PRODUCTION OF GROUND SUBSIDENCE SUSCEPTIBILITY MAP AT ABANDONED UNDERGROUND COAL MINE USING FUZZY LOGIC

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ABSTRACT In this study, we predicted locations vulnerable to ground subsidence hazard using fuzzy logic and geographic information system (GIS). Test was carried out at an abandoned underground coal mine in Samcheok City, Korea. Estimation of relative ratings of eight major factors influencing subsidence and determination of effective fuzzy operators are presented. Eight major factors causing ground subsidence were extracted and constructed as a spatial database using the spatial analysis and the probability analysis functions. The eight factors include geology, slope, landuse, depth of mined tunnel, distance from mined tunnel, RMR, permeability, and depth of ground water. A frequency ratio model was applied to calculate relative rating of each factor, and the ratings were integrated using fuzzy membership function and five different fuzzy operators to produce a ground subsidence susceptibility map. The ground subsidence susceptibility map was verified by comparing it with the existing ground subsidences. The obtained susceptibility map well agreed with the actual ground subsidence areas. Especially, γ-operator and algebraic product operator were the most effective among the tested fuzzy operators.

KEY WORDS: Abandoned underground coal mine, ground subsidence, susceptibility, fuzzy logic, GIS

1. INTRODUCTION

Since the beginning of coal industry rationalization in 1989, most underground coal mines were abandoned. Ground subsidence around abandoned coal mine areas has become a serious social problem in Korea since that time. But quantitative analysis of the presumptive ground subsidence area near the abandoned underground coal mines is difficult especially where geologic structure is very complicated. Goel (1982) suggested a method of ground subsidence assessment using several factors including intact strength of the rock, stress field, geological structure of the rock, depth of the mining horizon, areal extent of mining, and volume extracted per unit area of mining. The National Coal Board published a basic technique to find out estimated area of influence by ground subsidence with height of cavity, width of mined panel and inclined angle of coal seam (National Coal Board, 1975). However, the prediction of subsidence area is very dependent on a structure of local geology and mining method and the empirical methods were developed under conditions of horizontal coal seam and longwall working dominant in Europe. In Korea, the widths of coal seam vary due to the complex geologic structure so that irregularly inclined coal seam and strata and slant-chute caving method have been prevailed. As a result, a sink-hole type subsidence is general and the factors associated with ground subsidence are different (CIPB, 1997).

The purpose of this work is to quantitatively predict ground subsidence area and to construct subsidence susceptibility map near an abandoned underground coal mine area using a fuzzy logic and GIS. A spatial database of the factors affecting the ground subsidence in the former mining regions was constructed using GIS. The rating of each factor representing the degree of influence to the subsidence occurrence was determined by using a frequency ratio model. The rating was converted into fuzzy membership function and integrated by using five fuzzy combination operators. Ground subsidence susceptibility map of the study area was produced and verified.

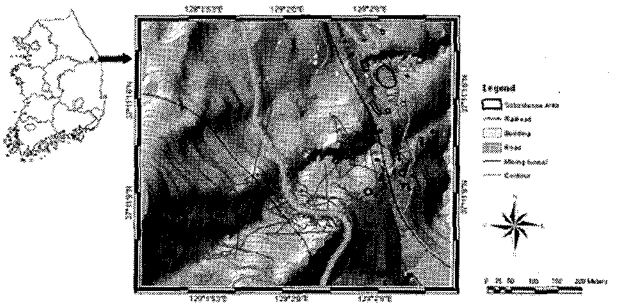

Figure 1. Study area overlaid with mined tunnel and existing subsidences.

The study area is located around the former Hanyang Gallery on the Jangseong and Keumcheon Formation near Simpori at Samcheok City lying. An average thickness of coal seam was about 1 m (CIPB, 1997). The location map of this study area with ground subsidence occurrence is given in Fig. 1.

A few researches in Korea were performed for ground subsidence prediction using fuzzy relations or GIS. Choi *et al.* (2004) attempted a quantitative prediction of ground subsidence using artificial neural network and developed a prediction method of sinkhole-type ground subsidence using the theory of fuzzy relations. Kim *et al.* (2005) predicted ground subsidence area quantitatively using GIS.

2. DATABASE

Control factors affecting to ground subsidence around coal mines have been known as depth and height of the mined cavities, excavation method, degree of inclination of the excavation, scope of mining, structure of the geology, flow of groundwater, and the mechanical characteristics of the RMR (CIPB, 1997; Waltham, 1989). The factors relating to ground subsidence were collected in a vector-type spatial database such as 1:50,000 scaled geological map, 1:5,000 scaled topographic maps, 1:5,000 scaled land use maps, 1:1,200 scaled mined-tunnel maps, and borehole data.

Geology of the study area was obtained from a 1:50,000 scaled geological map. The geology of the study area comprises two types of Jangseong and Keumcheon Formation of the Paleozoic Era. Contour read from the topographic map was converted into the digital elevation model (DEM) from which slope gradient was calculated. There are 7 classes of land use, which were obtained from the land use map published by the National Geographic Institute. Many references suggest that the major factor in ground subsidence is the scope of the mined cavities (CIPB, 1997; Waltham, 1989), and consequently the depth of mined cavity was very important for this study. To achieve the depth of mined tunnel map, (1) GPS measurements were used to determine the exact positions of mine heads; (2) a hard copy of the mined tunnel map was vectorized from this point; and (3) the vectorized mined tunnel map was converted to an ASCII grid file and subtracted from the DEM raster data. Also, the map of horizontal distances from mined tunnel map was constructed using 1 m-interval buffer analysis. All the calculated and extracted raster database were mapped to a ArcGIS grid file, the cell unit of which was decided by 1 m by 1 m having 659 columns and 597 rows separately. The total number of cells of study area becomes 373,653.

There were 24 boreholes at the study site, but some boreholes did not have values. As a result 15 RMR values, 12 permeability values and 10 ground water level values were available. Inverse distance weighting (IDW) interpolation method was used to contour the values for RMR, groundwater levels, and permeability, and these were reclassified by 10 subgroups using GIS. The resultant raster data were also constructed to 1 m resolution ArcGIS grid files.

Eight major factors affecting to ground subsidence were considered. These factors are geology, slope, land use, depth of mined tunnel, distance from mined tunnel, RMR, permeability, and depth of ground water. The grid files constructed for each factors are listed in Table 1.

Table 1. GIS database for ground subsidence study.

Category	Extracted Factors in this study	Classification of extracted factors
Geology	Geology	Jangseong formation and Geumcheon formation
Topo-graphy	Slope	10 levels from 0 to 65 degree
Landuse	Landuse	7 classes by NGI in Korea
Mined Tunnel map	Depth of mined Tunnel	10 levels of mined tunnel depth from 0 m to 237m
	Distance from mined tunnel	10 levels of mined tunnel distance from 0m to 318m
Borehole data	Interpolated Depth of Groundwater level	10 levels from 15m to 160m
	Interpolated permeability	10 levels from 4.00 to 4.49
	Interpolated RMR	10 levels from 3.00 to 4.79

3. METHODOLOGY

To estimate ground subsidence susceptibility, fuzzy relation concept defined by Zadeh (1973) was used. In general, fuzzy relations can be considered as the fuzzy sets. In the fuzzy set theory, a membership function of an element has a value in the range [0, 1] as an integer or a floating number. The 1 represents full membership and 0 non-membership (Murat *et al.*, 2004; Park *et al*, 2005).

We used the rating of each factor calculated by a frequency ratio model as the input value of fuzzy membership function. The resultant frequency ratio of each factor represented the rating of each factor and was normalized to a value in the range [0, 1]. The normalized rating was assigned to the corresponding pixels of eight raster data files respectively as the fuzzy membership values.

In the next step, the fuzzy membership values of eight factors were integrated as single membership value using five fuzzy combination operators. The resultant value was assigned to each pixel in the study area as ground subsidence susceptibility and then the ground subsidence susceptibility map was produced.

Finally, the ground subsidence susceptibility maps were verified by compared with the existing ground subsidence occurrence map.

3.1 Application of Frequency Ratio

The frequency ratio approaches are based on the observed spatial relationships between distribution of ground subsidence areas and each subsidence-related factor, and is to reveal the correlation between ground subsidence locations and the factors in the study area.

Table 2. Frequency ratio value and corresponding fuzzy membership value

Class		Frequency Ratio	Membership Value
slope	0 – 9.37	0.25	0.200

	9.38 – 12.85	2.82	0.738
	12.86 – 16.06	1.10	0.524
	16.07 – 19.28	1.45	0.593
	19.29 – 21.96	1.22	0.549
	21.97 – 24.90	1.05	0.513
	24.91 – 27.85	0.43	0.299
	27.86 – 31.33	0.54	0.350
	31.34 – 36.15	0.64	0.389
	36.16 – 68.30	0.31	0.239
Landuse	Field	2.14	0.681
	Plot	1.39	0.581
	Road	0.20	0.169
	Hybrid Land	0.55	0.354
	Railroad Reservoir	0.40	0.284
	Wood Land	0.90	0.474
	River	0.00	0.001
Depth of Mined Tunnel (meter)	3.83 – 39.33	14.38	0.935
	39.34 – 102.13	1.40	0.584
	102.14 – 133.07	0.00	0.001
	133.08 – 150.36	0.29	0.223
	150.37 – 156.73	0.00	0.001
	156.74 – 166.74	0.48	0.322
	166.75 – 176.75	0.00	0.001
	176.76 – 191.32	0.00	0.001
	191.33 – 235.92	0.00	0.001
	no data	0.97	0.493
Distance from Drift (Buffer, meter)	0 – 1.23	2.08	0.676
	1.24 – 4.93	2.58	0.720
	4.94 – 11.11	2.79	0.736
	11.12 – 20.98	1.67	0.626
	20.99 – 34.57	0.28	0.220
	34.58 – 49.38	0.11	0.100
	49.39 – 67.90	0.12	0.106
	67.91 – 95.06	0.00	0.001
	95.07 – 149.39	0.00	0.001
	149.40 – 314.84	0.00	0.001
Geology	Geumcheon	0.00	0.001
	Jangseong	1.21	0.547
Depth of Ground water (meter)	4.50 - 14.28	5.47	0.845
	14.29 - 16.30	4.32	0.812
	16.31 - 21.36	0.58	0.369
	21.37 - 30.13	0.06	0.060
	30.14 - 37.55	0.00	0.001
	37.56 - 45.98	0.00	0.001
	45.99 - 54.07	0.00	0.001
	54.08 - 60.14	0.00	0.001
	60.15 - 67.90	0.00	0.001
	67.91 - 90.50	0.00	0.001
Permeability (Grade)	4.00 - 4.19	2.60	0.722
	4.20 - 4.29	2.84	0.740
	4.30 - 4.32	0.80	0.443
	4.33 - 4.34	0.56	0.358
	4.35 - 4.34	0.17	0.144
	4.35 - 4.36	0.11	0.097
	4.36 - 4.39	0.48	0.326
	4.40 - 4.46	0.33	0.245
	4.47 - 4.54	0.84	0.457
	4.55 - 5.00	1.63	0.620
RMR (Grade)	3.00 - 3.38	0.00	0.001
	3.39 - 3.54	0.00	0.001
	3.55 - 3.67	0.05	0.044
	3.68 - 3.85	0.06	0.058
	3.86 - 3.98	0.14	0.119
	3.99 - 4.07	0.25	0.197
	4.08 - 4.17	1.32	0.570
	4.18 - 4.26	1.12	0.527
	4.27 - 4.38	2.49	0.714
	4.39 - 4.80	4.86	0.829

Therefore, the frequency ratios of each factor were calculated from their relationship with ground subsidence occurrence. The maximum and minimum frequency ratio value were 14.38 and 0, respectively, and the average value was 1.08 (Table 2).

In the relation analysis, the ratio of the area where ground subsidence occurred to the total area is used. It is a higher correlation if the value is greater than 1, while the value lower than 1 means lower correlation (Kim *et al.*, 2005).

The frequency ratio represents the rating of each factor, and in the study area, depth of mined tunnel showed relatively high rating (Table 2.).

3.2 Application of Fuzzy Logic

To convert the frequency ratio to the range [0, 1], the following three rules were applied(Park *et al.*, 2005):

1) The ratio value of 0 means non-membership, thus the value should be a membership function value of 0. However, the fuzzy membership function value for the frequency ratio value of 0 was set to 0.001 to avoid numerical instabilities in the fuzzy combination step.

2) The ratio value of 1 means independent relationship between data and the target, and thus the value is a membership function value of 0.5 by considering that 0.5 is the neutral fuzzy membership value.

3) A very large ratio value that converges to infinity is the full membership value of 1.

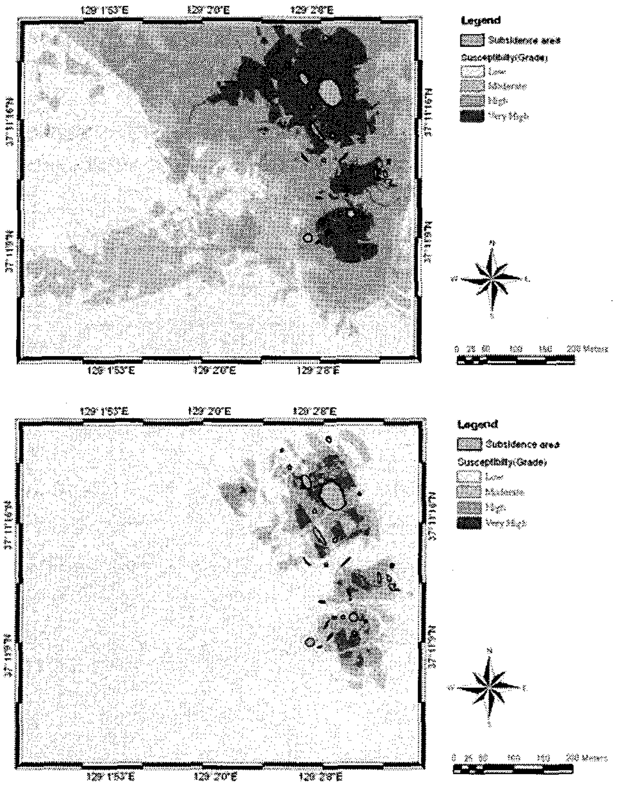

Figure 2. resultant ground subsidence susceptibility maps for the γ - operator; γ = 0.9999(above), γ = 0.0001(below)

To satisfy the above three rules, the following relationship (Park *et al.*, 2005) was used.

$$\mu = R / (1 + R) \qquad (1)$$

where μ is the fuzzy membership value and R is the frequency ratio.

Table 2 shows the resultant fuzzy membership values of each factor's subgroups with corresponding frequency ratio values.

After calculating the final fuzzy membership functions of all input spatial data, they were integrated using fuzzy combination operators as the single membership value for each pixel in the study area. We tested 5 operators: intersection (logical and) operator, union (logical or) operator, algebraic sum operator, algebraic product operator and ɣ operator. The intersection is corresponding to the minimum operator and the union the maximum operator.

4. VALIDATIONOF SUSCEPTIBILITY MAP

The resultant fuzzy membership value of each pixel can be considered as ground subsidence susceptibilities. Using these values, susceptibility maps of study area were made for each fuzzy combination operator (Fig. 2).

In order to evaluate the susceptibilities, we calculated root mean square error (RMSE):

$$RMSE = \sqrt{(1/N) * \sum_{i=1}^{N} (y-y')^2}$$

where, y is the actual subsidence occurrence, y′ is the estimated susceptibility, and N is the number of pixels. Table 3 shows the value of calculated RMSE.

Table 3. The value of calculated RMSE between susceptibility maps and actual subsidence occurrence map

Fuzzy combination operators		RMSE value
Intersection (logical and)		0.137
Union (logical or)		0.690
Algebraic product		0.005
Algebraic sum		0.974
ɣ - operator	ɣ = 0.0001	0.005
	ɣ = 0.1	0.008
	ɣ = 0.2	0.011
	ɣ = 0.3	0.017
	ɣ = 0.4	0.026
	ɣ = 0.5	0.041
	ɣ = 0.6	0.065
	ɣ = 0.7	0.105
	ɣ = 0.8	0.179
	ɣ = 0.9	0.337
	ɣ = 0.9999	0.972

5. RESULTS AND DISCUSSION

The results and discussion drawn from this study are as follows:

1) The rating of each factor representing the degree of influence to the subsidence occurrence was calculated by a frequency ratio model, and depth of mined tunnel showed relatively high rating.

2) Among the tested fuzzy operators, algebraic product operator and ɣ - operator with very low value of ɣ were the most effective for ground susceptibility map.

3) Union operator, algebraic sum operator and ɣ - operator with very high value of ɣ are not suitable for determining the locations vulnerable to ground subsidence.

4) So far, we used only RMSE method for validation of the susceptibility map, but other methods, such as field survey and success rate curve, are needed for better evaluation.

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