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Sugeno fuzzy inference algorithm and its application in epicentral intensity prediction

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ABSTRACT

In this paper, the epicentral intensity prediction model based on Sugeno fuzzy inference system has been proposed where the earthquake magnitude and the depth of hypocenter are input and the epicentral intensity is output. The parameters of the proposed model are estimated by statistical analysis based on the historical data for Sichuan earthquake in the last decades. Finally, by comparison with the existing fitting model, the proposed model has better efficiency and higher accuracy.

1. Introduction

The earthquake has caused a great amount of loss in China both people's lives and property. In order to minimize the loss as much as possible, there is an urgent need to make rapid and specific judgment for the earthquake disaster based on the intensity distribution, and the epicentral intensity analysis for the historical data can be able to provide some reasonable applications such as seismic zoning, engineering site selection, and so on. Considering that the epicentral intensity is a common characteristic of complex system with multiple variables that determine the state of the system, an expert may not make a specific judgment based on all monitored data, and in some cases experts are not aware of all probable cause and effect relationships that govern earthquake disaster, even multiple observations that may carry conflicting or redundant information about the system make it more difficult to provide a specific judgment. Therefore, the prediction model of epicentral intensity has drawn the attention of many researchers and warranted the simultaneous use of soft computing algorithms such as fuzzy logic and probabilistic reasoning methods to deal with these complexities. For example, Li et al. [1] proposed the method for calculating intensity by the equivalent peak of complete vibration A_{max}, Aghaarabi et al. [2] investigated the comparative study of fuzzy evidential reasoning and fuzzy rule-based approaches, Wang [3] investigated the fitting function and the correlation analysis, in which the ground motion parameters are independent variable and the intensity is dependent variable, Wan et al. [4] investigated the regression analysis of intensity by using Joyner–Boore(J–B) method based on elliptic intensity model, Qin [5] investigated the quantitative relationship between the epicentral intensity and the earthquake magnitude by data fitting method, Du [6] studied the functional relationship among epicentral intensity, earthquake magnitude and depth of hypocenter based on data fitting method, Zhang et al. [7] investigated the relationship

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between intensity distribution and area statistics, Ma et al. [8] investigated statistical relationship between magnitude and epicentral intensity of southeast littoral, Wang [9] investigated the transformation of seismicity and seismic intensity scale.

Soft computing methods including fuzzy set theory and its numerous extensions have been extensively applied for uncertainty modeling in several fields such as environmental decision making, risk assessment and so on. Neuro-fuzzy models are employed for mathematical modeling of nonlinear and uncertain systems. For example, Raptis et al. [10] investigated the classification of aged wine distribution by using fuzzy and neural network systems, Huang [11] put forward the epicentral intensity prediction model based on fuzzy neural network, Chen and Chen [12] investigated fuzzy analytic hierarchy process and applied in multi-attribute decision making for airline operational networks, Russo et al. [13] proposed neuro-fuzzy computational approach to optimize the quality of products in food industries, Li et al. [14] investigated coupling fuzzy-chance constrained program with minimax regret analysis for water quality management.

Another relevant category is fuzzy synthetic evaluation that can capture uncertainty in the sampling and analysis process and summarize each input attribute in decision making and assessment problems. Several fuzzy synthetic evaluation techniques can be employed for risk assessment and quality evaluation when the definition of decision making output is vague and the quality of risk criteria is uncertain. For example, Chen and Chang [15] proposed three different fuzzy synthetic evaluation approaches for a relative quality assessment of river water, Su et al. [16] established the intensity prediction model based on fuzzy synthetic evaluation with the earthquake magnitude and the distance to epicenter, Feng and Lin [17] proposed the fuzzy intensity prediction model with building damage index, Zhang [18] proposed the epicentral intensity prediction model based on fuzzy synthetic evaluation. Considering the correlation between the earthquake magnitude and the distance of epicenter, different fuzzy synthetic evaluation methods are proposed by employing different fuzzy classification mechanisms and fuzzy implication techniques in the output layer to accommodate the practical needs of decision makers.

In this paper, the epicentral intensity prediction (EIP) model based on Sugeno fuzzy inference system is proposed where the earthquake magnitude and the depth of hypocenter are input, and the epicentral intensity is output, and estimate the parameters for the EIP model by using the historical data for Sichuan earthquake in the last decades. Finally, the EIP model is applied in Wenchuan of Sichuan province and a comparison is made with the existing fitting model.

This work is organized as follows. In Section 2, some basic notions of Sugeno fuzzy inference system are reviewed. In Section 3, the epicentral intensity prediction (EIP) model based on Sugeno fuzzy inference system is proposed and a comparison is made with the existing fitting model. The conclusion is given in the last section.

2. Sugeno fuzzy inference system

Throughout this paper, $U = \{u_1, u_2, u_3, \ldots, u_n\}$ is used to denote the discourse set, $\mathcal{F}(U)$ stands for the set of all fuzzy subsets in *U*, *X*, *Y* and *Z* stand for the set of earthquake magnitude, depth of hypocenter and epicentral intensity, respectively.

The theory of fuzzy set introduced by Zadeh [19] has achieved a great success in various fields to handle imprecise knowledge and incomplete information. With more and more imprecise and vague information in the real life, different extensions of the traditional fuzzy set have been developed by some researchers, including the intuitionistic fuzzy set pioneered by Atanassov [20], type-2 fuzzy set pioneered by Dubois and Prade [21] and fuzzy multiset introduced by Yager [22]. Aimed at the application of fuzzy set theory, one important class of fuzzy relational functions is fuzzy rule-based systems (FRBSs), the input–output relationship can be defined using fuzzy IF-THEN rule. It is well known that different rule structure has different rule form in FRBSs, where "AND" and "OR" connections in fuzzy IF-THEN rule are the most common. And the most important advantage of FRBSs is its ability to deal with linguistic variable and a vocabulary represented using fuzzy sets. Usually, the earthquake magnitude and the depth of hypocenter are presented by evaluation grades such as "low(L)", "medium(M)", "high(H)", and so on. Liu et al. [23] pointed out that the proposed hierarchical FRBSs is capable of modeling uncertain expert knowledge without using precise analysis.

In general, fuzzy rules can be presented as the format such as "IF antecedent THEN consequent", the antecedent of fuzzy rule may include several parts which may join together by "AND" disjunctive (e.g. minimum or product operator) or "OR" disjunctive (supremum or maximum operator), and the consequent of fuzzy rule is a collection of fuzzy sets. Namely, the consequent of fuzzy rule can be obtained to form a new fuzzy set based on implication operator and the aggregation operation of antecedents. Two of the most commonly used implication methods are the minimum, which truncates the fuzzy membership function, and the product, that scales the membership function. For example, minimum and maximum implications were used, and Eqs. (1) and (2) demonstrate the calculation of "AND" and "OR" operators for fuzzy sets *A* and *B*:

$$A\bigcup B : (A\bigcup B)(x) = A(x)\bigvee B(x), \tag{1}$$

$$A\bigcap B : (A\bigcap B)(x) = A(x)\bigvee B(x), \tag{2}$$

where $A(x)$ and $B(x)$ denote the membership functions of fuzzy sets *A* and *B*, respectively.

Fuzzy rule-based system is an important fuzzy inference system, in which a given input is mapped to a specified space based on the fuzzy logic method. The core of the fuzzy rule-based system is made of some rules, and the rule's form is