Rock engineering challenges in post-mining

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Abstract. A legacy of environmental challenges with abandoned mines remains for many generations. The challenges include among others: (i) danger from sinkholes above shallow old mine workings and (ii) effects of rising water level in deep mines. Abandoned shallow mines show after > 20 years no damaging subsidence. Sinkholes, however, may still develop by structurally controlled failure. Main contributing factors are the geometry of an underground opening. Geological factors include the resource type (orebody or seam), height of rock overburden and cohesive soil, water flow and discontinuity spacing. The latter determines the bulking factor of the displaced roof and thus the maximum caving height. For steeply inclined openings it must be considered whether the caved rock moves down the dip and prevents self-stabilization. Rising water levels in deep abandoned mines may induce seismic events. Despite significant progress in monitoring and numerical methods there is still no appropriate geological or rock mechanical basis for explaining or predicting water pressure induced seismic events. Some research topics are suggested to approach this issue.

1. Introduction
The typical life-cycle phases of an underground mine encompass exploration and discovery – feasibility and construction – mining and extraction – closure and site rehabilitation. While mining is accepted in broad terms – if you cannot grow it, you have to mine it – it is often challenged on the individual mining project level. During mining, there is added value due to jobs, manufacturing and often prosperity. The negative impact on the environment was countered by improved environmental standards and the slow acceptance of sustainability as well as improvement of miner’s health and safety led to an increased social license to mining operations. The regulation about ownership of minerals is important for all mining phases. The first mining law originated in 1185, which stated that minerals were at the king’s disposal, later that right was transferred to the nobility. Two different views of ownership developed then. In German-speaking countries, the owner of land owns only the surface minerals. In English speaking countries the owner of the land owns the minerals to indefinite depth. Some exemptions to those rules for strategic minerals are still in order. Particularly coal mining in the Ruhr area led to the first mining law in 1865 by the Prussians. They made the mining company responsible for damages at the third party property and pay compensation had to be executed. Different institutions such as arbitration boards and finally mining authorities developed over time. Any younger legislation in Germany followed this Prussian mining law. In essence, mining companies are liable for loss or injury of men as well as property damage due to mining and abandoned mines, and accruals must be established.
In this context, abandoned mines involve all underground openings where mining activities ceased. Any dangers from abandoned mines must be evaluated by suggested procedures. According to various regulative laws, dangers are derived from construction laws (impact of old mines on the surface), water act (alteration of a water body) and general police and public order law (elimination of concrete dangers to the common goods, i.e., life and property). A good overview of the issues, methods, and measures to be taken is provided by the ISRM mine closure commission [1]. The first step is to distinguish between effects from active mines and those from abandoned mines, which leads to the question when the effects of active mining cease. It is believed for coal or ore mining that the surface movements cease after 20 years at most. For room-and-pillar mining the time span will be much shorter than for longwall mining, where the compaction of the gob takes some time. Figure 1 shows the subsidence from coal mining in the Ruhr area. No significant further singular movements of the surface are to be expected as the last coal mine closed in 2018. However, the rise of the water level when mine dewatering stops will lead to a rise of the surface. Experience from other coal fields suggests that the rise is about 2% - 5% of mined coal thickness. This will involve numerous engineering projects for infrastructure in an area inhabited by 5 million people. Fortunately, damaging differential displacements are typically associated with NW-SE striking faults only.

![Figure 1. Subsidence from coal mining in the Ruhr mining district (modified after [2]).](image)

While subsidence is no cause for concern anymore there exists the risk of collapse-like failure above shallow abandoned mines. German mining authorities distinguish between risks from deep (> 100 m), shallow (100 – 30 m) and near-daylight (<30 m) abandoned mines. Deep mines produce subsidence and shallow / near-daylight mines may lead to collapse-like failure or sinkholes. In North Rhine-Westphalia alone are 60,000 abandoned shallow mine openings and an area of 600 km² may be endangered. Aside from this known number there are historic mines and “wild mining” without any documentation. Clearly, risk management in the post mining era - be it the assessment of collapse-like failure or the effects of rise of mine water – is a formidable task for mining engineers, geologists, and rock engineers. Figure 2 gives an overview of the situation and tasks.

There exists a great body of rather scattered knowledge and some of the pioneers are Whittaker & Reddish [3], Betournay et al. [4], Carter [5], Potvin et al. [6], Hollmann and Nürenberg [7], to name a very few. A committee within the German Society of Geotechnics published 2020 suggested methods about geotechnical and mine survey investigations for risk assessment and remediation of abandoned mines [8]. This paper attempts to demonstrate the workflow in the risk assessment of abandoned mines with respect to sinkhole development as well mine water rise and focuses on the rock engineering challenges.
2. Workflow for risk assessment

When dealing with abandoned mines the first task is to define the location and geometry of the underground openings. Next, the mining method(s) needs to be determined, followed by geological and geotechnical information. Risk assessment involves often only the definition of the area endangered by sinkholes. If the risks are deemed too high, remediation has to be exercised. These steps involve skills from mining, geology and rock engineering.

2.1. Defining the location and geometry of abandoned mines

Particularly for historic and old mines, this is a difficult task. Due to old mining laws in Germany, there was and is the obligation to exercise mine surveys and to produce maps of the mine. This task may only be done by qualified and certified mine surveyors. Figure 3 shows the oldest mine map in North Rhine-Westphalia from 1737. It depicts a plan view and crosscut of the Dörnberg lead-zinc mine in Ramsbeck. Also shown is an extraction map of a shallow coal mine in the Ruhr mining district. There are two problems associated with those maps. The local coordinate system used back then must be georeferenced and the underground openings shown are a snapshot of that time. The standardized symbols in the mine maps must be understood as they provide a wide range of information such as the type of drifts, backfill, mining method, structural geology, rock type, to name a view. Figure 4 (left) shows a cross-section of a zinc-lead ore mine with 16 levels and ore extractions from 1874 – 1945. Together with the individual plan views (Fig.4, right) a 3D model was established (Fig 5).

2.2. Geological – rock engineering model

After establishing the geometrical model, the geology and rock engineering properties of the rock mass have to be assigned. This is particularly difficult because the mines are often not accessible. For near
daylight abandoned mines in most cases only rotary drilling without coring is available and from drill advance rates, drill thrust and observation of backflow of the drilling mud, the geology is estimated. This is only meaningful if local experience from other mines or analogous outcrops and a good drilling operator are available. With sufficient experience in the Ruhr mining district the prevailing rock types sandstone, shale and coal can be assigned. Underground mine openings can be assumed from drill fluid losses and a geological model may be developed by combining observations from drilling, mining and geological maps. Special focus has to be placed on faults. Here, the value of century long geological mapping cannot be overestimated. Often the development of knowledge stops at this point and the risk from shallow mines to the surface are assessed by empirical models, i.e., the surface areas being influenced by shallow mines are delineated from geometrical relations [7,8].

**Figure 3.** Plan view and crosscut of the Dörnberg mine from 1737 (Left, [9]) and plan coal mining map from the Ruhr area (right).

**Figure 4.** Cross-cut (left) and plan view of level 1 and 2 (right) of a lead-zinc mine.
Figure 5. 3D model for numerical analysis developed from drawings shown in Figure 4.

Recently, Clostermann et al. [10] published a comprehensive review and the development of some new geometrical relations between mine openings, seam depth and inclination, and the surface area at risk. An example of that approach is shown in Figure 6. For a given coal seam inclination and rock cover the critical extraction length has to be determined. Beyond that length the caved rock reaches the surface and no further displacements are envisioned as compaction ceased. The critical length and the angles of draw were estimated by numerical modelling using the ubiquitous joint approach. The friction angles of discontinuities have been varied between 15° for slickensides and 30° for sandstone [11]. The blue lines in Figure 6 delineate the overstressed rock mass above the mined coal seam. Depending on the depth of the mined coal seam, the surface area at risk might be substantially smaller. The bulking of the overstressed rock mass determines the final risk area. Bulking means here the increasing volume from falling rock blocks. The bulking factor k is positively correlated with the uniaxial compressive strength, the block dimensions and shape, and the falling height (flat falling or rotation).
Figure 6. Approach for delineating the surface area at risk from sinkholes over abandoned shallow coal mines [10].

The UCS of the rocks is well above 50 MPa and the typical seam height $H = 2$ m allows the rotation of falling blocks. From measurements of 1400 blocks in shale and sandstone the relations between bedding spacing, joint spacing and block volume for the coal measure rocks in the Ruhr area have been determined (Fig. 7). It should be noted that block volumes are smaller near a syncline or an anticline axis. With reference to the approach from Palchik [12], the bulking factor may be determined.

When choosing a conservative bulking factor $k = 1.25$, any void from mining in a coal seam of height $H$ is filled if the depth of rock cover is $\geq 4 H$. This bulking factor includes effects from compaction. Thus, the surface area at risk in Fig. 4 is much smaller. Here, the voids beneath that area should be filled and foundations of infrastructure have to be designed for avoiding differential settlements.

Figure 7. Relation of bedding and joint spacing and block volume for coal measure rocks in the Ruhr mining district.
While this approach works well for shallow abandoned coal mines in the Ruhr mining district there are difficulties with shallow ore and stone mines. Most ore bodies in the Rhenish Massif are associated with steeply inclined Variscan faults. They may be folded and faulted, too, as shown in Figure 8 for the Ramsbeck zinc-lead mine.

![Figure 8. Schematic geological cross-section of the Ramsbeck mine [13].](image)

Here, the mine openings need to be checked for stability of the hanging wall and crown pillar, respectively. The Ramsbeck mine provided an outstanding place to study the behavior of failed rock strata in low angle (Fig. 9) or steep (Fig. 10) orientations of the ore body. The Vousoir approach (Diederichs and Kaiser [14]) and the Scaled Span Method [5] were successfully employed for assessing stable and unstable hanging wall conditions. Additionally, the bulking factor was estimated from underground measurements with $k = 1.6$ for schist and up to $k = 2.4$ for quartzite. Most surprisingly was the fact, that even in steep mine openings (dip 60° - 70°) the fallen rock blocks got stuck and led to a stable “back-fill”. One finding was that for a solid rock cover $h \geq 3H$ the surface is not affected by shallow mining openings.

![Figure 9. Roof failure above mined flat orebody. Long scales are 2 m.](image)
Another ore mine, shown in Figure 11, provided an excellent opportunity for studying structural failure, estimating the bulking factor and calibrating numerical models. Figure 11 shows an unfavorably oriented adit which led to structurally controlled failure. Here the bulking factor was about $k = 1.7$ which translates to an unaffected surface when the solid rock cover is $h \geq 3 \, H$. In this mine, rock mass classifications were performed, strength tests on intact rock and discontinuities were executed and a numerical model calibrated. Of particular interest was the slow failure of the left side of the adit shown in Figure 12. As the mine was abandoned in 1945, an educated guess about the long-term strength of shist may be executed.
Figure 12. Numerical model of the rock fall (left) and failure of the shist in the left springline.

Many rock engineering challenges arise when the overburden height is not enough for an unaffected surface. A spectacular case is the underground basalt mines in Mendig (Rhineland-Palatia), see Figure 13. Here, millstones were mined in a high-porosity basalt using the room-and-pillar method. There are numerous shafts to access the 50 individual micro-mines, which cover an area of approximately 400,000 m². The “basalt” is in fact trachyte with an average porosity of 25%, UCS 60 MPa, and Young’s Modulus of 16 GPa. After the mid-19th century, the rooms were used as fermentation and storage of beer from the 28 local breweries. The overburden (loess and pumice) is typically 15 – 20 m, roof spans of up to 20 m, heights of up to 10 m and pillars with a width-to-height ratio of 1:5 to 1:10 are common. Rooms are often circular and supported by 3 – 4 pillars leading to local extraction ratios between 65% - 95%. The roof consists of pentagonal columns of diameter 0.4 – 0.6 m and a height of appr. 0.8 m. The pentagonal blocks are completely separated by undulating discontinuities of amplitude ~0.1 m. Some blocks are missing or moved halfway out of the roof, which is still stable. The roofs show many old support measures such as wood wedges or metal pins forced into the open joints. Many pillars show vertical – subvertical cracks, many of them are fresh. The basalt columns in the pillars show an average diameter of 1 m. Some pillars have been supported by artificial bullflex columns, others by metal sheets or chains (Fig. 15) around them to provide some lateral restraint. Even with a high bulking factor, there will be no self-stabilizing failure preventing a sinkhole, as it happened a few times. Numerous roads, homes and even a hotel are at the surface above the underground openings and a rigorous risk assessment has to be exercised. Two rock engineering tasks are predominant: evaluation of the i) roof stability and ii) pillar stability.

Roof stability may be evaluated by the Voussoir-arch or roof beam analogy. When using the approach presented by Diederichs and Kaiser [14] or Pariseau [15], the Young’s Modulus of the roof plate, consisting of pentagonal blocks, should be known – a particularly difficult task. However, the columns in the roof had originally a tight fit and the stiffness of it was estimated to be within 80% of the intact rock’s modulus. A 2D numerical model shows some possible failure mechanisms in the roof. The roof is stable over wide roof spans, but the bending decreases the contact area between the undulating joints. Local stress peaks lead to the crushing of the intact rock not only at the built-in ends. As long as the horizontal stresses in the roof sustain there should be no immediate risk of collapse. At some openings there are straight and vertical tectonic joints where slip might occur. One cause for roof collapse is probably the instability of the numerous shafts. When failing, the lateral restraint is removed and the pentagonal blocks fall, causing a complete roof collapse. Another cause for roof collapse is pillar failure. Many fresh fractures were observed in pillars but there is no rock mechanical explanation for this. The overburden is just 20 m of low-density material, the roofs are not stiff plates and from tributary area
calculations the pillars have Factors of Safety well above 5. Joints in the pillars have a friction angle of 70° and are not going through. Stress corrosion at joint tips was not observed and fracture mechanics calculations to explain fracture propagation also led to no explanation.

**Figure 13.** Map of the possible extension of shallow millstone mines in Mendig (left) and detailed risk map (right). Here, S denotes shafts, and the red or yellow shapes denote pillars with different states of risk [16].

**Figure 14.** Schematic geological profile (left) with room-and-pillar micro-mine (right) [17].
**Figure 15.** Fractured basalt pillar with bullflex support (left) and lateral support by chains and metal sheets (right).

**Figure 16.** Roof of a mine entry (left) and a pentagonal roof rock block (right).
Figure 17. High risk situation at the basalt mine with failed pillars and some support measures.

Figure 18. 2D numerical model of the room-and-pillar basalt mine (left). The fractured roof sags and leads to high stresses in the abutments and in higher parts of the joints as observed (right).

In summary, risk assessment for the shallow abandoned Mendig mines remains a difficult task with many rock engineering challenges to be tackled. For example, induced stresses from buildings are negligible at the roof level of the underground openings, but is this knowledge enough to tell the owners of surface infrastructure that their properties are safe? The mine itself poses great educational value to anybody involved in rock engineering.
3. Water in abandoned mines

After mining operations ceased it is typically attempted to flood the mines. This process is highly regulated as questions arise about contamination of groundwater, methane degassing, movements of the surface, stability of underground openings and shafts, and induced seismicity as well. In the German coal mining districts Ruhr and Saar yearly 110m$^3$ of mine water is pumped out. There exists often a basic misconception associated with the term “mine flooding”. It is not as if a plug is pulled from a gigantic bathtub at the surface and mine is flooded rather than that pumping is reduced or stopped and the water level in the underground openings and shafts rises. The peak rates in rising water levels in coal mine shafts have been measured to be between 0.4 m/d and 1.7 m/d. For the Aachen coal district peak ingress rates from meteoric water in the deep mines of up to $12 \text{l/(s km}^2\text{)}$ have been calculated by Rosner [18].

3.1. Water in shallow mines and shafts

Which risks arise when water enters a shallow abandoned mine or a shaft? If the water rises from below the gob is subjected to little pore pressure and settles. The settlement is typically compensated by the rise of the surface and no risks are foreseen. Weathering of water sensitive rocks may pose a problem in the long term. However, if the water is entering from the surface and flows through the shallow abandoned mine, then the loss of mass, particularly the fines, over time has to be anticipated. Generally, any significant flow velocity should be avoided. Disused shafts are often not secured to their entire depth. Fills secure a shaft to a depth well below the bedrock or weak strata. Above a footing with a steel plate or beams, the shafts have been filled with any available material (waste rock, demolition material). Provided the abutment is stable and the shaft lining is in a satisfactory structural condition the effect of water rising from below will lead to a settlement within the fill and a void between the top of the fill and the shaft cover will develop. Particularly unfavorable is the situation when unsealed adits are connected to the shaft’s fill. Water can access the fill through adits and remove any fines, leading to unstable shafts in the long term. In North Rhine-Westfalia all the old shafts will be secured in the future by closing the adits with dams and by the construction of a concrete plug. Several empty pipes are placed in the concrete for inspection purposes or to lower a submersible pump, if necessary. Around 2600 disused shafts have to be secured in the next decades.

3.2. Water in deep mines

A major concern with the rise of the mine water level is induced seismicity. This topic is also regulated and “mine flooding” may be exercised only when danger to life and damage to surface structures can be excluded or at least minimized. There is some experience about mine water induced seismicity from the uranium mine Schlema-Alberoda and the deep coal mine in Ensdorf. In the Schlema mine the mine water rose about 1700 m and induced numerous seismic events with $M_{L,\text{max}} = 1.8$ near faults in the granitic base rock [19]. During mining the largest seismic events were recorded in the same location with $M_{L,\text{max}} = 2.9$. In the Ensdorf coal mine the seismic events during longwall mining were associated with discontinuity orientations consistent with the Variscan faulting pattern. During double longwall mining numerous seismic events were recorded, culminating in a $M_L = 4.0$ event, which led to immediate mine closure [20]. During the rise of the water level the largest event was $M_L = 2.8$. It appears from these two examples that magnitudes during water ingress are smaller than during mining.

The basic estimates about fault stability can be gained by using the approach from Sibson [21] or the Mohr circles. Figure 19 shows Sibson’s method for the case of mine water rise in the Ruhr mining district. Here, for a mining level at depth $z = 1450$ m the in-situ stresses are $\sigma_{\text{i}(1)} = 43.2 \text{MPa} > \sigma_{\text{i}(2)} = 37.4 \text{MPa} > \sigma_{\text{i}(3)} = 20.7 \text{MPa}$, respectively, and the ratio $\sigma_1/\sigma_3 = 2$. With a planned rise of the mine water level of $600$ m ($\Delta p = 6 \text{MPa}$) the effective stress ratio will be $\sigma_{\text{eff}}/\sigma_{\text{eff}} = 2.5$. The Sibson approach suggests that in the dry case no faults with a friction angle $\phi > 20^\circ$ may fail. For the wet case faults with friction angle $\phi < 26^\circ$ over a wider orientation $\theta$ may fail.


Figure 19. Sibson’s method for the estimation of fault stability for the case of 600 m rise of mine water in the Ruhr area. The hatched area denotes the safe faults with the specified friction angles and orientations of the faults w.r.t. the major principal stress.

The use of Mohr circles for a generic case is shown in Figure 20, considering a fault with friction angle $\phi = 30^\circ$ is exposed to in situ stresses $\sigma_1 = 30$ MPa and $\sigma_3 = 15$ MPa, respectively. The fault is then stable. If the discontinuity water pressure rises to $p = 8$ MPa, then the Mohr circle of effective stresses touches the line of the shear strength criterion and faults in two specific orientations will fail. If the discontinuity water pressure rises further to $p = 12$ MPa, faults of two ranges of orientations will fail. Clearly, with rising pore pressures faults will fail in a wider range of orientations.

Figure 20. Mohr circles and discontinuity water pressure. The red lines or areas denote the orientations in which faults with a friction angle $\phi = 30^\circ$ may fail. Explanation see text.
There are at least two inherent problems with these approaches. First, the water level is usually measured in a shaft and it is unknown how the pore pressure in the rock mass or within a fault develops. Second, the term fault implies structures such as the St. Andreas fault or similar large localized relative movements. Geophysicists in particular consider a fault to be a planar, singular fracture; that a fault is a complex pattern of discontinuities with distinct extension is generally ignored. It is proposed that faults involved in natural earthquakes are not – or not often – involved in mine water induced seismicity.

How does water propagate through a mine? There are numerous underground openings. Many of them – such as shafts, main gates etc. allow free flow of water. Others like head- and tailgates may be filled with broken rock mass and may slow down water flow. The hydraulic properties of the gob vary with compaction time and finally the deformed rock mass around the extracted resource and gob will provide preferred pathways for fluid flow. In essence, it is a mixture of domains with matrix porosity near the extracted resource and with discontinuity-dominated fluid flow further away, the latter will be highly anisotropic. All the geometries of the respective domains and their hydraulic properties must be known when modelling fluid flow. Figure 21 shows several computed water heads at the largest mine-water induced seismic event at the Endsorf mine. Clearly, the choice of the conductivity model supports any argument about the mechanism of water induced seismicity, as heads between 0.3 m and 214 m may lead to a seismic event. Without a substantiated knowledge about the rock mass hydraulic conductivity around underground mining openings, the prediction of mine-water induced seismicity remains at an unsatisfactory level which does not inspire trust.

Figure 21. Measured water level in the shaft of the Ensdorf mine (left scale) and numerically evaluated heads at the focal depth of the largest seismic event (right scale).

Often poroelastic models using the Biot’s constant $\alpha$ are employed. In a Biot material elastic strains $\varepsilon$ and fluid content are linearly related to stresses $\sigma$ and excess pore pressure $p$. The theory has been successful applied to 1-D consolidation problems in granular media (soil) and for subsidence over gas.
or oil fields and it seems to work well in rather high-porosity rocks. The fluid pathways around mines are however determined by conductive discontinuities. Few practical publications exist on how to implement discontinuity dominated flow in poroelastic modelling [22]. Numerical codes are available to execute models accordingly but the geomechanical input properties remain to be educated guesses. Detournay and Cheng [23] published \( \alpha \)-constants from 0.19 – 0.85 for several intact rocks. Poroelastic modelling was used to estimate the effects of the rise of mine-water in the Ensdorf mine [24]. Figure 22 shows the geological-hydraulic model using anisotropic conductivities. In Figure 22 (right) shown are the deformations from poroelastic modelling around mined-out double longwall panels. The simulated deformations coincide well with the hypocenters, but it remains unclear which Biot constant is appropriate. Lab testing on Biot’s constant involving fractured specimen could shed some light on this issue.

![Figure 22. Geological model around a double longwall panel with anisotropic hydraulic conductivity (left). Displacements induced by pore pressure computed with various Biot constants \( \alpha \). The red dots denote the hypocenters [24].](image)

The topic of induced seismicity is widely dominated by geophysicists, but their original focus is on earthquakes in the deeper crust (> 5 km, > 100°C). A look in the standard textbook of Scholz [25] provides information about the experimental basis for earthquakes mechanics, which often is in stark contrast to rock engineering knowledge about mining-induced seismic events at depths < 3 km. Temperature effects are minimal to insignificant here. In-situ stresses are with mining lower (\( \sigma_V < 80 \) MPa) although stress concentrations might become, depending on the geometry of the mine opening, quite high. Some particularly mesmerizing approaches by geophysicists include the assumed shape of faults – typically an unfavorably oriented, straight plane in an isotropic medium – and the coefficient of friction used.

Gay and Ortlepp [26] mapped and analyzed mining-induced rock mass failure and found the “anatomy” of the shear zone shown in Figure 23. There are many discontinuities which terminate in rock and there is little resemblance with mature and natural fault systems associated with earthquakes. It seems unlikely that a straight fault yields enough seismic energy when subjected to slowly increasing fluid pressure. This would only happen when the “rupture” area is large as well as the shear displacement is high; the latter was never observed in underground mines. However, when the rock bridges between the intermittent discontinuities are overstressed, then brittle failure with a corresponding significant stress drop may occur.
Figure 23. Mapped seismogenic mining-induced shear zones [26].

A sketch adapted from Spottiswood et al. [27] may explain this approach (Fig. 24). Large amounts of seismic energy $E_M$ may be expected when intact rock under stress experiences elevated pore pressure and fails in a brittle manner. If the rock contains intermittent joints (cf. Fig. 23) the radiated energy from pore pressure induced failure will be less as fewer intact rock bridges have to be destroyed. Furthermore, a shallow fault will produce even less energy when failing by pore pressure.

Figure 24. Sketch of water-induced failure of intact rock, intermittent joints and a fault associated seismic energy $E_M$. Adapted from [27].

This approach about mechanisms of induced seismicity is supported by maps of epicenters from events in coal mines with increasing water levels. For the Ensdorf mine (Fig. 25) there are two clusters of seismic events, one associated with the longwall panels (green dots) and one (red dots) far away from any mine openings aside a 5 m x 5 m adit. The mining area is surrounded by faults with throws of 5 m to $>>$ 25 m. The events in the area of the panels have similar characteristics as the events while mining [24]. The events between the shaft and the panels have not been observed while mining and are caused by rising mine water. Here, no continuous faults with significant throw have been mapped and failure of rock bridges (intermittent discontinuities) may be assumed. A similar situation can be observed in the Ruhr area (Fig. 26). Mining (hatched area) took place by multiple longwalls between two large faults. The seismic events are associated with a 250 m rise of water level in a shaft. The large faults show only minor seismic response. Some of the 888 detected and located events were associated with the mined area but the bulk of the events were outside the mined longwall panels. The area was very well mapped and numerous discontinuous faults with throw $< 1$ m were found.
Figure 25. Tectonic setting and epicenters of mine water-induced seismic events in the Ensdorf coal mine. The grey dots are from initial localization and the coloured dots from re-localization [28].

Figure 26. Tectonic setting and epicenters of mine water-induced seismic events in the East-Ruhr area coal mine. Hatched areas indicate longwall panels at the 1100 m bsl level (modified after [29]).

When researching earthquakes or human-induced seismic events in the majority of the cases Beyerlee’s [30] friction angle, either \( \varphi = 40^\circ \) for \( \sigma_N < 200 \) MPa of \( \varphi = 31^\circ \) for \( \sigma_N > 200 \) MPa, is used for fault stability considerations. Please note, 200 MPa translates to a depth of > 7km! As stated above, the stresses in a mining regime are typically much lower than 100 MPa. Exemptions are pillar and face stresses in ultra-deep South African and Canadian Mines. Beyerlee’s graphs are shown in Figure 26 along with shear strength envelopes after Barton [3]. The non-linearity of discontinuity shear strength at low \( \sigma_N \) is not addressed at all with Beyerlee’s approach. The shear strength of discontinuities in the range 25 MPa < \( \sigma_N < 80 \) MPa is not well understood due to the lack of experiments. There are few experiments (e.g. Jaeger [32]) using a triaxial setup producing normal stress in that range of interest. The rock types described by Beyerlee are limited and do not include shales or shists, typically associated with coal seams or ore bodies. The notion of Beyerlee that “at high normal stress…friction is nearly independent of rock type” may lead to serious under- or overestimation of the frictional properties of discontinuities. The widespread, unreflected use of Beyerlee’s \( \mu = 0.6 \) (\( \varphi = 31^\circ \)) for fault friction is strongly discouraged.
4. Conclusions

Abandoned mines pose fascinating tasks for risk assessment and associated rock engineering works. Some years after active mining, typically after 20 years, subsidence ceases and chimney type of failure, if at all, takes over. With shallow mines, discontinuity related failure is the predominant mechanism for producing sinkholes. The knowledge about discontinuity orientation and spacing is mandatory to estimate the bulking factor and thus how far the distance between mine opening to the surface has to be for self-filling. A major task is the definition of the accurate geometry of the abandoned mine as the old mine maps are not georeferenced and often do not show the last mining operations. Mapping of abandoned underground mines is an educational experience. Failure mechanisms may be seen, the durability of support can be assessed, and the actual geological and geotechnical situation are at hand. With this information a meaningful numerical model may be developed and calibrated for the observed failure mechanism. Mine water is a major issue in long-term stability of shallow mines and shafts. Any significant flow of water through the gob or a shaft fill leads to suffusion, loss of density and loss of cohesion.

Rising water levels in deep mines may lead to induced seismicity. The risk assessment here is particularly difficult as many unknowns prevail. A first warning signal is when seismic events occur during mining. Then, a suitable seismic network should be available by which epicenters as well as the focal depth of the events can be determined with an accuracy of ± 30 m. Tectonic inventory should be mapped during mining and checked if they may serve as sources for seismic events by comparing the spatial discontinuity features with orientations from fault plane solutions. During the rise of mine water there is little knowledge about pore pressure distribution in the mine. This must be estimated from numerical simulation using the appropriate anisotropic hydraulic conductivities. The simple model of a fault slip by increased pore pressure appears to be inappropriate for explaining the seismic events and brittle failure of intermittent shear zones reflects the geological situation better. Research topics include the development of knowledge about rock mass conductivity, poroelastic material parameters as well as failure mechanisms for intermittent discontinuities. Furthermore, the shear strength of discontinuities at mining-relevant stresses should be addressed by experimental work.
Risk assessment for abandoned mines is a truly multidisciplinary task involving geologists, hydrogeologists, geophysicists, mining engineers, civil and rock engineers. There are always regulatory aspects to consider and finally, the safety of men and infrastructure are the top priority. With the last stage of the mine life-cycle successful managed, there will be more trust of the people in mining. After all: if you can’t grow or recycle it, you have to mine it.

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