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Modelling subsidence of the ground surface over a flooded coal mine due to hydrological processes and corrosion of main support equipment

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SUMMARY

This study presents a forecast model of ground surface subsidence based on the observed corrosion-induced degradation of metal mining supports in the flooded coal mine "Centralna". The loss of structural integrity of these supports over time is quantified using corrosion rate data and integrated into a subsidence forecasting model. The geological and structural context of the mine area is characterized by a monoclinal setting with distinctly stratified sedimentary layers, which strongly influences the spatial pattern of ground deformation. This anisotropic behavior of surface settlement is critical for assessing long-term environmental and infrastructural risks in post-mining regions. The research results open up new possibilities for studying the interrelated effects of corrosion of underground structures, geological structure and the stability of the ground surface above flooded mines. This approach can be applied to other similar post-mining environments where corrosion processes play a significant role in the development of subsidence over several decades.

Introduction

The closure of coal mines and their flooding has long-term catastrophic geoecological consequences for the Donetsk region. Continuous and discontinuous deformations of the ground surface (sinkholes and subsidence troughs) of anthropogenic origination implicate hazards for the ground surface, even many decades after completion of mining work. One of the most dangerous consequences is the subsidence of the ground surface due to uncontrolled flooding of mine workings. Such deformations can lead to the destruction of buildings and infrastructure, loss of land suitability, and in some cases, to the formation of sinkholes and local disasters. Nowadays, when decommissioning and flooding of mines happens, ground movements as well as seismic events related to flooding of abandoned underground mines can be observed *(Strozik et al., 2016)*. Areas where there is no monitoring of the underground environment after mining has stopped are particularly vulnerable to such phenomena. Prediction of the subsidence of the ground surface caused by uncontrolled flooding of mines, is essential for preventing environmental and socio-economic disasters, especially in densely populated areas.

Various modelling techniques have been developed to forecast surface changes, including interpolation and polynomial models, as well as finite element methods. Ground surface displacements can also lead to the creation of much more dangerous phenomena that involve discontinuous deformations which are a particular threat for buildings located on the land surface in the region of the mine that is being liquidated *(Dudek et al., 2020)*. The advantage of the software is the ability to monitor the amount of subsidence at any point in the model, so it is more applicable to continuous and uniform subsidence with small subsidence values *(Zhang et al., 2021)*. Using numerical modelling of rock mass demonstrates the possibility of predicting uplifting of the surface caused by flooding of underground workings *(Wesołowski et al., 2018)*. Methods for modeling the subsidence of the ground surface during its preparation by cleaning workings in the mines of Western Donbass are well-founded. These ground surface and aquifer models are designed to calculate the volumes between the initial ground surface and the compacted surface, and between the aquifer and the compacted surface to identify flowage lands *(Zelenskyi et al., 2020)*.

Modelling is also actively used for forecasting and simulation purposes to predict hydrological, geochemical and other processes in coal mines, which eventually affect the processes of the ground surface subsidence *(Zhang et al., 2018)*. Studies of corrosion of metal equipment, including mining supports, contribute to understanding the complex picture of the ground surface sedimentation due to anthropogenic activities *(Craig et al., 2015; Dorion et al., 2014; Preston et al., 2019; Shvets et al., 2025a)*. Corrosion of metal equipment in a flooded coal mine results in a gradual loss of strength of supporting structures. Over time, the destruction of corroded structures causes local collapses of roof rocks. Collapses of workings create voids and disrupt the equilibrium of the geomechanical system of the massif. This leads to a redistribution of loads and the development of deformations in adjacent rocks. As a result, subsidence funnels or wide zones of slow subsidence appear on the ground surface. Thus, corrosion of equipment becomes an indirect but significant cause of underground deformations and surface subsidence.

Results

The "Centralna" coal mine in the city of Myrnohrad is one of the largest mines in the Donetsk region with extensive underground workings at depths from 450 to 700 m. After water pumping stopped in 2024, the mine was flooded by mid-2025. Taking into account the depth of occurrence, the length of the mined-out spaces and the lithological heterogeneity of the above-mine massif, there is a significant risk of gradual or sudden subsidence of the ground surface. Currently, the city of Myrnohrad is located in a zone of active military operations, which is an additional risk factor for subsidence of the ground surface. Bombing and shelling, destruction of infrastructure, underground vibrations from explosions can not only cause new deformations, but also activate existing geomechanical processes. Under these conditions, traditional methods of active observation and monitoring are unavailable, and modeling is the only possible method for predicting the processes of ground surface subsidence.

The "Centralna" mine is characterized by specific geological and hydrochemical conditions. The mine workings are monoclinal, with dip angles from 12° to 18°. The immediate roof of the seem consists of weakly to moderately competent argillites and siltstones. In places where argillites and siltstones pinch out, occurrences of a "false roof" with a thickness of up to 0.5 - 1.2 m are possible. The main roof consists of sandy shale with a layer height of 3 to 7 m, turning into sandstone with a layer height of up to 34 m. Support systems include steel arches and concrete elements. The cross-section of the workings is arched with a height of 3.2 m and a width at the base of 4.13 m.

An analysis of the physical and chemical parameters of the groundwater in the "Centralna" coal mine showed that the metal mining equipment in the flooded mine is in a slightly alkaline environment with a pH of 7.7 with elevated temperature and a high content of chlorides and sulfates. An increased chloride content was detected in the water (267 mg/l), which significantly increases the corrosion of flooded metals, especially iron, steel and aluminum. The presence of sulphide minerals (e.g. pyrite) and variable redox conditions further enhance iron leaching. The electrical conductivity of the mine water is high (3610 µS/cm), therefore, the ionic conductivity is high *(Shvets et al., 2025b; Bohomaz et al., 2025)*.

In a flooded mine, the chemical composition of groundwater significantly affects the destruction of metal and concrete mining supports. This factor should be taken into account in the model of support degradation and prediction of subsidence of the ground surface above the flooded mine. The model of mining support degradation takes into account the kinetics of thickness loss of metal support elements and chemical destruction of concrete. Metal supports are subject to accelerated corrosion in the presence of chlorine ions, which disrupt the passive protective film. It has been established that for the conditions of the "Centralna" mine, the rate of metal corrosion is from 0.05 to 0.15 mm/year *(Shvets et al., 2025a)*. As a result, there is a loss of sections of metal elements of supports up to 90% and a complete loss of their bearing capacity. Concrete supports are vulnerable to sulphate corrosion. Sulphate ions interact with tricalcium aluminate in cement to form ettringite, which causes expansion and cracking of the concrete. The rate of destruction can reach 20 mm/year. The model of supports' degradation assumes calculation of the loss of metal supports' thickness in the flooded "Centralna" mine under three scenarios of corrosion rate: optimistic, moderate and pessimistic for a forecast horizon of 30 years (Fig. 1).

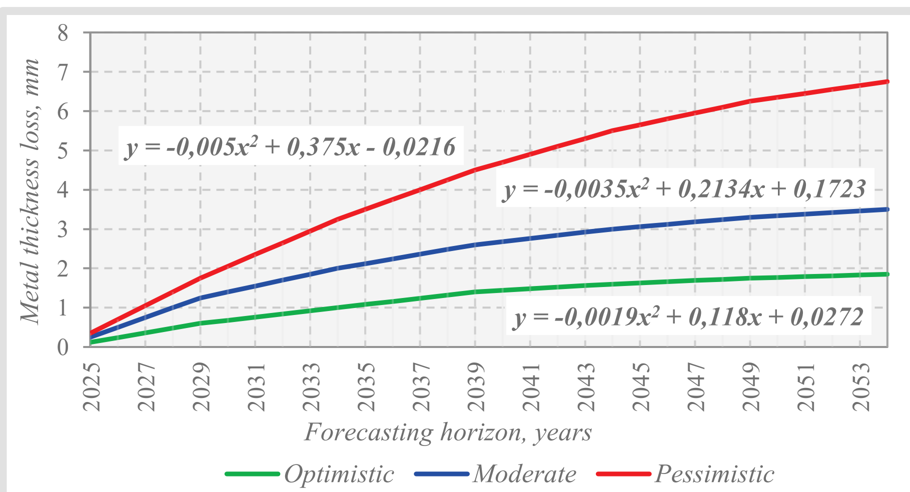

Figure 1 *Forecast of the loss of metal support thickness at the flooded "Centralna" mine under three scenarios of corrosion rate: optimistic, moderate and pessimistic.*

For the conditions of the "Centralna" mine, three scenarios of degradation of mining supports were considered, taking into account the instability of the chemical composition of groundwater and the complexity of hydrogeological processes affecting the subsidence of the ground surface above the mine workings. Based on the obtained data on the thickness loss of metal structures, a forecast of the subsidence of the ground surface was calculated for three scenarios that characterize the collapse of the arched vaults of the mine workings in 30 years after flooding (Fig. 2). Given the monoclinal structure and stratified geology, the subsidence of the ground surface will be asymmetrical and elongated along the direction of the fall of the layers.

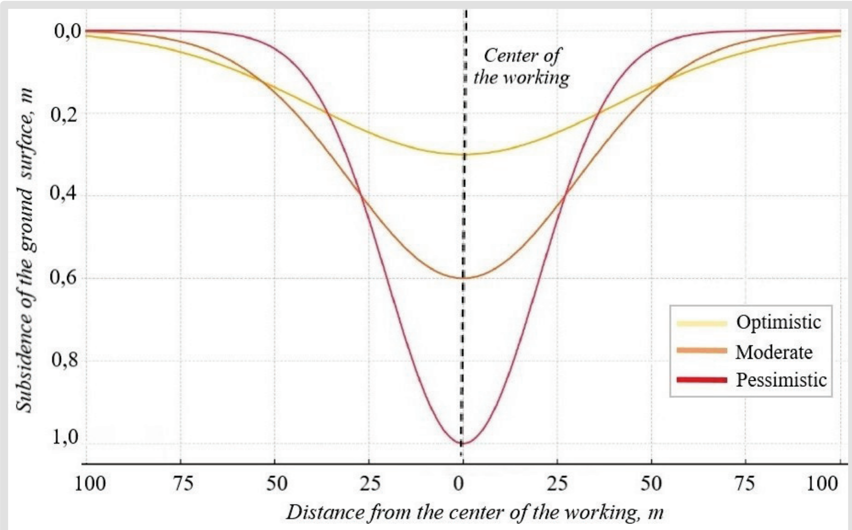

***Figure 2** Forecast of subsidence of the ground surface above the mine workings of the "Centralna" mine*

The optimistic scenario assumes partial destruction of the supports, accompanied by stabilization of the stress state of the rock mass. Subsidence is limited and reaches no more than 0.3 m in 30 years. This scenario can take place under the condition of weak corrosion and the absence of significant external impacts. The moderate scenario assumes gradual destruction of metal supports due to slow corrosion. The geomechanical model displays the plastic behavior of argillites and siltstones with partial preservation of stability. The maximum subsidence is up to 0.6 m. The pessimistic scenario of accelerated subsidence is the worst possible one. The destruction of the supports occurs quickly and is intensified by external dynamic loads (explosions, bombing and shelling). Voids and cracked zones are formed, leading to intense subsidence. It may reach 1.0 m within 10-15 years, which will pose a danger to infrastructure on the ground surface. The obtained forecast data demonstrate a symmetrical distribution of the surface subsidence area, deepest in the center and decreasing exponentially towards its edges.

Conclusions

Due to the massive uncontrolled flooding of coal mines in the Donetsk region, there is a change in the physical and mechanical properties of rocks and the activation of geomechanical processes. The result of these processes is the subsidence of the ground surface over flooded mine workings, which is especially evident during shelling and bombing. The rate of subsidence of the ground surface is significantly affected by the destruction of metal mining supports under the influence of aggressive groundwater. Modeling the corrosion processes of metal mining equipment in the flooded mine "Centralna" allowed us to predict the rate of degradation of metal supports and determine the period of their destruction. According to the pessimistic scenario, the loss of metal thickness could be 6.7 mm over 30 years, which would lead to a complete loss of the bearing capacity of the supports and cause accelerated subsidence of the ground surface. The land subsidence forecast showed expected vertical deformations in three scenarios: optimistic, moderate and pessimistic. According to the pessimistic scenario, the greatest subsidence could reach 1.0 m in 30 years.

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