

CHALLENGES IN MINING SUBSIDENCE ENGINEERING

Nenad Vušović^{1a}, Milica Vlahović^{2a*}

¹ University of Belgrade, Technical Faculty in Bor, Vojske Jugoslavije 12, 19210 Bor, Serbia;

² University of Belgrade, Institute of Chemistry, Technology and Metallurgy-
National Institute of the Republic of Serbia, Njegoševa 12, 11000 Belgrade, Serbia

^{1a} nvusovic@tfbor.bg.ac.rs, 0000-0001-5246-4243

^{2a,*} m.vlahovic@ihtm.bg.ac.rs, mvlahovic@tmf.bg.ac.rs, 0000-0002-7893-9101

Abstract

Subsidence represents one of the most complex and debated issues in rock mechanics and geotechnical engineering. It can significantly impact the environment and endanger the stability of surface and subsurface structures and infrastructure. Reliable prediction methods are therefore essential to mitigate the adverse effects of mining-induced subsidence. This paper examines the mechanisms of mining subsidence and outlines different excavation-induced forms, with emphasis on trough and sinkhole subsidence. The key factors influencing subsidence above underground workings are briefly reviewed. Finally, several case studies of sinkhole subsidence worldwide are presented to highlight the scale and significance of the problem.

Keywords: *underground mining, mine subsidence, sinkhole subsidence, residual subsidence*

1. INTRODUCTION

Underground excavations disturb the natural equilibrium of the rock mass, causing load redistribution that leads to deformation and displacement of surrounding strata. As these displacements propagate towards the surface, they result in ground subsidence, which typically manifests in two main forms:

- **Displacement** refers to changes in the position of specific points within the undermined rock mass and on the ground surface, as primary or secondary consequences of underground mining. Geometrically, it is defined as a vector connecting the initial position of a point in the undisturbed rock mass with its new position after equilibrium has been re-established. If the displacement process is ongoing, the vector represents its instantaneous value. The vertical projection of this vector corresponds to settlement, while the horizontal projection represents horizontal displacement [1].
- **Subsidence** is a general term describing the downward vertical movement of the Earth's surface, which may result from both natural processes and human activities [2].

Mining subsidence, a universal phenomenon associated with voids formed by the extraction of solid or liquid resources under the surface, is influenced by multiple factors including mining method, extraction depth, deposit thickness, topography, and the geomechanical properties of the overlying strata.

Certain underground mining methods, particularly those designed to induce caving (e.g., pillar extraction, longwall mining, block caving, sublevel caving) commonly result in surface subsidence. While mining-induced subsidence is often relatively predictable in magnitude, extent, and pattern, unexpected collapses of pillars or shallow workings (typically in old mines) can lead to sudden, severe ground failures [2]. Associated surface effects such as horizontal tensile and compressive strains, curvature, tilting, and horizontal displacements are among the most frequent causes of damage to buildings and infrastructure [3].

2. SUBSIDENCE AND THE DIFFERENT SUBSIDENCE TYPES

The development of mining subsidence is primarily governed by geological and mining-related factors such as the mechanical behavior of the rock mass, mining depth, excavation geometry, surface topography, and the applied mining method. For example, partial extraction methods (e.g., shallow room-and-pillar mining in weak rock) show distinct subsidence mechanisms compared to total extraction methods (e.g., deep longwall mining or top-coal caving). In longwall mining, caving progresses rapidly, and surface subsidence occurs almost immediately after extraction, typically stabilizing within a short period. However, a portion of ground movement continues later, caused by the re-compaction of caved material. The rate and duration of these movements depend on the depth, extraction speed, and geotechnical properties of overburden strata. This form of ground depression, common in longwall mining, is known as *trough subsidence*, a broad, shallow sag of the surface [3,4]. Another form, more typical of shallow excavations with partial extraction, is *sinkhole subsidence* (also referred to as pit, crown-hole, or chimney subsidence). It occurs due to localized mine roof failure that propagates upward to the surface, resulting in sudden sinkhole formation.

Research shows that a large share of surface structure damage and casualties is caused by sinkhole subsidence. The reason lies in the fact that trough subsidence can be recognized early in its development, allowing for preventive measures to reduce its impact [1,3,4]. By contrast, sinkhole subsidence is often catastrophic, appearing without warning and without reliable prediction of timing or location. Moreover, while longwall mining affects vast areas and thus causes relatively uniform deformations, sinkhole subsidence is localized, leading to more severe structural damage on the surface [5].

2.1 Sinkhole Subsidence

Sinkhole subsidence represents one of the most hazardous post-mining problems, with highly complex mechanisms. Before investigating subsidence processes, it is essential to understand the modes of failure and conditions that trigger sinkhole formation. This type of subsidence is usually caused by the sudden collapse of roof strata into underground voids, progressing upward through the overburden in the form of a chimney until it reaches unconsolidated surface materials. Alternatively, sinkholes may develop when loose sediments and rock debris migrate downward into mine voids through fractured or weathered overlying strata.

Such failures are especially common in shallow, abandoned room-and-pillar workings where the roof lacks long-term stability. Over time, progressive collapse of roof layers and flow of broken material into the void ultimately leads to sinkhole formation at the surface [5].



Figure 1. Sinkholes above Berezniki potash mine, Russia: a) June 2007 and b) November 2008 (source: Itar-Tass news agency and ru.wikipedia.org).

Most sinkholes appear circular or elliptical, with typical diameters of less than 10 m and depths under 15 m. However, in extreme cases, their dimensions may exceed several hundred meters [5,6]. Typical examples are shown in Figure 1, illustrating sinkholes above the Berezniki potash mine in Russia (June 2007 and November 2008).

2.2 Trough Subsidence

The mechanisms of trough subsidence caused by longwall mining have been widely investigated and documented in the literature. Although this phenomenon is generally well understood, a number of questions still remain concerning the role of certain influencing factors. Subsidence development in such excavations is controlled by a range of geological and mining conditions, and therefore requires detailed study to fully capture the contribution of each parameter [1].

The most significant factors include, but are not limited to: the mechanical behavior of rock masses, the geometry and properties of discontinuities and their mechanical responses, groundwater levels and their adverse influence on rock mass strength, the magnitude and orientation of in-situ stresses, the extraction method applied, and the rate of resource exploitation.

Accurate determination of rock mass parameters is a fundamental prerequisite for analyzing the mechanisms of mining subsidence, since they serve as input data for analytical and numerical deformation simulations [3,4]. However, estimating these parameters is often extremely delicate. Without reliable values for the mechanical properties of rock strata, the outcomes of subsidence modeling cannot be considered trustworthy.

Surface topography is another key factor controlling the development of trough subsidence. When mining takes place beneath sloping terrains, the mechanisms of ground movement differ substantially from those observed in flat terrains, where the overburden behaves more symmetrically [3].

2.3 Active and Residual Subsidence

Subsidence may accompany both active and abandoned mining operations. *Active subsidence* encompasses all ground movements that occur simultaneously with the mining process, while *residual subsidence* refers to deformations that develop after mining activities have ceased [7].

Understanding the forms of deformation and their timing is essential for predicting the impacts on surface structures and planning mitigation measures.

Although predicting the duration of subsidence is a critical aspect of mine design and land-use planning, only limited research has addressed the influence of geological and mining factors on the length of deformation processes [3,4].

At present, there is no universally accepted and practical method for estimating subsidence duration. Experimental approaches are often costly and technically demanding. For longwall operations, considerable effort has been devoted to analyzing the time frame of subsidence development, but in the case of sinkhole subsidence, especially above room-and-pillar mines, reliable predictive models are still lacking.

One of the main reasons is that the duration of such deformations is largely governed by the long-term mechanical response of roof and floor strata, as well as the stability of the supporting pillars.

The interactions between pillars and surrounding strata play a crucial role in this mechanism [5].

Residual subsidence is a particularly severe issue in urban areas built over abandoned mine workings. Assessing long-term stability in such settings is a highly complex task, because time-dependent processes such as creep, progressive weakening, and deterioration of rock mass properties must be considered. These effects may extend subsidence over several decades. Reliable

prediction of residual subsidence is therefore of great importance for evaluating the long-term safety of surface structures and infrastructure [3,6].

3. CONCLUSION

Mining-induced subsidence has long been recognized as a serious geotechnical challenge. Consequently, extensive efforts have been devoted to the development of theories, empirical models, and analytical methods for estimating the magnitude and geometry of subsidence profiles. Nevertheless, accurate prediction, particularly of sinkhole subsidence, remains a difficult task. The complexity of the problem arises from numerous interrelated factors, including uncertainties in the mechanical behavior of the rock mass and caved materials, the in-situ stress regime, groundwater conditions, and the geometry and properties of discontinuities such as joints, bedding planes, and faults. The progressive deterioration of rock mass properties further complicates prediction and analysis.

Although a variety of approaches, such as graphical methods, profile function models, and influence function techniques, have been successfully applied to estimate the shape and extent of trough subsidence above longwall panels, these methods are generally unsuitable for shallow excavations where sinkhole subsidence dominates. In such cases, both the magnitude and duration of ground movements are far more difficult to forecast. Sinkhole subsidence above room-and-pillar workings may be delayed for decades, and its sudden occurrence poses severe risks to infrastructure and human safety.

Developing reliable methods to approximate the timing and scale of these deformations remains a priority in geotechnical engineering, particularly for stability assessments of structures in undermined areas.

ACKNOWLEDGEMENTS

This study was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (grant numbers 451-03-137/2025-03/200131 and 451-03-136/2025-03/200026).

REFERENCES

- [1] D. Đorđević, N. Vušović., Prognosis of the Displacement and Deformation of the Underground Terrain, University of Belgrade, Faculty of Mining and Geology, Belgrade, 2014, p. 19-28.
- [2] M. Allaby., A dictionary of Geology and Earth Sciences, Oxford: Oxford University Press, Oxford, 2013.
- [3] N. Vušović, R. Hejmanowski, M. Vlahović., Appl. Sci. 15 (2025) 1-30.
- [4] N. Vušović, M. Vlahović, D. Krzanović., Environ. Earth Sci. 80 (2021) 67.
- [5] T. Waltham, F.G. Bell, G. Martin, M.G. Culshaw., Sinkholes and Subsidence, Karst and Cavernous Rocks in Engineering and Construction, Springer with Praxis Publishing, Chichester, 2005.
- [6] E.F. Salmi, M. Karakus, M. Nazem., Tunn. Undergr. Sp. Tech. 88 (2019) 169-185.
- [7] E.F. Salmi., A numerical investigation of the mechanisms of post-mining subsidence, Doctoral thesis, The University of Newcastle, Australia, 2016.