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Development of Impact Evaluation and Diagnostic Indicators for Sinkholes

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ABSTRACT

Based on the previous studies on sinkholes and ground subsidence conducted until date, the factors affecting the occurrence of sinkholes can be divided into natural environmental factors and human environmental factors in accordance with the purpose of the study. Furthermore, to be more specific, the human environment can be classified into the artificial type and the social type. In this study, the assessment indices for assessing risks of sinkholes and ground subsidence were developed by performing AHP analysis based on the results of the study by Lee et al. (2016), who selected the risk factors for the occurrence of sinkholes by performing Delphi analysis targeting relevant experts. Analysis showed that the artificial environmental factors were of significance in affecting the occurrence of sinkholes. Explicitly, the underground factors were found to be of importance in the natural environment, and among them, the level of underground water turned out to be an imperative influencing factor. In the artificial environment, the underground and subterranean structures exhibited similar importance, and in the underground structures, the excessive use of the underground space was found to be an important influencing factor. In the subterranean ones, the level of water leakage and the erosion of the water supply and sewage piping system were the influential factors, and in the surface, compaction failure was observed as an imperative factor. In the social environment, the regional development, and above all, the groundwater overuse were found to be important factors. In the managemental and institutional environment, the improper construction management proved to be the most important influencing factor.

Key words*: AHP, Assessment Indices, Sinkhole, Subsidence.*

1. INTRODUCTION

In the downtown area of the country, the extraordinary phenomena are coming about: roads and sidewalks suddenly fall into the ground. They are called sinkholes. When a sinkhole occurs, it causes a massive property loss and a lot of damage to human life, causing anxiety towards citizens. This is higher than the damage caused by normal ground subsidence. The principle is that as the seepage force into the solid particles by the excessive flow of underground water increases and the support force (effective stress) decreases within the ground, a multi-phase substance that is composed of solid particles and the underground water flowing between them, sinkholes usually occur. There are various causes for this sequence of processes to occur. In our country, the Environmental Impact Assessment System is operated to manage these risks. The Environmental Impact Assessment is a system that pre-investigates and assesses how large-scale development projects like a expressway, a dam, a flying field, a huge factory, a golf course etc., affect the environment, minimizes environmental impacts, and prepares measures to prevent environmental destructions. In Korea, after it was introduced in 1977, with increasing awareness of the importance of the environment, the Environmental Impact Assessment Act was enacted and came into effect in 1993 (Lee, 2002) [1] Article 1 in the Environmental Impact Assessment Act states that in planning and implementing the project plan for environmental impact assessment, this act is for foreseeing and analyzing the harmful impact that the project will have and take measures against this matter, and that its purpose is to promote a comfortable and secure national life by making the development environmentally sound and sustainable. From a macroscopic perspective, the projects concerned with sinkholes among the projects for environmental impact assessment include all the engineering works. And in addition to the engineering works, the operation and the mutual causal influential relationship should be considered. After all, from the perspective of a urban engineering, the sinkhole phenomenon is the problem that occurs in the development and the aging of the city. Therefore, merely engineering factors should not be considered to foresee and prevent the occurrence of sinkholes. And the laws from the multifocal views to prevent sinkholes shall be made and specific causes of occurrence shall be derived. An

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environmental impact assessment system to prevent sinkholes shall also be made based on this aim. However, it is very difficult for us to realize and manage all of these because we live on the limited time and resources. So we need to assess relative risks through the comparison of each risk factor with another. We can choose the most likely factors to administer the time and resources because we can realize what are the risk factors that are necessary first of all to manage and control through the assessment of the relative risks. Such studies will be the best effort to protect citizens' wealth and life.

The results of researches about sinkholes are as follows: Lee(2014) [2] separated the causes of the occurrence of sinkholes into the natural ones for which the surface of the earth sinks due to melting of lime underneath it and the artificial ones that occur due to road and subway constructions, overuse of the underground water, excavation and blasting impact, the aging of the water supply and sewage piping system that is buried in the ground, and the exterior impact. Jo(2014) [3] sought measures in the construction industry to solve the problems of sinkholes that occurred, as mentioned above, in the Seokchon underground road and during the construction of the subway line 9 and pointed out the self-consciousness about sinkholes in the construction industry, the search of the notices of TBM construction methods, the establishment of reporting system for abnormal symptoms, the active utilization of the information about the underground facilities, the reexamination of overuse of the underground space, and the prevention from poor construction. Lee(2014) [4] pointed out that the main causes of the occurrence of sinkholes are the damage of the sewage pipe line, the problems related with the nearby construction, the damage of the water supply line and the like. Park and Park(2014) [5] mentioned that the artificial causes of the occurrence of sinkholes are the rapid pupillation of surrounding soil caused by the aging of the buried pipes and the leakage of the junctions in the sewage pipe line and the water supply line, the electric power and the gas pipe lines. Lee *et al.*(2016) [6] found the risk causes of the occurrence of sinkholes with the expert groups by using the Delphi technique. The Delphi technique is the decision methodology with which the comprehensive causes like sinkholes are found out with expert groups. To look at the causes of sinkholes, they occurred due to the pupillation caused by melted limestone in the limestone area in the foreign countries, and due to comprehensive causes in Korea: pumping around the subway stations, vibration caused by subway and large vehicles, breakage of the sewage and water supply pipes, change of the level of the groundwater around excavation work. The purpose of this study is to perform AHP analysis based on the causes of the occurrence of sinkholes that Lee *et al.*(2016) [6], selected, and to develop the risk assessment indices of sinkholes by selecting the relative weight of each factor.

2. SCOPE AND METHOD OF RESEARCH

In this study, it is important by what risk factors sinkholes occur because this study is for the effective prevention of sinkhole disasters by finding priority through the selection of risk causes of sinkholes. Although a lot of studies have been carried out about the clear definition and the pattern of a sinkhole, it has not been established yet. That's because the cause of the occurrence of a sinkhole is not simple, and it is found that as the research progresses, it occurs for multiple complex causes. Thus, by recognizing the trends of antecedent studies, the risk factors influencing the occurrence of a sinkhole were selected. The study procedure for this study is shown in Fig. 1.

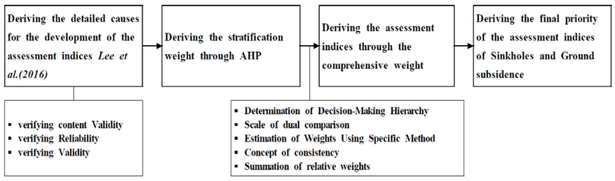

Fig. 1. Research Flow Chart

2.1. AHP Analysis

AHP(Analytic Hierarchy Process) methodology was used for selecting the risk causes of sinkholes for environmental impact assessment. AHP is the Multi-based decision-making technique in which the assessment criteria are stratified and the weight is determined according to the stratum if decisions are made based on a number of assessment criteria. This was developed by Saaty (1990) [7], and a systematic process that effectively interprets complex decision-making problems. AHP is a technique that calculates the weight of each alternative by dividing hierarchically and realizing the weight among target values, and is suitable for stratifying and resolving decision-making problems, including multiple goals, criteria, and decision-makers. That is to say, after stratifying the given decision-making problems, it is to determine the priority of the alternatives at the bottom stratum by looking for relative importance or weight through pairwise comparisons of elements in the immediate sub-layer from the perspective of a component (or criteria) at a higher stratum(Choi *et al.*, 2008) [8].

In relation to assessment of AHP, Saaty and Kearns(1985) [9] evaluated that AHP has been successfully applied in a variety of fields, such as plans for energy distribution, designs of transportation systems, future plans for the corporation, designs of the future scenario for higher education, planning for running and elective processes, Oil price prediction, etc. They also evaluated that AHP is a very useful way for decision-making and planning (Saaty and Vargas, 1982) [10].

According to decision making process of AHP, the first is setting study model among evaluation factors. It composes study model by comparing subelement of evaluation that belong to one higher evaluation element by class. Second is to make the sum of significance of sub elements and higher evaluation elements to 1. For this, the significance of subelement of evaluation within study model is multiplied with significance of higher evaluation element. Finally, the third is credibility review of study results. At this step, the consistency ratio of each evaluation result is calculated. In AHP, the consistency ratio of evaluator is important. Higher ratio refers to stronger agreement among evaluator. Thus, in AHP method, consistency ratio plays significant role in securing credibility of study results. Thus, it requires verification on consistency ratio. The calculation of consistency ratio is as below.

$$C.R. = \frac{\text{C.I.}}{\text{R.I.}} \times 100\% \qquad (1)$$

C.R.(Consistency ratio) is the value dividing C.I.(Consistency index) by the R.I.(Random index) The random index is the average consistency index of equation generated randomly based on sample size 500. Thus, the random index is decided by the size of equation. Consistency ratio decides credibility of multiple evaluation results. In general, if the average consistency rate of evaluator is below 10%, the result of evaluation become credible.

Table 1. R.I. According to Size of the Matrix (Satty, 1990) [7]

n	3	4	5	6	7	8	9	10
R.I.	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.2. Selection of Factors

The study on the risk factors of sinkholes for AHP was performed based on the risk factors of the occurrence of sinkholes that were derived by Lee *et al*.(2016) [6]. Lee *et al*.(2016) [6] composed the group of 6 experts at first and chose a factor that could pose a risk through the first brainstorming and literature research. And then they composed the group of 30 experts again, and performed the 2nd and the 3rd Delphi analysis. By doing this, they divided three areas in total and composed a sub-area corresponding to each of them.

Due to recent climate change, the natural environment of the Korean Peninsula is changing rapidly. In 2016, the number of scorching heats and localized torrential rains has soared, and we have has been suffering from the drought nationwide over several years. The population of cities continues to increase, and to meet this situation, high-rise buildings are being built high into the sky, and underground facilities, and basements deep into the ground. A lot of vehicles and cargos are being transported on the new roads and railroads and lots of water are being drawn to be used. New towns continue to be developed and the sewage and water supply pipes of existing towns are increasingly becoming aged. This results in a weakening stress on the ground, causing sinkholes in the center of the city. The factors for the occurrence of these sinkholes are too complex to establish precisely the causal relationship. But various opinions about the causes of the occurrence are being provided with the broad sense with the use of terms ununified - sinkhole, ground subsidence, etc.

All the conditions surrounding and affecting the human life is called environment. The environment is largely divided into natural environments, such as climate, location, and topography, and into human environments, such as cultures, politics, transportation, communication, made by human beings and altered by a human power. To assess the risk of potentially possible sinkholes, the causes of the occurrence of sinkholes are divided into those of the natural environment and into those of the human environment. The human environment was divided into artificial environment and social environment. The natural environment is divided into underground and ground conditions. The artificial environment is subdivided into underground structures and underground construction materials and the social environment is subdivided into regional development and management/institutional environment. The details include difference between pervious soil and Impervious one, the flow of surface water and management thereof, changes in effective stress of soil layer due to global warming, distortion of groundwater flow according to the impact of underground structure and problems due to construction method, vibrations caused by railway and traffic, the impact according to types of structure excavation method and types of pseudo-construction methods of a retaining wall, the degree of aging of the sewage and water supply pipes, etc.

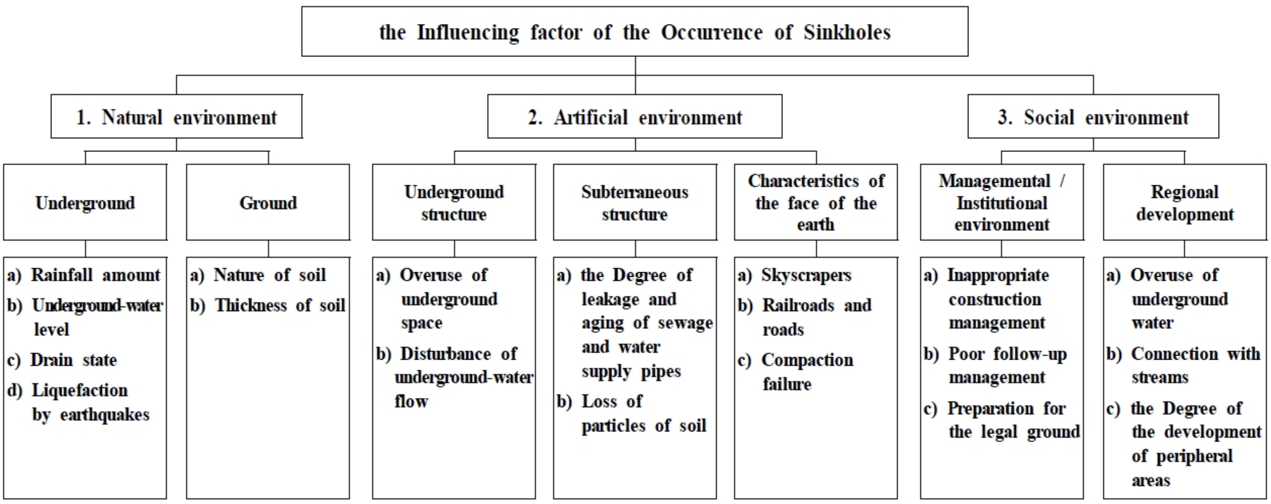

Fig. 2. Results of Selection of Risk Factors of the Occurrence of Sinkholes (Lee et al., 2016) [6]

Table 2. Demographic Characteristics of the Expert Group

Division		Frequency	%
Sex	male	44	84.6
	female	8	15.4
Occupation	technician	4	7.7
	researcher	48	92.3
Age	under 29	8	15.4
	under 39	28	53.8
	under 49	16	30.8
Career	under 5 years	16	30.8
	under 10 years	20	38.5
	under 20 years	16	30.8
Final educational attainment	bachelors	4	7.7
	masters	48	92.3
	Total	52	100.0

Table 3. Results of AHP analysis of the First Stratum

Variables / Weight	Natural environment	Artificial environment	Social environment
Average of Overall Respondents (n=52)	0.320	0.450	0.230

C.R.(consistency ratio)=0.078

The study of Lee *et al.*(2016) [6], in addition to these factors, selected an increase in the frequency of installation of underground infrastructure due to urban growth and expansion, poor construction, and climate changes, such as heavy rain, cold weather, scorching heat, etc. Differently from other studies, this study added managemental and institutional environment factors, such as inappropriate construction management, poor follow-up management and preparation for the legal ground, etc. In the local development, this study also showed that the degree of the development of peripheral areas is an influencing factor that contrasts with other studies.

3. ANALYSIS RESULT

3.1 Composition of the Expert Group

A total of 52 people have been chosen as a expert group, and their demographic characteristics showed 84.6 percent of males and 15.4 percent of women. Their occupational characteristics showed 92.3 percent of researchers and 7.7 percent of technicians. Their age showed the highest 53.8 percent of under 39, followed by 30.8 percent of under 49 and 15.4 percent of under 29. Their career showed the highest 38.5% of under 10 years, followed by 30.8% of under 5 years and 20 years respectively. Their Final educational attainment showed 92.3% of masters, and 7.7% of bachelors (Table 2).

3.2 Stratum Analysis

(1) Results of the First Stratum

The highest and first stratum showed 0.450 of the artificial environment, followed by 0.320 of the natural environment and 0.230 of the social environment. At this, the C.R. showed 0.078 (Table 3). Namely, it is shown that the expert group recognized the underground structure, the subterraneous structure and the characteristics of the face of the earth as the major influencing factors.

(2) Results of the Second Stratum

Table 4 shows the results of AHP analysis of the second stratum. As a result of the analysis, in the natural environmental factors, the underground showed 0.724 and the ground showed 0.276. At this, the C.R. showed 0.000. Namely, it was shown that the underground factors were the more important risk ones in the occurrence of sinkholes than the ground factors. Based on the results of AHP analysis of the 2nd stratum in the artificial environment, the underground structure showed the highest 0.427, followed by the subterraneous structure at 0.414, and the characteristics of the face of the earth at 0.159. At this, the C.R. showed 0.069. Namely, it was shown that in the artificial environment, the underground structure and ground one were more important influencing factors than the characteristics of the face of the earth. Based on the results of AHP analysis of the 2nd stratum in the social environment, the managemental and institutional environment showed 0.366 and the regional development showed 0.633. At this, the C.R. showed 0.000. Namely, it was shown that in the social environment, the regional development was a more important influencing factor of sinkholes than the managemental and institutional environment.

(3) Results of the Third Stratum

Table 5 shows the results of the AHP analysis of the third stratum in the natural environment. As a result of the analysis, in the underground factors, the level of underground water showed the highest 0.328, followed by the drain state at 0.298, the liquefaction by earthquakes at 0.239, and the rainfall amount at 0.135. At this, the C.R. showed 0.190. Namely, it was shown that the underground-water level of the underground factors was the most important factor. In the ground factors, the nature of soil showed 0.697, and the thickness of soil showed 0.303.

Table 6 shows the results of the AHP analysis of the third stratum in the artificial environment. As a result of the analysis, in the underground structure, the overuse of underground space showed 0.665, and the disturbance of underground-water flow showed 0.335. At this, the C.R. showed 0.190. Namely, it was shown that in the underground structure, the overuse of underground space was a more important factor than the disturbance of underground-water flow. In the subterraneous structure, the degree of leakage and aging of sewage and water supply pipes showed 0.608, and the loss of particles of soil showed 0.390. At this, the C.R. showed 0.000. Namely, it was shown that in the subterraneous structure, the degree of leakage and aging of sewage and water supply pipes was a more important factor than the loss of particles of soil. In the characteristics of the face of the earth, the compaction failure showed the highest 0.555, followed by the railroads and roads at 0.225, and skyscrapers at 0.220. At this, the C.R. showed 0.078. Namely, it was shown that in the characteristics of the face of the earth, the compaction failure was the most important influencing factor.

Table 7 shows the results of AHP analysis of the third stratum in the social environment. As a result of the analysis, in the managemental and institutional environment, the inappropriate construction management showed the highest 0.468, followed by the poor follow-up management at 0.337, and the preparation for the legal ground at 0.220. At this, the C.R. showed 0.100. Namely, it was shown that the inappropriate construction management was the most important influencing factor on sinkholes. In the regional development, the overuse of underground water showed the highest 0.420, followed by the degree of the development of peripheral areas at 0.373, and the connection with streams at 0.204. At this, the C.R. showed 0.054. Namely, it was shown that the overuse of underground water was the most important influencing factor on sinkholes.

The sum of the relative weights of this study is calculated as one point. This is standardized by 100 points and applied with the relative weight, resulting in a corresponding weighting factors of Table 8. As a result, the degree of incidence of sinkholes in a particular area can be quantified through the assessment indices on Table 8. This allows us to identify specific risks and to derive the risk factors in detail.

Table 4. Results of AHP analysis of the Second Stratum

Variables		Weight	C.R.(consistency ratio)
Natural environment	Underground	0.724	0.000
	Ground	0.276	
Artificial environment	Underground structure	0.427	0.069
	Subterraneous structure	0.414	
	the Characteristics of the face of the earth	0.159	
Social environment	the Managemental and institutional environment	0.366	0.000
	the Regional development	0.633	

Table 5. Results of AHP analysis of the Third Stratum in the Natural Environment

Variables		Weight	C.R.(consistency ration)
Underground	Rainfall amount	0.135	0.190
	Underground-water level	0.328	
	Drain state	0.298	
	Liquefaction by earthquakes	0.239	
Ground	Nature of soil	0.697	0.000
	Thickness of soil	0.303	

Table 6. Results of AHP analysis of the Third Stratum in the Artificial Environment

Variables		Weight	C.R.(consistency ratio)
Underground structure	Overuse of underground space	0.665	0.000
	Disturbance of underground-water flow	0.335	
Subterraneous structure	the Degree of leakage and aging of sewage and water supply pipes	0.608	0.000
	Loss of particles of soil	0.390	
Characteristics of the face of the earth	Skyscrapers	0.220	0.078
	Railroads and roads	0.225	
	Compaction failure	0.558	

Table 7. Results of AHP analysis of the Third Stratum in the Social Environment

Variables		Weight	C.R.(consistency ratio)
Managemental and institutional environment	Inappropriate construction management	0.468	0.100
	Poor follow-up management	0.337	
	Preparation for the legal ground	0.193	
Regional development	Overuse of underground water	0.420	0.054
	Connection with streams	0.204	
	the Degree of the development of peripheral areas	0.373	

Table 8. Assessment Indices of the Environment Impact Assessment of Sinkholes

Making-decision elements			Relevant weight	Conversion score	A	B					Sum total (A×B)
					5point scale (1-point basis)	5 very good	4 good	3 normal	2 bad	1 very bad	
Natural environment	Underground	Rainfall amount	0.135	3.13	0.63						
		Underground-water level	0.328	7.60	1.52						
		Drain state	0.298	6.91	1.38						
		Liquefaction by earthquakes	0.239	5.50	1.10						
	Subtotal		0.724	23.14	4.63						
	Ground	Nature of soil	0.697	6.18	1.24						
		Thickness of soil	0.303	2.68	0.54						
	Subtotal		0.276	8.86	1.77						
Mid-total			0.320	32.00							
Artificial environment	Underground structure	Overuse of underground space	0.665	12.80	2.56						
		Disturbance of underground-water flow	0.335	6.40	1.28						
	Subtotal		0.427	19.20	3.84						
	Subterraneous structure	the Degree of leakage and aging of sewage and water supply pipes	0.608	11.30	2.26						
		Loss of particles of soil	0.390	7.30	1.46						
	Subtotal		0.414	18.60	3.72						
	characteristics of the face of the earth	Skyscrapers	0.220	1.60	0.32						
		Railroads and roads	0.225	1.60	0.32						
		Compaction failure	0.558	4.00	0.80						
	Subtotal		0.159	7.20	1.43						
Mid-total			0.450	45.00							
Social environment	Managemental and Institutional environment	Inappropriate construction management	0.468	4.00	0.80						
		Poor follow-up management	0.337	2.90	0.58						
		Preparation for the legal ground	0.193	1.60	0.32						
	Subtotal		0.366	8.50	1.70						

	Regional development	Overuse of underground water	0.420	6.10	1.22						
		Connection with streams	0.204	3.00	0.60						
		the Degree of the development of peripheral areas	0.373	5.40	1.08						
	Subtotal		0.633	14.50	2.90						
Mid-total			0.230	23.00	-						
Sum total			1.000	100.0	-						

4. CONCLUSION

A city is like a creature composed of substances. When it is first created, all functions work well according to the initial purpose, but as time goes by, aging makes the functions obsolete. A lot of residents live in the city. And water that is the most fundamental thing in maintaining a human life is the essential prerequisite for keeping the city alive. So As the city grows, more water is needed. However, the growth of cities that are likely to last forever becomes stagnant at some point, and fewer people live in it. That will result in the inability to pay the cost of maintaining the city's function any longer. From that point, the sinkholes in the city will occur.

As the result of AHP analysis, it has been shown that the artificial environmental factor among the influencing factors of the occurrence of sinkholes is the most important influencing factor. Specifically, in the natural environment, the underground factors are crucial, and among the underground factors, it has been shown that the level of underground water is a crucial influencing factor. It has been found that in the artificial environment, the underground structure and the subterraneous structure are nearly similar in the weight, and the overuse of the underground space in the underground structure and the degree of the leakage and the aging in the subterraneous structure are important factors and in the characteristics of the face of the earth, the poor compaction is a critical influencing factor. It has also turned out that in the social environment, the regional development is an important influencing factor, and in it, the overuse of the groundwater is a crucial one, and in the managemental and institutional environment, the inappropriate construction management is the most important influencing one.

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