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A GIS-based prediction method of 3D ground movements induced by underground mining sequence

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This paper proposes a stochastic method combined with Geographic Information System (GIS) to predict progressive 3D ground movements. A new GIS based prediction method has been developed to calculate 3D movements at any surface points. Using a GIS component, it is effective to handle the spatial geometry panel for calculating 3D movements. A case study of multi-seam layers considering the effect of dip panel and irregular geometry is used to demonstrate the efficiency and capability of the GIS-based prediction method. The progressive ground movements in the study area were predicted rigorously. As a result, GIS-based method permits better implementation prediction of 3D ground movements due to underground mining sequence.

Key Words : *underground mining, ground movements, stochastic prediction method, GIS*

1. Introduction

With the accumulation of engineering experiences, there are numerous method and ways of prediction that have been developed for calculating ground movements such as Subsidence Engineer's Handbook (SEH), profile function, influence function and numerical model. The most widely used method is SEH empirical prediction for calculating two-dimensional (2D) movements of a ground surface. SEH empirical prediction is applied to represent the consequence of major factors by series of nomographs based on numerous movements curves collected under similar mining (Braeuner, 1973). However, SEH empirical prediction is only applicable for simple geometry of mining panel. Meanwhile, the profile function method has been successfully applied in many countries to predict subsidence profiles (Torano et al., 2000). It should be emphasized that the profile function cannot be accounted for three-dimensional (3D) subsidence prediction and irregular mining panel. Influence function method is considered as a powerful application for 3D subsidence prediction (Sheorey et al., 2000; Cui et al., 2000). The calculation procedures are entirely based on the law of superposition and can be applied to any extraction area and any surface point. However, influence functions can not be directly found by measurement and are consequently site-specific and time consuming to develop. At the same time, numerical model have been used to calculate surface subsidence due to coal mining (Yang et al., 1993). The drawback of numerical method does not cope well with area of large displacement. Simple numerical models cannot simulate the complex strata behavior in the 3D subsidence process (Sheorey et al., 2000). Most of the methods have been advanced so far for predicting surface subsidence. However, these methods have not been effectively applied to predict 3D ground movements of a surface point due to extraction sequence (Esaki et al., 2004).

In recent years, Geographic Information System (GIS) as a flexible platform can be used to develop applications and integrate spatial models[7]. GIS make available the framework to acquire, develop, and interpret the complex spatial and tabular datasets used for 3D sequence subsidence prediction analysis.

In this research, the stochastic method (Litwiniszyn, 1957) is used to predict surface subsidence which consists of vertical displacement, slope, curvature, horizontal displacement and horizontal strain. Based on a 3D GIS-polygon stochastic prediction method, a new GIS-based prediction system has been developed to calculate 3D ground movements due to underground mining sequence, called *MSDAS-GIS*[8]. Technique for algorithm and implementation of stochastic method using GIS components has been developed. All calculations are implemented by a computational program where the components of GIS are used to fulfill the spatial analysis function. Furthermore, to confirm the reliability of the GIS based prediction method, a case study of multi-seam layers considering the effect of dip panel, irregular geometry and extraction sequence is used to demonstrate the efficiency of the system.

2. GIS-based prediction method of 3D movements

(1) Stochastic influence function coefficient

It is complicated to model ground movements due to mining since the overburden strata behaves in a complex manner. Several kinds of idealized medium have been used in subsidence prediction[9]. The degree of freedom of a single block is too large for classical mechanics to be able to define the motion trajectories of rock particles precisely. According to J. Litwiniszyn (1957), since a rock mass can be considered as a stochastic medium, its motion problem can be solved by stochastic method.

In Fig. 1, according to stochastic method of ground movements, an underground extraction panel can be divided into infinitesimal extraction areas. The consequence due to the original extraction would be equal to the sum of the effects caused by those infinitesimal extractions. An extraction with an infinitesimal unit of width, length and thickness ($\partial w \partial l \partial m$) is called the extraction elements[10]. The vertical displacement of any point in the subsidence trough is called the basic influence function of vertical displacement S_e.

A rectangular coordinate system is chosen with vertical axis z directed upward from the extraction element. Based on the stochastic method, the occurrence of a rockmass motion over the extraction element may be a random event which takes place with a certain probability. The occurrence of the event that surface movement in an infinitesimal area $dA = dx.dy$ at the horizon z with point $P(x,y,z)$ 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.

The probability for a simultaneous occurrence of these two events is

$$P(dA) = C(x^2)dx.C(y^2)dy = C(x^2)C(y^2)dA \qquad (1.a)$$

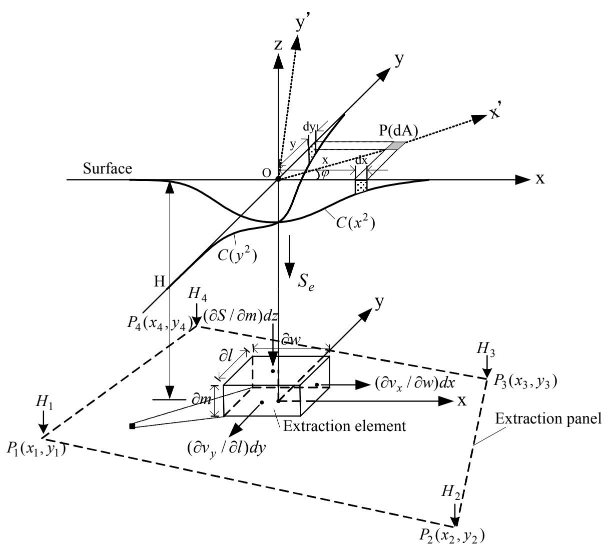


Fig. 1 A sketch to illustrate the effects of the extraction element upon the arbitrary point P at the surface.

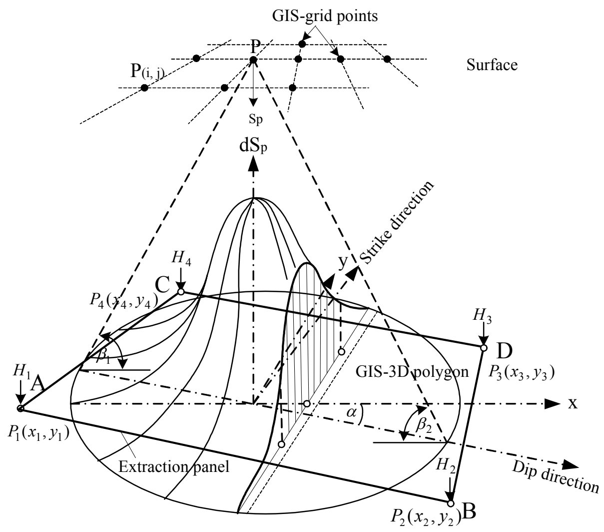


Fig. 2 Illustration of GIS-based 3D-polygon as a panel to calculate subsidence at GIS point as surface points.

Finally, the calculation point $P(x, y)$ is located at the origin of the local coordinates, then the subsidence of a surface point P can be derived as follows:

$$S(x,y) = m.a.z.\cos\alpha \cdot C_y \cdot C_x, \qquad (1.b)$$

$$C_y = \frac{1}{2}(Erfc(\sqrt{\pi}\cdot\frac{y}{r}) - Erfc(\sqrt{\pi}\cdot\frac{y-l}{r})), \qquad (1.c)$$

$$C_x = \frac{1}{2}(Erfc(\sqrt{\pi}\cdot\frac{x}{r_1}) - Erfc(\sqrt{\pi}\cdot\frac{x-w}{r_2})). \qquad (1.d)$$

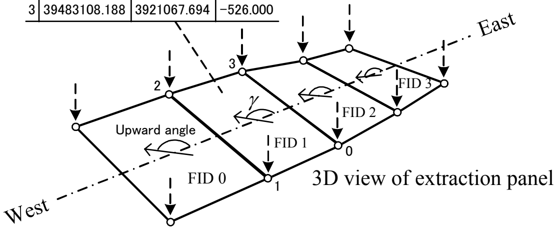
where a = subsidence factor; m = extraction thickness; α = angle of dip; l = panel length along strike; w = panel width along dip; $r = H/\tan\beta$, $r_1 = H_1/\tan\beta_1$, $r_2 = H_2/\tan\beta_2$, radius of the influence circle; β = angle of draw; and H = depth along strike, H_1 = depth along the boundary of rise side, H_2 = depth along the boundary of dip side; z = subsidence time factor.

(2) Stochastic prediction using GIS based components

The stochastic influence coefficient can also be applied for 3D GIS-polygon as geometry model for subsidence prediction of surface points. By the integration of all small extraction elements into a extraction panel as shown in Fig. 1, all the subsidence components related surface calculation point can be illustrated by the 3D view of GIS-grid points (calculation points) and 3D polygon (extraction panel) as shown in Fig. 2. The extraction area can be divided into panels and related to polygon-based areas. For each panel, with reference to the vector-based polygon (Fig. 3), the spatial data of geometry, panel sequence, subsidence parameters, and extraction depth can be obtained from the 3D polygon. In this polygon panel dataset, a feature table of 3D polygon is used to relate the subsidence parameters. In 3D polygon attribute table, the item of "PolygonZM" is the shape of 3D polygon attributes and the item of "ID" is the extraction sequence; the items of "AngDip.(Dip inclination)", "UpwardAng.(panel upward angle)" and "Thick.(Extraction thickness)" are related to the geometrical parameters.

Vertices panel FID 1

	x	y	z
0	39483108.188	3920887.694	−561.000
1	39482988.188	3920887.694	−543.000
2	39482988.188	3921067.694	−513.000
3	39483108.188	3921067.694	−526.000



3D polygon panel attributes dataset

FID	Shape	ID	AngDip	Thick	SubFac	HoMoFac	TiFac	UpTan	DownTan	UpwardAng
0	PolygonZM	1	9.481	6.29	0.70	0.30	0.50	1.428	1.428	123.45
1	PolygonZM	2	12.907	6.29	0.70	0.30	0.50	1.428	1.428	125.34
2	PolygonZM	3	10.796	6.29	0.70	0.30	0.50	1.428	1.428	126.24
3	PolygonZM	4	2.130	6.29	0.70	0.30	0.50	1.428	1.428	146.31

Fig.3 An example of 3D GIS-polygon panels and its related spatial data geometry with attribute dataset.

The subsidence parameters are represented by the items of "SubFac.(Subsidence factor)", "HoMoFac.(Horizontal movement factor)", "TiFac.(Time-delay subsidence factor)", "UpTan. (Tangent of draw angle in rise side)", and "DownTan.(Tangent of draw angle in dip side)". Each 3D panel has depth vertices value that giving a spatial geometry in x, y, and z. Therefore, a 3D panel has spatial geometry which can be used to identify the main strike direction and dip inclination of each panel. In addition, a spatial model and TIN (triangulated irregular network) model in GIS are employed to analyze a 3D panel for identifying strike direction and dip inclination.

(3) Algorithm implementation of GIS stochastic prediction analysis

The whole underground mining area can be divided into many panels that are the same as the GIS-based 3D-polygon panel layer. The prediction system has been developed in the most popular of GIS software. GIS software is based on a common modular COM-based library of shared GIS components called ArcObjects. For subsidence prediction system, the stochastic calculation procedures are programmed by Visual Basic (VB) 6.0 using ArcObjects. In this program, the VB 6.0 and ArcObjects are employed, ArcObjects as a GIS component is used to implement GIS data processing and spatial-temporal analysis.

All input data for subsidence prediction are available using the function of GIS. The input parameters for subsidence calculations are divided into two categories. The first parameter is to generate surface grid points for providing calculation points, including the distance of each grid point in x and y directions. The second parameter is to input subsidence calculation data including extraction sequence number (panel ID), dip inclination, upward angle, extraction thickness, subsidence factor, horizontal movement factor, time factor and angles of draw. Fig. 4 illustrates the flow chart for computational process. In computational subsidence process, the panel on the global coordinate system is transformed into the local coordinate system. The transformation coordinate panel is performed to obtain the angle direction of zone radius of main subsidence influences.

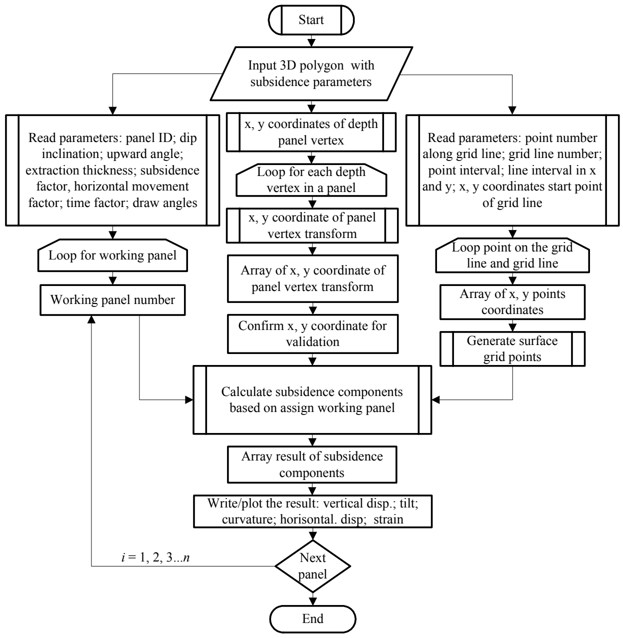


Fig.4 Flow chart for algorithm of subsidence prediction.

The confirmation of x, y coordinate transform panel is taken to ensure a validation of geometry model before stochastic calculation process. By inputting calculation points, subsidence parameters and 3D polygon panel, 3D ground movements are calculated in the stochastic function procedures according to working panel (extraction sequence). After the entire calculations are finished, the movement components which consists of vertical displacement as well as slope, curvature, horizontal displacement and horizontal strain can be created to GIS-grid points as a database. Without GIS, a 3D subsidence calculation based on stochastic influence function would be a difficult and time-consuming, and multi panel-case study analysis would also be problematic. However within GIS system, subsidence calculation related data of the whole study area can be represented as GIS vector layers. For each vector layer, a 3D polygon and grid point-based layer can be constructed using GIS and the calculation grid points can be set with the requisite precision.

(4) Computational processes using GIS spatial analysis function

The subsidence calculations can be carried out within or outside the GIS. If the calculations are performed outside the GIS, the GIS system is only used as a spatial subsidence database for storing, displaying and updating the input data. The main advantage of this approach is that external existing subsidence prediction models can be used without losing time in programming the model algorithms into the GIS. However, prediction models calculate the movements of a surface point for an extraction panel in three dimensions. Since an area consists of many panel and complex geometry, the use of this 3D model of subsidence is very time-consuming, as each panel has to be analyzed separately. In order to overcome the problem of complex geometry data conversion, model of subsidence calculations should be performed within the GIS.

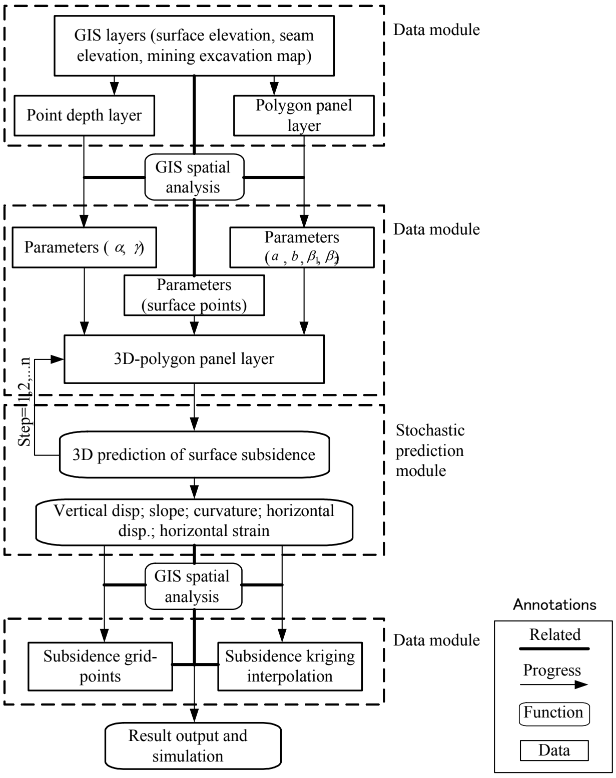


Fig.5 Entire subsidence computational processes using GIS spatial analysis.

In Fig.5, it can be seen that all modules are related to the GIS spatial analysis function that implemented by a GIS component. In this process, the function of data module is used for getting all the subsidence related spatial geometry, surface point calculation data and the subsidence parameters. The stochastic prediction module is used for calculating surface subsidence as well as slope, curvature, horizontal displacement and strain.

(5) Implementation steps for predicting subsidence in GIS

There are three-step processes in order to implement a 3D ground movement prediction in GIS environment. In *Step 1*, It involves establishing the spatial extents of the study area, deciding an appropriate working projection, and assembling the various spatial data to be used in the study in digital form to be properly registered that the spatial component overlap correctly. This step is to bring all the appropriate source data together into a GIS spatial database such as mining panel map, seam layer, surface elevation layer and spatial information of overburden strata. In *Step 2*, it involves constructing the spatial geometry of mining panel for subsidence calculation parameters. In common case, the mining panel map must be digitized manually, transformed from image into a 3D GIS-polygon vector data. Since, it is necessary to input the elevation value of 3D polygon panel into the subsidence computation model, each panel is required for panel vertices depth (coordinate in z direction). In *Step 3*, it involves applying the subsidence prediction, combining all the prepared data that provided the value of subsidence calculation. All parameters of subsidence must be inputted and corresponded to 3D GIS-polygon panels. For stochastic subsidence analysis, all of the above calculation procedures are programmed by VB 6.0 using GIS, assigns 3D-polygon panels as a mining geometry model to the boundary extraction panel vertices and writes the subsidence components result to GIS grid-points.

3. Application of GIS-based prediction method

(1) Background of study area (Fig.6)

Seita water reservoir as a part of study area is located in KitaKyushu, Japan. There are four dams along the reservoir with the height and length of 23.5/217.6 m, 18.0/49.4 m, 21.0/186.2 m and 17.0/76.3 m, respectively. Underground coal mining was started from 1944 and finished in 1965. The direction of coal seam along the strike is N20°~30°SW and dip direction is 15°-20°NE according to the geological condition in mining practices and borehole data at several measurement points in the previous study. There are four levels of coal seam layers with extraction ranged depth from 200 m to 1200 m below surface, thickness of first, second, third, and fourth coal seam layers are 1.20 m, 0.83 m, 1.43 m, and 1.80 m, respectively. The coal mining is extracted by the longwall method. Fig.6 shows the 4 level seam layers of all extracted panel area over 22-year mining period.

(2) Calculation of 3D ground movements and simulation

Sequential subsidence calculations simulating the extraction process between 1944 and 1967 were carried out employing parameters of subsidence factor (*a*) = 0.85, horizontal movement factor (*b*) = 0.21, tangent of draw angle = 1.428 obtained from previously experienced results. Effect of time factor which expresses the time-delay subsidence shows the final value completed in 3 years (first year ($z1$) = 0.83, second year ($z2$) = 0.90, third year ($z3$) = 1) after complete mining even at depth, and the maximum subsidence records 3.27 m up to 1967.

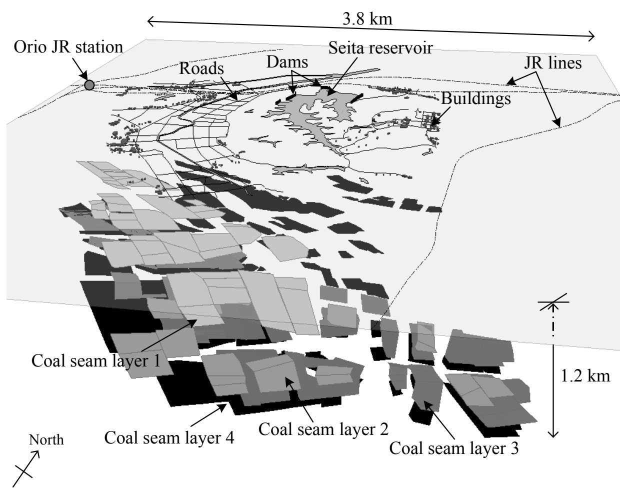


Fig.6 3D view of underground coal mining panels under Seita reservoir area.

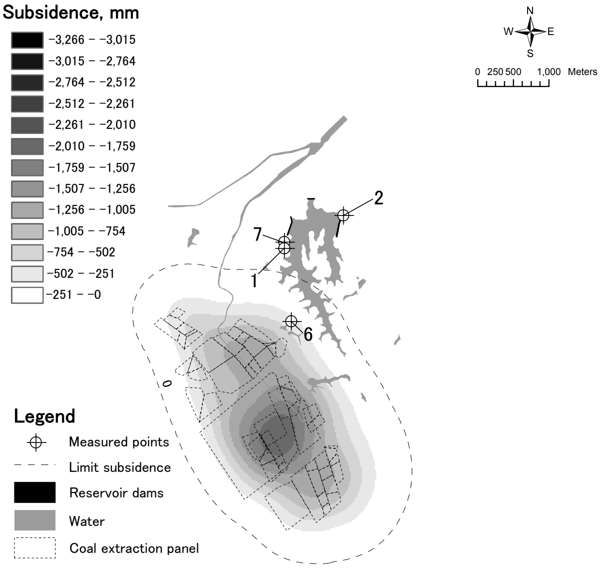


Fig. 7a 3D subsidence prediction due to coal mining up to 1955.

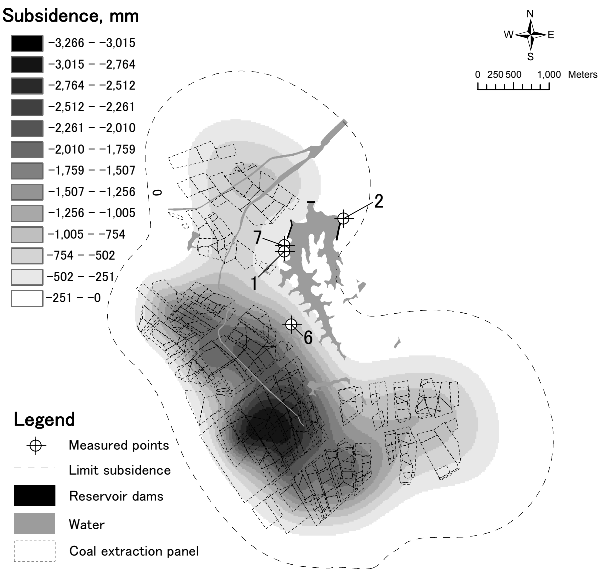


Fig. 7b 3D subsidence prediction due to coal mining up to 1961.

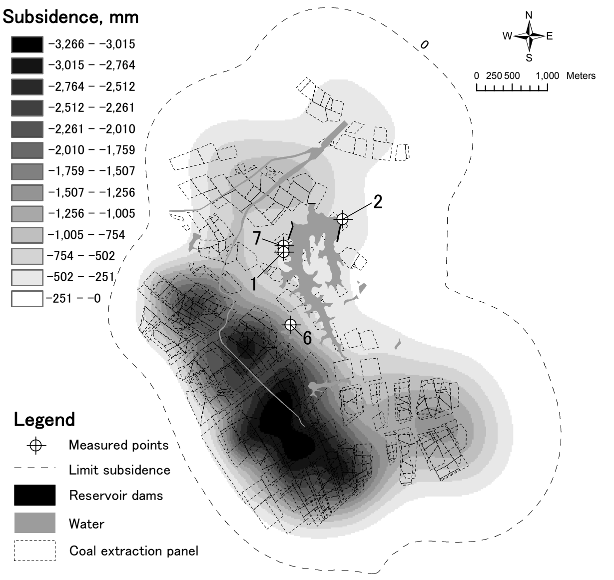


Fig. 7c 3D subsidence prediction due to coal mining up to 1967.

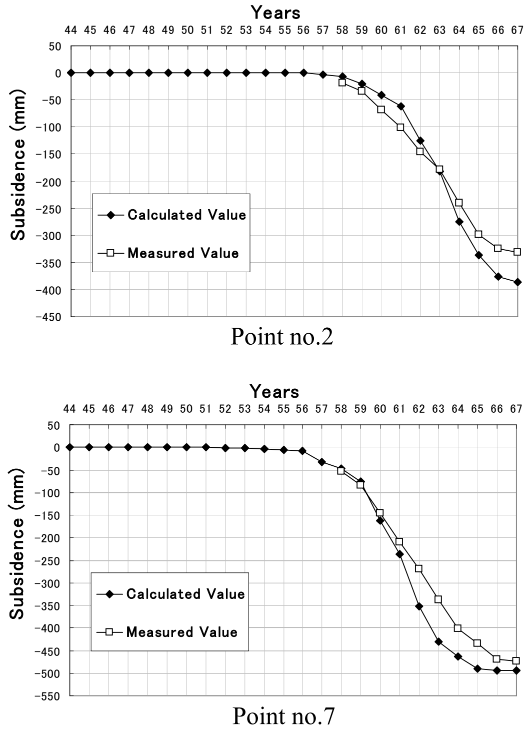


Fig. 8 Comparison of measured and predicted subsidence values .

In addition, the calculation time consumed using this developed system indicated approximately 100 times faster than that of the previous method which was developed by Esaki (1996)[11]. The detail of ground movements due to coal mining, which can be sequentially predicted and simulated in term of year, is shown in Fig. 7 as an example. Final subsidence distribution simulation due to 22-year extraction is shown in Fig. 7c.

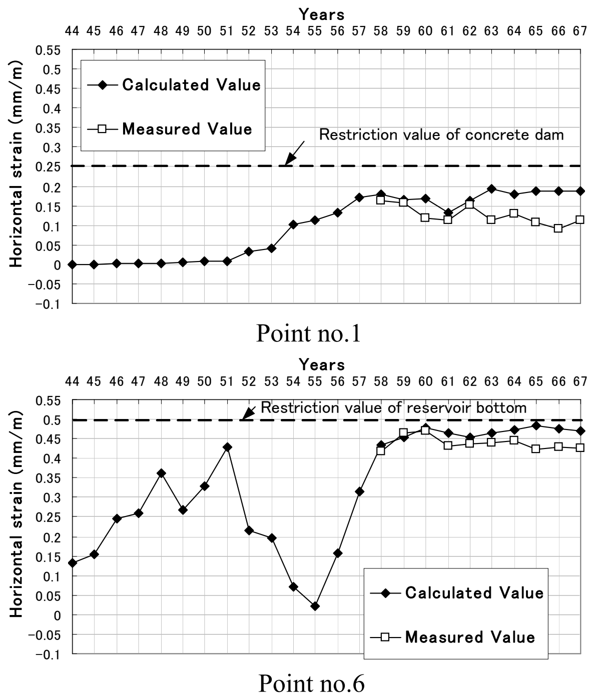


Fig. 9 Comparison of measured and predicted horizontal strain values.

Several measurement points studied to obtain movement data year by year. The comparison of calculated and measured subsidence values is shown in Fig. 8. The calculation of horizontal strains can also be obtained over time. As shown in Fig. 7, the measured points for horizontal strains along the survey line on the concrete dams and reservoir bottom obtained over years. The comparison of measured and predicted horizontal strain values that shows the dynamic strain at the reservoir dams and strain recovery response to mining extraction sequence is shown in Fig. 9. The calculated strains were conformed to the allowable strain of dams to ensure the safety against tensile failure of concrete and water inundation.

4. Conclusion

A GIS-based prediction method has been developed for calculating 3D ground movements at any surface point with any shape of extraction covering a wide range of mining geometry. Unlike most research that has taken the 2D prediction method to calculate final subsidence process, in this study, the stochastic method integrated with GIS component is used for the 3D ground movements due to underground mining sequence. A computational program called *MSDAS-GIS*, in which GIS component is used to fulfill the GIS spatial analysis function and effective data management, has been developed to implement all calculation of the 3D ground movements. Using a 3D GIS-polygon and GIS-grid points for subsidence prediction analysis, an efficiency calculation process is developed for predicting 3D ground movements. The ground movements due to 22-year underground coal extraction in the study area were simulated and predicted rigorously and the best efficiency. Within GIS, the data preparation and visualization for progressing subsidence distribution, the phenomena of 3D ground movements sequence is ideal to study. The comparison between calculation and measurement values show good concurrences.

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GISを用いた地下採掘による三次元地表移動の予測法

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地下採掘による地表移動について，これまで多くの予測計算法が用いられてきた．しかし，従来の予測計算法は，採掘の進行に伴う地表の限られた地点の挙動しか得ることができなかった．本研究では，GISを用いた影響係数沈下予測法を提案したものである．この方法では，進行しつづける採掘にともなう地表の地盤移動を連続的に三次元的に求めることができる．特に複雑な形状をした採掘パネル毎にポリゴン化する方式は精度向上に寄与する．この方法の有効性および格段の効率性は累層採掘の実例により検証された．