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GIS-based calculation method to predict mining subsidence in flat and inclined mining: A comparative case study

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ABSTRACT Prediction of ground movements in the case of continuous subsidence is critically important for the planning of underground mining. Many calculation models are used to predict mining subsidence. A comprehensive method to render current calculation models superfluous can only come from a theoretical model, but the challenge remains in defining the parameters, given the great variety of rock structures found. Hence, innovation through a conceptual and technological study of the subsidence mechanism is needed to ensure that this problem can be solved satisfactorily. In this study, a new method is proposed to predict ground surface subsidence by combining a stochastic medium concept with Geographic Information System (GIS) technology. All subsidence computations are implemented within GIS, where spatial components are used to conduct the subsidence prediction analysis. This paper includes simulations of basic subsidence phenomena and a comparative study of the GIS-based calculation method's suitability against the empirical method from the Subsidence Engineer Handbook (SEH), semi-empirical influence function models, and numerical modeling. First, the influence of basic extraction area categories on the character of mining subsidence at the surface for flat seam layers is verified. Second, subsidence and horizontal displacement profiles are compared for both gently and steeply inclined mining. Finally, the verification of calculated horizontal strain values for an actual case of inclined irregular mining is also conducted. The comparative results of subsidence predictions for flat and gently sloping mining demonstrate the suitability of the GIS-based calculation method for use in underground mining strategy.

KEYWORDS Subsidence; GIS; 3D calculation model; Coal mining; Ground movement, Stochastic

1 INTRODUCTION

1.1 Mining Activities and Their Impact on Environment

Mining-induced surface subsidence is a recognized geo-environmental issue worldwide, largely due to energy resource development. Historically, much of this development involved underground mining methods, leading to severe subsidence issues in several developed countries, including Japan, the United States, and various European nations. In Japan, underground mining, particularly on Kyushu Island, was practiced for approximately 500 years, resulting in significant environmental damage from coal mining subsidence (Esaki et al., 1989). Similarly, it is estimated that over 2,000,000 acres of land in the United States have been affected by mining subsidence, with about 140,000 acres located in urban areas (Singh, 1978). In the Ruhr district of Germany, surface subsidence has been a concern since the introduction of the longwall mining method in the mid-19th century (Bell et al., 2000). Mining has been crucial to economic development in many Asian countries. However, its impact has led to significant negative consequences due to extensive energy development (Wang and Shen, 2003).

The harmony between development and the natural-social environment is crucial. The issue of mining subsidence involves not only the technical prevention and reduction of subsidence hazards but also the need to consider how it integrates with surface environmental management and resource security (Esaki, 1999). As the demand for energy grows due to increasing population, rising standards of living, and industrial development, managing mining subsidence becomes increasingly challenging, particularly in densely populated and monsoon-prone regions. Ensuring safety and mitigating economic losses in such areas is a formidable task and raises significant socio-environmental concerns. Additionally, because underground mining activities are often located near cities, rivers, or major transportation lines, subsidence can disrupt urban and regional economic planning and implementation. If subsidence and its impacts are ignored or poorly managed, their effects will likely expand, worsening environmental conditions. Subsidence-related environmental damage can lead to social instability, substantial economic losses, and severe disruptions to economic development. Therefore, it is essential to view surface subsidence as a global geo-environmental issue, given its widespread impact. With most remaining energy resources concentrated in Asia, the future expansion of mining in response to the energy crisis will likely exacerbate this problem. Accurate subsidence prediction and rigorous environmental impact assessments are necessary to establish land-use priorities that minimize hazards to life and property, reduce environmental degradation, and limit financial losses. Thus, environmental preservation will be key to the successful and sustainable development of energy in the future.

1.2 Subsidence Prediction Methods

Mining subsidence refers to the progressive movement and horizontal-vertical displacements that occur at the ground surface due to a loss of underground support (Whittaker and Reddish, 1989). While subsidence at any point is typically described in terms of vertical displacement, horizontal displacement often also results from ground movements. Subsidence can be categorized into continuous and discontinuous types. Continuous subsidence is characterized by a smooth surface subsidence profile with no abrupt changes. This type of subsidence results in a trough-shaped profile where the surface subsides gently without significant breaks. The extent of surface damage depends on the location along the trough and the extent of progressive subsidence. In contrast, discontinuous subsidence features steps or discontinuities in the surface profile. It can be associated with various mining methods and mechanisms and may develop either suddenly or gradually across different scales (Kratzsch, 1983). Discontinuous subsidence has the potential to cause severe damage to surface features. Although continuous subsidence generally has less dramatic consequences than discontinuous subsidence, it can still affect large surface areas, especially with methods like longwall mining that often impact built-up areas and services. Differential vertical displacements, horizontal compressive and tensile strains, and changes in the curvature of the ground surface can cause distress to structures such as buildings, roads, railways, pipelines, and water reservoirs. Different components of subsidence impact various structures in distinct ways. For example, horizontal strain can lead to cracking and tensile failure in concrete dams and cause leakage in undermined reservoirs. The Subsidence Engineer's Handbook National Coal Board (Great Britain) (1975) provides an extensive range of examples illustrating the damage to structural facilities caused by mining subsidence.

Most prediction methods developed so far focus on calculating surface subsidence resulting from mining activities. Recently, Sai et al. (2023) developed a machine learning approach to predict mining-induced stress in underground mines, aiming to mitigate ground control disasters and accidents. Similarly, Jahanmiri and Noorian-Bidgoli (2023) utilized machine learning models and optimization techniques for predicting land subsidence in coal mining. Additionally, Zhou et al. (2022) proposed a practical subsidence prediction model based on slope slip combined with parameter optimization. However, there is a challenge in capturing the full movement process across the entire ground surface (Deck et al., 2003). To address this, Zhongyuan et al. (2022) proposed an object-oriented method combined with classical probability integration techniques to predict surface subsidence more accurately and efficiently. This approach suggests that instead of relying solely on mechanical models, simpler abstract or analytical calculation procedures should be used to model surface subsidence.

The mechanical characteristics of rock strata relevant for calculations include details such as the mine's geometry, area, seam thickness, depth, and observational data like the angle of draw. The accuracy of various methods and the choice of the best method depend on correctly selecting parameters. Each method can yield good results if its parameters are appropriately chosen. Current calculation methods need to be tailored to specific strata and extraction conditions, with a focus on ease of measurement rather than the sheer number of parameters. A comprehensive method that could render current prediction methods obsolete would require a theoretical model. However, defining parameters remains problematic due to the variety of rock structures. Therefore, innovation through conceptual and technological studies on the mechanism of subsidence is necessary to address this problem effectively. In the current study, a new prediction method based on a Geographic Information System (GIS) has been developed. This method calculates the distribution of surface subsidence for any mining extraction shape by integrating the theoretical concept of the probability integration method (stochastic medium model of rock mass) with a spatial model (Esaki et al., 2004, 2005; Cai et al., 2016).

Many publications address the prediction of mining subsidence, employing methods ranging from numerical modeling to empirical and semi-empirical techniques. Most tolerable subsidence criteria have been established empirically based on observations of ground movement and damage to existing buildings across various countries (Peng and Chyan, 1981). The empirical prediction method described in The Subsidence Engineer's Handbook is widely used due to its simplicity and reliance on field data. This technical manual, published by the National Coal Board in the United Kingdom, has served as a comprehensive guide for engineers and professionals managing subsidence issues in coal mining regions. It has been a critical resource for understanding and mitigating the impacts of mining operations on surface environments and infrastructure. Semi-empirical methods, which build upon the influence function prediction method, extend the capabilities of empirical models by accommodating irregular mining geometries. These methods integrate theoretical principles with empirical data from past mining experiences, making them more broadly applicable (Lin et al., 1992; Sheorey et al., 2000). Numerical prediction methods offer distinct advantages for investigating specific problems and calculating rock strata movement and surface subsidence (Zhao et al., 2004; Zhongyuan et al., 2022; Zhou et al., 2022; Sai et al., 2023). For instance, FLAC (Fast Lagrangian Analysis of Continua) is a finite difference numerical modeling software used in geotechnical engineering, including mining subsidence applications. FLAC simulates the behavior of soils and rock masses under various loading conditions, such as those induced by mining activities, and models' complex interactions between underground mining operations and the overlying ground surface. In this paper, a comparative study is conducted on fundamental cases of mining subsidence and the suitability of the GIS-based calculation method. This study includes comparisons with the empirical method from the SEH, semi-empirical influence function models, and numerical modeling. Additionally, a comparison of subsidence calculations for an actual case of irregular mining is presented to evaluate the accuracy of the GIS-based method.

2 CALCULATION MODEL USING GIS

2.1 Spatial Functions and Coupling Model

GIS is a particularly versatile technology with wide-ranging applications (Harmon and Anderson, 2003). GIS analysis involves examining geographic patterns in spatial data. The GIS calculation model primarily consists of five steps. (1) Problem Definition: Determine what information is needed and frame the analysis. This step often involves questions about how to approach the analysis, which method to use, and how to present the results. (2) Understanding Data: Assess the types of data and features available. This helps in selecting the appropriate method. If additional information is required to achieve the desired level of detail, you may need to obtain extra data. (3) Choosing a Method: There are usually multiple methods for obtaining the information. Some methods provide approximate results with less effort, while others require more detailed data and processing time but offer more precise results. (4) Data Manipulation and Analysis: Apply the selected method to perform the necessary steps within the GIS. This includes setting parameters needed for the analysis. (5) Data Output/Display: Present the results as a map, table, or chart. Interpreting these results helps determine their validity and usefulness. If necessary, adjustments can be made by rerunning the analysis with different parameters or methods. GIS makes it relatively easy to make these changes and generate new outputs.

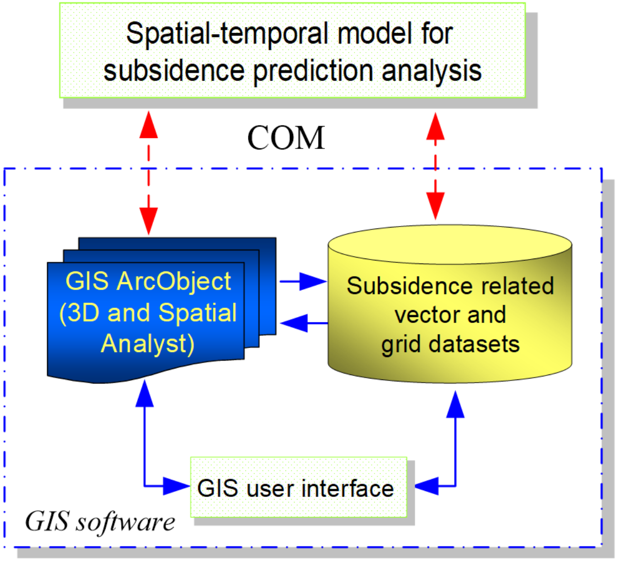


Figure 1 Coupling subsidence computational model and GIS

The architecture of the GIS data model determines how easily GIS and spatial models can be integrated. Coupling a model with a GIS is an information integration challenge, similar to linking one GIS to another for data transfer purposes (Marble, 2000). A coupling method based on the Component Object Model (COM) has been employed, allowing subsidence calculations to be performed within the GIS (Figure 1). COM enhances GIS software interoperability by enabling different components, which may be written in various programming languages, to communicate directly. The GIS-based subsidence calculation model, which utilizes COM technology within developed programs, assigns a 3D mining geometry and records the prediction results in GIS data models using both vector and raster formats. The vector data model represents information about points, lines, and polygons using x, y, and z coordinates. For example, the location of a point feature, such as a surface subsidence calculation point, is described by a single x, y coordinate. Linear features, such as mining roads or railway lines, are represented as a series of point coordinates. Polygon features, such as mining extractions, are stored as a closed loop of coordinates. In the raster data model, the subsidence prediction map is represented as a continuous surface divided into a regular grid of cells. The cell size impacts the accuracy of representing surface subsidence, as it affects the interpolation from calculation points.

2.2 Subsidence Prediction of Stochastic Theory

Modeling ground movements due to mining is complex because the overburden strata behave in a mul-

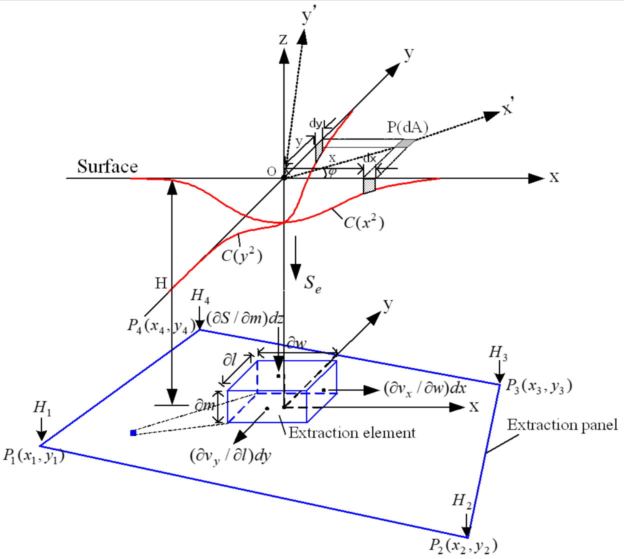


Figure 2 Development of subsidence trough functions due to the extraction element within a given extraction panel using the stochastic medium concept and GIS

tifaceted manner (Gil, 1991). Several theoretical concepts have been employed in mining subsidence prediction (Liu, 1995), with the stochastic medium model being among the most frequently used. According to Litwiniszyn (1957), since a rock mass can be considered a stochastic medium, mining subsidence prediction can be approached using stochastic methods. The development of movement in a stochastic medium can be illustrated by the rhombic packing of spheres (Kratzsch, 1983). When a lower sphere is removed, a neighboring higher sphere can only fill the vacant space. The probability distribution governing the changes in the positions of all spheres, or the graph of probability values (i.e., the frequency of sphere exchanges), resembles a bell-shaped Gaussian curve, which represents infinitesimal surface subsidence. In the superposition principle of ground movement, the mining extraction panel can be divided into infinitesimal extraction areas. The extraction panel would be equal to the sum of the effects caused by those infinitesimal extractions. Extraction with an infinitesimal unit width, length, and thickness ($\partial w \partial l \partial m$) is called the extraction element. The vertical displacement and horizontal displacement of any point in the subsidence trough are called the basic subsidence function of vertical displacement (S_e) and horizontal displacement (v_e) (Figure 2). Based on the stochastic theory, the occurrence of a rock mass motion over the extraction element may be a random event that takes place with a certain probability. The occurrence of the event that surface movement in an infinitesimal area $dA = dxdy$ at the horizon z with a point $P\left(x, y, z\right)$ at its center is equivalent to the simultaneous occurrence of two events composed of a movement in the horizontal strip dx and the horizontal strip dy through P. Therefore, it can be written the probability separately for these two events by $C\left(x^2\right) dx$ and $C\left(y^2\right) dy$ respectively, where C is the subsidence trough function. Finally, the stochastic function governs the geometric law for the distribution of subsidence due to the extraction element. As the extraction element is a component of the extraction panel, the basic subsidence trough function must be rational in irregular panel cases. The basic subsidence distribution with the stochastic medium model is given by Equation 1.

$$S_e\left(x, y, z\right) = B\left(z^2\right) exp\left[-\frac{\pi}{r^2\left(x\right)}\left(x^2 + y^2\right)\right] dwdldm \tag{1}$$

For two-dimensional (2D) analysis, the length of extraction is infinite in the y-axis direction. Integration of Equation 1 is given by Equation 2.

$$\begin{aligned} S_e\left(x, z\right) &= \textstyle\int_{-\infty}^{+\infty} \frac{1}{r^2(z)} \exp\left[-\frac{\pi}{r^2(z)}\left(x^2 + (y-1)^2\right)\right] dwdldm \\ &= \frac{1}{r\left(z\right)} \exp\left[-\frac{\pi}{r^2\left(z\right)} x^2\right] dwdm \end{aligned} \tag{2}$$

Furthermore, the following integration of Equation 3 can be applied in order to predict subsidence caused by an irregular panel.

$$S_e\left(x, y\right) = \textstyle\int\int \frac{S(w,l)}{r^2} exp\left[-\frac{\pi}{r^2}\left(x - \xi\right)^2 + \left(y - \varsigma\right)^2\right] dwdl \tag{3}$$

where,

$S\left(w, l\right)$ is subsidence above the extraction panel.

Based on the stochastic medium concept, Djamaluddin et al. (2006) proposed a 3D subsidence calculation model within GIS that accounts for irregular extraction panels. This model allows all input data to be easily managed using a 3D polygon vector-based GIS. The subsidence calculation models can be implemented either within or outside the GIS system. When calculations are performed outside the GIS, the GIS system serves primarily as a spatial database for storing, displaying, and updating the input data related to subsidence. A disadvantage of performing model calculations outside the GIS is the complexity involved in converting geometry data to and from external models. This conversion process can be problematic, as many programs use their own data formats and structures. Data conversion is relatively straightforward only when programs accept input data in ASCII files. Another drawback of using external models is the challenge in representing the results of 3D subsidence calculations.

Given that mining areas often involve irregular extraction panels, obtaining the spatial distribution of subsidence using the stochastic medium model can be time-consuming without GIS, as each mining panel must be analyzed individually. Moreover, performing model calculations outside the GIS limits the application of complex prediction models, as only simpler models are easily manageable due to constraints in using advanced algorithms and iterative procedures. To address these issues, Cai et al. (2016) developed a computational implementation model for subsidence algorithms within GIS, which helps overcome the challenges associated with complex spatial geometry data conversion and 3D subsidence calculations.

2.3 Interpretation of 3D mining panels

In GIS, several key processes are used to generate 3D extraction panels, including scanned map projection, raster-to-vector conversion, and 3D analysis. (1) Scanned Map Projection: Digital mining maps, using a coordinate-projection system and scanned images, must be geometrically rectified to match the actual coordinate system. This ensures that the scanned images align correctly with the real-world coordinates. (2) Raster-to-Vector Conversion: To obtain the polygons of extraction panels from scanned-image mining maps, an on-screen digitizing method or an automatic method is employed. (3) 3D Analysis: An interpolation analysis predicts the unknown z-values of the 3D extraction panels based on the observed mining depth values. Spatial analysis is used to determine the general strike and dip directions of the mining areas from the measured reference depth points of the mining panels. Figure 3 illustrates the flowchart for spatial data analysis in the interpretation of 3D extraction panels. In this process, 3D polygons representing extraction panels are converted to depth points in the output point feature class. This point feature class is generated based on the point vertices of the 3D polygons. Using this point feature class, linear-trend interpolation is applied to create a surface raster layer representing the mining layer. This interpolation fits a smooth surface, defined by a mathematical function, to the input depth measurement points, which are used to derive aspect and slope raster layers. The strike and dip directions of each 3D extraction panel are then calculated from the main slope and aspect values.

3 COMPARATIVE OF SUBSIDENCE MODELS

3.1 Subsidence and strain comparisons with SEH model

The empirical SEH prediction of subsidence and strain profiles is most widely used worldwide, most probably because it is based on observed subsidence phenomena. Three categories of extraction areas basically influence the character of mining subsidence trough at the surface for flat seam layers case is compared. Surface subsidence and horizontal strain profiles are carried out by employing basic mining parameters: the thickness of 1.5 m, the constant depth of 400 m, and extraction length of 1000 m, and the three widths of 200 m, 560 m, and 760 m. Subsidence troughs and horizontal strains in the transverse direction predicted by the SEH and GIS-based calculation model are presented in Figure 4a. The SEH prediction model is indicated by the dash-line plotted to refer to transverse profiles and the GIS-based calculation model is indicated by a solid line that describes quite similar subsidence profiles at the center of mining with SEH. Then, all the calculated data and results can be visualized and simulated in this system. Figure 4b shows the 3D view of the distribution of surface subsidence and horizontal strains for the subcritical area (the width of 200 m).

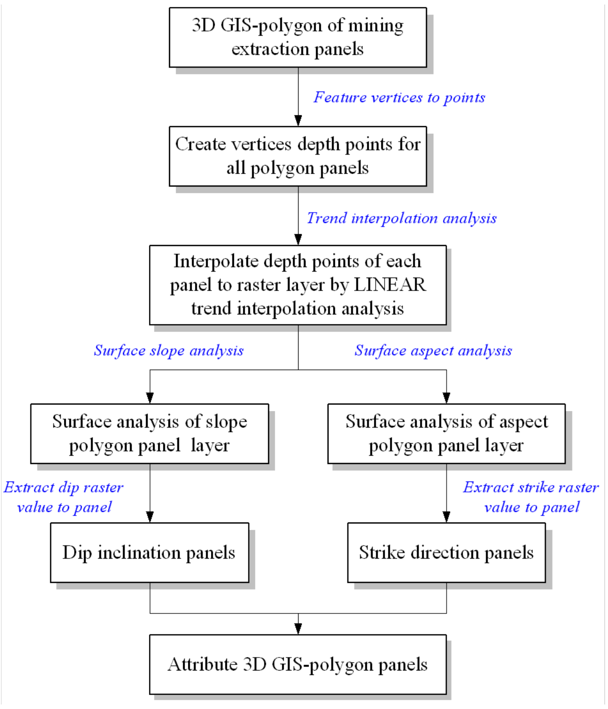
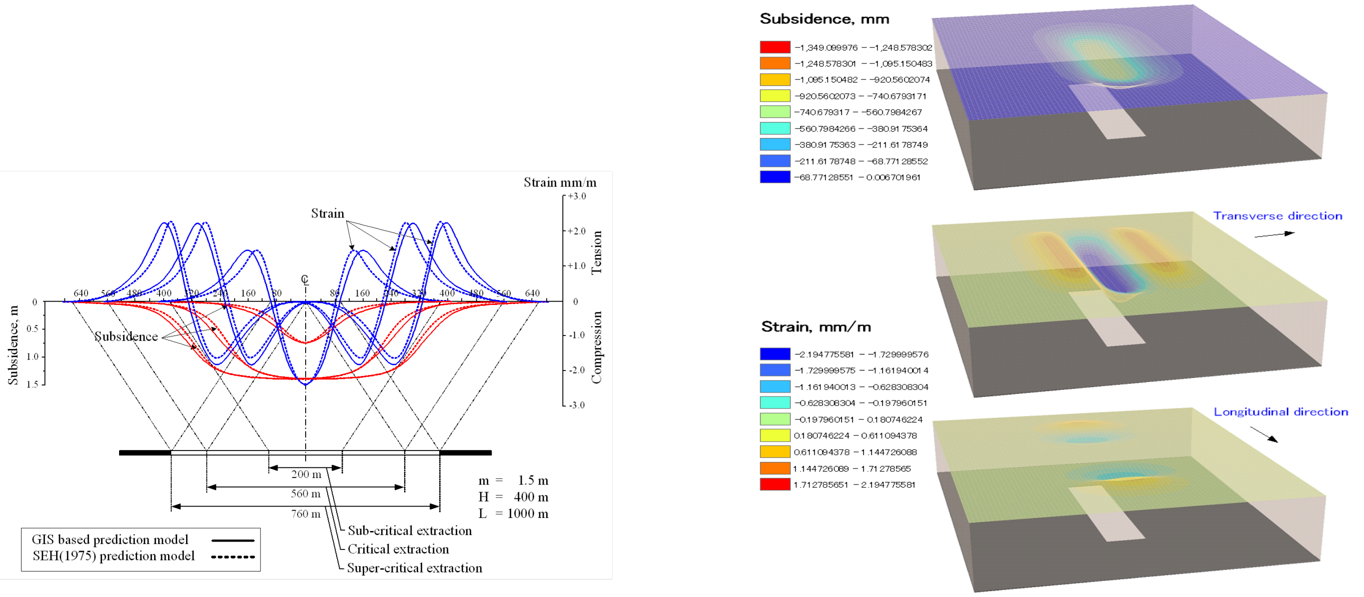


Figure 3 Flow chart of GIS data analysis for interpretation of 3D extraction panels

3.2 Subsidence comparison with influence function model

Figure 5 shows subsidence prediction by the influence function prediction method with basic underground mining data which was studied by Ren et al. (1987). The case was employed for comparison results which involved the longwall method with full caving in a level seam layer having a flat surface topography. The overburden of the extraction layer is 200 m; the extracted panel height is 3 m; the length of the longwall panel is 1000 m, and the widths employed in the calculations are 100 m, 200 m, and 400 m. In this case, Ren et al.



(a) Comparative results of GIS-based calculation method with SEH prediction model for three categories of extraction areas

(b) Distribution of surface subsidence and horizontal strains in the case of the sub-critical extraction

Figure 4 Overall caption for Figures 4a and 4b.

(1987) used a three-dimensional (3D) influence function with weighting factors of each extraction element to model the surface subsidence associated with a horizontal seam layer. Graphical outputs of vertical displacement for the transverse profile (center profile) are compared. The influence function model calculated by Ren et al. (1987) is indicated by a big dash-line, whereas the GIS-based calculation model is indicated by a solid line, which shows a favorable comparison with the influence function method. In addition, the SEH model is indicated by a small dash-line.

3.3 Subsidence comparisons with numerical model

The comparative study of the GIS-based calculation model is conducted with numerical modeling, which was studied by Alejano et al. (1999). They used the two-dimensional finite-difference code (FDM) of FLAC2D (Fast Lagrangian Analysis of Continua) to model initially the subsidence associated with a horizontal seam which was validated against SEH (1975) data. Figure 6 shows the subsidence profiles for a range of width-to-depth (w/H) ratios for a constant mining depth of H = 300 m and mining thickness of m = 2m. The numerical prediction and empirical prediction results are calculated by Alejano et al. (1999), indicated by a blue line and green line, respectively, whereas the GIS-based calculation model is indicated by the red line.

3.4 Subsidence and horizontal displacement comparison for inclined mining

Subsidence and horizontal displacement comparisons in inclined mining refer to the effects observed on the surface due to underground mining activities where the coal or minerals are extracted along an inclined plane or seam rather than horizontally. Inclined mining may exhibit more localized and uneven subsidence patterns compared to horizontal mining. In order to compare the subsidence prediction and horizontal displacement for inclined mining, two cases are taken from the previous study (Whittaker and Reddish, 1989). The mining inclination considered are $\alpha = 13.4°$ and $\alpha = 43°$. Figure 7 shows that the GIS-based calculation model also gives the closest comparison regarding subsidence profile position and magnitude. The SEH prediction model tends to displace the subsidence trough too far on the dip side. For inclined mining, the SEH model adjusts its calculations to account for the angle of inclination of the mining seam relative to the horizontal plane. This adjustment considers how the orientation of the seam influences the distribution of mining-induced stresses and subsequent subsidence patterns at the surface.

Although the SEH prediction model offers a practical and relatively straightforward approach to subsidence estimation, it has limitations. SEH prediction model may not account for complex geological conditions or variations in mining practices that can significantly impact subsidence. Accuracy may vary depending on the quality and relevance of the empirical data used to develop the model.

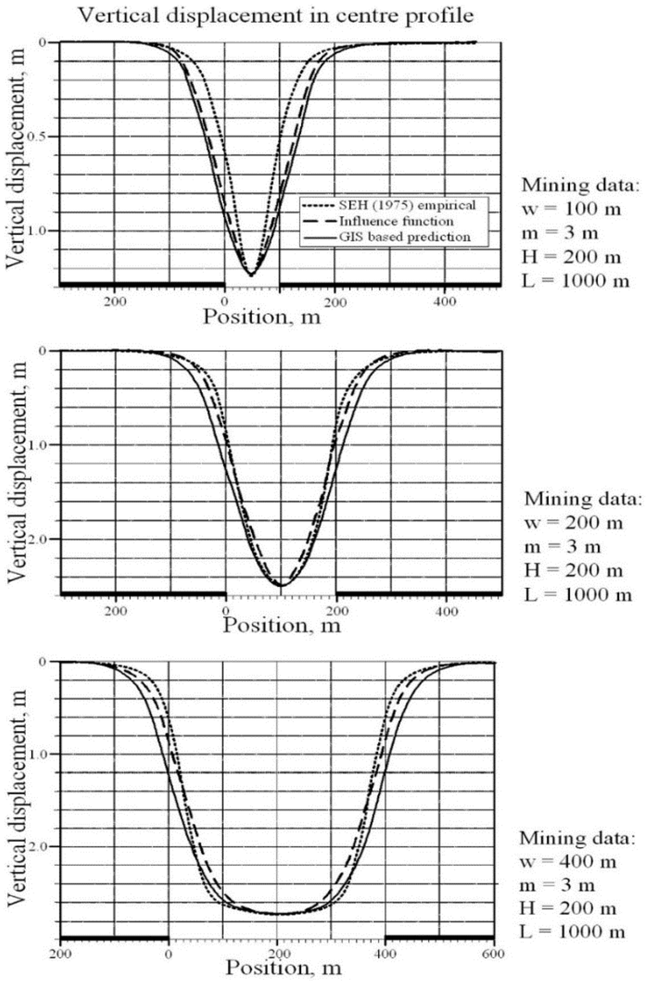


Figure 5 Comparative results of GIS-based calculation method with influence function model and SEH prediction model

3.5 Horizontal strain comparison for the actual case of irregular mining

Underground coal mining began in 1944 and concluded in 1965. The coal seam direction along the strike is approximately N20°-30°SW, and the dip direction is 15°-20°NE, based on geological conditions observed in mining practices and borehole data from several measurement points in previous studies. The coal seam layers consist of four levels, with extraction depths ranging from 200 meters to 1200 meters below the surface. The thicknesses of the first, second, third, and fourth coal seam layers are 1.20 meters, 0.83 meters, 1.43 meters, and 1.80 meters, respectively. Over the 22-year mining period, several measurement points were studied to obtain horizontal strain data annually located around the water reservoir. The subsidence strain distributions in the North-South direction were predicted using a 20-meter surface grid mesh with calculation points. The maximum compressive and tensile strains in the North-South direction are -2.37 mm/m and 1.56 mm/m, respectively. The horizontal compressive strain area is indicated by the red zone, while the horizontal tensile strain area is indicated by the green zone on the map (Figure 8a). Figure 8b shows a comparison between the calculated horizontal strains and the observed strains in the North-South direction at two specific locations.

4 DISCUSSIONS AND CONCLUSION

The integration of the stochastic medium concept with Geographic Information Systems (GIS) for subsidence prediction in underground coal mining offers several valuable advantages. Underground coal mining occurs in geologically diverse environments where rock and soil properties can vary significantly. The stochastic medium concept enables the characterization of this variability through probabilistic models. When combined with GIS, which provides robust spatial data management and analysis capabilities, engineers can incorporate geological data such as rock type and strata thickness into their subsidence models. This integration enhances prediction accuracy by considering the spatial distribution of geological properties that influence subsidence. Subsidence prediction inherently involves uncertainties due to the complex interactions between mining activities and geological conditions. Stochastic modeling addresses these uncertainties by generating multiple realizations of subsidence scenarios based on probabilistic distributions of geological parameters. GIS aids in visualizing and analyzing these uncertainties spatially, offering insights into the range of possible subsidence outcomes and their spatial variability. Furthermore, GIS facilitates the integration of various spatial datasets, including geological, environmental, and infrastructure data, into the subsidence prediction framework. This centralized data management improves information accessibility for stakeholders and fosters collaboration among multidisciplinary teams involved in subsidence management and mitigation.

To verify the GIS-based calculation method, several basic mining cases were studied to compare subsidence predictions with those obtained using the empirical SEH method, the semi-empirical influence function model, numerical modeling, and actual case studies. In flat mining, subsidence often follows a predictable pattern, characterized by a broad area of depression or sagging on the surface directly above the mined area. The extent and severity of subsidence can vary based on factors such as mining depth, the thickness and strength of the overlying strata, and the mining method employed. The comparative results of the GIS-based calculation method, the influence function model, and the SEH prediction model were analyzed for flat mining scenarios. The SEH and influence function models require extensive data on geological characteristics, mining history, and ground monitoring, which can be time-consuming to gather and interpret. While numer-

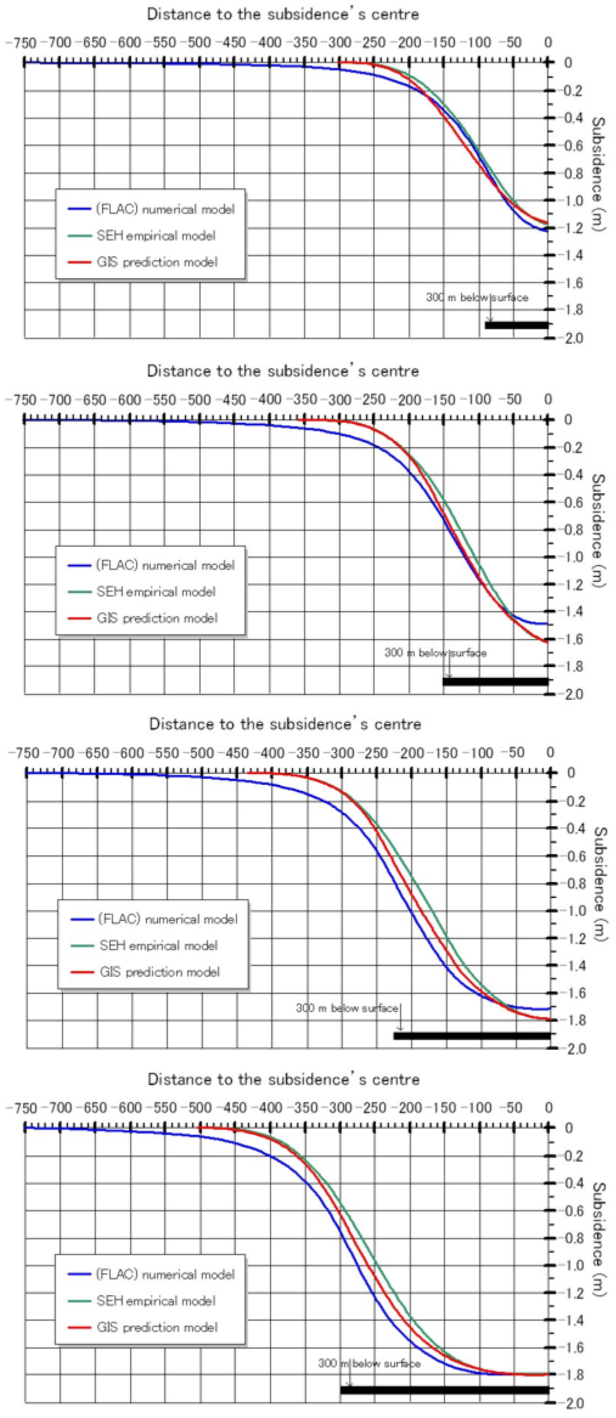


Figure 6 Comparative results of GIS-based calculation method with a numerical model and SEH prediction model for w/H = 0.6, 1.0, 1.5 and 2.0

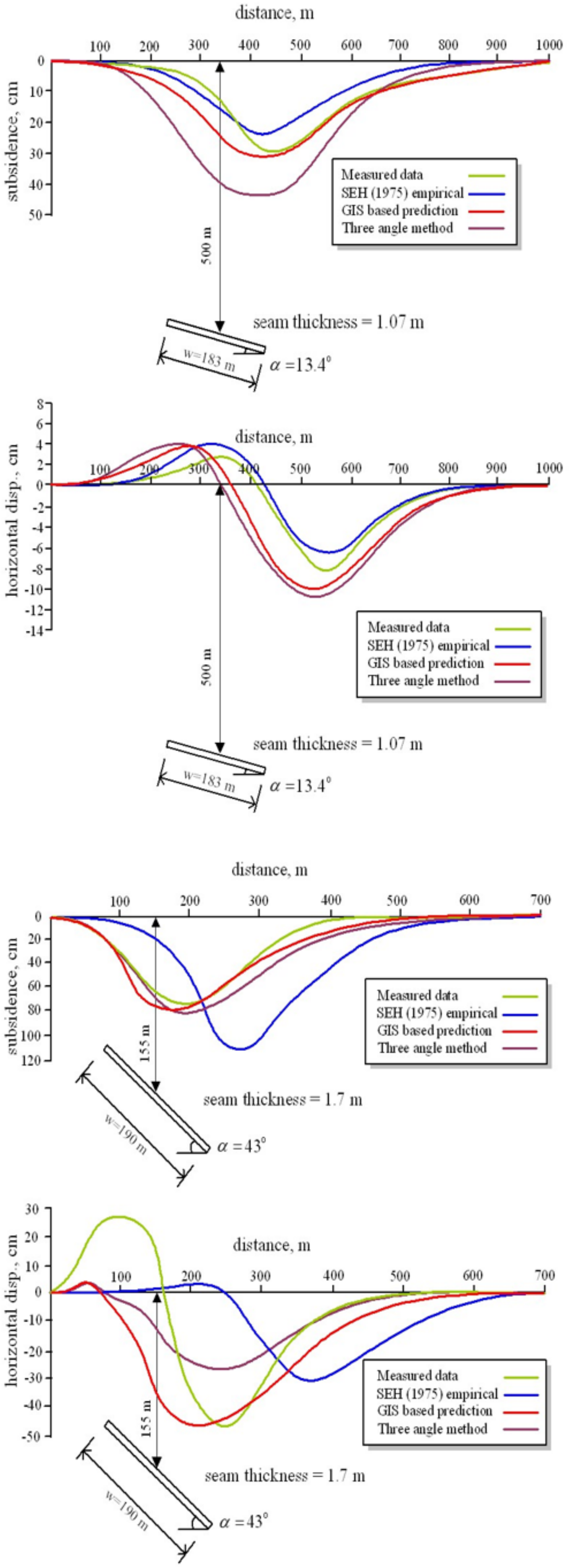
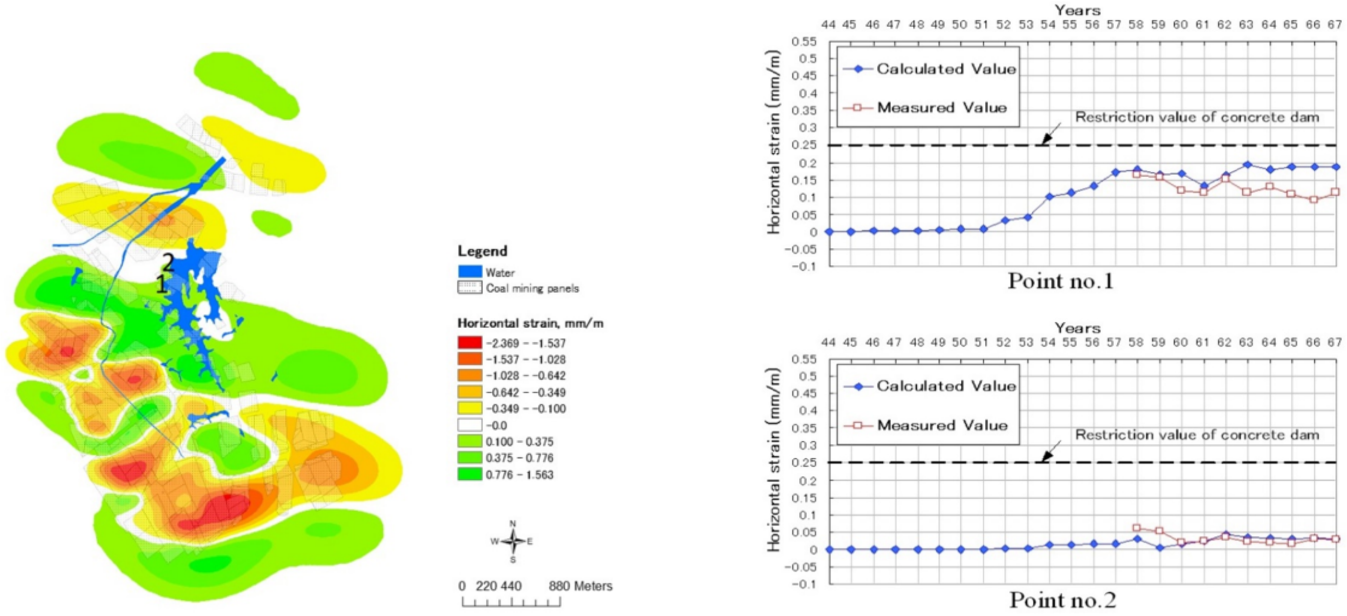


Figure 7 Comparison of subsidence and horizontal displacement profiles for steep and gently mining inclinations ($\alpha = 13.4^\circ$ and $\alpha = 43^\circ$)



(a) Distribution of surface horizontal strain in North-South direction simulated by the GIS-based calculation method

(b) Comparison of measured and calculated horizontal strain values in North-South direction for two-point observation locations

Figure 8 North-South direction

ical models offer superior accuracy and versatility in predicting mining subsidence, they demand substantial data and computational resources. In contrast, the SEH model provides quicker estimates but may lack precision, particularly in complex mining environments. However, the GIS-based subsidence prediction model can be developed to offer good accuracy and realistic predictions with relative ease.

Additionally, the results of subsidence profiles, transverse horizontal strains, and cases of inclined mining were examined. The comparison of the GIS-based calculation method with the empirical SEH method, the influence function model, and numerical modeling demonstrated good agreement across various underground mining scenarios. The calculated subsidence and horizontal displacement profiles were compared for gentle and steep-inclined mining, revealing slightly different results for steeply inclined mining. In steeply inclined mining, the angle of the seam or deposit relative to the horizontal affects how stresses are transmitted through the overlying strata. Steeper angles can induce higher vertical stresses and greater horizontal displacements compared to gentler inclinations. This variation in stress distribution results in differing patterns of subsidence and horizontal displacement on the surface.

The verification of calculated horizontal strain values for gently inclined mining also indicated that the GIS-based calculation method yields more satisfactory results in this actual case. The simulations and comparative results of subsidence predictions demonstrate the suitability of the GIS-based calculation method. Within a GIS system, the prediction model and data analysis can be developed easily, even for irregular mining geometries, without requiring exhaustive characterization of inclined mining or complex geometries. GIS enhances the accuracy of analysis by incorporating 3D coordinates of mining geometries and utilizing spatial analysis functions. It also facilitates thematic interpretation of underground mining through various data layers. In summary, integrating the stochastic medium concept with GIS improves the reliability, accuracy, and usability of subsidence prediction models for underground coal mining. This integration supports proactive planning, risk management, and sustainable development practices in mining-affected regions.

DISCLAIMER

The authors declare no conflict of interest.

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