Proceedings of the 9th World Congress on Civil, Structural, and Environmental Engineering (CSEE 2024)
London, United Kingdom – April 14-16, 2024
Paper No. ICGRE 152
DOI: 10.11159/icgre24.152

Comprehensive Methodology for Landslide Risk Assessment Using Fuzzy Logic Systems: A Step-by-Step Approach

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Abstract **-** This paper aims to address the limitations of traditional landslide risk assessment methods by proposing an innovative approach using Fuzzy Logic Systems (FLS). Traditional methods often struggle with the inherent uncertainties associated with landslide risks, including data ambiguity and subjective expert opinions. The paper describes a fuzzy inference system designed to manage such uncertainties by offering a mathematical framework that transforms qualitative risk factors into quantitative risk assessments. This framework uses fuzzy set theory and Mamdani-type inference systems to evaluate landslide risk based on two key variables: the probability of landsliding and the potential adverse consequences. The system employs membership functions to fuzzify these variables and produces a comprehensive risk severity that captures the intricacies of real-world risk factors.

Keywords**:** Landslide Risk assessment, Fuzzy Logic Systems, Fuzzy Set Theory, Mamdani -type inference systems

1. Introduction

Landslides are one of the most dangerous geological phenomena that pose substantial danger to modern developed societies since they are closely connected to human and property losses and have important economic impact on the regional economy[1]. The definitions of landslides vary slightly among professionals in different fields such as geology and engineering, reflecting the complex nature of studying landslides. In this context, the term "landslide" refers generally to the downhill displacement of soil, rock, and organic materials caused by gravity, as well as the resulting landform[2].

Landslides can arise from multiple factors, such as geological, morphological, physical, and human causes. However, only one trigger is responsible for initiating the landslide. A trigger refers to an external stimulus, such as an earthquake, volcanic eruption, or heavy rainfall, which causes the slope materials to weaken rapidly or experience increased stress, leading to an almost instantaneous landslide response. In some cases, landslides may occur gradually due to a combination of several causes, including chemical or physical weathering of materials.[3].

Landslides are a common natural hazard that can cause severe damage to human life, property, and infrastructure. Therefore, the assessment of landslide risk is of paramount importance to reduce the associated impacts. Risk assessment can help identify and prioritize areas that are susceptible to landslides and determine the likelihood of a landslide occurring. Through risk assessment, responses measures [4]can be implemented to reduce the risk of landslides, such as the construction of retaining walls, stabilization of slopes, and development of early warning systems.

2. Literature Review

2.1. Qualitative & Quantitative risk assessment methods

There are three main landslide risk assessment approaches: qualitative, semiquantitative and quantitative.

Management of landslide hazards poses two difficult and opposing challenges. Underestimating that such a hazard could endanger lives and property. However, over-estimating can also extract damage on the society, in its potential for disrupting communities, wasting resources, and sterilizing land. The best way to deal with these challenges is through Quantitative Assessment of Risk (QRA)[5].The process of quantitative risk assessment is separated into two stages: the first stage is the hazard assessment that refers to geo-scientific work. It includes investigation and analysis, to identify and quantitatively describe the potential landslide hazards. Hazards must first be identified and typified, then their magnitude, probability, areal extent, and intensity must be determined. The second stage, "risk assessment" begins with the identification of elements at risks: persons, buildings, infrastructure, property, or environmental values; both existing ones and those that will appear within the hazard area in the future[5]. As a result of the two stages, the qualitative approach for landslide risk assessment is then based on risk classes (typically 'very high', 'high', 'moderate', 'low' and 'very low' risk area) categorized by the experience of experts.

In the semi-quantitative approaches, weights are assigned under certain criteria which provide numbers as outcome instead of qualitative classes. The semi-quantitative estimation is generally used as an initial screening process to identify hazards and risks. A range of scores (0 –1, 0 –10 or 0 –100, 1–9) and settings is used to evaluate each factor according to the occurrence of instability (hazard) and the occurrence of loss or damage/consequence[1].

On the other hand, several tools have been created to tackle risk assessments, such as risk registers, relative risk scoring, risk ranking matrices, relative risk rating, and failure modes, effects, and criticality analysis (FMECA). These methods are qualitative in nature.

Traditional methods of landslide risk assessment, including quantitative, semi-quantitative, and qualitative approaches, have some drawbacks. Quantitative methods often require enormous amounts of data, which may not be available or reliable, and are prone to uncertainties and errors. Semi-quantitative methods rely on expert opinions, which may vary and be subjective, leading to inconsistencies and biases. Qualitative methods are typically simple but may oversimplify the problem, leading to inaccurate assessments.

However, the most crucial drawback of these traditional methods is ignoring the uncertainty. Although uncertainty is an inevitable part of a landslide risk assessment procedure resulting from data uncertainty, including incomplete data or measurement errors (systematic and random), and environmental uncertainty, it may lead to comprising imprecise predictions of future conditions.

2.2. Innovative techniques for landslide risk assessment: Neural Network and Fuzzy approach

Due to its major focus on knowledge representation and reasoning, Artificial Intelligence (AI) was bound to deal with major notable paradigms for the handling of uncertainty including fuzzy logic (FL), neural networks (NNs), and genetic algorithms (GAs)[6]. Fuzzy logic, which was formulated by Zadeh[7], provides a framework for approximate reasoning allowing qualitative knowledge about a problem to be translated into an executable rule set[8]. In other words, this enables a condition to be in a state other than true or false, creating flexibility to capture human reasoning in expert systems[9]. Another advantage of fuzzy logic is its potential to enable developing a model of human reasoning proceeding in natural language with the help of linguistic variables[10]. Moreover, fuzzy logic appears as a suitable attractive approach for investigating uncertainties in the probability and severity dimensions of risk, since there is a lack of consensus in the literature regarding the impact of these uncertainties on landslide risk estimation, and thus overall risk assessment. Consequently, fuzzy logic is a powerful theoretical framework for problems dealing with inexact or imprecise information that characterize real-world systems[11].

2.3. Fuzzy Logic Systems

In recent decades, the utilization of Fuzzy Set Theory has become prevalent in geotechnical engineering. The theory has been employed to handle imprecise data that arise due to various factors such as lack of precision, vagueness, incompleteness, and randomness of information. Additionally, it allows for the inclusion of subjective opinions of experts in problem analysis. Initially, the need to appropriately address subjectivity in geomechanics decision-making processes motivated Nguyen and Ashworth (1985) to apply FST in rock engineering classification systems. Similarly, Kacewicz (1987) utilized it in slope stability analysis to overcome the limitations of probability theory, which can only address problems related to randomness but not epistemic uncertainties. The effectiveness of FST in modeling imprecision of data has been demonstrated in various geotechnical problems[12].

The mathematical foundations of fuzzy logic rest in fuzzy set theory (Kosko, B. 1992). Fuzzy set theory is a generalization of the classical set theory. Fundamentally, sets are categories. Defining suitable categories and using operations for manipulating them is a major task of modelling and computation. Fuzzy Systems are applied for a qualitative qualitative (descriptive or linguistic) definition of functions f:X ® Y using < if/then > rules[2].

3. Methodology

Figure 1 illustrates the proposed mathematical fuzzy system.

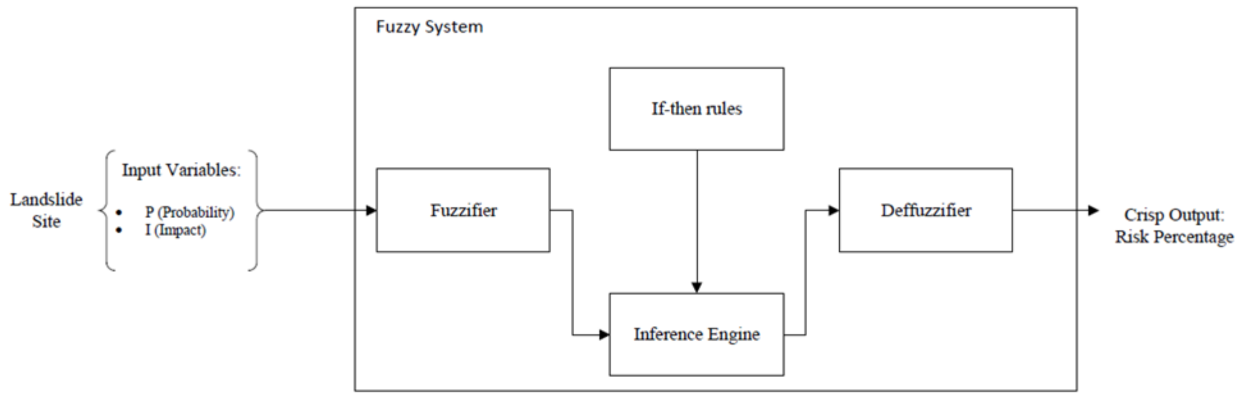

Fig. 1: Proposed Mathematical Fuzzy System

As shown in the figure above, the probability of land-sliding of a particular magnitude (Hazard Number), and the impact of the resulting risk (Adverse Consequences) form the input variables (or attributes) of the fuzzy inference system, and directly affect the output. The output is actually the total value of the risk, expressed as a risk number or risk percentage. The first component of the system includes the fuzzifier which uses membership functions to practically transform crisp (real-valued) input values to fuzzy values. A membership function (MF) is a curve that mathematically specifies the degree of an element's membership in a fuzzy set. The input variables are assigned degrees of membership in various classes or linguistic term sets. In this study, the suggested two input variables can have values of very high, high, medium, low, and very low depending on the value of each. The subjective measures of these linguist terms are defined using either triangular or trapezoidal-shaped membership functions. After defining the fuzzifier component, the next step is to define the logical statements or the if-then rules. These fuzzy inference rules represent the knowledge base feeding the fuzzy inference engine of the fuzzy system to perform reasoning and formulate decisions[13]. Typically, this popular computing framework supports one of two formats of fuzzy inference systems, Takagi-Sugeno or Mamdani[14]. Since the input in our system is intuitive and is expected to be provided by geotechnical engineering experts, the Mamdani paradigm is selected (Sivanandam et al., 2007). In a Mamdani system, the output of each rule is a fuzzy set and thereby a defuzzifier is needed as depicted in Figure 2. The defuzzifier converts the fuzzy output given by the fuzzy inference engine to produce a crisp output. Among the different defuzzification methods, the most prevalent and physically appealing is the Centroid of Area Method [15] . It simply returns estimates right at the center of gravity of the graph of the membership function curve involved; not too low or too high[16]. The following subsection describes the two input variables.

Fuzzy Input Variables

In risk analysis, risk is traditionally defined as the product of the probability of an occurring event and the potential impact or consequence[17]. Therefore, risk is mathematically quantified as follows[18]:

$$R = P\ x\ I \qquad (1)$$

For the current study, R is the degree of risk (of landsliding), P is the probability of landsliding of a particular magnitude, and I is the impact or the possible adverse consequences of landsliding.

Probability of Landsliding:

The probability of landsliding of a particular magnitude can be represented by a hazard number as follows:

$$Hazard\ Number = Hazard\ Score\ x\ Probability\ Score \qquad (2)$$

Where, Hazard Score represents the nature of the landslide failure with a scoring scale that goes from 1 to 5, and Probability Score represents the chance of occurrence in ten years also having a scoring scale that goes from 1 to 5.

Impact of Landsliding:

The impact of landsliding of a particular magnitude can be represented by the adverse consequences as follows:

$$Adverse\ Consequences = Exposure\ x\ Vulnerability \qquad (3)$$

Where, Exposure represents the relative value of assets or the elements at risk with a scoring scale that goes from 1 to 5, and Vulnerability represents the potential to suffer harm or loss also having a scoring scale that goes from 1 to 5.

4. Conclusion

Landslides are complex geological phenomena that necessitate accurate and reliable risk assessment methods. Traditional approaches, whether qualitative, semi-quantitative, or quantitative, face critical limitations when it comes to handling uncertainties and ambiguities in the data. This paper has explored the application of Fuzzy Logic Systems in addressing these limitations. The proposed fuzzy inference system employs a Mamdani-type model that uses two input variables - probability of landsliding and potential adverse consequences - to calculate a comprehensive risk number. With its focus on approximative reasoning and flexible categorization, fuzzy logic offers a powerful tool for capturing the uncertainties and imprecisions that characterize landslide risk assessments. As a future avenue of research, the incorporation of additional variables and the testing of this methodology in real-world scenarios would prove beneficial.

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