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Design-by-analogy: A characteristic tree method for geotechnical engineering

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ABSTRACT

Geotechnical engineers frequently use design-by-analogy methods to promote innovative design solutions, or reuse existing design schemes. However, this approach has not yet provided a means for comparing various potential project solutions quantitatively. Moreover, while geotechnical engineering has accumulated data in large quantities, the value of this historical data has not been exploited fully for the identification of useful analogies. To address these challenges, we proposed the characteristic tree analogy method and a key algorithm for calculating the similarity index between objects. On this basis, we developed a decision support system that makes comprehensive use of geotechnical engineering historical data. We applied the system successfully to the roadway support design for Liangjia coal mine. The results verified the applicability of the characteristic tree analogy method for realizing geotechnical engineering designs, making maximum use of historical data. This approach can be extended to other areas of geotechnical engineering that have large quantities historical data.

1. Introduction

Geotechnical engineering studies rock mass, soil, and other aspects of the geological environment as required for civil engineering projects. The non-uniformity, non-continuity, and uncertainty of natural conditions present challenges that cannot be solved by simple analytic methods. From the perspective of system engineering, geotechnical engineering is a complex system, making the precise design by geotechnical theoretical models is difficult to realize. Often, in real-life projects, geotechnical engineers can achieve efficient reuse of design solutions by employing analogies that reveal the similarity between projects based on generalized rock mass characteristics or expert experience [1–3]. It is well known that human thinking can promote and clarify decision-making by combining imagination with abstract thinking organically. However, it has obvious limitations. For instance, analogies can be influenced easily by subjective factors or restricted by an expert's own knowledge, and the results might provide only qualitative judgements [4].

For geotechnical engineering, there are two important keys to design development using analogies: the quick retrieval of the objects in the domain to which the analogy is applied, and the effective analysis of similarities and differences. In geotechnical engineering, the integration of influential factors to make quantitative judgments about similarity remains a challenge to be solved. Various scholars have explored the analogy methods in this field. For instance, Yang [5] proposed the "analogic index" as a semi-quantitative experience index to describe the comparability between different projects. Zhou [6] applied a fuzzy mathematical method to estimating quantitatively, or semi-quantitatively, the influence of a single influential factor on the overall evaluation of landslide control engineering. Nevertheless, the present quantitative analogy methods still face many limitations. (1) They do not take into consideration the hierarchy of the various influential factors on geotechnical engineering, and cannot reflect the incidence relation between the influential factors at different levels. (2) They are unable to adjust flexibly to the analogy patterns according to a specific objective. (3) Each calculation step involves repeated artificial judgment and intervention, which makes it difficult to realize these steps by programming.

In recent years, there have been advances in research focused on the application of decision support systems in real-life projects. Accorsi [7] developed a decision support system for storage design and operations based on a top-down methodology. Scott [8] integrated the AHP–QFD method with chance constrained programming, and developed a decision support system for supplier selection and order allocation. Tormina [9] proposed a new hydrological model for input variable selection, and applied it to streamflow forecasting. Further, Wang [10] presented an auto-regressive integrated moving average model coupled with ensemble empirical mode decomposition for forecasting an annual

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runoff time series. Chau [11] developed a hybrid model integrating artificial neural networks and support vector regression for daily rainfall prediction.

With the arrival of the era of big data, more attention is being given to the value of data resources. The practice of geotechnical engineering has accumulated a large quantity of data, but the value of this data has not been explored thoroughly. Research focused on mining this historical data is rare, even though design-by-analogy methods need data to develop appropriate and effective analogies. To overcome the shortcomings of the prior methods, in this paper we proposed a method that uses a characteristic tree model to describe the experience of experts. Based on this method, we provided a decision support system for the Liangjia coal mine roadway that made comprehensive use of the available historical data. The application of this method effectively solved two difficulties for practical engineering: the complete dependence of support design on the experience of experts, and the inability to utilize historical design data fully.

2. Characteristic tree analogy

The characteristic tree analogy method begins by using expert knowledge and experience to break down the overall concept of an object into microscopic characteristics from the top down. Next, the method develops a contrast mapping between characteristic values through computational means, and then calculates the degree of analogy between objects quantitatively from the bottom up. Finally, the calculated results are fed back to the experts for comprehensive evaluation. In this way, the model's intelligent human-computer interaction provides an analysis of similarities and differences between objects. In essence, the characteristic tree analogy method is a form of meta-synthesis [12] composed of an expert system (made up of domain experts), knowledge representation system (with the characteristic tree as the carrier), and tool system (database and computer program).

2.1. Basic theory and hypothesis

The characteristic tree analogy method considers that every object possesses numerous attributes. The attribute subset demonstrating the similarities and differences between objects is called a characteristic. Characteristics are divided into concrete characteristics and abstract characteristics. The idea is that all objects can be represented through their various characteristics according to a certain hierarchy.

2.1.1. Concrete characteristics

Concrete characteristics have their own characteristic values. They can be used to describe abstract concepts, but they cannot be described by other characteristics. Concrete characteristics are classified into qualitative and quantitative characteristics. The set of qualitative characteristics is a finite set. For example, the “degree of weathering of rock mass” is considered to be a qualitative characteristic, with its five different weathering degrees – non-weathered, slightly weathered, weakly weathered, fully weathered, and strongly weathered – set as its characteristic values.

The characteristic value of a quantitative characteristic can be measured in terms of quantity or amount. For instance, “compressive strength”, “slope height” and “tunnel length” can have certain numeric values as their characteristic values. The differences between the characteristic values of various objects can be evaluated quantitatively using a mathematical method.

2.1.2. Abstract characteristics

Abstract characteristics are abstract concepts without concrete characteristic values. They can be described by other abstract characteristics or by concrete characteristics that are sub-characteristics of abstract characteristics. For instance, as the abstract characteristic, “rock mass integrity” can be described by the concrete characteristic “elastic wave velocity” and the abstract characteristic “structural plane characteristic”.

2.2. Precondition for applying characteristic tree analogy

The precondition for the application of a characteristic tree analogy is that the attribute data of the object must be stored in a relational database. Moreover, the data relations should at least meet the requirements of the second normal form (2NF) of the database.

2.3. Characteristic tree model

Each characteristic of the object is regarded as a node. Together, these nodes constitute a tree-shaped data structure, called a characteristic tree model. The abstract characteristics are on non-leaf nodes, while the concrete characteristics are on leaf nodes. The root node is a special abstract characteristic, representing the overall concept of the object.

To evaluate the analogy criteria quantitatively, the concept of characteristic weight is introduced to indicate the degree of influence of sub-characteristics on parent characteristics. The root node weight is set as 1. If the abstract node ANode has n sub-characteristics, that are ANode(i), where $i \in [1,n]$, then

$$\sum_{i=1}^{n} \text{ANode}(i).\ \text{weight} = 1$$

Different from the Analytic Hierarchy Process (AHP), the weight of each sub-characteristic in the characteristic model represents the importance of its parent characteristic rather than the root node directly. This weight representation avoids the difficulty of making a direct comparison of the importance of sub-characteristics belonging to different parent characteristics. This approach accords with the cognitive thinking mechanisms of humans about objects.

For our work, we applied the precedence chart method to assign weights to the sub-characteristics. As shown in Table 1, we compared the importance of sub-characteristics in pairs according to experts' knowledge and experience. For $i,j \in [1,n]$, if ANode(i) is more important than ANode(j), then $Wij = 1$ is obtained; if ANode(i) and ANode(j) are of the same importance, then $Wij = 0.5$ is obtained; otherwise if ANode (j) is more important than ANode(i), then $Wij = 0$ is obtained.

The comparison results are input into the precedence chart to obtain the priority sequence value (PSV) of ANode(i):

$$Ai = \sum_{k=1}^{n} Wik$$

The weight of ANode(i) is the ratio of its priority sequence value to the sum of priority sequence values of all sub-characteristics in the precedence chart:

$$\text{ANode}(i).\ \text{weight} = Ai/\sum_{k=1}^{n} Ak$$

A simple characteristic tree model is shown in Fig. 1.

2.4. Analogy quantitative index: similarity index

A similarity index (SI) reflects the degree of similarity between two

Table 1
Precedence chart of sub-characteristics.

	ANode(1)	ANode(2)	……	ANode(n)
ANode(1)	W11	W12	……	W1n
ANode(2)	W21	W22	……	W2n
……	……	……	……	……
ANode(n)	Wn1	Wn2	……	Wnn