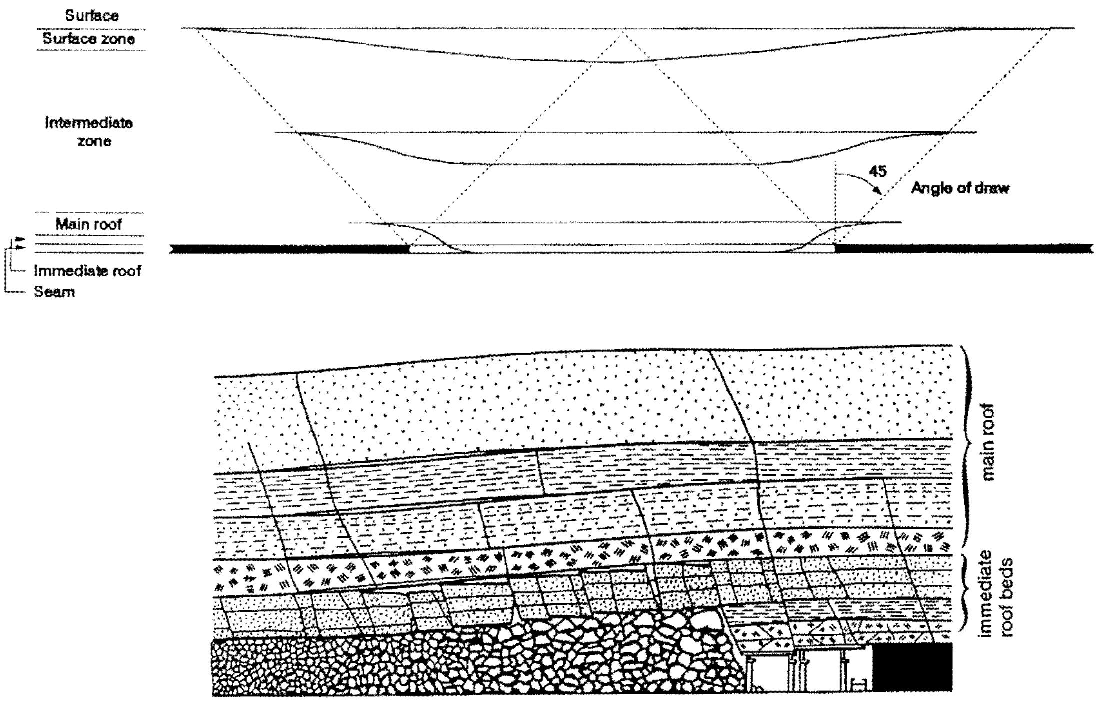

Fig. 1 Zones of deformation over an undermined rock mass, critical case (after Kratzsch, 1983).

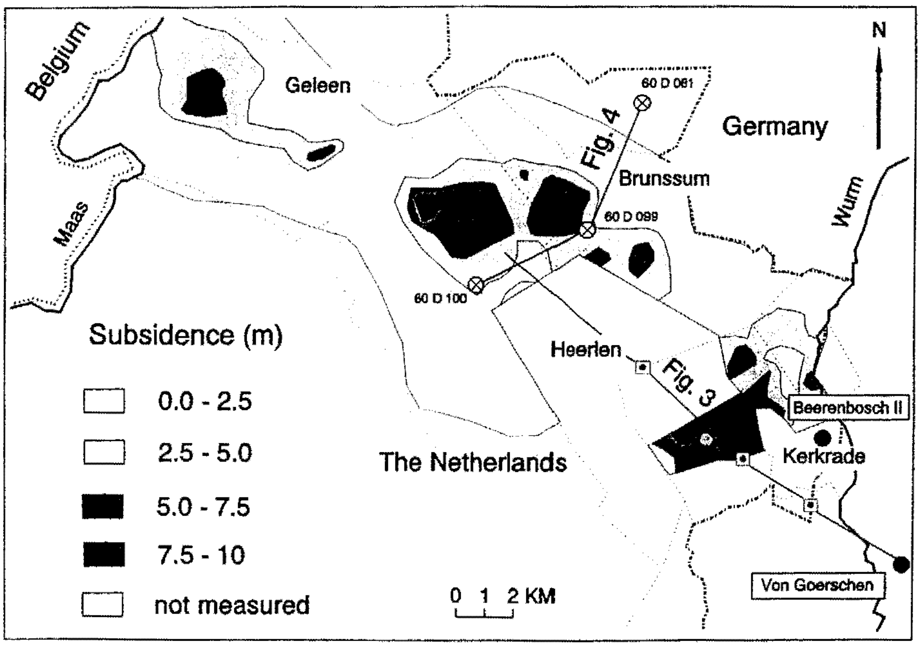

Fig. 2 Map of the coal mining area of southern Limburg showing the amount of surface subsidence.

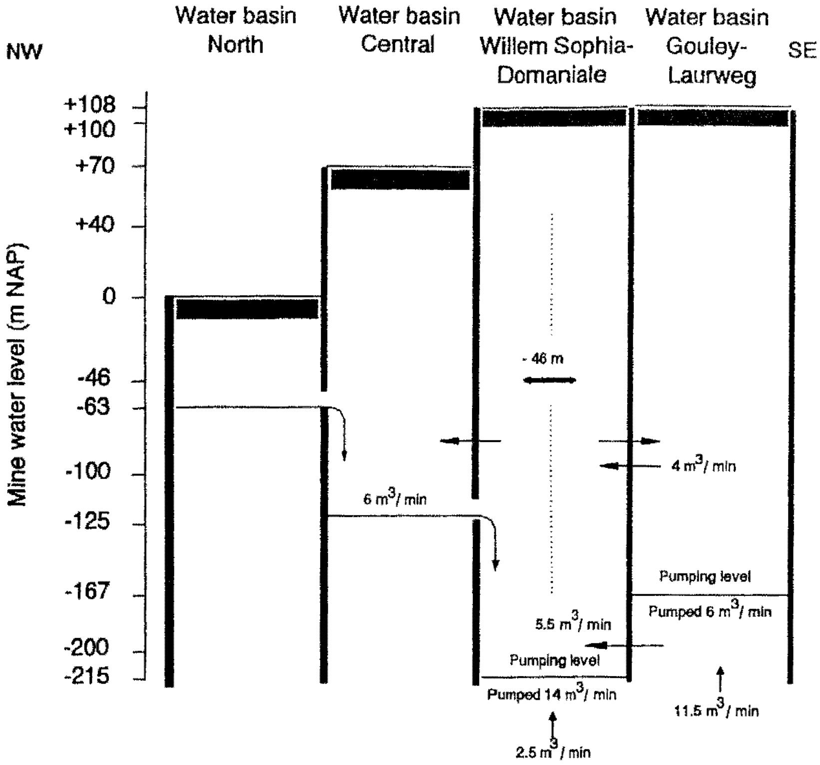

Fig. 3 Profile of the mine water basins showing overflow levels and discharges. The section is indicated in Fig. 2.

of separate basins. The mines out of production became flooded up to a series of overflow levels. The mine water economy is explained in Fig. 3. In the western basins the mine water rose to −61 m NAP. An overflow at −63 m NAP connects the western basins with the central basin, where the mine water reached a level of −125 m NAP. The water in this basin flows over at −138 m NAP into the basin of the Willem-Sophia Domaniale, which is also in hydraulic connection with the German Gouley-Laurweg basin. Till the beginning of 1994 the neighbouring mines Anna and Emil Mayrisch near Aachen, just across the Dutch-German border, were still in operation. To protect these mines mine water was pumped respectively through the shaft of Beerenbosch II from −220 m NAP and through the shaft of Von Goerschen from −169 m NAP and drained off into the River Wurm.

As a result of the rising mine water the mine workings became flooded, which brought about some uplift. This uplift is explained by an increase of pore pressure in the disturbed rock over the longwall panel (Pöttgens, 1985). The zone of main roof layers contains open fractures and the zone of immediate roof layers is even disintegrated. Hence in both zones the porosity and permeability is increased considerably and this disturbed rock mass becomes prone to the ingress of mine water. The total thickness of both zones together is estimated at about four times the seam thickness. The pore pressure in the disturbed rock mass can increase up to the hydrostatic pressure if the mine water reaches the topographic surface. This pore pressure increase brings about an expansion of the zone of disturbed rock. As a consequence uplift will occur at the surface.

The surface uplift is analysed with the help of the theory of poro-elasticity, which considers a linear relation between the increase of pore water pressure and the vertical expansion of a rock mass of infinite horizontal extent:

$$\Delta h = h * D_m * \Delta p \tag{1}$$

where:
h = thickness of the zone of disturbed rock, taken as four times the seam thickness;
D_m = uniaxial dilation coefficient (bar^{-1}) of the disturbed rock mass;
Δp = increase of pore pressure (bar) within the disturbed rock mass.
The uplift at the surface is linearly dependent of Δh and thus increases linearly with the rise of the mine water level. This is in contrast with uplift related to swelling of the disturbed rock mass due to water absorption of the rock material. According to this mechanism, suggested by Oberste-Brink (1940), surface subsidence is expected to be independent of the mine water level, once the zone of disturbed rock has been completely flooded. The field data will demonstrate that the latter mechanism is of minor importance.

In order to determine the uplift at the surface the theory of subsidence due to reservoir compaction of Geertsma (1973) is applied. The application of this theory, based on the concept of strain nuclei, involves the assignment of linear elastic properties to both disturbed rock mass and surrounding rock and soil. Additionally the elastic constants inside and outside the disturbed rock mass are assumed to be identical, which is probably not correct but justifiable for a rough estimation of the surface uplift.

The surface uplift over the centre of a circular zone of disturbed rock of radius R and thickness h at a depth c, where $C = c/R$, is equal to:

$$u_z(0,0) = 2(1-\nu)\left(1 - \frac{C}{\sqrt{(1+C^2)}}\right) * D_m * h * \Delta p \tag{2}$$

where ν is Poisson's ratio. The value of D_m has been determined indirectly, by relating the measured surface uplift near shafts with the mine water level. A rough estimation of D_m is 0.35 bar^{-1}. This value proved to apply more or less for the whole area, despite the varying composition of the overburden.

It has to be noted that the ratio of uplift due to rising mine water and subsidence developed before is not constant. Uplift and subsidence are affected in a different way by a change in depth and horizontal extent of a mined seam. Moreover, uplift increases at a mine water rise. If we consider the critical case ($C = 1$ at an angle of draw of 45°) the surface subsidence over the middle of the mined area is approximately equal to the seam thickness if no stowing has occurred. Equation (2) shows that in this case the surface uplift is only 29% of the surface uplift over a mined area of infinite horizontal extent. It can be determined that, if the mine water has reached the surface and assuming $D_m = 0.35 * 10^{-3}$ bar^{-1} and $\nu = 0.25$, the surface uplift over a panel of critical width and at 500 m depth is about 3% of the surface subsidence.

In the profile of Fig. 4 are depicted the surface subsidence resulting from mining from 1915 to 1974, the surface uplift from 1974 to 1984 and the mined coal seams. The thickness and depth of the coal seams at levelling point 60D099 are shown in Fig. 5.

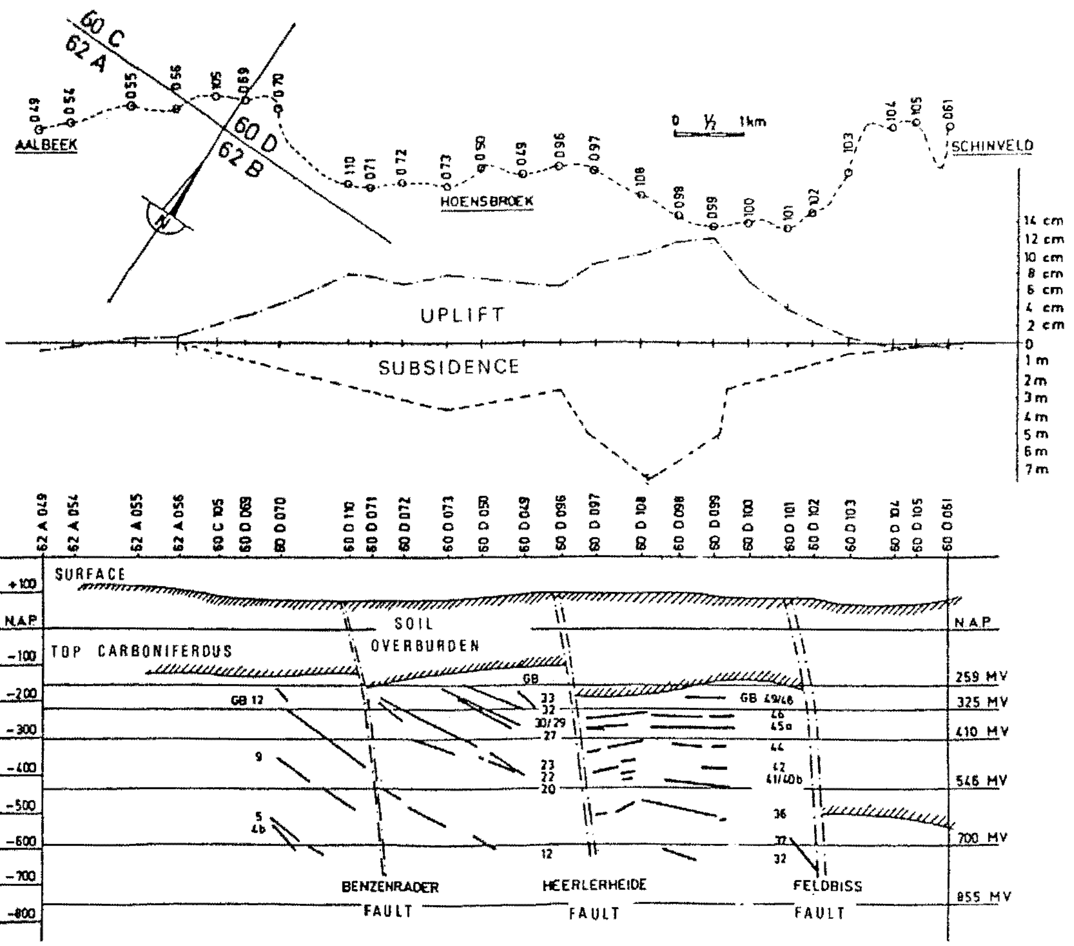

Fig. 4 The section Aalbeek-Hoensbroek-Schinveld showing the measured subsidence and uplift due to coal mining. The section is indicated in Fig. 2.

Obviously a rough correlation exists between surface subsidence and uplift but the uplift/subsidence ratio is varying considerably from point to point. The point of maximum subsidence, point 60D108, does not coincide with the point of maximum uplift, which is point 60D099. However, it should be noted that subsidence has been measured less accurately because at that time less levelling points were available. Generally the uplift is 2 to 4% of the subsidence. Detailed profiles have shown that faults and locations of maximum horizontal extension are accompanied by a sudden "subsidence step" of up to 0.5 m at the surface. Irregularities of surface uplift have not been measured up to now and are not to be expected if the theory of uplift mentioned before is assumed.

The uplift in the course of time of point D099 is shown in Fig. 5. The theoretical results are in good agreement with the measured data. A mine water rise is immediately followed by a surface uplift. In 1990 the mine water reached the overflow level at −63 m NAP. The mine water level did not rise any more and no further uplift has developed accordingly. But, since the pumps have been switched off in the beginning

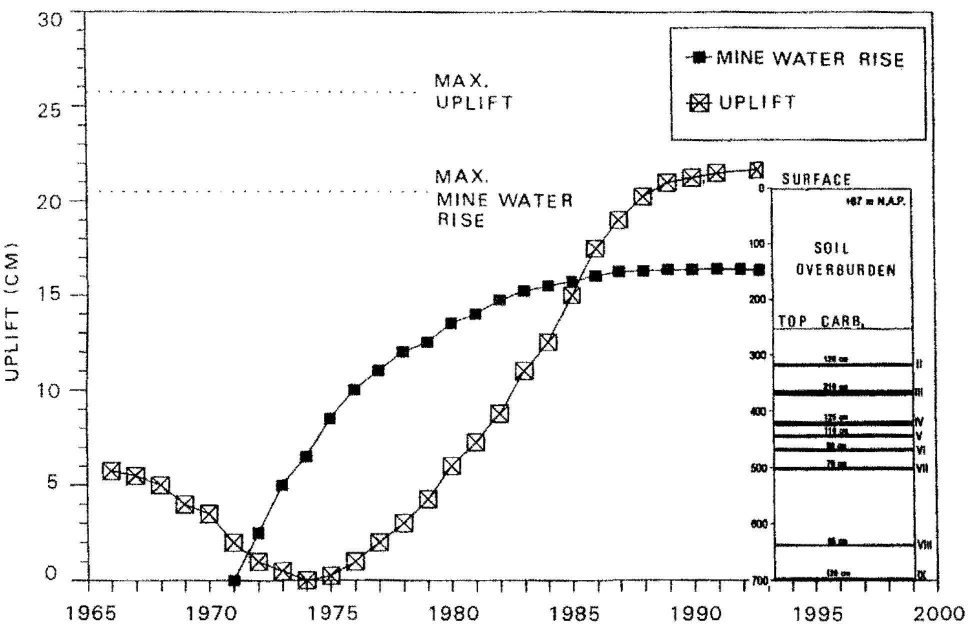

Fig. 5 Mine water level and uplift as a function of time at levelling point of 60D099.

of 1994, the mine water will rise again in the near future and uplift will attain a final value of about 26 cm.

RISK OF SINKHOLE DEVELOPMENT DUE TO RISING MINE WATERS

When pumping through the shafts of Beerenbosch II and Von Goerschen was stopped in the beginning of 1994 the mine water started to rise. In January 1995 levels of −75.85 and −69.45 m NAP were reached in the Willem Sophia-Domaniale and Gouley-Laurweg basins respectively (Fig. 6). The mine water level reached the −125 m NAP level in the spring of 1994. Hence also the level in the central basin has started to rise (Fig. 3). The mine water is expected to reach the overflow level of the northern basins at −63 m NAP in the summer of 1995.

The rise of mine water towards the surface will bring about a risk of sinkhole development in the southeastern concession areas of the Domaniale-Neu Prick and Gouley-Laurweg, situated in the Dutch-German borderland. As mentioned before, coal was to be found here close to the surface and the heritage of former coal mining comprises many shallow, still open long pillar mines and shafts often not adequately filled and plugged.

Although the water will give some support pressure inside the galleries all in all the presence of water in the shallow mines and its overburden will reduce the stability of roof and pillars. Especially roof collapses at gallery intersections might occur. For example effective stresses inside the rock mass will decrease, and cohesion and angle of friction, both internal and in discontinuities, will diminish. As a consequence the failure envelope and Mohr circle will shift towards each other, increasing the probability

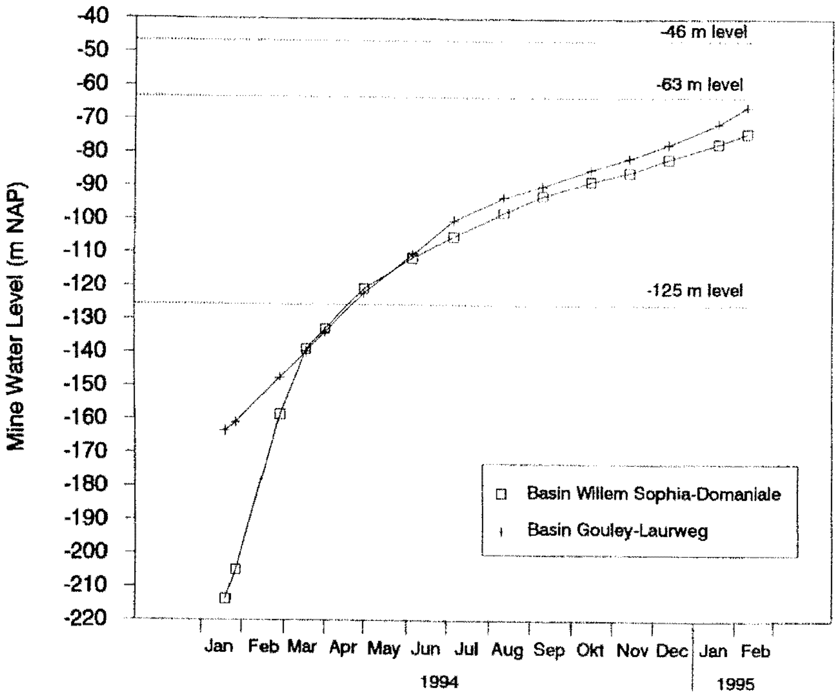

Fig. 6 Graph depicting the mine water rise in the basins of Willem Sophia-Domaniale and Gouley-Laurweg.

of failure. It is known that the presence of water brings about a reduction of unconfined compressive strength for all types of rock. This loss of strength varies significantly per rock type and can amount to 78% for certain sandstones (Hawkins & McConnell, 1992). Furthermore, saturation of the soil overburden brings about an increase of vertical stress at depth resulting in less stable roof conditions.

A roof collapse might result in sinkhole development at the surface if the cavity resulting from the collapse reaches the rock-soil interface. Whether this occurs or not depends on the dimensions and shape of the roof collapse, the height of the gallery, the distance between the gallery roof and the top of the solid rock, and the scree angle and bulking factor of the roof debris. Important contributions in this field have been established amongst others by Fenk (1981), Garrard & Taylor (1988) and Meier (1988). Water entered into the mine may reduce the scree angle of the debris pile. In the galleries generally inclined at about 10 to 30° the debris may even be washed away. Consequently more roof material may accumulate into the gallery and the probability of cavity migration towards the rock-soil interface might increase. Finally, it has to be noted that, if the cavity and the water level reach the soil overburden, cavity migration towards the surface and hence sinkhole formation become more likely because soil becomes less stable on saturation.

Experience acquired in the Westphalian coal fields (Hollmann & Nürenberg, 1972), similar in many aspects to the coal fields considered here, indicate that instability of a shallow mine can result in the formation of a sinkhole if the mine has been excavated within 20 m under the top of the rock-soil interface, which is in this case the boundary between the Carboniferous sandstone/shale strata and the overlying sands, gravels and clays of the Quaternary and Tertiary. Within the concession of the Domaniale this applies to more than 20 mine workings, which corresponds with a total area of more than 150 ha in a densely populated area. Up to now a few sinkholes have been formed over these mine workings. It has to be found out now how much the probability of sinkhole development might increase as a result of rising mine water.

Within the concession areas of the Domaniale-Neu Prick and Gouley-Laurweg more than 900 shafts, most of them located in Germany, are to be found. In contrast to the other concession areas, here the shallow shafts have been filled with soil and rubble and have not been provided with an adequate concrete cover. Rising mine water would reduce the friction angle of the filling material, which might flow into the open mine workings resulting in a sinkhole at the surface.

In the end of 1995 the mine water is expected to reach the open connection at −46 m between the Dutch and German coal fields. At a further rise of the water much more shafts would be flooded. At the moment the German authorities investigate if all of the about 30 shafts with a base below the −46 m level have been closed off adequately. Whether the mine water will be allowed to rise beyond the −46 m level depends on the outcome of the this study. It has become clear already in February 1995 that not all shafts are safe. During remedial works at an old shaft in a district of Kohlscheid it was discovered that the ancient filling material had, possibly due to the rising mine water, collapsed about 110 m into the 270 m deep shaft. In one day about 542 m^3 of concrete fill was applied. This shaft had collapsed earlier, in 1861, when eighteen people were killed.

Within the Dutch coal fields only one shaft, the Catharine shaft in the city of Kerkrade, has its base below the −46 m level. The base of this shaft at −98 m NAP has been reached by the mine water in the summer of 1994. The terrain over the shaft has been closed off and remedial measures are planned.

During many centuries the mine water has been drained off through canals into the River Wurm. When the mine water is allowed to rise further the old drainage canals might function again. Then the mine water will reach a final level of +108 m NAP at the beginning of the twenty-first century and a few hundred shafts, including about 35 within the Dutch coal fields, will be flooded additionally. Additional research must ascertain if such a rise can be tolerated in view of the safety at the surface.

Finally, it has to be noted that part of the water supply might be affected by the rising mine water. At a few sites water has been pumped since long from reservoirs situated in the Tertiary overburden. In 1995 the mine water will reach the base of one of the reservoirs. To detect pollution of the drinking-water salt concentrations are measured in four wells.

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