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Review article

Overview of converting abandoned coal mines to underground pumped storage systems: Focus on the underground reservoir

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ABSTRACT

The utilization of Underground Pumped Storage Power Systems (UPSP) addresses the growing need for energy storage in the face of increasing intermittent energy sources. Simultaneously, the closure of mining activities has resulted in vast underground spaces potentially becoming available for alternative purposes. This paper explores the potential of repurposing abandoned mines, particularly coal mines, as lower reservoirs for UPSPs.

The challenges associated with employing abandoned mines as lower reservoirs are multifaceted. The foremost challenge stems from limited knowledge about the current state of the mines due to post-mining processes, such as weathering, dissolution, hydration, leaching, swelling, slacking, subsidence, creeping along faults, gas migration, and precipitation, along with corrosion and deterioration of the support elements. This study documents and discusses the various processes related to cyclical pumping and discharge within the context of UPSPs, encompassing hydraulic discharge processes, cyclic loading, dry and wet processes, as well as fatigue and thermal stress. These processes significantly impact the safety, productivity, and stability of the lower reservoir.

To address these challenges, the paper presents different numerical solutions available to comprehend and mitigate cyclical processes in abandoned mines. Finally, it explores the economic feasibility of repurposing mines as lower reservoirs and the conditions required are examined, including favorable rock mass properties, reduced land acquisition costs, the necessity of permanent water pumping, and the potential income from excavated rock as a revenue source in case of new excavations.

This research contributes to the understanding of utilizing abandoned mines for UPSPs, highlighting the challenges associated with the use of coal mines as lower reservoirs and presenting several main processes to prevent safety and productivity issues.

1. Introduction

In response to reducing carbon emissions, many countries are currently undergoing an energy transition to mitigate their environmental impact with a growing reliance on renewable energy sources like solar and wind power, which exhibit great variability. Consequently, to address the challenge of temporal matching between energy supply and demand, various energy storage technologies have emerged as potential solutions [1] such as pumped-storage hydroelectricity (PSH) representing 99 % of global storage capacity [2]. PSH systems have gained recognition for their extended operational lifetimes, high reliability, and remarkable efficiency [3].

On the other side, the global closure of underground mines has presented a promising prospect for future underground spatial utilization ((COLOR) Fig. 1) and can provide answers to the significant apprehensions related to local economic development, such as the cessation of energy production [5,6], underground stability issues, subsidence [7,8], and environmental challenges including mine water

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exchanges and mine gas migration [9,10].

Therefore, Underground Pumped Storage Power Plants (UPSP), as first introduced in the early 20th century by Fessenden [11], offer a viable solution that capitalizes on the utilization of abandoned underground spaces and effectively circumvents topographical constraints and limitations associated with surface footprint [5,12]. Furthermore, UPSP presents an opportunity for revitalizing energy production following the closure of coal mines [5,13,14].

The first pumped storage hydropower system with an underground storage was constructed and operationalized at the Nassfeld plant in Austria [15]. Subsequently, the Socorridos pumping and water storage facility emerged as a prominent example of a fully realized UPSP, situated in the Madeira Islands, where the lower reservoir was excavated in volcanic rocks [16].

Although risks associated with underground cavity project and hydropower plants are well known, there is currently no successful project that converts an abandoned mine into a lower reservoir for a UPSP. Ongoing effort to realize such projects as for example in China [17], Netherlands [18], or Germany [224] raise the need to compile the different design, construction and operational challenges, with a focus on mine conditions and processes.

Tong et al. [19] reports key problems often encountered in abandoned mine. These problems include issues related to mine gas (such as excessive gas concentration and gas discharge), tunnel instabilities (such as floor instabilities, subsidence, rock burst, pillar failure and roof collapse, sinkholes), progressive deformation of the surrounding rock (resulting in cavity formation), and support system degradation (such as lining cracks, spalling, and bending/shearing of steel bars) [20–24]. Additionally, during the operating phase, new challenges arise from cyclic discharge/pumping, hydraulic processes, and tunnel stability, potentially limiting the production of the system [25]. Therefore, the primary objective of this paper is to employ the principal requirements pertinent to UPSP within the context of abandoned mining sites, regarding the inherent constraints associated with data availability, stability assessments, productivity evaluations, and conformity with local regulations (Fig. 2).

The present study compiles current knowledge concerning potential processes implicated in the conversion of a mine into a UPSP and, in doing so, furnishes a comprehensive overview of the manifold challenges in the domains of mining, geological, geotechnical, and hydraulic sciences. In effect, this paper serves as a reference document designed to facilitate the comprehension of pertinent facets by regulatory authorities with an interest in undertaking such a project, and offers a fundamental framework for the initiation of a feasibility study for a specific coal mining.

The matrix (Fig. 3) serves as a guideline for the results presented in the following parts and the discussion describing the processes involved at each phase of UPSP life cycle, highlighting their influence on the initial requirements and emphasizing the interactions between rock mass stability, the support system, mine gas risks, and hydraulic management.

2. Pre-operation phase: insufficient knowledge of the current geometry

2.1. Documentation of the geometry

Knowledge of the current situation of an abandoned mine is the first step in a pre-feasibility study of a project. Often the lower reservoir geometry is determined by the geometry of the abandoned mine and cannot be modified to a larger extent without significant monetary costs [26]. Typical structures in abandoned mines that can be used as lower reservoirs are often manifolds of tunnels with sidearms, bifurcations and dead-end passages, forming either a fish-grid network of branches or ring-type roadways [15].

The aim of using the original documentation (mine plans) is the estimation of the underground volume accessible for the dimensioning of the UPSP (e.g. storage volume, depth, choice of turbomachinery and plant efficiency). This documentation might be insufficient for the purpose of detailed planning and depend on local regulations (e.g. presence or not of a regulative framework), the date of the operation cease, and the accessibility of the data set. Also, initially, detailed plans may no longer provide a full picture of the mine geometry if structural changes such as settlements or collapses have occurred since the mine was closed [27].

After assessment of these documentations, the initial estimation of the geometry and stability of the mine might be insufficient. A cavity detection survey can be operated with photogrammetry and laser

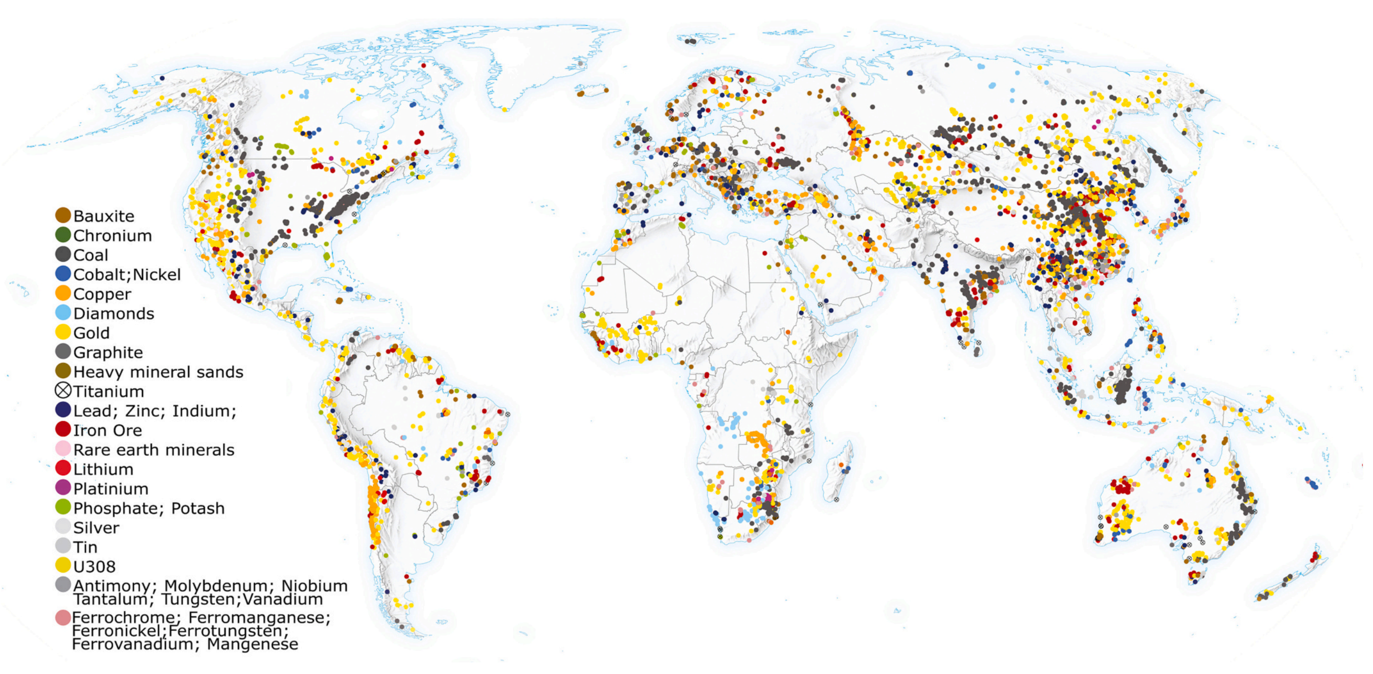
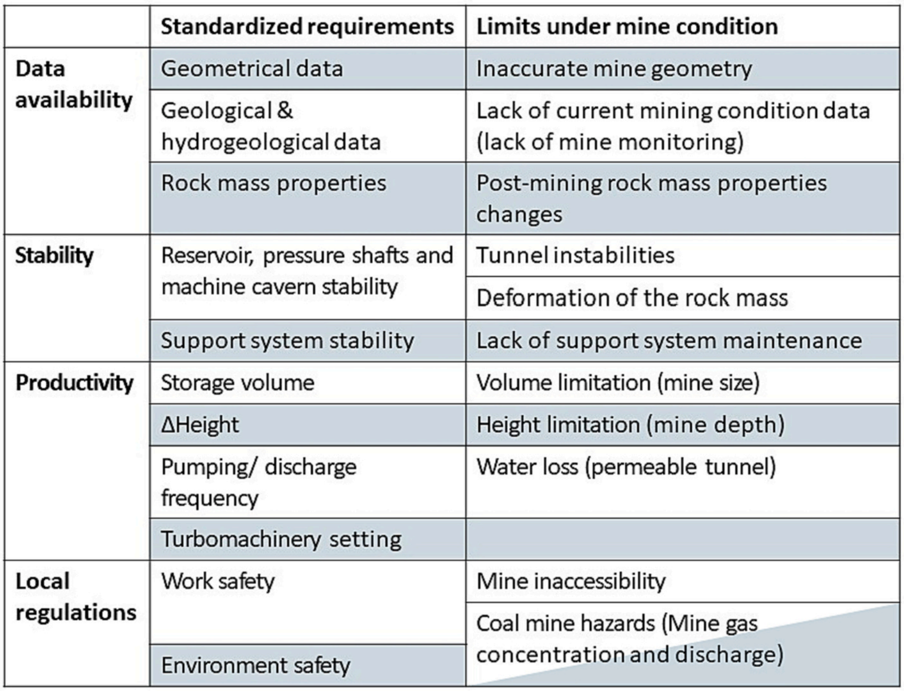
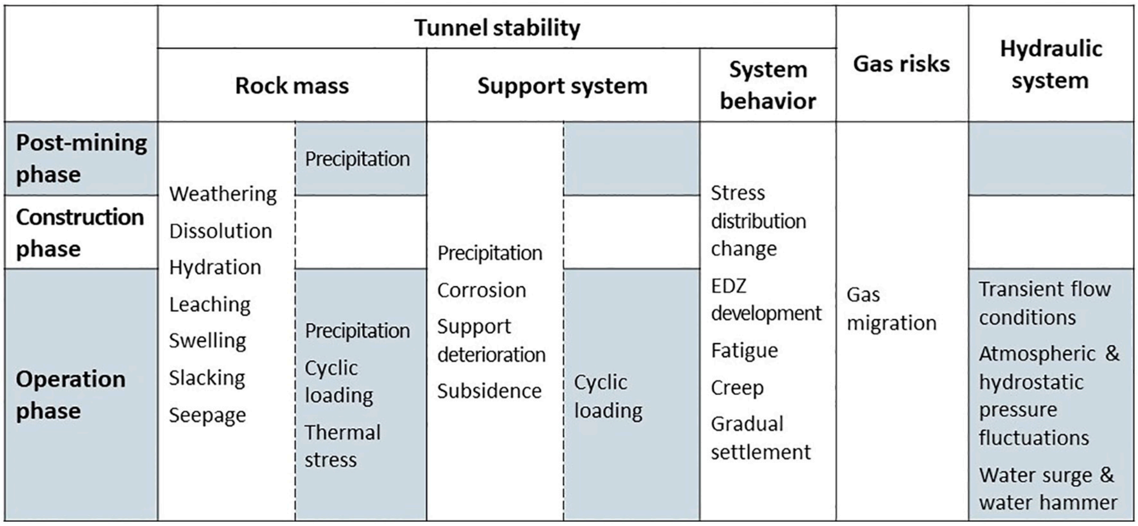


Fig. 1. Map of the mining capacity zone of coal and metal mines (Non exhaustive) ([4]).



	Standardized requirements	Limits under mine condition
Data availability	Geometrical data	Inaccurate mine geometry
	Geological & hydrogeological data	Lack of current mining condition data (lack of mine monitoring)
	Rock mass properties	Post-mining rock mass properties changes
Stability	Reservoir, pressure shafts and machine cavern stability	Tunnel instabilities
		Deformation of the rock mass
	Support system stability	Lack of support system maintenance
Productivity	Storage volume	Volume limitation (mine size)
	ΔHeight	Height limitation (mine depth)
	Pumping/ discharge frequency	Water loss (permeable tunnel)
	Turbomachinery setting	
Local regulations	Work safety	Mine inaccessibility
		Coal mine hazards (Mine gas concentration and discharge)
	Environment safety	

Fig. 2. Requirements necessary for a UPSP in an abandoned mine and the limits influencing the decision-making.



	Tunnel stability					Gas risks	Hydraulic system
	Rock mass		Support system		System behavior		
Post-mining phase	Weathering Dissolution Hydration Leaching Swelling Slacking Seepage	Precipitation	Precipitation Corrosion Support deterioration Subsidence		Stress distribution change EDZ development Fatigue Creep Gradual settlement	Gas migration	
Construction phase							
Operation phase		Precipitation Cyclic loading Thermal stress		Cyclic loading			Transient flow conditions Atmospheric & hydrostatic pressure fluctuations Water surge & water hammer

Fig. 3. Processes matrix influencing the stability, productivity and safety of the lower reservoir in a UPSP based on the different boundary conditions that the lower reservoir will face.

scanning technology to build a reconstruction and visualization of the 3D structure of the cavities [28–32].

Due to the expected conditions in an abandoned mine, exploration technology may be mounted on carriers and navigable in these conditions. In non-flooded surroundings, exploration can only be performed if the mine gas situation allows for a safe work environment with regards to personnel and explosion protection. Automated measurements could also be considered as an option. Other methods such as Radar and Sonar remain experimental [33,34].

2.2. *Time-dependent geometrical changes: The rock mass*

Stability of the underground space will strongly influence the size of the underground reservoir and the construction cost of the project. Years passed after the excavation, and the condition of the underground space may have changed. The underground space conditions depend on the system behavior (i.e. rock mass and the support system behavior). These two elements have faced boundary conditions changes due to, on one side, rock mass deformation, and on the other side support system degradation.

First, the changes in the rock mass properties depend on the initial properties of the excavated rock mass. In a coal mine environment, the most common rocks are coal, sandstone, siltstone, mudstone, shale, carbonates and clay. The nature of these sediments spans in short distance from clay- and mud- rich weak mineral bonds to coarser and stronger sediment rocks. Therefore, the uniaxial compressive rock strength (UCS) can vary from 2 MPa for clay shale to 140 MPa for sandstone [35,36]. Secondly, coal measure rocks are typically heterolithic, with interbedded deposits of sands and muds and reflecting rapidly changing flow regimes. They are subsequently subject to erosion, differential compaction associated with their burial history and the formation of faults and joints that formed during tectonic processes [35]. These discontinuities modify the rock properties, cohesion, and strength in all directions and increase the difficulty of assessing the rock mass strength and behavior around the mine [20,21,37–41].

2.2.1. *Humidity changes*

Rocks in coal mines can be sensitive to high humidity and humidity changes in the mine and might lead to rock mass degradation processes such as weathering, dissolution, hydration, leaching and precipitation (Fig. 3) may alter geomechanical properties of the host rock [23,42–44]. These processes can be accelerated with water circulation (e.g. seepage) along fractures [45]. Soluble rocks such as evaporites and carbonate rocks are particularly sensitive to long-term water circulation. Wetting of the rock around the cavities after long-term exposure to atmospheric conditions (including the ventilation) can cause a decreasing strength and stiffness [46–51]. For instance, clay [52], siltstone and sandstone [50,53,54] show a strong relationship between total suction and strength/stiffness. Dyke and Dobereiner [55] demonstrated a decrease of 25–30 % of the UCS for sandstones with increasing moisture content. On the other side, carbonate rocks are less sensitive to strength degradation with increasing water content ((COLOR) Fig. 4).

Rock mass degradation's processes lead also to changes in hydraulic properties of the rock such as permeability, hydraulic conductivity and porosity. They can enhance seepage (e.g. exfiltration, infiltration) with the surrounding rock [60–63].

In addition, the phenomenon of swelling (Fig. 3) is a time-dependent process commonly observed in soft-rock masses surrounding coal mine tunnels, including mudstone, clay rock, shale, and coal measure strata, as defined by the Society for Rock Mechanics (ISRM) [64–66]. Under humid conditions, the excavation and unloading of the tunnel can trigger mechanisms such as stressed-dilatation and physicochemical swelling, leading to stress redistribution and deterioration of the rock mass [65,67,68].

Furthermore, rock formations containing clay fractions can undergo a slaking process (Fig. 3) when subjected to alternating wetting and drying cycles resulting from variations in humidity. Slaking occurs as a result of differential pore pressure between air-filled and water-filled voids, leading to the breakdown of the rock structure [69–71]. It is important to note that slaking can only take place if the rock was previously dry and the severity of slaking increases with the presence of discontinuities, such as fractures [72]. This process is well-documented in the context of coal mines and has been associated with potential roof instabilities [73,74].

2.3. *Time-dependent geometrical changes: The support system*

Support structures in underground tunnels were initially designed to withstand the stresses and strains associated with mining activities. However, their suitability for long-term use and their current condition can often be uncertain due to a lack of data or the gradual degradation of the support system over time due to a lack of maintenance (Fig. 3). The deterioration of the support system's original condition over the long term poses a significant challenge to the overall stability of the tunnel, particularly in the presence of water [19,45,75].

Corrosion phenomena (Fig. 3) pose a significant risk to the stability of tunnels, as they can lead to premature failure of crucial support elements such as steel roof supports, wire ropes, and rock bolts. Premature rock bolt failures in coal mines are often attributed to stress corrosion cracking, while environmental cracking, including hydrogen cracking mechanisms, and corrosion fatigue can also contribute to support failures [76–80]. Corrosion in underground coal mines can be categorized into two types: atmospheric corrosion, resulting from humidity and pollutants in the ventilation, and aqueous corrosion, caused by groundwater present in the mine [77,81,82].

Multiple parameters influence corrosion processes. The composition and corrosivity of mine water, which is primarily responsible for steel corrosion in coal mines, can vary [78,81–83]. The acidity of mine water can be attributed to pyrite oxidation, the presence of peaty acids, and bacteria [78]. Other factors such as high humidity (>90 %), temperature (around 30 °C), airborne dust, in-situ stress, and the coal itself significantly influence corrosion [78,84–86]. The most common forms of corrosion encountered are uniform corrosion, pitting corrosion (which poses challenges in detection and can lead to sudden failure of ground support elements), and stress corrosion (particularly relevant to pre-stressed supports or those subjected to loading and straining after installation) [82].

Corrosive groundwater containing salts, sulfuric acid root ions, chloride ions, and bicarbonate ions can cause concrete damage and cracks due to its interaction with the tunnel structure. This erosion can occur on a micro to macro scale, leading to spalling and flaking of shafts and tunnels [87–89].

Finally, mineral precipitation (Fig. 3) resulting from the dissolution of surrounding rock in water can lead to the deposition of minerals on the support system, potentially compromising its stability [90].

As previously discussed, reinforcing or renewing the support system

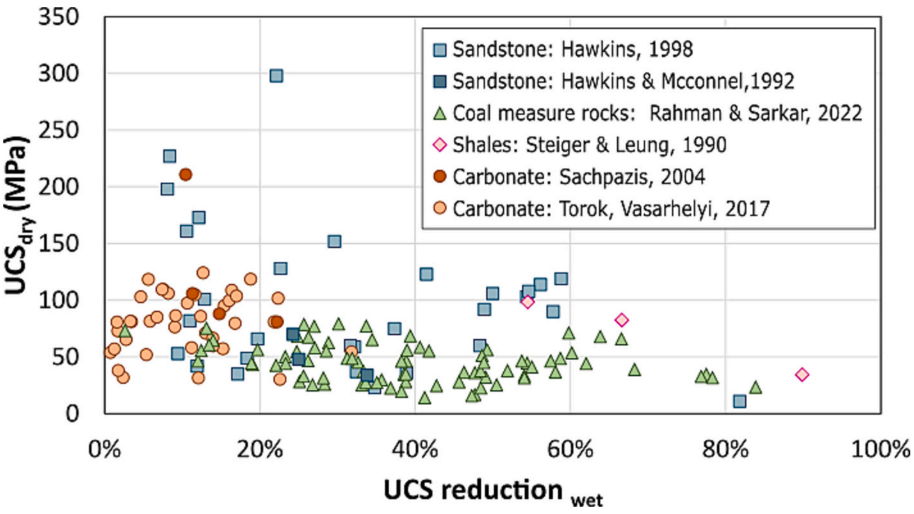


Fig. 4. Percentage of UCS loss for wet rock samples compared to dry samples [47,49,56–59].

is crucial for ensuring tunnel stability. However, estimating the support requirements presents challenges in identifying and predicting the hydro-mechanical properties, dimensions of the tunnel (e.g., shape, size), ventilation-associated pumping/discharge, and hydrogeological conditions of the abandoned mine [48,91–93].

2.4. *Time-dependent geometrical changes: System behavior*

Because of the deterioration of rock mass properties, on the one hand, and the weakening of the support system, on the other hand, the tunnel might face failures and instabilities.

The progressive weakening of the rock's micro- and/or macrostructure, the loss of strength and stiffness, enhancing creep [94–96] can lead to a reduction in fracture strength [97,98]. Moreover, failure is enhanced by the presence of rock discontinuities (e.g. faults) and depends on their orientation and dip [17,37,65,99,100], the distance to the cavity [101], the thickness [102], the filling of the discontinuities [103], and the support system condition (e.g. corrosion of the concrete, rock bolt and anchor bolt steels) [78,104]. The initiative and growth of those cracks, particularly influenced by dynamic disturbances resulting from stress redistribution (see Section 5.2), leads to the formation or extension of an excavation damage zone (EDZ) [105,106] if the rock mass strength is exceeded [107]. The EDZ is defined by the change of rock properties (i.e. deterioration of the rock mass) and extensive studies have been conducted to understand and predict the extent of excavation damage zone [107–114]. The development of an EDZ is a complex time-dependent process that involves several mechanisms such as stress redistribution, increased permeability, thermal effects, chemical effects, mechanical effects [106,107,115] (Fig. 5).

Reinforcing, creating systems for failure detection or renewing the support system is crucial for maintaining tunnel stability, but challenges arise in predicting requirements based on hydro-mechanical properties, tunnel dimensions, ventilation management, and hydrogeological conditions. Proper support system management and monitoring are vital.

3. Mine gas

Harmful gases may potentially be present in a coal mine that can be combustible, explosive, asphyxiating and/or toxic [116] such as methane, carbon dioxide, hydrogen sulfide or radon [117]. Methane and carbon dioxide being the predominant mine gas contents in coal mining [117,118].

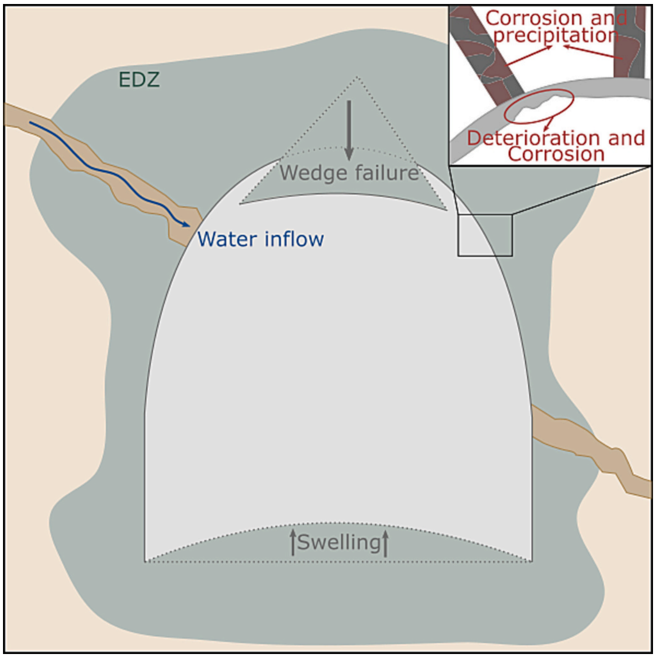


Fig. 5. System behavior instabilities and support system deterioration.

3.1. *Migration sources*

These gases are adsorbed to the internal surface of the coal but also in the pore space of the coal and the surrounding rock [118] ((COLOR) Fig. 6). Gas release mainly occurs during the mining process due to the unloading of the rock mass, the opening of existing fractures and the formation of new gas migration flow paths [120] (Fig. 3). Gas sources may be site-specific and often associated with gas reservoirs in surrounding strata due to gas generation from organic matter or migration, organic-rich structures with originally low permeability [121]. The amount of released gas is highly dependent on the geological characteristics of the coal (e.g. permeability and inner structure) [119], the permeability of the surrounding rock, the presence of geological features (e.g. sandstone paleochannels or clay veins) [122–127], the stress state (that has changed due to the mining activity), tectonic structures [128,129] and fracturing processes during the mining process [119,121]. This migration occurs through several transport mechanisms (e.g. pressure gradient, diffusion through concentration gradient and capillary suction and adsorption of liquids) enabled gas and liquid inflow. Moreover, an increase in permeability will occur over time due to the long-term degradation of host rock and concrete properties [130].

Degassing of the remaining coal continues after the mining operation has ceased. Pumping operations usually decrease or cease completely, depending on the targeted final water level, resulting in a rise of the water table. The rising water can displace released mine gas from flooded sections towards higher levels of the mine, mainly through cavities, natural and anthropogenic [131].

3.2. *Cases with ventilation and/or drainage*

The construction of an entirely gas-tight lower reservoir is not possible. Therefore, drainage and ventilation systems are designed to mitigate gas accumulation in the mine. The ventilation system can release mine gas from shafts, nevertheless, due to the impact of methane on the climate, all mines try to avoid methane emissions and collect methane through drainage systems, to convert it into power production [117]. The drainage would mitigate the gas inflow in the UPSP and it is also often used after active mining as a safety measure to prevent gas leaks to the surface and through vent lines [132]. An operating drainage system, associated with operating monitoring allows an accurate knowledge of the gas condition in the mine and mitigates gas-related risks [133].

3.3. *Cases without gas risk prevention*

In certain instances, the cessation of ventilation and mine gas extraction activities has resulted in an ongoing influx of gas into the mine, consequently leading to increased gas concentrations [117,134]. Furthermore, weathering processes and the propagation of fractures have facilitated the release of gas and the creation of pathways for gas migration. The absence of proper ventilation systems poses a risk of significant gas accumulation and subsequent gas migration, with uncertainties surrounding the mapping of potential accumulation areas due to limited monitoring outside of former mine openings [135]. Although a theoretical assessment of potential gas accumulations can be conducted to some extent based on mine plans that delineate former excavation areas and roadways [134].

Moreover, in flooded mines, the water is likely to contain substantial quantities of carbon dioxide and hydrogen sulfide, both of which are highly soluble gases. Additionally, relatively lower amounts of radon and methane may also be present. According to Henry's law, the solubility of gases in water increases with higher pressure and lower

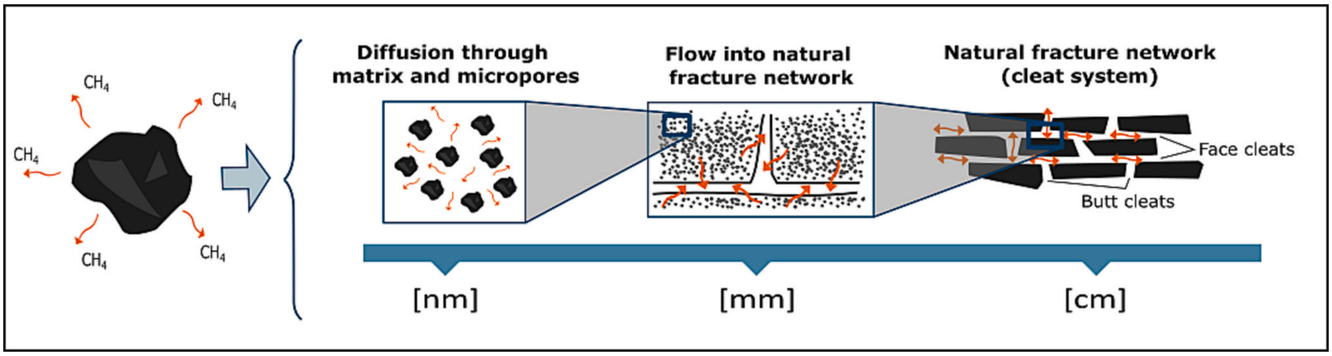


Fig. 6. Presence and distribution of methane within a coal deposit: Desorption of methane from the coal surface and subsequent diffusion in the coal matrix and flow into natural fracture network (based on: [117,119].

temperature. During the ascent of water to the surface, the temperature may rise while the pressure experiences a significant decrease, particularly if the water originates from deep sources. This phenomenon can lead to the release of dissolved gases into the atmosphere [135].

4. Hydraulic management

Hydrodynamic (i.e. the flow conditions of water) and aerodynamic (i.e. air under gravity or pressure flow conditions) processes are of major importance for the efficiency as well as safety of hydroelectric power plants in general, and UPSP in particular [136]. Key parameters to describe flow conditions are the hydrodynamic pressure, the water height, the flow velocity, the shear stress and the evolution and propagation of waves.

The lower reservoir of a UPSP creates two specific boundary conditions regarding hydrodynamic aspects. Firstly, the reservoir's spatial extent is confined compared to conventional PSP. Secondly, the plant operation is based on a free surface flow in an enclosed environment, which poses the possibility of changes in the flow condition under specific operational conditions. These specific boundary conditions lead to several relevant hydrodynamic processes that need to be considered during the operation of a UPSP.

4.1. Position of turbomachinery and its connection to the lower reservoir

As with all other hydropower projects, the selection of the type of turbomachinery in a UPSP is critical for power production. Plant efficiency, investment cost and operational flexibility of the plant [137]. Similar to conventional PSP, there is a choice between individual turbines and pumps or reversible pump-turbines [138]. Morabito et al. [137] give an overview of advantages and disadvantages of different types of turbomachinery for UPSP highlighting that impulse turbines such as Pelton turbines are unsuitable for a UPSP. Therefore, mostly Francis turbines or Francis pump-turbines are an eligible choice. Their operating concept allows for heads of several hundred meters and the machinery to be submerged while still remaining a good efficiency. Special care has to be taken for dampening flow oscillations at start and stop of operation and to avoid possible cavitation, which usually is done with a water lock in conventional pumped storage plants. This, however might be not possible in UPSP for reasons of accessibility or additional costs.

In practice, the draft tube of a UPSP is connected at one point to the network of channels, without the benefit of the kinetic energy conversion effects of a diffusor or an open surface reservoir in conventional PSP. This structural situation can lead to a high speed inflow being directed at a bend or a T-Junction [139] into the channels, In general, flows in simplified 90°-bends and T-junctions show a high likelihood for oscillating flow features such as swirl-switching phenomena [137,140] or vortex-induced instabilities. Pressure and force fluctuations are expected to be coupled with these oscillations. In Francis turbines, pressure fluctuations in the draft tube should be avoided since they affect the power stability and longevity of the turbine [141,142]. Hence, the placement of the draft tube outlet into the lower reservoir and the subsequent fluctuations need to be considered in the choice of an abandoned mine as an UPSP as well as the UPSP's structural and operational design and the selection of the type of turbomachinery (Fig. 7).

4.2. Hydraulic processes during operation

Hydrodynamic (i.e. the flow conditions of water) and aerodynamic (i.e. air under gravity or pressure flow conditions) processes are of major importance for the efficiency as well as safety of hydroelectric power plants in general, and UPSP in particular [136]. Key parameters to describe flow conditions are the hydrodynamic pressure, the water height, the flow velocity, the shear stress and the evolution and propagation of waves.

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Firstly, during the filling or emptying of the lower reservoir of a UPSP, the water level rises or falls from an initial water level h_0 to a final water level of h_{end}. From a global point of view, the rate of water level change and its duration depend solely on the discharge, the chosen values for h_0 and h_{end}, the available volume of the reservoir and its cross-section [144]. While these global processes are similar to those in conventional pumped storage plants, recent studies have shown that so-called local processes superimpose the global hydrodynamic processes in a UPSP [144]. This can lead to changes in for example the water level of up to 50 % [145].

These local flow processes are characterized by the appearance of waves. When the reservoir is filled, a wave moves from the opening in the direction of flow along the channel and causes higher water levels and flow velocities to occur at the wave head. If the wave height exceeds the remaining freeboard in the channel, there may be a sudden increase in pressure within the channel. If the wave height reaches the reservoir ceiling and the flow changes from a free surface flow to a pressure flow, it can cause locally increased hydrostatic pressures. Pressure surges especially in the vicinity of the turbomachinery can affect their longevity and efficiency.

The wave height and wave speed that occur depend on the type of wave that arises in the specific situation. There can be undular bores, undular bores with secondary waves and breaking bores in a UPSP [144]. Pummer and Schüttrumpf [144] showed in experimental and

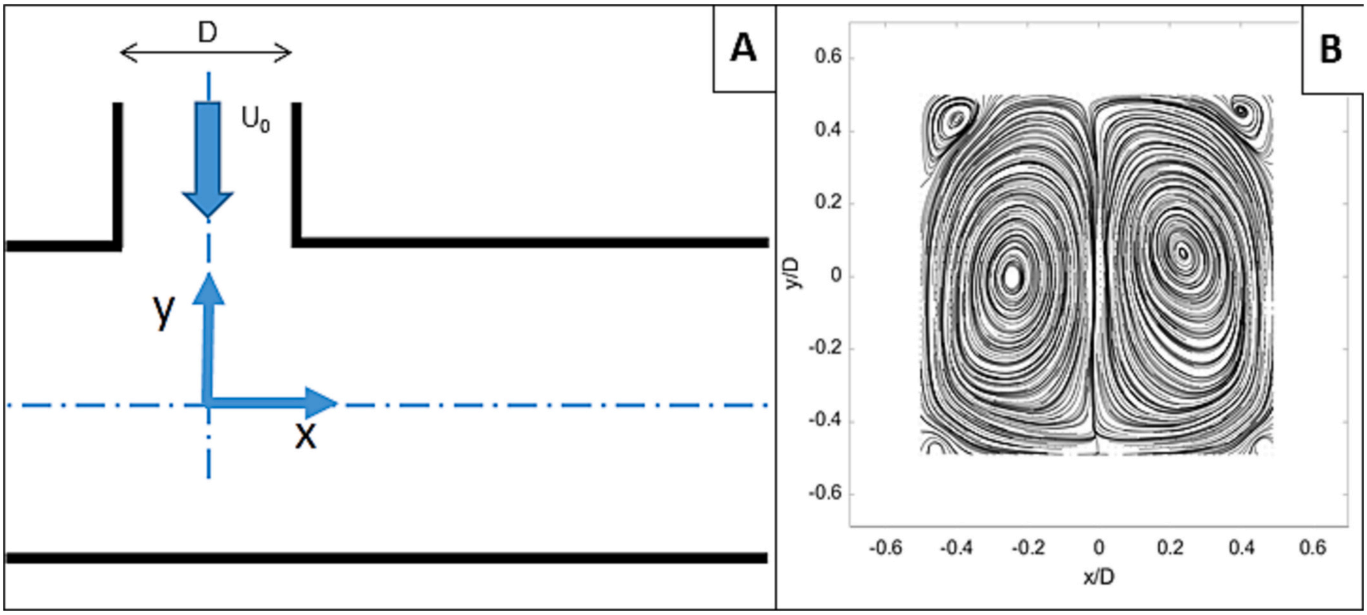

Fig. 7. A. Experimental setup of a T-junction flow with an inflow velocity of U0 = 0.46 m/s in the junction and a diameter of the main channel of D = 0.05 m. B. Top view of the time-averaged streamlines captured with Particle Image Velocimetry in the cross-section at 1D downstream of the junction [143].

CFD models that for the maximum water level the first waves that occur near the inlet of the reservoir are crucial ((COLOR) Fig. 8).

With time and through changes in the channel's cross-section or the impermeable reservoir boundaries the waves are reflected and change direction [145]. Partial reflection, Mach reflection or total reflection of waves can occur and lead to changes in their hydraulic characteristics making the predictability of the hydraulic parameters more complex [145]. When the discharge in the reservoir stops, the wave heights and wave velocities decrease over time. Since strong oscillations in the reservoir can affect UPSP operation negatively, the dampening process is relevant for UPSP operation.

The global and local flow processes are strongly affected by the operational parameters of a UPSP. Whereas global processes mainly depend on the discharge, the initial and final water level, the volume of the reservoir and its cross-section, local processes have further relevant influencing parameters (Table 1). The dependency especially on local flow processes from operational and structural parameters makes a detailed development of determination equations necessary [144]. No comprehensive state of knowledge is known so far regarding the description of flow processes in UPSP that takes all relevant operational and structural parameters into consideration.

In addition, similar to a conventional hydropower plant, in a UPSP,

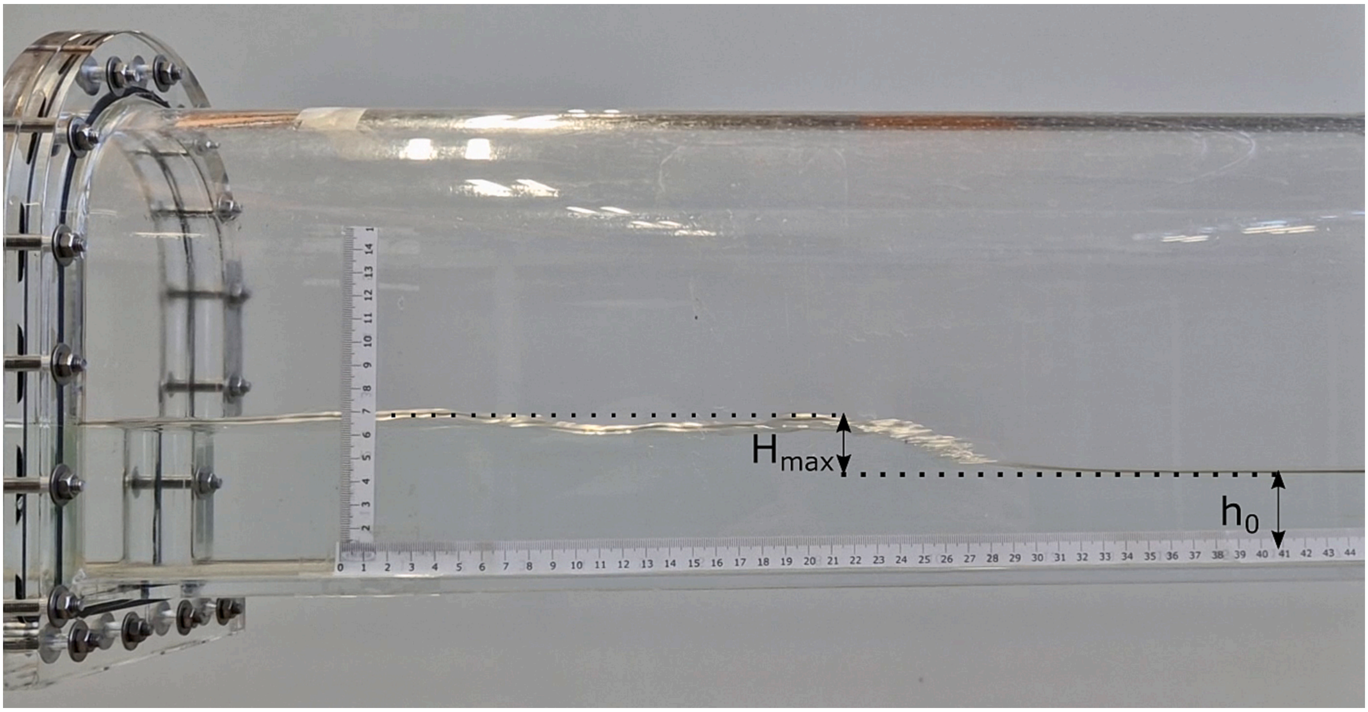

Fig. 8. Wave at the inlet during the filling of an underground reservoir, h_0: initial water level, H_{max}: maximal top wave water level (scale in centimeters).

Table 1
Relevant hydraulic parameters in UPSP and known relevant operational and structural design parameters [144,146].

Relevant hydraulic parameters	Relevant operational parameters	Relevant structural parameters
Actual water level Wave height Flow velocity Oscillation period	Discharge Initial water level Final water level Total filling and emptying duration	Channel cross-section Channel length Channel geometry incl. number of channels and direction changes Wall roughness Bottom slope

global and local flow processes in the lower reservoir are closely linked to the phenomenon of water surges or water hammer [147]. A water hammer occurs during changes in operating points or emergency shutdowns and can be triggered or enhanced by the operating time of wicket gates or valves, the geometry and general set-up of a hydropower plant's components such as the penstock, or the reservoirs as well as the turbomachinery characteristics such as runner speed [147,148]. They can affect all components of a hydropower plant negatively either by direct damage due to high-pressure surges or by fatigue of material due to the highly dynamic, cyclical loadings [149,150].

Surge tanks or surge shafts to mitigate the negative effects of water hammer are regularly installed in conventional hydro power schemes. They are often designed specifically for each scheme depending on the actual hydraulic and geological boundary conditions [151], and can be found on the tailrace side of the system. Calculating the mass oscillation in the surge tank and therefore designing the structure increases in complexity when dealing with a pumped-storage scheme instead of a hydropower plant. This is due to more complex hydraulic transients, pressure conditions during filling and emptying as well as possible air entrainment [152,153]. Due to the special boundary conditions of a UPSP being underground, the relationships with influencing factors and the effects of the hydraulic phenomenon can be predicted with even less certainty than in a conventional PSP. Surge tanks in the headrace and tailrace side of the turbomachinery could be a suitable solution to mitigate the effect of water hammer in a UPSP in an abandoned mine. However, the positioning and construction of these components still needs to be investigated for a UPSP to ensure their effectiveness under special circumstances of an abandoned mine. A surge tank is best positioned close to the valves, which means in case of a UPSP that the space for the tank needs to be excavated. Especially with regard to a UPSP in an abandoned mine this leads to additional construction costs.

Finally, unlike conventional PSP, the air pressure in a UPSP is variable and differs from the atmospheric conditions [136]. Without ventilation, air gets trapped in the lower reservoir during its filling and compresses, which results in higher air pressure and thus in less favorable flow conditions. As the air pressure increases, so does the hydrostatic pressure in the reservoir, which leads to a reduction in the net head between the upper and lower reservoir. This reduces the available stored energy in the UPSP.

Menéndez et al. [136] have shown that for a specific UPSP scenario pressure-induced head loss could account for 12.5 % loss of available energy.

The excavation of ventilation shafts is necessary to allow the exhalation of the trapped air which is displaced during the turbine process [154]. Placement, geometric design and quantity of ventilation shafts need to be considered in the design of a UPSP to ensure good aerodynamic conditions while maintaining economic viability [155].

5. Stability under operation phase

5.1. Cyclic wetting and drying

It has been explained before (see Section 2.2) that mechanical properties of various rock types vary greatly due to processes occurring under wet conditions (e.g. weathering, dissolution, hydration, leaching, swelling, slacking) (Fig. 3). Regarding the long-term effect of cyclic dynamic water and water wave on host rock in UPSP systems, the mechanism of the water-rock interaction become more complicated.

In clay and mudstone formations, the alternation of wet and dry cycles induces a cyclic swelling-shrinkage phenomenon, resulting in the disintegration of the rock mass and deterioration of rock properties [71]. Mudstone exhibits a progressive increase in maximum swelling strain with each cycle, eventually reaching a nearly constant value after multiple cycles [156]. This behavior can be attributed to mechanisms such as air breakage, crack opening, and stress relaxation at crack edges. The presence of swelling minerals in mudstone can cause cyclic stress accumulation and release, potentially leading to rock fatigue [157].

In the case of sandstones, cyclic wetting and drying treatments have been reported to decrease tensile strength, although there is some discrepancy among research studies [157,158]. It is plausible that an increased number of wetting and drying cycles could result in noticeable strength reduction [157]. However, the mineralogical composition of sandstone plays a crucial role in the underlying weakening mechanism during cyclic wetting and drying, as it primarily involves chemical and corrosive deterioration processes such as dissolution, precipitation, dehydration, hydration, or swelling [158]. Consequently, the cyclic wetting and drying of sandstone can lead to enhanced softening and ductility, causing a shift in failure characteristics from brittle to ductile failure, particularly when subjected to a high number of cycles [159].

In addition, rapid water fluctuations can accelerate deformation accumulation and the damage development and expansion of the radius of EDZ [160].

Finally, cyclic filling and emptying of the tunnel lining might cause mechanical erosion and may increase the sediment concentration in the water. Suspended particles may increase the turbidity of the water and enhance sedimentation in the reservoir. The erosion rate depends on several parameters such as cohesion and grain-size distribution of wall material, bottom slope and shear stress [25]. Especially hard sediments such as quartz [223] but also others such as silt [161] can lead to a gradual removal of turbomachinery material [162]. Sediment-related erosion causes changes in the runner profile and subsequently leads to changes in flow patterns, turbine efficiency, vibrations and even breakdown of turbines [163] While a precise prediction of erosion rates due to sediments is still difficult, it has been studied that site-specific factors are the most influential in the process [163,164]. It has been shown that sediment size, sediment concentration, water velocity, properties of base material of turbine components as well as operating hours of the turbine strongly influence the loss of efficiency [161].

Turbine wear due to sediment erosion is likely to happen in a UPSP in an abandoned mine if loose material is transported into the lower reservoir and the cyclical flow processes likely even leach more material. A loss of efficiency of up to 1 % per year has been observed in a hydro power plant [163]. Similar developments are possible in a UPSP and should be considered in the design process of turbomachinery e.g. when choosing base material of the machinery or reducing sediment load.

5.2. Cyclic loading

During the operational period of UPSPs, the rock mass around the underground reservoir is continuously subjected to hourly/daily cyclic loads due to the fluctuation of internal water pressure (e.g. waves). The maximum amplitude of the pressure cycles is very small (i.e. a few kPa), compared to the gravitational and tectonic stresses in the surrounding rock mass (i.e. several MPa). However, under cyclic loading, many damage indicators develop imperceptibly or without fatigue failure, when the maximum cyclic stresses in the rock are below the crack initiation threshold σ_{ci} (elastic range) [165,166]. However, it is well known that if rock undergoes cyclic loading, it often fails at a lower stress than its monotonic strength if the stress is above the crack initiation threshold. Existing micro-cracks, fissures, defects and voids grow slowly in the rock and may cause fatigue failure [167–171]. This type of repetitive stress typically leads to loosening and decohesion of the rock grains [107,172]. Stress corrosion is thought to be the most relevant mechanism of fatigue that causes sub-critical crack growth.

Additionally, fatigue is usually accompanied by accumulated deformations in the rock based on a time-dependent mechanism primarily due to the growth of pre-existing microcracks [62,173]. A typical deformation curve observed in cyclic loading tests consists of three stages as shown in Fig. 9: I) the initial stage: axial strain increases rapidly in the first few cycles due to the development of new cracks and the strain increases at a deceleration rate (deceleration region); II) steady-state stage: the crack propagation and damage evolution occur with a constant rate leading to steady-state strain accumulation (stable propagation region); III) the accelerated stage: the rate of strain accumulation increases rapidly and leads to fatigue failure of the rock (acceleration region) [25,174–176]. The fatigue behavior of a rock material may depend on several factors, such as frequency, loading-unloading rate, waveform and amplitude of cycles as well as the applied confining pressure [166,171,177,178]. For instance, the influence stress frequency upon failure strain, low cycle fatigue testing (LCF) involves high stress amplitudes and low-frequency plastic strains, while High cyclic fatigue (HCF) is characterized by lower stress amplitudes and higher-frequency strains, resulting in distinct accumulated deformation behavior and rates of damage evolution [174].

The delayed failure of a rock sample under constant applied stress is known as brittle creep [179,180], which is associated with the stability of many buildings and underground structures in mining and rock engineering, notably, creep and fatigue exhibit similarities in their characteristics. Both phenomena show time-dependent behavior and fail at an applied load lower than its monotonic strength (subcritical crack growth [173]), characterized by three stages of deformation rate: the primary (or transient) creep stage, the secondary (or steady) creep stage, and the tertiary (or accelerating) creep stage. The underlying mechanisms involved in these processes are intricate, complex, and influenced by various parameters, e.g. stress corrosion [173,179,181,182].

As mentioned above, the weakening effect of water on the strength/properties of the rock can have a stronger influence on the rock during cyclic loading and makes the deformation process complex [183]. For example, the hydro-mechanical properties of the rock, strength, Young's modulus, are increasingly degraded under cyclic loading and may even cause dynamic instability events in the tunnel [184–186].

Another critical loading condition that can occur in an underground reservoir of a UPSP are the hydrodynamic forces during the switchover phase from pump to turbine operation, or vice versa (e.g. shock waves or high frequency impact loads). In such cases, the adjacent rock mass of the underground tunnel is subjected to rapid dynamic forces, which may cause instabilities [136].

Based on the comprehensive analysis of instability factors encountered during cyclic loading, it can be concluded that these factors have a significant influence on the hydro-mechanical condition of the tunnel circumference at a macroscopic level. Consequently, the integrity and overall condition of the tunnel are highly susceptible to adverse consequences. Dynamic disturbance can accelerate deformation accumulation and the intersection between cracks, also causing the rock mass around the tunnel to lose its integrity [110,187–189]. In addition, a coupled hydromechanical process and local heterogeneity can initiate and accelerate the damage development of rock mass, which may lead to expansion of the radius of EDZ [160]. In such circumstances, it presents a challenge to theoretically define the Excavation Damaged Zone (EDZ) and accurately quantify the radius of the fractured and irreversible deformation in UPSP. Several studies have explored the stability of underground spaces under cyclic loading using numerical stress analysis and have determined that dynamic loading significantly impacts the mechanical behavior and displacement of the surrounding rock mass [176,190–192].

5.3. *Thermal-induced fracturing*

The cyclic circulation of cold water in a UPSP system creates a so-called thermally affected zone (TAZ) around the lower reservoir. Depending on the depth of the lower reservoir and the water temperature, a temperature gradient of −5 to −40 °C can be expected within this zone (especially during the winter). From a geomechanical perspective, such a temperature drop can cause the surrounding rock to undergo transient thermal contraction, resulting in thermally induced tensile stresses. The magnitude and extent of the zone affected by the thermal stresses depend on several factors, such as the temperature gradient and the thermal properties of the rock, including its thermal expansion, heat capacity, and thermal conduction coefficients.

While the scientific literature on the potential consequences of thermal stresses in UPSPs is scarce and seldom explored, this topic has gained significant attention in other subsurface applications. For example, numerous studies on compressed air energy storage (CAES) in salt caverns have shown that rapid temperature drops can cause local mechanical instabilities in the form of spalling and tensile fractures on the cavern wall [193,194]. The formation of thermal cracks was also observed in a novel field experiment where the salt experienced a temperature drop of $\Delta T = -20C^{\circ}$ [195]. Moreover, cyclic thermal stresses may even lead to the so-called thermal fatigue in the long term [196], a process that has rarely been studied so far. This phenomenon has been observed in mine shafts due to seasonal temperature fluctuations [197,198].

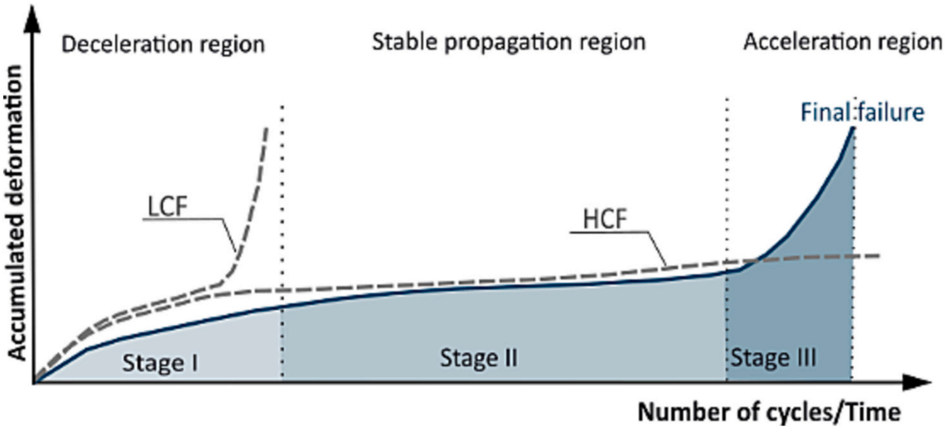

Fig. 9. Typical deformation accumulation observed in cyclic loading tests (low cycle fatigue test (LCF): small number of cycles with high loads; high cycle fatigue test (HCF): large number of cycles with low loads) [25,174–176].

5.4. Water exchanges with the surrounding rock mass

In the case of an impermeable reservoir, pumping and discharge can lead to variations in the water level in the surrounding rock mass. In several pumping and discharge scenarios, simulations show this oscillation (Fig. 3) with an exchange from the cavity to the aquifer during the discharge phases and an exchange from the aquifer to the cavity during the pumping phases [60,199] (Fig. 10). In most cases, infiltration is more important than exfiltration, which causes a reduction of the available volume in the lower reservoir and affect the efficiency of the UPSP [90].

However, exfiltration may lead to environmental issues (e.g. contamination of the aquifer). Indeed, in coal mines, pyrite is a common sulfide mineral and its oxidation leads to a drop in pH. On the contrary, calcite present in carbonate rocks can lead to an increase in the pH [90]. Due to water exchange with the surrounding media, hydrochemical changes might lead to a change in the water chemistry in the surrounding aquifer [90]. Therefore, simulation has to be done to estimate the chance of mixing mine water with water from a nearby aquifer [201]. However, Poulain et al. [199] estimated in a chalk aquifer, a hydrochemical evolution in the aquifer only within a zone limited to the first 20 m around the cavity.

Finally, water inrush in the roofs and floors can deteriorate the stability of tunnel circumference due to upward development mechanism of water-conducting fractures which accelerate the damage process [202].

6. Discussion

6.1. Reviewed of empirical, analytical, and numerical approaches

As explained previously, several unpredictable severe problems may endanger the stability and safety of the abandoned mine area [203]. Therefore, identifying a suitable location for the underground reservoir in an abandoned mine and estimating the current condition of the mine can be challenging [92,146,155,204]. This section aims to highlight the technical approaches and contributions of the research focusing on the reuse of abandoned mines. Implementing geological assessment and geotechnical design criteria to evaluate the long-term stability and serviceability of the underground reservoir prior to UPSP operation follow similar approaches than tunnelling and conventional PSH. However, to date, only a few case-studies have been carried out to identify the required geotechnical design factors in UPSPs [75,205]. A summary of the studies available in the literature on the geotechnical aspects of UPSPs is given in Table 2. In these studies, geotechnical stability analysis is performed by empirical, analytical, and numerical approaches.

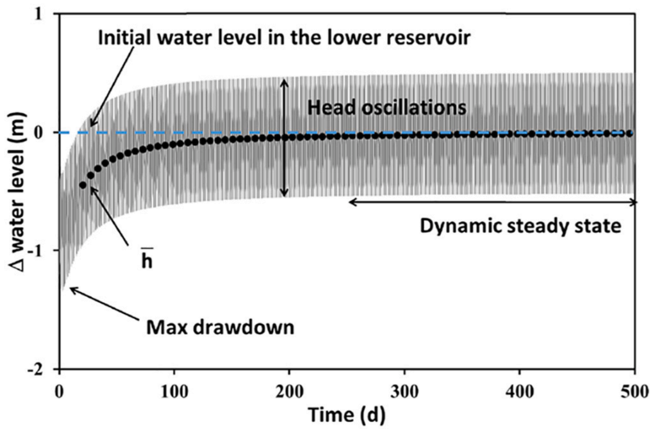

Fig. 10. Computed variation of the piezometric head in the surrounding porous medium (synthetic scenario). It is considered that the water table is located at its natural depth before starting the activity of the UPSH plant. $\boldsymbol{h}^-$ is the mean water level during one cycle (from [62,200]).

As an example, the stability of a network of tunnels used as a lower water reservoir at 450 m depth was analyzed in a closed coal mining area at the Asturian Central Coal Basin (ACCB), Spain [146]. For a preliminary design of the support systems and in order to determine the rock mass characteristics, empirical approaches based on rock mass classification systems were used. In addition, 3D numerical modeling was carried out to ensure the stability of the underground excavations. The deformation and extension of the critical zones were evaluated in the simulation with/without support systems (rock bolts) [146]. Also, three-dimensional numerical models were built for water exchange of the Martelange slate abandoned underground mine in Belgium, which is a potential site to install a UPSP. These models helped to investigate the influence and evolution of the water exchanges between the underground reservoir and the surrounding medium and how they may affect the groundwater behavior around the tunnel and the hydraulic properties inside the underground reservoir [209]. Finally, in the Prosper-Haniel hard-coal mine in Germany, geological, economic, environmental, geotechnical feasibility and hydraulic aspects were analyzed during feasibility studies [213,214].

However, only a few studies have addressed all geotechnical aspects related to the stability of underground reservoir, especially under cyclic water-rock interactions. Characterization of strengths, hydromechanically coupled behavior, and deformation evolution (potential fatigue failure) both in the field and in experiments is of great importance to study the long-term stability of an underground water reservoir. A comprehensive understanding of these aspects requires further experimental and field investigations.

6.2. Cost estimation and economical limits

The economic feasibility of Pumped Storage Hydroelectric (PSH) projects primarily depends on capitalizing on price differentials between high and low peaks of energy demand [215,216]. While PSH systems

Table 2

Case study and stability consideration.

Study area	Literatures	Stability considerations for design an UPSP
Asturian central coal basin (ACCB), Spain	[75]	• The stability of the powerhouse cavern • The effect of air pressure on the tunnels and shafts
	[206]	• Stability of a network of tunnels • The deformations and thickness of the excavation damage zones (EDZs) • Support system
	[207]	• The behavior of lower reservoir of UPSP during operation • The existence of water and air interaction
	[208]	• The flow behavior in the tunnels. • The behavior of the water-air mixture during the operation
Matelange, Belgium	[209]	• Water exchange between the underground reservoir and the surrounding medium. • Two scenarios: completely full or totally drained
	[210]	• Hydrogeological features: hydrogeological properties and the groundwater characteristics and behavior • The consequence of the hydraulic conductivity and elevation of the piezometric head
	[211]	• Groundwater flow impact • Water exchanges
Prosper-Haniel mine, Ruhr in Germany	[212]	• Hydraulic aspects for developing the project, considering construction, geotechnical, geological, and energy market restrictions.

can have extended lifetimes, the initial investment required for an Upper Reservoir Pumped Storage (UPSP) remains substantial, posing challenges for governments and energy companies [136,217].

Menéndez et al. [136] conducted a comprehensive examination assessing the economic efficiency of existing UPSP projects and identified their considerable construction costs. Excavating underground caverns and shafts, creating entirely new underground chambers, is the primary cost component, accounting for 30 % to 60 % of the total project expenditure [40]. However, constructing new excavations allows for selecting high-quality rock formations and tailoring the dimensions of the underground reservoir, as demonstrated by the UPSP project in Bukit Timah granite, Singapore [218], and the O-PAC project in the Netherlands [18,219].

Utilizing existing caverns presents potential cost savings in excavation but requires additional investments in reinforcing the initial support system and implementing supplementary grouting measures to mitigate water seepage. For example, a limestone mine project in the USA requires approximately 200 million euros for grout curtain requirements [220]. Costs associated with implementing UPSP in abandoned mines can exceed those of conventional PSH projects, such as the Grund mine project in Germany with an investment cost of 180 million euros for a storage capacity of 400 MWh [221].

However, certain projects demonstrate economic feasibility under favorable conditions, especially when rock mass properties are favorable [18,218,222]. Wong [218] study showed that utilizing a stable quarry as the upper reservoir requires minimal investments to address limited instability concerns, resulting in a project cost equivalent to that of an oil-fired plant.

Lyu et al. [215] estimated that investments for UPSP projects in China should be comparable to conventional PSH projects, thanks to shorter construction periods, reduced rock excavation requirements, and avoidance of land acquisition costs. Additionally, implementing UPSP in mines can lead to cost savings associated with post-closure water management [216] and water treatment expenses [45]. Some UPSP projects can even generate income from the excavated rocks, as seen in limestone mines [220].

In summary, while the economic viability of UPSP projects can vary depending on factors such as construction costs, rock mass properties, and post-closure considerations, they present opportunities for cost savings and revenue generation in certain circumstances.

7. Conclusion

This paper provides an overview of the current state of research on the challenges of repurposing abandoned coal mines for UPSP projects. The central focus of the paper is to investigate the three main factors that significantly influence the decision-making process in the context of UPSP projects within abandoned mines:

1. Stability factors: Time-dependent processes caused by changes in humidity(e.g., weathering, dissolution, hydration, leaching, swelling, slacking, creeping, precipitation, corrosion) and/or stress re-distribution (subsidence, fatigue, cyclic loading, support system degradation?, thermal stresses)can affect the local and global stability of the tunnel, particularly in the EDZ.
2. Environmental and human safety: Hazards associated with abandoned mines, such as mine gas accumulation and water contamination, require careful attention to protect the environment and human populations.
3. Productivity: Time-dependent water height oscillations, pressure fluctuations, and variable hydrodynamic pressure (e.g., atmospheric pressure changes, hydrostatic pressure changes) significantly affect the system's discharge performance. Additionally, water surges and water hammer processes (e.g., high-pressure surges) pose risks that can compromise the operation of the UPSP, impacting all components of the hydropower plant.

However, it is imperative to acknowledge that additional research is requisite for the refinement of the decision-making process. This forthcoming phase of our research plan entails the application of these methodologies to a practical case study, with the principal aim of achieving a more precise quantification of the influence these criteria upon the decision-making. Quantitative assessments of critical processes, such as concrete and support system fatigue, cyclical thermal stress induced by small temperature fluctuations, and hydraulic factors such as turbine efficiency, water hammer mitigation and wave propagation are essential to evaluate their implications on system stability and productivity. Additionally, detailed evaluations of long-term environmental impacts, including water exchange in lined underground reservoirs and changes in water chemistry interacting with the shotcrete, as well as the migration of gases in response to rock mass humidity changes, are essential to establish a robust framework for compliance with local regulations and to address potential social acceptance issues. Moreover, further research about the influence of groundwater flow in the original mine during the construction and how does it influence the hydraulic management.

Moreover, this paper presents the state-of-the-art empirical, analytical, and numerical approaches that contribute in the assessment of suitability of underground mines for UPSP projects. Among them, numerical approaches allow for the simulation of more complex processes, such as air pressure effects on tunnels and shafts, coupled hydro-mechanical processes around the tunnels, flow characteristics in tunnels, and water exchange dynamics between the underground reservoir and the rock mass. Despite significant progress in numerical modeling of complex processes in other applications, further research is still needed in the context of UPSPs, particularly in regard to understanding the intercorrelations and importance of all the aspects mentioned in this paper.

Furthermore, the paper offers insights into the economic aspects of converting abandoned mines into UPSP facilities. These encompass construction costs, post-closure considerations, land acquisition costs, and water treatment expenses. However, cost estimates depend to a large extend on the specific attributes of the abandoned mine, including its volume, height, length, support system condition, and rock mass conditions.

Finally, real study cases could provide opportunities to overcome these challenges and unlock the potential of abandoned coal mines as sustainable sources of pumped storage hydropower.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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