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ANALYSIS AND PROGNOSIS OF SURFACE SUBSIDENCE IN THE JIU VALLEY

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ABSTRACT

Surface subsidence resulting from underground mining activities is a critical environmental and engineering concern that has garnered substantial attention in both academic and practical contexts. The phenomenon occurs when the removal of underground materials, such as coal, minerals, or ores, leads to the collapse or settling of the surface. This study examines mining operations conducted within the thick coal seams of the Jiu Valley Coal Basin in Romania, which utilize longwall mining techniques featuring roof control through caving or top coal caving methods. The analysis focuses on the complex deformations of the ground surface that have occurred over time as a direct result of coal extraction activities in specific mining sectors of the basin. Furthermore, the phenomenon of ground surface subsidence is investigated using the CESAR-LCPC finite element code. The modeling is conducted under the assumptions of elastic and elasto-plastic behavior. A temporal analysis of ground surface deformation is also conducted using a profile function. The results obtained from the modeling are subsequently compared with a comprehensive dataset of in situ measurements.

KEYWORDS: surface subsidence, finite element modeling, underground mining, profile function

1. Generalities

1.1. Mechanisms of Surface Subsidence

The mechanisms underlying surface subsidence are complex and multifaceted, often influenced by geological, hydrological, and mining factors. Subsidence can be categorized into two primary types: immediate and delayed [1]. Immediate subsidence occurs shortly after mining activities commence, while delayed subsidence manifests over a longer timeframe, often years after mining has ceased. The timing and extent of subsidence are influenced by the type of mining method employed, the geological characteristics of the overburden, and the depth and extent of the mined-out area [2].

Numerous studies have explored the mechanics of subsidence. For instance, the work of Zhang *et al.* [3] emphasizes the role of stress redistribution within the overburden strata as a primary driver of subsidence. When coal or minerals are extracted, the stress previously supported by the mined material is redistributed to the surrounding rock, leading to the potential failure of the overburden and resultant surface displacement.

Additionally, the interaction between surface and underground hydrology can exacerbate subsidence. As noted by Xu *et al.* [4], changes in groundwater levels due to mining can lead to increased pore water pressure in the overburden, further destabilizing the surface layers.

1.2. Impacts of Surface Subsidence

The impacts of surface subsidence are extensive and can affect both the environment and human infrastructure [5-7]. One of the most significant concerns is the potential for damage to buildings, roads, and other forms of infrastructure [8, 9]. Research by Li *et al.* [10, 11] highlights the fact that subsidence can lead to structural failures, creating safety hazards and economic burdens for communities. In addition to physical damage, subsidence can also disrupt local ecosystems, affecting soil stability, vegetation, and water drainage patterns [12-14].

The socio-economic implications of subsidence are also noteworthy. Many mining regions are home to vulnerable populations that may not have the resources to adapt to or mitigate the impacts of subsidence. As outlined by O’Neill *et al.* [15], the displacement of communities due to subsidence-related hazards poses significant social challenges, including the loss of livelihoods and cultural heritage. Furthermore, the psychological impacts of living in subsidence-prone areas can lead to increased stress and anxiety among residents [16].

1.3. Impacts of Surface Subsidence

Given the potential consequences of surface subsidence, numerous strategies have been proposed and implemented to mitigate its effects. One common approach is the use of subsidence monitoring systems, which utilize techniques such as InSAR (Interferometric Synthetic Aperture Radar) and ground-based surveys to detect and measure ground movement [17]. These monitoring systems allow for the early detection of subsidence, enabling timely intervention measures.

Another mitigation strategy involves the design of mining operations that minimize subsidence risk. For example, the implementation of stope design principles that maintain a stable roof can reduce the likelihood of immediate subsidence [18]. Additionally, backfilling techniques, in which mined-out areas are filled with waste material, have been shown to effectively reduce subsidence by providing additional support to the overburden [19].

Community engagement and education are also vital components of effective subsidence mitigation. As highlighted by Smith *et al.* [20], involving local communities in monitoring efforts and decision-making processes can enhance resilience and foster a collaborative approach to managing subsidence risks. This participatory approach not only empowers communities but also improves the effectiveness of mitigation strategies by incorporating local knowledge and perspectives.

1.4. General information regarding underground mining in the Jiu Valley

The Petroşani Hard Coal Basin constitutes the most significant hard coal deposit in Romania, with an estimated balance reserve of approximately one billion tons. This coal deposit has been recognized and exploited since 1788, during the era of the Austro-Hungarian Empire. However, substantial coal extraction commenced concurrently with Romania's industrialization following World War II, peaking at over 9 to 10 million tons annually after 1980.

Following the reorganization of the Romanian industrial sector post-1990, in response to the evolving demands of a market economy, coal production from this basin was curtailed to approximately 3.5 million tons per year. Initially, the coal deposit was divided into 16 mining fields; however, subsequent reorganizations and closures have resulted in the operational status of only 7 mining fields.

The complex tectonic structure of the deposit necessitates the delineation of geological blocks of limited extent, typically ranging from 200 to 300 meters, which presents significant technical challenges for mining operations. Furthermore, the deposit is characterized by methane gas emissions, with levels exceeding 10 to 15 cubic meters per ton of coal, and a notable propensity for self-ignition of coal.

The genesis of the deposit is sedimentary, with prevalent rock types in the basin including limestone, marl, argillaceous or marly sandstone, and conglomerate. The strength of these rocks varies between 15–16 MPa and 50–60 MPa, with instances of even higher strength, indicating a general trend of relatively low stability.

The primary factors influencing the stress and strain conditions surrounding excavations resulting from coal seam mining, particularly with respect to roof rock caving in the Jiu Valley Coal Basin, include excavation dimensions, seam inclination, the geomechanical properties of the coal and surrounding materials, mining depth, characteristics of face supports, face advancement rates, and distances from adjacent panels and nearby coal seams.

Through surface measurement analyses conducted under the influence of underground mining, optimal design parameters for the main safety pillars have been established, leading to the determination of subsidence limit angles for various coal mining fields within the Jiu Valley Coal Basin.

This study focuses on analysing the impact of underground mining on the ground surface above coal seam No. 3 in the Uricani, Vulcan, Lonea, and Petrila mines, utilizing a newly developed profile function. Additionally, numerical modeling of the subsidence phenomenon has been performed for the Uricani Mine employing the CESAR-LCPC finite element software.

Typically, the temporal evolution of the subsidence basin is dynamic. As longwall face mining progresses, the length of the panel increases, and the subsidence basin transitions through subcritical, critical, and supercritical stages. Following the cessation of mining activities, the subsidence phenomenon gradually diminishes, coinciding with the settlement of caving rocks, resulting in residual subsidence. A pertinent case study is provided by Panel 5 of coal seam No. 3 at the Livezeni Mine, characterized by a dip of 15-22

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degrees, a thickness of 12.5 meters, and a mining depth of 340 meters.

The findings from the 2D finite element modeling using the CESAR-LCPC code indicate that the development of the subsidence basin is dynamic and contingent upon various panel mining dimensions. It has been established that at the maximum panel size of approximately 440 meters (the actual length of Panel 5), critical subsidence had not been attained. Critical subsidence is projected to occur at a panel extension of 2000 meters; beyond this threshold, the subsidence is classified as supercritical.

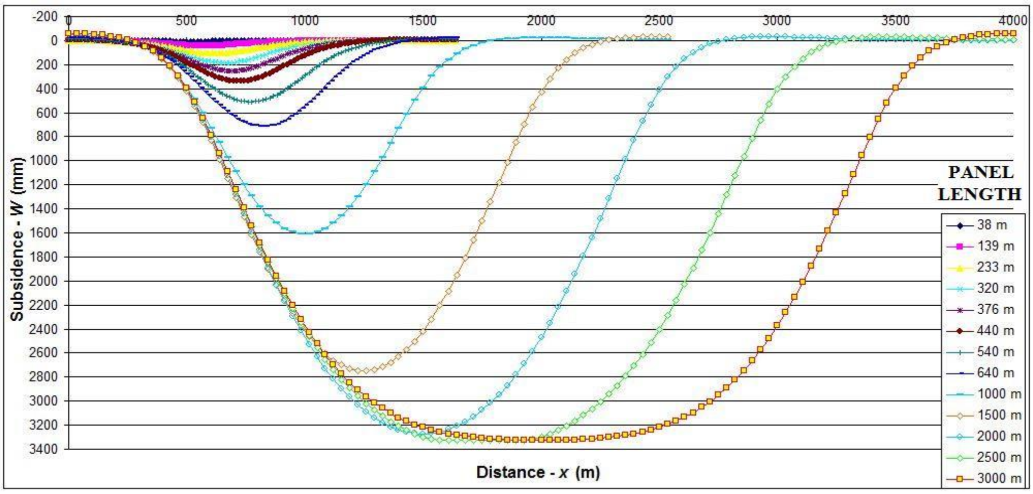

Fig. 1. Dynamic Subsidence Trough

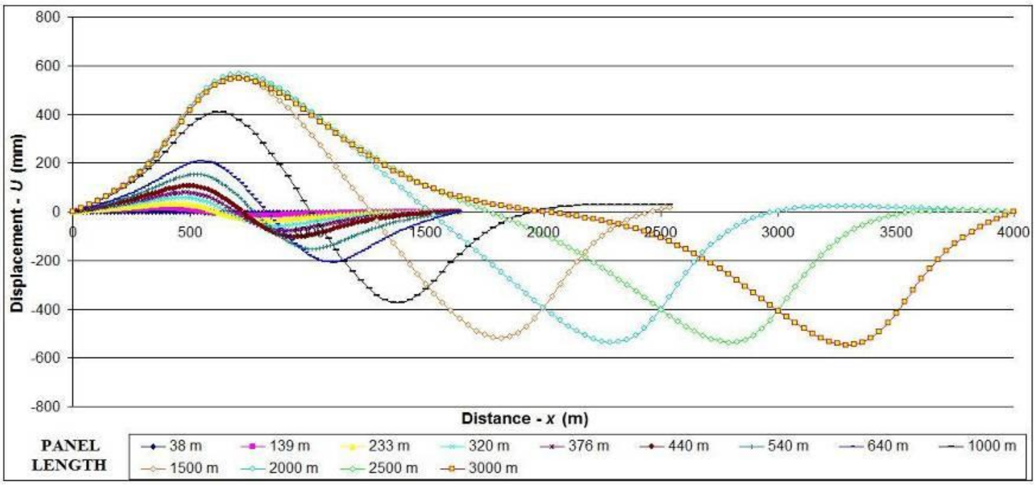

Fig. 2. Dynamic Horizontal Displacements

2. An Examination of Subsidence Phenomena Associated with underground mining at the Uricani Mine

The monitoring of ground surface displacement in response to underground mining activities at the Uricani Mine is conducted through a designated monitoring station comprising ten observation benchmarks, spanning a total length of 563.6 meters. Topographical measurements have been systematically performed on a quarterly basis, commencing in October 2007. This monitoring station is instrumental in providing empirical data regarding the displacements and deformations of the ground surface attributable to the exploitation of coal from Seam No. 3, Block V, Panel 1 (Figure 3).

The extraction process involved the mining of a thick, gently inclined coal seam, characterized by an inclination of less than 10 degrees, utilizing the top coal caving longwall mining method. This method was employed over the entire thickness of the seam and across a panel length of 354 meters. The mining operations for this panel commenced in 2003 and reached completion in the latter half of 2007.

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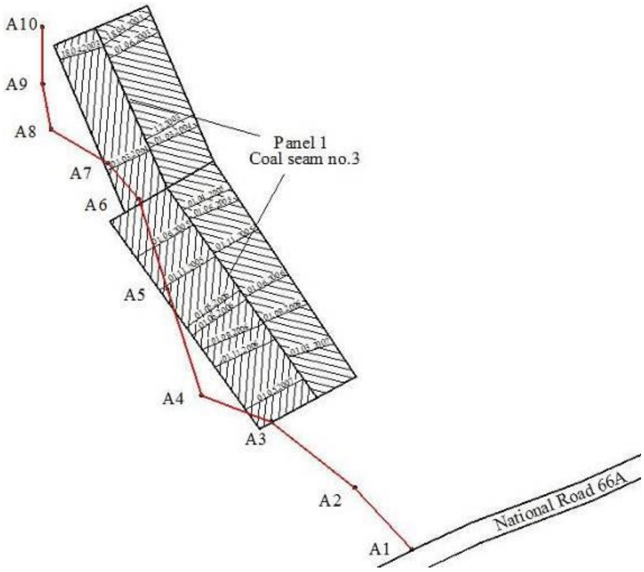

Fig. 3. *Surface displacement monitoring Station, Uricani Mine*

2.1. Statistical Interpretation of the Measurements

The subsidence basins that were measured were subjected to a statistical analysis utilizing a profile function represented by the following equation:

$$W(x) = a \cdot x^{b} \cdot e^{-c \cdot x} \tag{1}$$

To incorporate time into this function, a regression analysis was performed on all regression coefficients as a function of time t. This process yielded a novel generalized profile function that is dependent on time, expressed as follows:

$$W(x,t) = a_1 \cdot t^{a_2} \cdot x^{b_1 \cdot ln(t) + b_2} \cdot e^{-(c_1 \cdot ln(t) + c_2) \cdot x} \tag{2}$$

Where: *x* is the distance measured from the limit of the subsidence trough; *t* is time;
$a_1 = 2 \cdot 10^{-31}; b_1 = -2.593; c_1 = -0.0074;$
$a_2 = 12.936; b_2 = 15.365; c_2 = 0.0435$ (R^2=0.971) are the coefficients of regression for this profile function.

Figure 4 illustrates the actual subsidence graphs as a function of time alongside the outcomes generated by the time-dependent profile function.

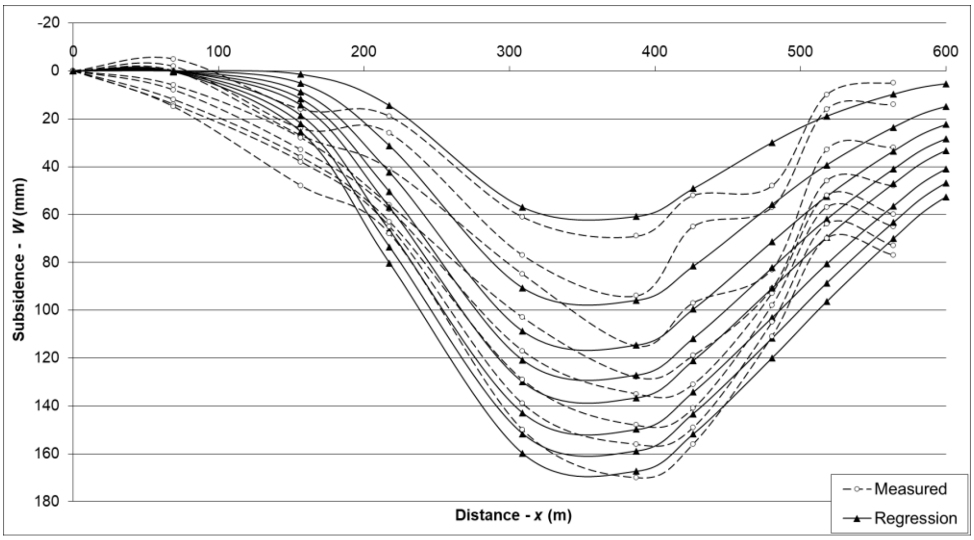

Fig. 4. *Measured subsidence curves and the Corresponding Profile Functions, Uricani Mine*

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2.2. 3D Finite Element Modeling

To develop the three-dimensional (3D) finite element computational models, the CESAR-LCPC software, version 4, was employed. In the context of the Uricani Mine, two distinct models were constructed to assess ground surface subsidence and displacement, adhering to the plane strain hypothesis. Model 1 was oriented along the seam dip, as a vertical cross-section at point A6, as shown in Figure 3. The second model was aligned with the seam strike, depicting a directional cross-section through the central portion of the goaf space.

The computations were conducted under the assumption of elasto-plastic behavior without hardening, positing that both the surrounding geological formations and the coal seam are continuous, homogeneous, and isotropic. The geomechanical parameters utilized in the calculations were average values (γ_a = 26.6 kN/m^2, E = 5 035 000 kN/m^2, ν =0.19 and ϕ =55°). Additionally, the caved roof rocks were modeled as a highly compressible medium, characterized by a Young's modulus of E = 15 000 kN/m^2 and a Poisson's ratio of ν =0.4.

To calibrate the models in accordance with the measured values of maximum vertical displacements and to adjust laboratory characteristics to reflect *in situ* rock properties, successive calculations were performed with the characteristic values reduced by 50%, 60%, and 70%, corresponding to structural weakness coefficients K of 0.5, 0.4, and 0.3, respectively, as depicted in Figure 6b.

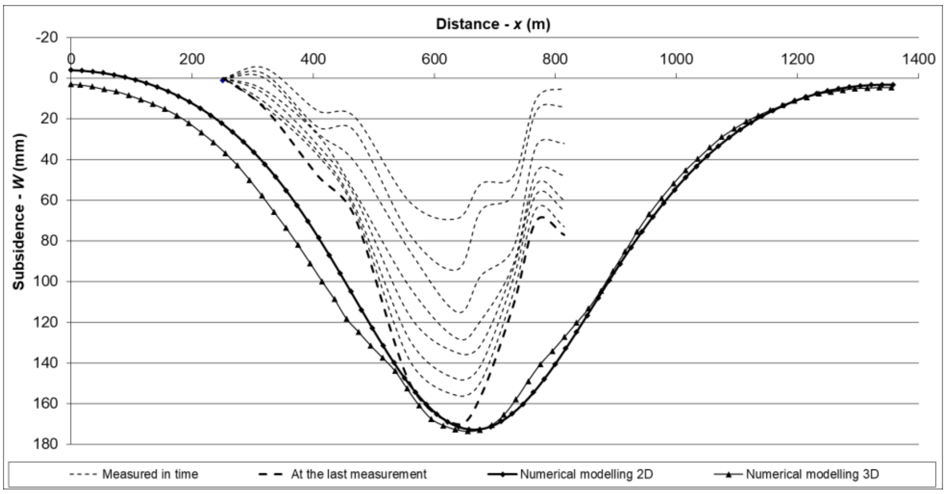
The initial loading conditions were established as geostatic $[\sigma_o]$, corresponding to a depth of approximately 390 meters. This resulted in vertical geostatic stresses of σ_{oy} = 102.4 MPa; and horizontal geostatic stresses of $\sigma_{ox} = k_o \cdot \sigma_{oy} =$ 24.6 MPa (where:$k_o = \frac{\nu}{1-\nu} = 0.24$). The stresses induced by the excavations were also calculated $[\sigma_e] = [-102.4;\ -24.6]$ MPa. Ultimately, the models were subjected to total stress loading conditions:$[\sigma_T] = [\sigma_o] - [\sigma_e]$.

The analysis indicated that the model with a 60% reduction in characteristics closely approximated real-world conditions. Consequently, the "strike model" was analyzed under the Mohr-Coulomb elasto-plastic behavior hypothesis, incorporating a structural weakness coefficient K of 0.4. In this model, a coefficient was introduced to account for the third dimension (panel width), which reduced the mining void stresses $[\sigma_e]$ by approximately 60%.

For the construction of the 3D finite element models, the CESAR-LCPC finite element code was utilized. The model designated "with mining voids" was developed to evaluate displacements and ground surface deformations in three dimensions, employing an elastic behavior hypothesis that involved reducing the properties of the rocks and coal.

The model dimensions were specified as X = 1354 m, Y = 1100 and Z = 470 m. The meshing of the model, as well as each region, was accomplished with hexahedral elements employing linear interpolation. Thus, a number of 48000 nodes and 44800 volume elements resulted.

The subsidence basins derived from measurements, as well as from both 2D and 3D numerical modeling, were compared along the monitoring station's approximate route, as illustrated in Figures 5 and 6. Figure 6a depicts the displacement along the X-axis obtained from the 3D numerical modeling, following the monitoring station's approximate route shown in Figure 5. A comparison between the numerical model's subsidence basin and the measured subsidence (Figure 5) revealed that while the maximum subsidence values were equivalent, there were deviations in the overall subsidence profile.



a)

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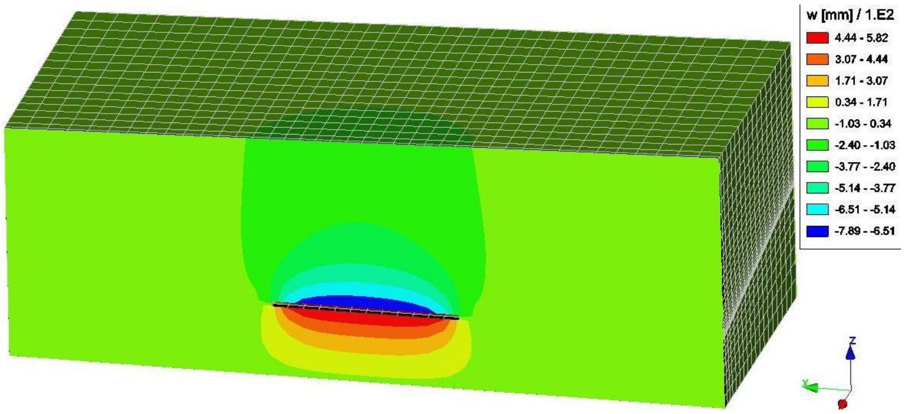
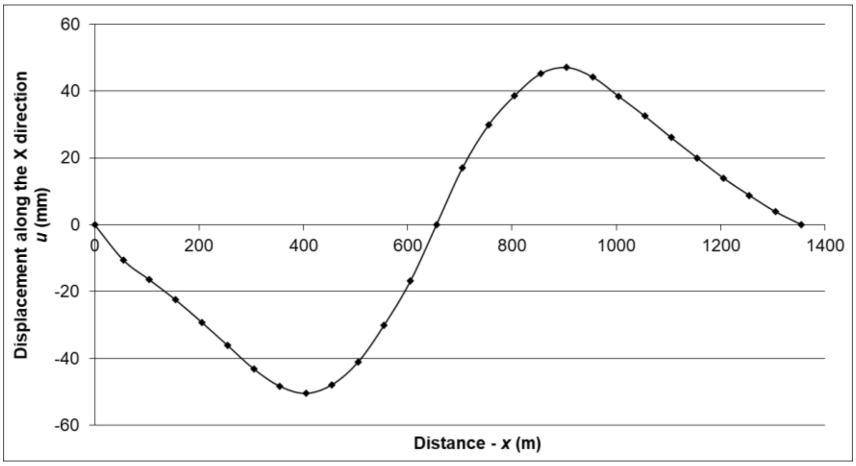


b)

Fig. 5. *Subsidence trough resulted from 3D Numerical Modelling and measured subsidence*



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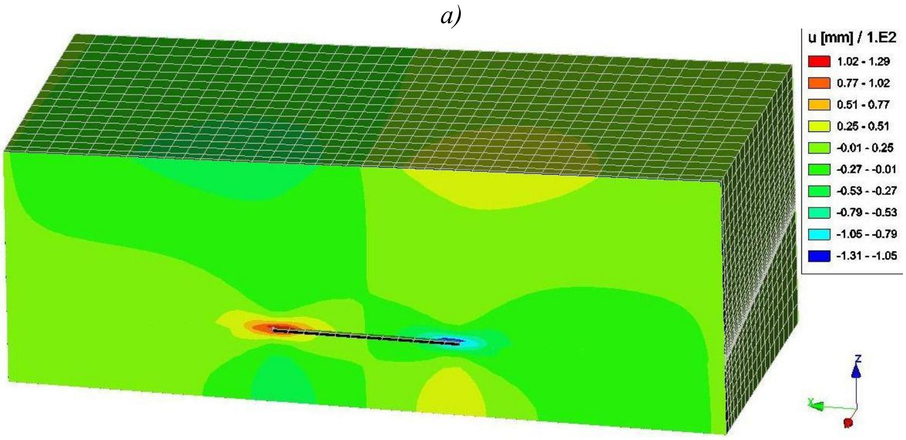

b)

Fig. 6. *Horizontal displacement from 3D Modelling (along the X Direction)*

3. Analysis of Subsidence Associated with Coal Seam No. 3 at the Vulcan Mine

The assessment of ground surface subsidence attributable to underground mining activities at the Vulcan Mine is conducted utilizing a monitoring station comprising 16 benchmarks, which collectively span a length of 620.8 meters. This monitoring station is instrumental in providing data regarding ground surface subsidence and deformation resulting from the extraction of coal seam No. 3, specifically within Block VII-VIII, at Faces No. 366 and 376 (Figure 7).

Coal seam No. 3, characterized by an average thickness of approximately 50 meters, is extracted

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using a top coal caving mining method, which is associated with the aforementioned coal faces. The commencement of mining operations dates back to 1964, at which time a roof control technique involving rock caving was implemented.

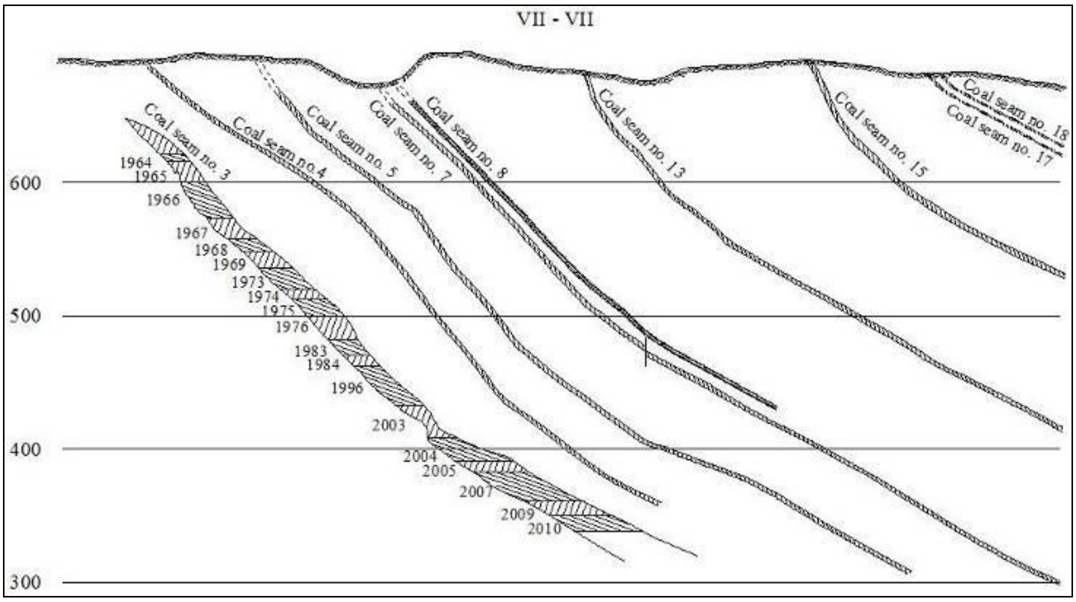

Fig. 7. *Cross - Section, Vulcan Mine*

Following the statistical interpretation of the measurements utilizing the profile function (1), a regression operation was conducted to determine the coefficients of regression for each measurement phase. Consequently, the generalized time-dependent profile function (2*)* was derived, yielding a coefficient of determination R^2 of 0.95 $a_1 = 7 \cdot 10^{-13}$; $b_1 = -4.186; c_1 = -0.0113$;
$a_2 = 21.23;\ b_2 = 60.35; c_2 = 0.1363$

The subsidence curves, which were measured periodically, along with the approximation curves of the time-dependent profile function, are graphically depicted in Figure 8. This figure illustrates a strong correlation between the *in-situ* measurements and the model, as evidenced by the high R^2 value of 0.95.

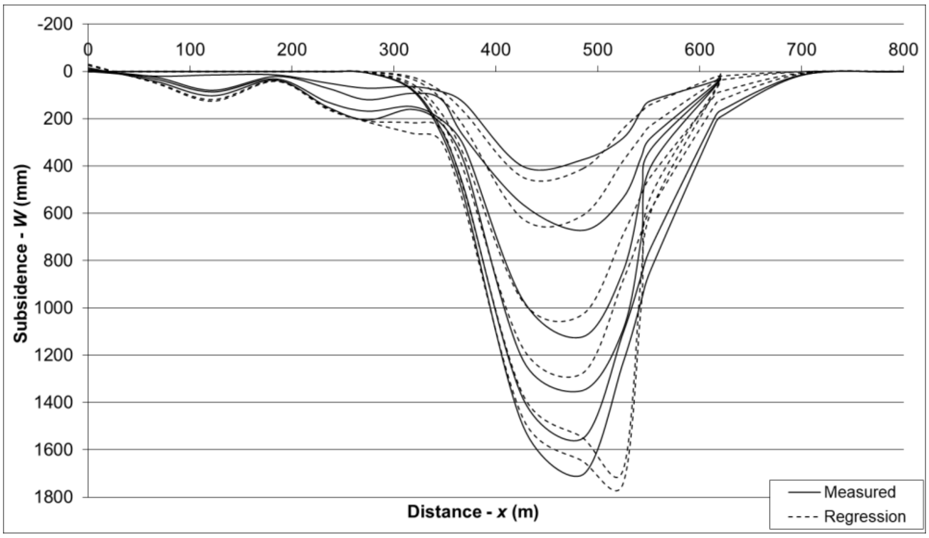

Fig. 8. *Measured subsidence and the temporal profile function curves at Vulcan Mine*

4. Surface Subsidence Analysis in the case of Petrila Mine

The measurements conducted along the alignment designated as 200, which was established in 1981, comprise 16 monitoring benchmarks arranged at intervals of 250 meters. Since 1978, mining operations for coal seam No. 3, located beneath the elevation of +300 meters, have been executed using a slice method, employing roof control through caving in the areas corresponding to Faces No. 138 and 139. By 1991, complete extraction was attained at Face No. 139 at the elevation of +200 meters.

Consistent with prior analyses, the statistical evaluation of the measurements was performed utilizing the profile function (1) and the generalized time-dependent function (2), resulting in the following regression coefficient of R^2 = 0.981:
$a_1 = 2{,}69 \cdot 10^{-4}; b_1 = -0{,}36; c_1 = -0{,}0025;$
$a_2 = 2{,}414; b_2 = 2{,}828; c_2 = 0{,}019876.$

The surface subsidence graphs derived from the data, alongside the results obtained from the profile function, are illustrated in Figure 11.

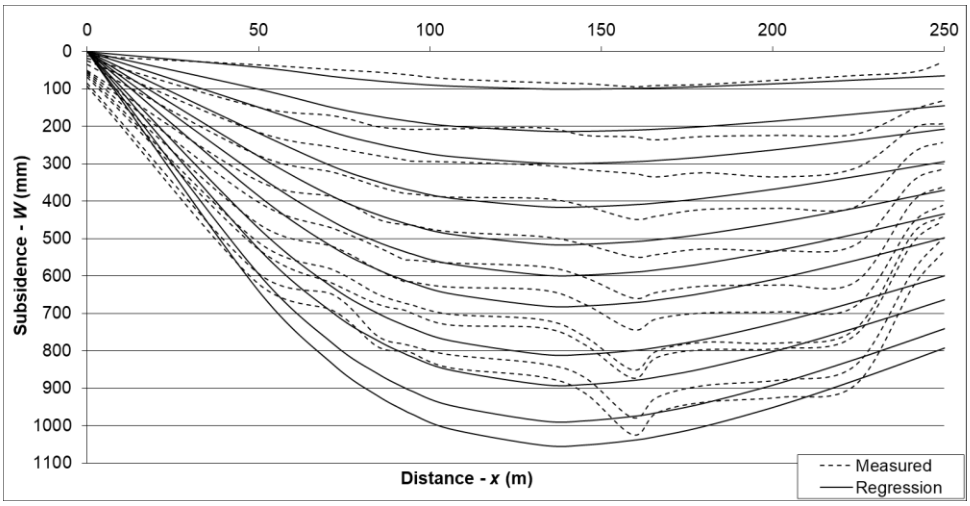

***Fig. 11.** Measured subsidence and the temporal profile function curves at Petrila Mine*

5. Future research directions

Despite the progress made in understanding and addressing surface subsidence, several gaps in the literature remain. Future research should focus on the development of more sophisticated predictive models that account for the complex interactions between geological, hydrological, and anthropogenic factors influencing subsidence [21]. Additionally, there is a need for interdisciplinary studies that integrate geotechnical engineering, environmental science, and the social sciences to comprehensively address the multifaceted impacts of subsidence.

Moreover, the role of climate change in exacerbating subsidence risks warrants further investigation. Changes in precipitation patterns and increased frequency of extreme weather events can alter groundwater dynamics and influence subsidence behavior [22]. Understanding these interactions will be crucial for developing adaptive management strategies in mining regions.

Finally, the implementation of innovative technologies, such as machine learning and artificial intelligence, in subsidence monitoring and prediction presents an exciting avenue for future research. These technologies have the potential to enhance the accuracy and efficiency of subsidence assessments, ultimately leading to more effective mitigation strategies [23].

6. Conclusions

In summary, surface subsidence resulting from underground mining is a complex phenomenon with significant environmental, social, and economic implications. A comprehensive understanding of the mechanisms, impacts, and mitigation strategies associated with subsidence is essential for effective management and policy development in mining regions. The existing literature provides a solid foundation for future research, which should continue to explore innovative solutions and interdisciplinary approaches to address the challenges posed by subsidence. By doing so, we can better safeguard communities and ecosystems affected by underground mining activities.

Simultaneously with the reevaluation of the mining activities associated with the Jiu Valley hard coal deposit, necessitated by the closure of some mining units and the initiation of new panel mining operations, there has emerged a pressing need to reassess the stability of surface lands and the integrity of existing structures. This context has highlighted the importance of evaluating ground surface stability in areas influenced by mining operations. Consequently, an intensive effort was made to assess historical measurements across various mining fields in the Jiu Valley, alongside an analysis of the associated data repository maintained by the Hard Coal Company of Petroșani. This paper presents several significant case studies derived from this analysis.

It is noteworthy that the data analysis encountered challenges because ground surface monitoring was conducted along monitoring stations which were not relevant from a scientific perspective. The main purpose of these monitoring stations was to monitor the behavior of features located in the exploitation's area of influence (roads, constructions, and land parcels.

As a result of this investigation, a time-dependent profile function was developed and validated, which can be used to predict the temporal evolution of subsidence trough resulting from underground mining (the function was validated using specific cases from the Jiu Valley). In addition to the profile function methodology, the subsidence phenomenon was also analyzed using the 3D finite element method. The calculations were executed under conditions of elasticity and elasto-plasticity, incorporating models that accounted for mining voids and caved zones. Following a sensitivity analysis and model calibration, significant results were achieved that are pertinent to the geological and mining conditions of the Jiu Valley.

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