Evaluation Method of Integrated Security for Highway Subgrade after Earthquake

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Abstract. Evaluation of integrated security situation for highway subgrade comprehensively and accurately has been able to provide the basis for repair of damaged subgrade in reconstruction stage after earthquake. Five indexes have been selected to figure characteristics of subgrade: damage condition, structural characteristics, such as height, slope ratio, etc., aftershock strength, features of terrain and physiognomy, rainfall intensity. Fuzzy AHP Comprehensive Evaluation Method, FACEM, has been introduced to determine weight of above-mentioned indexes and assess the general security degree of subgrade after earthquake. The research has shown that judgment results obtained by FACEM does almost match with advices given by professional experts after investigation. But there has been more persuasion and conviction with the quantitative approach to deal with uncertain information generated in process of evaluation for FACEM.

Introduction

Evaluation of highway subgrade safety after earthquakes aims at evaluating the integrated safety of subgrade after earthquakes and providing reference and basis for treatment or repair of the damaged highway subgrade at each stages from urgent repair, road clearance and reconstruction through the decision method combining qualitative and quantitative methods.

Indexes and Standards of Evaluation for Integrated Security of Subgrade after Earthquake

Integrated safety evaluation of highway subgrade after earthquakes, a systematic analysis and evaluation, highlights in evaluating the rationality of indexes and the scientificity of relevant evaluation methods. Since different evaluation index systems may lead to different evaluation results, the rationality of index selection is critical.

Principles for the Establishment of Evaluation Indexes. The establishment of evaluation index system of highway safety after earthquakes should not only adhere to the universal principles of scientificity, systematicness, effectiveness and objectivity, but also highlight the following aspects.

Selection of evaluation index system, determination of evaluation index weight coefficient, data selection and calculation should be based on scientific theories, be objective and reasonable and reflect the definitions and objectives of highway subgrade safety after earthquakes.

It should place highway subgrade safety after earthquakes, as an independent entirety, into the large social system. Evaluation index system should cover all important influencing factors, reflect completely the influence of a part to the overall function, as well as reflect structural characteristics of the system.

The evaluation index system should be as brief and clear as possible, be typical, be able to present the problems clearly and accurately, be with good workability and easy to be realized in actual work.

Determination of Evaluation Indexes. Firstly, on one hand, we have collected a large quantity of literature and data and obtained the influencing factors frequently occurred in safety and stability evaluation of highway subgrade in the conclusions [1-6]. On the other, we have investigated into the characteristics of highway subgrade damage types after earthquakes, analyzed its damage mechanism and influencing factors and found out the factors more greatly influencing highway subgrade safety after earthquakes, so as to combine the two and determine preliminarily the evaluation index system of highway subgrade safety after earthquakes.

Secondly, we have consulted experts for instructions on the preliminarily determined evaluation index system and considered repeatedly until we determined the evaluation index system finally based on experts' suggestions.

Finally, we have chosen the evaluation indexes of integral subgrade safety after earthquakes, including topographical and geomorphologic features, subgrade structural features (height and slope ratio), subgrade damage conditions, aftershock magnitude and rainfall intensity.

Safety class obtained from evaluation model established by the above index system can accurately reflect the damage level and safety performance of subgrade structures after earthquakes, help us make judgments on the availability and repair difficulty of highway subgrade after earthquakes and provide basis for engineering decisions.

Standards of Security Evaluation. According to the difficulty in the repair of earthquake-stricken subgrade and to the basic principles of safety evaluation, as well as to common practice of evaluation, the Paper classifies safety of subgrade after earthquakes into 5 grades: safe, basically safe, less safe, unsafe and extremely unsafe.

Safe indicates that post-seismic subgrade will not affect usual pedestrian and vehicle safety; various performance indicators of subgrade are fine; it is without overall or local deformation or crack; the overall and local safety coefficients can meet the requirements of criteria; subgrade only needs maintenance.

Basically safe indicates that subgrade has been slightly damaged after earthquakes, without overall deformation, but with local deformation; it will not affect pedestrians and vehicles and is basically safe as a whole; local deformation may affect safety in some certain degree, but it only needs local reinforcement at proper times.

Less safe indicates that subgrade has been damaged moderately after earthquakes and subgrade stability deteriorates and turns to unsafe continuously. The damage affects pedestrian and vehicle safety and regular highway operation. Traffic control should be executed to roads as per needs and traffic can only be re-opened completely after subgrade is reinforced.

Unsafe indicates that subgrade has been destroyed severely after earthquakes and is dangerous for pedestrians and vehicles. It should stop traffic completely and may establish a necessarily temporary access road. Normal operation can only be resumed after a large scale of repair and reinforcement to subgrade.

Extremely unsafe indicates that subgrade has been devastated after earthquakes. It should prohibit traffic and if necessary, carry out certain emergency measures to prevent disasters from extending. Such level of damage usually costs a large sum of money and a long period for treatment and brings great construction risks.

Evaluation Procedure for Integrated Security of Subgrade after Earthquake

In the Paper, we employ Fuzzy AHP Comprehensive Evaluation Method (FACEM) to evaluate integral subgrade safety after earthquakes. Fuzzy evaluation is to introduce fuzzy concepts in the process of evaluation and deals with some issues of subgrade seismic damage evaluation by using fuzzy mathematics, to reflect subgrade damage conditions after earthquakes and safety uncertainty. Analytic Hierarchy Process (AHP) compares various factors in pairs in the evaluation system, calculates the weight of each factor and makes decisions on the evaluated objects as per comprehensive weights. Combining the two methods in the comprehensive evaluation of the evaluated objects is the FACEM.

Mathematical Model of Fuzzy Comprehensive Evaluation. We assume that discourse domain $U=\{u_1,u_2,...,u_n\}$ are n factors relevant to the evaluated factors, the discourse domain U is called index set or factor set. $V = \{ v_1, v_2, \ldots, v_m \}$ is comment set, while the fuzzy relation between domain discourse of evaluation factor set and domain discourse of comment set can be indicated by matrix R:

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{1}$$

Where $r_{ij} = \mu(u_i, v_j)(0 \le r_{ij} \le 1)$ expresses membership degree of factor u_i evaluated to v_j; in the row i of matrix R, $R_i = (r_{i1}, r_{i2}, \ldots, r_{im})$ is the ith single-factor evaluation of evaluation factor u_i, as well as the fuzzy subset of V.

Actually, different factors play different roles in each evaluation grade, which means factor weights should be considered.

We assume that $w_1, w_2, \ldots, w_n$ are respectively the weights to evaluate $u_1, u_2, \ldots, u_n$ and satisfy $w_1 + w_2 + \ldots + w_n = 1$. If $W = \{ w_1, w_2, \ldots, w_n \}$, W is the fuzzy sets of factor weights (namely weight vector).

According to fuzzy comprehensive evaluation principle:

$$B = W \cdot R = (w_1, \ldots, w_n) \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = (b_1, \ldots, b_m) \tag{2}$$

We normalize results of B and take $b^* = \max\{ b_1, \ldots, b_m \}$, the corresponding grade is the evaluation grade, then we obtain the comprehensive evaluation result V.

Determination of Membership Degree. As for application, it needs to establish membership function of fuzzy sets firstly. On the basis of consulting reference materials, we, according to the practical conditions of integral safety evaluation of highway subgrade after earthquakes and to the features of each index, planned to determine each membership function as triangular fuzzy membership function, of which the mathematical expression is shown as equation (3), where a_1 and a_3 are end-points of sections and a_2 is the midpoint of sections.

$$u(x) = \begin{cases} 0 & x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & a_1 \le x < a_2 \\ \dfrac{a_3 - x}{a_3 - a_2} & a_2 \le x < a_3 \\ 0 & x > a_3 \end{cases} \tag{3}$$

Weight Determination. AHP is a kind of analytical tools for decision making which solves multi-purpose complicated issues by a combination of qualitative and quantitative methods, proposed by a U.S. operational research expert, Professor A. L. Saaty from the University of Pittsburgh in 1970s [7]. Principal steps determining evaluation index weight by AHP are as follows:

Determine influencing factors and establish a hierarchical structural model. First of all, we dissemble a complicated issue into several indexes and group these indexes to form different hierarchies to make it systematic. In practical application, we generally classify hierarchical structure into three levels. The first level is the goal, usually with only one index, indicating the aim to be finally achieved. The second is principle, indicating the standard for achieving the anticipated aim. And the third is index, indicating specific factors or indexes influencing the anticipated aim.

Establish a comparison and determination matrix. After establishing a hierarchical structure, the membership relationship between factors on the upper and lower levels has been determined. Determination matrix is the basic information of AHP. It judges relative importance of each factor at each level and the judgments are indicated by digits in matrix, which is determination matrix. We compare the importance of factors in pairs of this level regarding a factor in the last level as the evaluation principle to determine matrix factors. We establish a determination matrix for each level except for the highest level and the number of determination matrix of each level equals to the number of the factors of the last level. It is hard to obtain relative importance among all factors of a level by rigorous statistical methods. Hence, in AHP, we determine it by comparison in pairs. We assume the evaluation index is A, evaluation index factor set $F=\{f_1, f_2, ..., f_n\}$ and the structural determination matrix $P(A\text{-}F)$ is:

$$P=\begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix} \tag{4}$$

Where, f_{ij} indicates relative importance of factors. (i=1,2,…,n； j=1,2,…,n). To quantitatively describe relative importance of any two factors as per a principle, we employ 1~9 scaling procedure for scale of numbers in the Paper. See Tab. 1 for the specific values.

Tab. 1 1~9 Scaling Procedure and Their Significance

Scale	Definition	Description
1	Equally important	In comparison, two factors are equally important
3	Slightly more important	In comparison, one factor is slightly more important than the other
5	Distinctly more important	In comparison, one factor is distinctly more important than the other
7	Much more important	In comparison, one factor is much more important than the other
9	Extremely more important	In comparison, one factor is extremely more important than the other
1/3, 1/5 1/7, 1/9	Converse comparison	If we obtain r_{ij} by comparing factors c_i with c_j, then we get the determination $r_{ji}=1/r_{ij}$ by comparing c_j with c_i

Relative importance calculation. By using linear algebra, we acquire the feature vector corresponding to the maximum eigenvalue of determination matrix and then normalize the feature vector to obtain weight distribution. The feature vector corresponding to the maximum eigenvalue of determination matrix can be calculated by squareroot method.

Consistency test. Relative weight calculated based on determination matrix is to be conducted with consistency test of determination matrix. The test equation is:

$$CR = CI / RI \tag{5}$$

Where $CI=\frac{1}{n-1}(\lambda_{\max}-n)$, RI are random consistency indexes of determination matrix

Calculation of integral importance. Integral importance is calculated to acquire the importance of factors at each level to the whole system.

Due to subgrade damage conditions, environmental factors and complexity of rock-soil mass itself, the influence of many factors to its performance and their acting mechanism are not completely clear when evaluating subgrade safety after earthquakes. Since the system is featured as “fuzzy”, it is appropriate to employ FACEM for analysis.

Conclusions

The determination results obtained by FACEM are basically consistent with the treatment advice proposed by experts after investigation and evaluation. However, we can get to know the membership degree of each evaluation unit to each evaluation through the evaluation results of FACEM. The results obtained by quantitative method contain more information and are more persuasive and more reliable. Furthermore, FACEM provides fixed evaluation steps and achieves evaluation by fuzzy mathematics. It is reasonable to deal with the uncertain information produced in the process of evaluation by such quantitative method.

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References

[1] Shengxie Xiao, Pingyi Wang and Enlin Lv, Application of Fuzzy Mathematics in Civil and Hydraulic Engineering, Beijing, (2004), p. 72 (In Chinese)

[2] Liqiang Jin, Meihai Jin, "Optimization Design of Subgrade Slope Based on Fuzzy Theory", Shanxi Architecture, vol. 32, no. 17, (2006), p. 27 (In Chinese)

[3] Bingxian Fu, Fei Tang and Tianjiang Li, "Analysis of Subgrade's Long-term Stability by AHP and Fuzzy Mathematics Method", Geotechnical Engineering Technique, vol. 19, no. 6, (2005), p. 48 (In Chinese)

[4] Zhihai Deng, "Forecast Evaluation of Slope Stability of Pingshi-Zhangshi Section of Guangzhou-Lechang Highway", Research & Application of Building Materials, vol. 36, no. 8, (2010), p. 155 (In Chinese)

[5] Jian Zhang, Huoming Wang and Qiang Wei, "Fuzzy Comprehensive Evaluation Method in Highway Slope Stability Analysis", Building Scientific Technology and Management, vol. 18, no. 6, (2010), p. 6 (In Chinese)

[6] Wangping Wu, Specifications for Design of Highway Subgrades (JTG D30-2004), Beijing, (2004), p. 58 (In Chinese)

[7] Shubai Xu, Analytic Hierarchy Process, Tianjin, (1988), p. 267 (In Chinese)