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Decision Support Scheme for Lishan Landslide Prewarning System

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Abstract

Monitoring Systems for Lishan landslide are installed in regard to slope stability. Time domain reflectometry (TDR) coaxial cable for sub-surface deformation within slope together with the global positioning system (GPS) to monitor ground surface movement are set for each identified sliding block. Real time monitoring results can be accessed through internet. A GIS database server collects data from field station can calculate factor of safety in real time for slope against sliding. The evaluated results are provided for decision making for response action in protecting local civilian's life and properties.

The TDR cable works like a continuous sensor that can detect deformation at any point along its embedded length. The capability for TDR cable is judged better than in-place inclinometer in detecting sliding zone. Steady GPS device used to monitor the ground surface so to calculate its possible movement for points inside a sliding block is another application and proven to be effectively. 15 monitoring stations are set for possible sliding blocks. Stations monitor rainfall and groundwater level change automatically. Data from the whole system are applied to build up the criteria for risk estimation. Risks in this field are ranked into 4 stages, namely normal, attention, warning, and dangerous. Message in regards to safety should be announced to local people. When field condition moves into dangerous stage, evacuation of people should be considered by the director.

Using spatial analysis of geographical information system (GIS), the

database of hydrogeology helped in evaluating risk rank of landslide. The method of fuzzy analytic hierarchy process (FAHP) analyzes the weights of each sliding block and monitoring stations in Lishan area. Considering all the monitoring stations and instruments, the sum of possible sets is 4^{23} . The highest grade of fuzzy analysis is 211.30 that represents the most dangerous situation. The lowest grade is 44.37 that is the safest situation. The criterions of landslide are analysed by fuzzy theory and verified by the records from historical typhoons. The decision support system of this landslide monitoring method includes real-time monitoring information and the result of fuzzy analysis. Using the criterion of decision support system, judgement can be made easily and quickly. And, decision for response in regard to local residents' safety can be made by computer automatically.

Keyword: Landslide, Time domain reflectometry (TDR), Global positioning system (GPS), Fuzzy analytic hierarchy process (FAHP)

Introduction

The decision support scheme is provided with three functions. First, it provides a more accurate and effective method for new monitoring instruments; second, it builds a comprehensive assessment for building a management criterion through the theoretical architecture for the updating of real-time monitoring data and landslide risk degree; and third, combined with the internet, it transmits real-time monitoring and decision-making information through systematic integration for the efficacy of disaster prevention and monitoring.

Traditional monitoring equipment is sometimes not suitable for landslides covering wide areas or in high-altitude mountain zones. For example, the data analysis of inclinometers is time-consuming and difficult to interpret. The data

must be plotted, usually off-site, before any movement can be determined (Kane, 2000). When using the TDR monitoring system, this cable becomes a continuous sensor that can monitor any deformation along its length when sliding deformation occurs. Aside from landslides or rock displacements, structures can also use the TDR cable to monitor their deformation (Dowding and Pierce, 1994). In rock mechanics, the technique has been employed to identify zones of rock mass deformation and blasting performance (Dowding et al., 1988; Dowding et al., 1989; Blackburn and Dowding, 2004). Using GPS to monitor the ground displacement of a landslide is another new application. There have been many reports on the use of GPS in landslide monitoring in recent years (Kodama et al., 1997; Gili et al., 2000; Malet et al., 2002). Three GPS receivers for long-term monitoring are used to estimate the length variation of surface displacement. Between each of the two GPS devices, one fixed and the other mobile, the baseline vector calculation of the relative positions of the two points is called the static baseline measurement (Yang et al., 2001). Each station was also equipped with general and important facilities such as a rain gage and a piezometer for groundwater level with automated recording systems.

Salewicz and Nakayama (2004) explained the relationship among database, simulation model, user interface, and decision makers in building a decision support system. This study discusses the operating structure and organization of a landslide monitoring and decision support scheme, including the database, simulation models, analytic methods, and display interfaces. Many expert systems often adopt different methods to handle the uncertain factors. Fuzzy Logic is one of the methods utilized to handle uncertain data. It is specially designed to process some data that could not be quantitative. Tah and Carr

(2000) pointed out that vague terms are unavoidable in risk assessment and put forward a proposal for construction project risk assessment using fuzzy set theory. Kangari & Riggs (1989) presented an integrated knowledge-based system to describe risks using linguistic variables implemented as fuzzy sets. Cheng et al. (1999) proposed that fuzzy set theory can give a much better representation of the linguistic data. Therefore, this research proposes to use the fuzzy set theory for quantifying the linguistic variables.

This study applies the spatial decision-making ability and data layer integration ability of GIS in building a complete hydrogeological database and discusses the stability of the landslide zones. Using Fuzzy Theory, the study establishes the distribution of fuzzy sets for each monitoring station, and applies FAHP to build the assessment model of management criteria and specify the weight of each area and automatic monitoring station. The management criteria are established for four states (“normal”, “attention”, “warning” and “dangerous”). In light of all possible situations, the total weight of all combinations of situations monitored by each monitoring device is calculated through the FAHP to set up the analytic result of the weights for different degrees of risks, as well as to follow up the hazardous state of the landslide area. Decision support scheme for Lishan landslide prewarning system incorporates the real-time monitoring information, analytic result of the risk degree, hydrogeological display, and site image of the landslide area. When the risk degree of a landslide based on the system’s real-time analysis tends to aggravate, the system will warn relevant departments and officers to make the decision.

Li-shan landslide

The landslide area studied in Li-shan village is located at the intersection of the east-west cross-island highway route 8 and route 7A in central Taiwan (Figure

1). Topographically, Li-shan is located at the west wing of the Central Ridge with an elevation between 1,800 m and 2,100 m (mean sea level). Most slopes dip to the northwest with slope angles between 15° and 30° down to the Teh-Chi Water Reservoir. In April 1990, an intense and spectacular landslide occurred in this area following prolonged torrential rain. The catastrophe led to a destroyed pavement foundation on route 7A and disrupted transportation facilities. This landslide also affected nearby buildings such as the Li-shan Grand Hotel that suffered severe settlement and deteriorated cracks. The accumulated rainfall from 10 April to 20 April was 585 mm, while the monthly rainfall record for that April was 957.5 mm. Both rainfall records exceeded the record of a 50-year return period based on the frequency analysis. The continuous rainfall could have caused a tremendous amount of water infiltration and accumulation inside the slope. The infiltrated water may have increased the pore water pressure, subsequently decreasing the effective stress in the soil or rock mass and resulting in the instability of the slope. Based on this, it can be confirmed that the rainfall-induced increase of water pressure is the main factor that triggered the landslide of the highly weathered rock slope (ITRI, 1993).

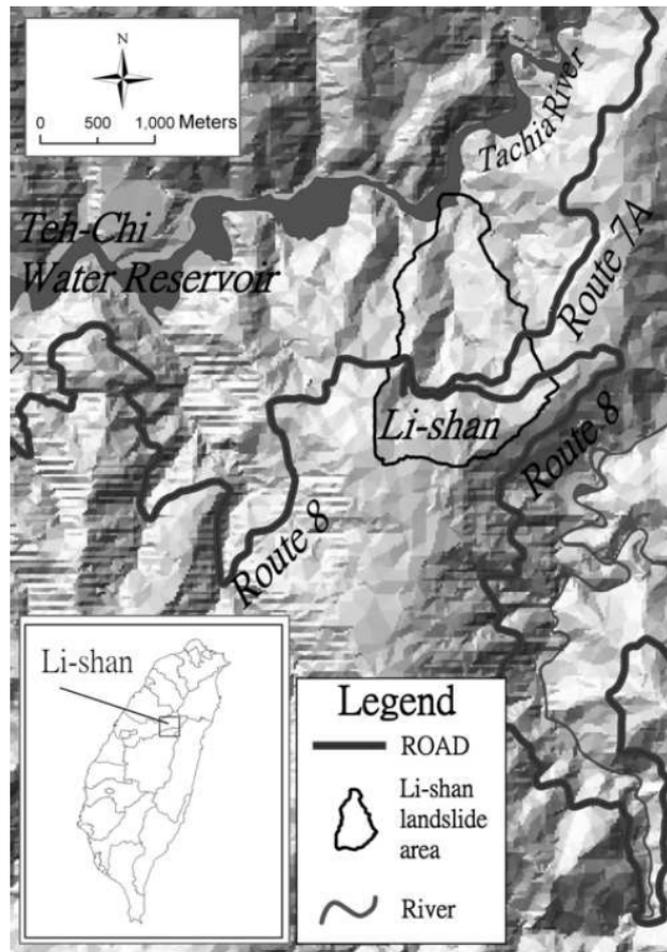


Figure 1. Topography of the Li-shan landslide

Geologically, the Li-shan area is located in colluvial formations originally from the Miocene Lushan slate formation. Due to the dynamic tectonic activities as well as the high precipitation, the surficial slate formations in this area are highly weathered. It is strongly supported by the occurrence of slaty cleavages, foliation shears, and interlayers of silty residual soil. The results of the compression strength test show that the Lushan unweathered slate is about 2.76 ton/m^3 in unit weight. The mechanical properties of the geomaterials with different weathering conditions are summarized in Table 1 (Shou and Chen, 2005).

Table 1. Mechanical properties of the geomaterials in the Li-shan area (Shou and Chen, 2005)

Geomaterial type	Unit weight* (ton/m ³)	Cohesion c(ton/m ²)	Friction angle ψ (°)
Colluvium	2.06	0.75	30
Medium to highly weathered slate	2.69	3.00	28
Fresh to medium weathered slate	2.76	30.00	33
Sliding plane	2.69	3.00	28

* Unit weight is used for dry solid particles.

The landslide area of Lishan is divided into four zones, West, Northeast, Central, and Southeast, based on the topography, geology, landslide blocks, and boundary of watershed. Eight monitoring stations were set up in this area. Each station was equipped with facilities such as the piezometer for measuring the groundwater level, the inclinometer for monitoring the ground deformation, and the extensometer for detecting the surface movement. Monitoring instruments for Li-Shan area were installed to measure the ground deformation and the groundwater level from 1995 but they were traditional instruments and equipment. From 2008, by combining the automatic monitoring station with internet embedded controller, real time monitoring results can be accessed through ADSL. A GIS database server collects data from field station to calculate factor of safety for slope against sliding. The location of auto-monitoring station is shown in Figure 2.

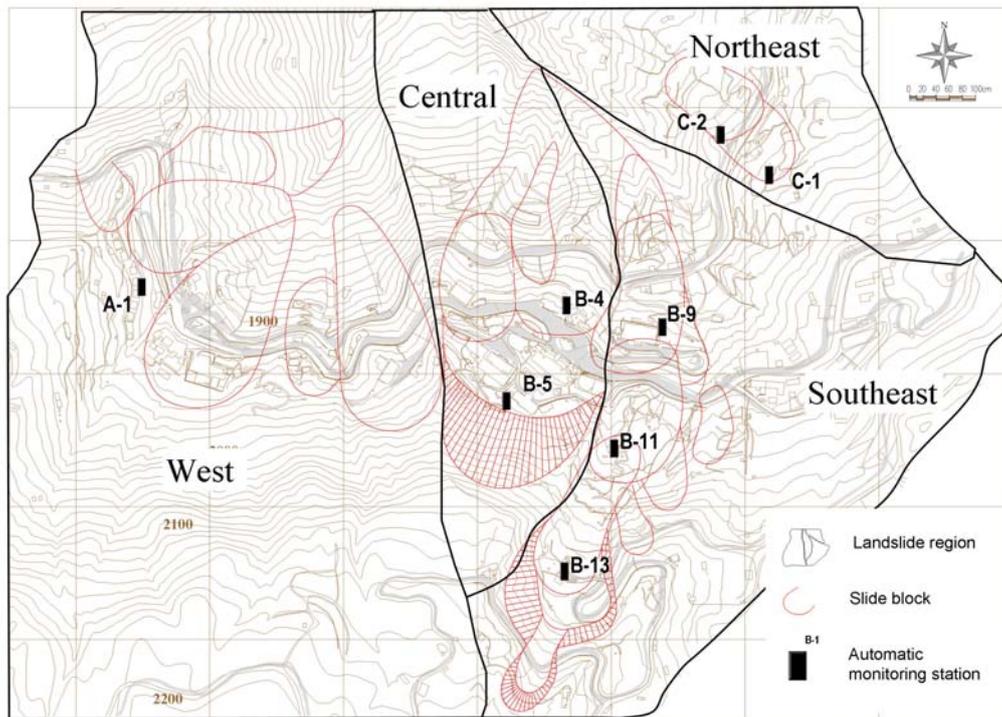


Figure 2. Location map of auto-monitoring station

Methodology

Automatic monitoring stations were built, including TDR, GPS, and others monitoring equipment in the landslide area. The weights of the different instruments under different safety coefficients are defined by building the fuzzy theory for management criterion of landslides in Lishan. We can obtain a better understanding of relationship with the landslide area and each monitoring system. This study builds an assessment model of management criterion using the FAHP method. Below is a brief introduction of the major steps of FAHP.

1. Build the Pairwise Comparison Matrix: A Pairwise Comparison Matrix is built through expert assessment of the relevant importance of elements i and j in one layer.
2. Build the triangular fuzzy number: Build the triangular fuzzy number based on the fuzzy theory.

3. Build the fuzzy positive reciprocal matrix (Buckley, 1985).

$$\tilde{A} = \left[\tilde{a}_{ij} \right], \tilde{a}_{ij} \times \tilde{a}_{ji} \approx 1, \forall i, j = 1, 2, \dots, n \dots\dots\dots(a)$$

4. Calculate the fuzzy weight of each criterion factor (Buckley, 1985).

$$\bar{Z}_i = \left[\tilde{a}_{ij} \otimes \dots \otimes \tilde{a}_{in} \right]^{\frac{1}{n}}$$

$$\tilde{W}_i = \bar{Z}_i \otimes (\bar{Z}_i \oplus \dots \oplus \bar{Z}_n)^{-1} \dots\dots\dots(b)$$

At the same time, $\tilde{a}_1 \otimes \tilde{a}_2 \cong (\alpha_1 \times \alpha_2, \delta_1 \times \delta_2, \gamma_1 \times \gamma_2)$

where \otimes represents the multiplication of fuzzy number, \oplus represents the addition of fuzzy number, and \tilde{W}_i is the column vector of fuzzy weight for each criteria.

5. Evaluate the fuzzy weight (Defuzzify) comprehensively

This study calculates the relative weight of each criterion using the geometric average method. The first calculation is to build the fuzzy set of monitoring instruments

The criterion of rainfall is established based on the analysis of storm frequency, the data of rainfall from the automatic monitoring station and the artificial neural network (ANN) forecast, and by reference to the “Remediation Plan and Hazard Prewarning System for Li-shan Landslide” (SWCB, 2005). The criterion of the underground water level is built by inverse analysis in the slope stability analysis procedure, and by discussing the correlation between the underground water level and the factor of safety. In the report “Lishan area Monitoring Management and System Maintenance Data Analysis” (NCHU,

2008), the criteria of GPS and TDR were developed by reasonably assessing the possible damage of slope through the surface displacement monitored by GPS and the deformation of rock formation monitored by TDR, as indicated in Tables 2, respectively.

Table 2(a). Criteria for TDR

Degree of risk	Attention	Warning
Shear deformation	10 mm	----
Tensile deformation	40 mm	100 mm

Table 2(b). Criteria for GPS

Degree of risk	Attention	Warning	Dangerous
Accumulated two-hour displacement	10 mm	20 mm	----
Tr	----	< 5hr	< 2hr

* Tr: using curve of reverse deformation speed to predict expected time of slope failure (Fukuzono, 1999)

Table 2(c) Criterion for elevation of groundwater level

Degree of risk	Normal	Attention	Warning	Dangerous
Corresponding factor of safety	1.15	1.10	1.05	1.00
A1 Elevation of G.W.L (m)	1890	1892	1897	1902
B4 Elevation of G.W.L (m)	1891	1897	1903	1908
B5 Elevation of G.W.L (m)	1945	1948	1953	1962
B9 Elevation of G.W.L (m)	1893	1902	1907	1913
B11 Elevation of G.W.L (m)	1978	1987	1991	2004
B13 Elevation of G.W.L (m)	2040	2050	2050	2060
C1 Elevation of G.W.L (m)	1874	1878	1882	1885
C2 Elevation of G.W.L (m)	1830	1835	1838	1843

Table 2(d) Criterion for rainfall

Degree of risk	1 hour	24 hours	48 hours
Attention	20mm	100mm	—

Warning	—	150mm	200mm
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Different weights are assigned to each instrument in each monitoring station since their different importance with management criterion. The importance of all monitoring instruments under different criteria is first classified based on their regions and an analytic hierarchy table is built (Table 3).

Table 3 Monitoring System Analytic Hierarchy Table in the landslide area of Lishan

Zone	Monitoring station	Instruments in the station
West	A1	Rainage, Piezometer, TDR
Central	B4	Piezometer, TDR
	B5	Piezometer, TDR, GPS
Southeast	B9	Rainage, Piezometer, TDR
	B11	Rainage, Piezometer, TDR, GPS
	B13	Piezometer, TDR
Northeast	C1	Rainage, Piezometer, TDR, GPS
	C2	Piezometer, TDR

The steps are to set up the classification of fuzzy set as follows: First, inputting and the fuzzy number, this study has the fuzzy model architecture of four monitoring instruments, namely, rainfall, underground water level, TDR, and GPS, which include membership functions such as “normal,” “attention,” “warning,” and “dangerous,” respectively. Second, defining the fuzzy rule, the fuzzy logic rule must be objective and reasonable. The rule consists of a series of “If, Then..., else...”. The “If” condition part is normally called the input fuzzy number and the “then” conclusion part is the output fuzzy number. The last, outputting the score of risk degree, the safety management score is obtained by defining the fuzzy rule and defuzzifying.

Results and Discussion

To highlight the importance of each region in the real-time monitoring system, each region should have different weights in the real-time monitoring system in light of the difference of the instruments installed for different monitoring stations, their position, geology and environment, and local importance. The weight should be decided based on the following conditions: (1) consider the topographical changes by analyzing the hydrogeology through GIS and judge whether it is the geologically sensitive zone; (2) utilize the direction and remediation of underground water in each region as an important basis for reference; (3) check whether the instruments in the automatic monitoring station are efficient and useful; (4) evaluate if the economic efficacy of the region includes the traffic influence, which is important for main roads and less important for other roads; (5) assess whether the area still needs engineering remediation; (refer to Table 4 for the assessed items in each monitoring station).

Table 4. Assessed Items for Each Monitoring Station

Zone	Monitoring station	topographically and geologically sensitive zone	Ample underground water	instruments' efficacy	Economic benefits (traffic, population and etc.)	Requires engineering remediation	Total score
West	A1	5	1	3	3	3	15
Central	B4	3	3	1	3	2	12
	B5	3	5	3	5	1	17
Southeast	B9	3	3	3	1	1	11
	B11	1	1	5	1	2	10
	B13	3	1	1	0	2	7
Northeast	C1	1	3	5	1	1	11
	C2	5	3	1	3	2	11

* 5: Complete conformance; 0: nonconformance, 4-1: intermediate

Based on the hierarchy established in Table 3, the assessed items in the same hierarchy and dimension are designed in pairs to compare their importance. This study uses a five-point scale to describe the relative importance between

pairs of elements and build a comparison matrix, as shown in Table 5. The second step is to assess pairs in the matrix. This study adopts the semantic description so that the fuzzy score can easily and adequately express the assessed value through subjective judging. It also uses triangular fuzzy numbers to express each semantic judgment and adequately indicates the fuzzy performance of decision making. This study uses a 1–5 scale (Saaty, 1996) and through testing the homogeneity of variances, it builds a fuzzy positive/inverse matrix (as shown in Table 6) and a fuzzy positive/inverse matrix of each monitoring station in each area (Table 7).

Table 5. Pair Comparison Matrix of Landslide Areas

A	A:B V. I.	A:B I.	A:B R. I.	A:B L. I.	S. I.	B:A L. I.	B:A R. I.	B:A I.	B:A V. I.	B
West							✓			Central
			✓							Southeast
				✓						Northeast
Central		✓								Southeast
			✓							Northeast
Southeast						✓				Northeast

* V. I.: Very important, I.: important, R. I. : Relatively important, L. I. Less important, S. I.: Similarly important

Table 6. Fuzzy Positive/Inverse Matrix for Each Zone of Landslide

	West	Central	Southeast	Northeast
West	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(1,2,3)
Central	(2,3,4)	(1,1,1)	(3,4,5)	(2,3,4)
Southeast	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,1,1)	(1/3,1/2,1/1)
Northeast	(1/3,1/2,1/1)	(1/4,1/3,1/2)	(1,2,3)	(1,1,1)

Table 7. Pair Comparison Matrix and Fuzzy Positive/Inverse Matrix of each Monitoring Station

Central Zone	B4	B5
B4	(1,1,1)	(1/5,1/5,1/4)
B5	(4,5,5)	(1,1,1)

Southeast Zone	B9	B11	B13
B9	(1,1,1)	(1,2,3)	(3,4,5)
B11	(1/3,1/2,1/1)	(1,1,1)	(3,4,5)
B13	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1,1,1)
Northeast Zone	C1	C2	
C1	(1,1,1)	(4,5,6)	
C2	(1/6,1/5,1/4)	(1,1,1)	

It is defuzzified through formulas (a) and (b) and then normalized to obtain the weight of each hierarchy. Taking the calculation of weight for each zone as an example, four fuzzy weights will be obtained: 0.24, 0.50, 0.10 and 0.16. The last step is hierarchy cascading. After assessing the different items of each station in Table 8, we can see that monitoring station B5 is the most important, followed by A1, C2, B4, and C1, and finally B9, B11, and B13. As to zone weight, the central zone is the most important. The study also considers the monitoring instruments and environmental factors of each monitoring station. It also defines the risk degree of each area and the entire zone of different monitoring instruments under different criteria.

Table 8. Fuzzy Weight of General Assessment Factors

Zone	Weight	Monitoring station	Weight	Multiplication	Sequence
West	0.24	A1	1.00	0.24	2
Central	0.50	B4	0.18	0.09	4
		B5	0.82	0.41	1
Southeast	0.10	B9	0.53	0.05	6
		B11	0.36	0.04	7
		B13	0.11	0.01	8
Northeast	0.16	C1	0.36	0.06	5
		C2	0.64	0.10	3

To understand the stability of all landslides in Lishan under a typhoon or storm in the real-time monitoring system, the total weight of the zone can be calculated by adding up the product of the weight of each automatic monitoring station

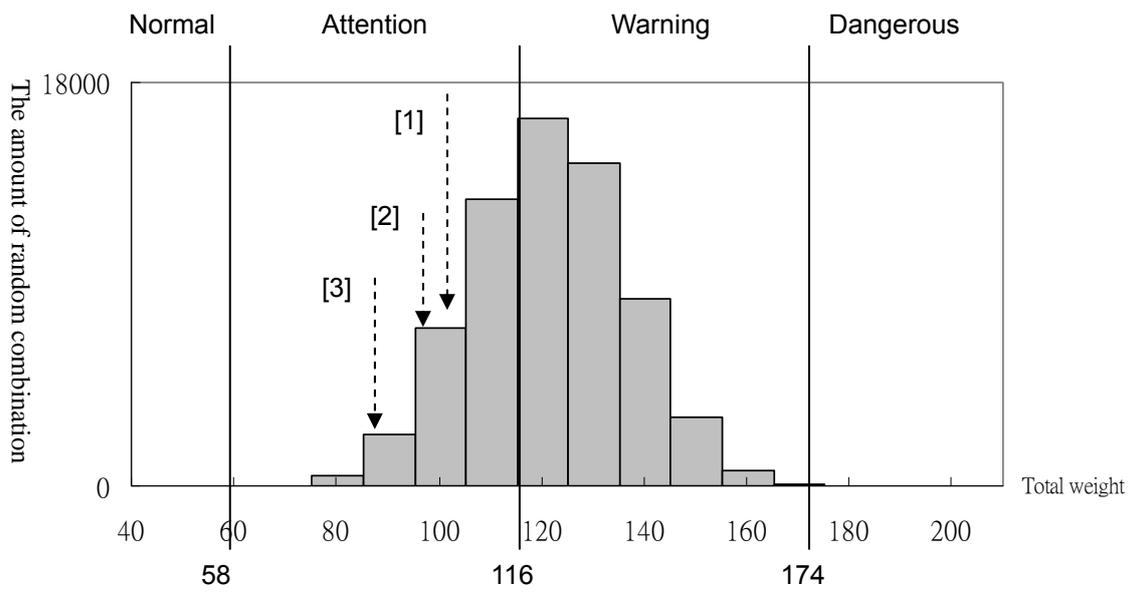
and the fuzzy number of instrument in that station. The fuzzy numbers and scores of calculations are shown in Table 9 for example as JANGMI Typhoon in 2008. Total weights calculated under different states are classified into four degrees, namely, “normal”, “attention”, “warning”, and “dangerous”. For reference by the decision makers, the degree is classified as “attention” if the total score is greater than 58; “warning” if the total score is greater than 116; and “dangerous” if the total score is greater than 174.

Table 9. Situation of Each Monitoring Instrument and Total Weight

JANGMI Typhoon (2008/09/26 ~ 2008/09/29)	fuzzy number				Weight	Score
	Monitoring station	Rainfall	Groundwater level	GPS		
LA01	15.3	15.3	----	40	0.24	16.94
LB04	----	17.3	----	15.3	0.09	2.93
LB05	----	15.3	43.6	40	0.41	40.55
LB09	15.3	25.6	----	15.3	0.05	2.81
LB11	15.3	26.3	15.3	40	0.04	3.88
LB13	----	25.8	----	40	0.01	0.66
LC01	15.3	15.3	84.7	15.3	0.06	7.84
LC02	----	34.1	----	15.3	0.1	4.94
Total score						80.55

To consider all possible situations, there are 23 monitoring instruments so the sum of all combinations of all monitored situations is 4^{23} . Based on the calculation of total weight of all situations, the largest total weight is 211.30, that is, all 23 monitoring instruments are at an “dangerous” state. The lowest total weight is 44.37, that is, all 23 monitoring instruments are at a “normal” state. Figure 3 is the chart plotted by the random combination of 60,000 data to indicate mainly the delimitation of the entire zone under the four degrees and

what would happen under which combination. It shows the total weight of rainfall, underground water level, GPS, and TDR during typhoons in Lishan since 2008. Their relationships are used to describe the degree and as basis for judging the four criteria of landslide management.



- * [1]: KALMAEGI typhoon (2008/07/16~07/18)
- [2]: FUNG-WONG typhoon (2008/07/26~07/29)
- [3]: JANGMI typhoon (2008/09/26~09/29)

Figure 3. Distribution of total weights and risk degree

This model can be subsequently written into the decision-making system to show the real-time monitoring data on the Web site of a single monitoring station and the risk degree of a landslide. The exhibition function includes real-time data such as the rainfall, underground water level gauge, TDR, GPS, and other observation data. Data would be refreshed every 20 seconds to display the real-time data. The fuzzy theoretical model for the comprehensive estimation of each zone is incorporated into the webpage to display the risk degree of each zone. Figure 4 illustrates the state of the monitoring station on the web site. Indicators are used to indicate the current state of the landslide

area in Lishan (Green = Normal, Yellow = Attention, Red = Warning).

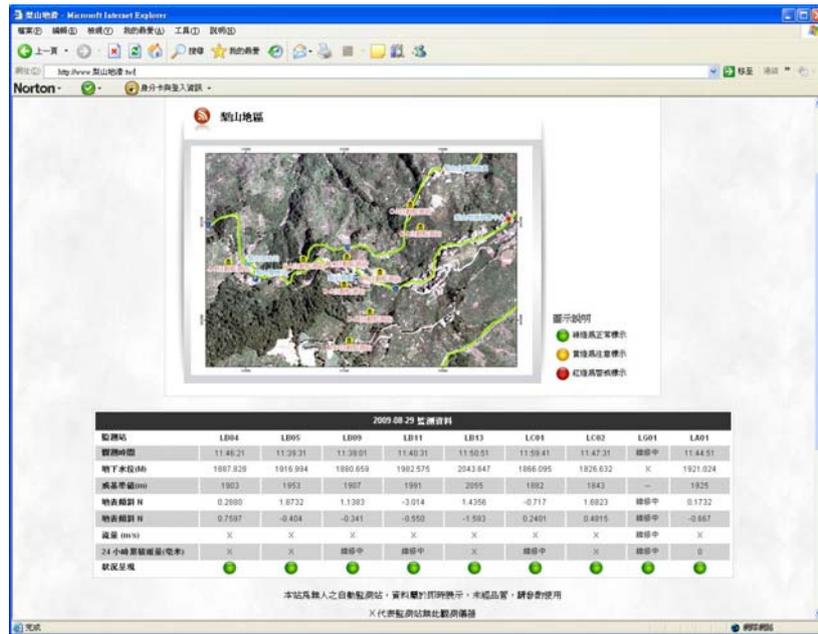


Figure 4. Illustration of the State of the Monitoring Station

Since GIS has true geographical coordinates, the variation as time goes by can be simulated in the dynamic 3D GIS environment by defining the time change of spatial objects or working together with the image analytic software. The change of surface and topography versus time can also be truly displayed, and system can combine the 3D image of site and the judgement of management criteria (Figure 5).



Figure 5. 3D Scene and Image Monitoring

Conclusion

This study proposes the building management criteria by combining the new automatic monitoring system and relevant theories, analyzing the risk degree of landslide zones with a multi-target decision-making model and fuzzy method, and building the decision support scheme for landslide monitoring. It sets up the management criteria for stratum deformation by TDR monitoring, ground surface displacement by GPS monitoring, underground water level, and rainfall. It then classifies the risk degree as “normal,” “attention,” “warning,” and “dangerous.” It has established an assessment model for management criteria by fuzzy theory. The system set up the distribution of fuzzy set for each monitoring station, applied the FHAP method, and got the weight of each landslide region (weight 0.24 for the West, 0.5 for the Central, 0.10 for the Southeast, and 0.16 for the Northeast). The weights of all stations were determined after FHAP analysis, followed by monitoring stations B5, A1, C2, B4, C1, B9, B11, and B13 at weights of 0.41, 0.24, 0.10, 0.09, 0.06, 0.05, 0.04, and 0.01, respectively. To consider all possible situations, the largest total weight is 211.30, that is, all 23 monitoring instruments are at an “dangerous” state; and the lowest total weight is 44.37, that is, all 23 monitoring instruments are at a “normal” state. The total weight is calculated by considering the typhoon rainfall, underground water level, and GPS and TDR monitoring data over the years to delimitate the analytic result of the weight of risk degree. For reference of the decision makers, the degrees are classified as follows: “attention” if the total score is greater than 58, “warning” if the total score is greater than 116, and “dangerous” if the total score is greater than 174.

Decision support scheme for landslide prewarning system incorporates real-time monitoring data, analytic result of the risk degree, 3D hydrogeological

data, and site image of the on-site monitoring system. Using the criterion of decision support system, judgement can be made easily and quickly. And, decision for response in regard to local residents' safety can be made by computer automatically.

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