SAFETY RISK DETERMINING AND DATA PROCESSING OF ROAD SUBGRADE

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ABSTRACT: Highway diseases such as embankment collapse, slope sliding, frost heaving and thawing and difference deformation always exist effected by topography, climatic conditions and traffic loads. How to effectively determine subgrade safety risks and scientifically analyze disease monitoring data to determine the safety status of highway subgrade is the key to the highway operation management and conservation decisions. This paper proposed two non-destructive methods for subgrade diseases according to actual project which provides basis for safety monitor. Fuzzy comprehensive evaluation method of subgrade safety determination is proposed through establishing different disease risk determination index to determine disease section of road. Monitoring data error criterion and improved high-accuracy Logistic curve model for deformation prediction were proposed based on monitoring data which provides the basis for safety risk determination and data processing of highway subgrade in operation period.

KEY WORDS: Highway subgrade, Safety risk, determination index, fuzzy comprehensive evaluation, monitor, logistic curve, prediction model

1. PREFACE

In operation period, road sections such as high fill and deep cut, unfavorable geological condition, low fill and shallow cut universally exist restrained by geological and hydrological conditions and alignment. Coupled with adverse weather conditions and heavy traffic, highway disease problems especially roadbed subsidence, slope slippage, frost-heaving and thaw collapse, difference deformation and excessive strength decaying disease problems become increasingly prominent, which threatening road traffic safety.

Developing safety monitoring is effective measure to judge safety status of subgrade in operation period. But it is not impossible to carry out safety monitoring for all road. In order to efficiently utilize maintenance funds, it is
very necessary to systemically detect diseases of subgrade to further define monitoring sections and points.

NDT and damage detection are two main detections according to method and mean. NDT is a kind of detection using sound, light, magnetism and electricity and other features, without affecting performance of subgrade to detect the existence of defects or inhomogeneity and to determine the use state of roadbed and specific sections for monitoring. Currently, ground penetrating radar and Rayleigh wave detection method are main NDT method. Damage detections including geological drilling and digging exploration have some damage to road, high cost and low efficiency, but more intuitive and credible.

2. SAFETY RISK DETECTION TECHNOLOGY OF HIGHWAY SUBGRADE IN OPERATION PERIOD

2.1 Ground Penetrating Radar detection technology
Ground penetrating radar (GPR) technology is an electromagnetic wave nondestructive testing technology, which uses electromagnetic waves underground mediator on different frequency response spectrum to determine the distribution of the target mediator. High frequency electromagnetic wave propagation in mediator, its velocity, path, electromagnetic field strength and the waveform will vary with the nature and power through the medium of geometry changes, so through the time-domain waveform acquisition, processing and analysis, the subsurface or geological the spatial location and structural state can be determined. Changbai Mountain zone has patchy permafrost distribution. Road subgrade in this zone has risk of thaw collapse. Changbai Mountain Southern slope tourism road detection by GPR shown that apparent subsidence of subgrade in patchy permafrost area(Figure 1).

![Figure 1. Changbai Mountain tourism road subsidence radar detection](image)

2.2 Rayleigh wave detection technology
Rayleigh wave can propagate along the free surface of mediator, which is characterized by the particle propagation direction in a vertical plane along the counterclockwise movement ellipse with its major axis perpendicular to the surface of the mediator with the long axis and short axis ratio 3 to 2 exponentially in depth, but very slow decay in the horizontal direction.

Rayleigh wave exploration is a new geophysical method, which takes advantage of Rayleigh wave propagation in layered mediator frequency dispersion properties, Rayleigh wave propagation velocity and the physical and mechanical properties of mediator is closely related to two properties. Therefore, in the geotechnical investigation, construction and supervision and monitoring work, Rayleigh wave velocity and shear wave velocity can be obtained according to frequency dispersion curves, which can be used to determine foundation
bearing capacity and scope of the soft ground to evaluate the integrity of the bedrock and soil classification.

![Figure 2. Instability slumping detected by Rayleigh wave chart](image)

![Figure 3. Rayleigh wave velocity of intact embankment](image)

As a kind of NDT method, Rayleigh wave detection has characteristics of lightweight, high efficiency and high resolution, which can accurately give longitudinal and shear wave speed of different rock layers. So mechanical parameters can be calculated. Through Rayleigh wave detection, internal damage of subgrade can be found. Discontinuous waveform in Figure 2 indicates that modulus of subgrade has been attenuating and subgrade has been stratified contrasted with intact embankment in Figure 3.

In highway and airport runway nondestructive testings, pavement flexural, compressive strength and load carrying capacity of the subgrade can be calculated to achieve quality variation with years of continuous detection.

3. SUBGRADE SAFETY RISK DETERMINATION IN OPERATION PERIOD

Affected by many factors, multi-index comprehensive method should be used to determine subgrade safety. Through typical working conditions of embankment safety risk detection to obtain internal working environment and performance changes state of road, based on the principle of fuzzy mathematics to analyze multiple effect factors of road safety and ultimately give the classification evaluation. Impact factors of different level and type can be considered in fuzzy analysis, with taking full account of the human experience to make the evaluation results more reasonable.

When safety evaluation objectives identified as road safety risks, and then determine the impact factors integration as U:
U = \{u_1, u_2 \cdots u_m\} \quad (1)

Establish analytic hierarchy process (AHP) model of impact factor, constitute a comprehensive evaluation classification assemble V.

V = \{v_1, v_2 \cdots v_n\} \quad (2)

Fuzzy relations between domain U and V can be expressed as matrix R:

R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \quad (3)

r_{ij} = \mu(u_i, v_j) \quad (4)

For evaluation classification, \( v_j \), \( r_{ij} \) is degree of membership of factor \( u_i \). In integration R, row i is a single-factor evaluation of factor i, which is the fuzzy sub-aggregate of integration V.

Due to the different role of impact factor in comprehensive evaluation, so weight factor must be considered:

Assumed \( a_1, a_2 \cdots a_m \) is the weight of \( u_1, u_2 \cdots u_m \) and meet \( a_1 + a_2 \cdots a_m = 1 \). A is the weight vector of the factor, where \( A = (a_1, a_2 \cdots a_m) \).

By fuzzy calculation \( B = A \cdot R \) to obtain fuzzy integration \( B = \{b_1, b_2 \cdots b_n\} \quad (0 \leq b_j \leq 1) \), where

\[ b_j = \sum_{i=1}^{m} a_i r_{ij} \]

according to the maximum degree of membership criteria \( b_{i_0} = \max_{1 \leq j \leq n} \{b_j\} \) where \( i_0 \) is the safety evaluation level.

According to the factors listed above, two types of safety evaluation model can be created, shown in Figure 4, Figure 5. The first layer of model is the target layer (i.e. road safety risk), the second layer is characteristic layer, the third layer is characteristic expansion layer (bottom evaluation factors).
4. MONITORING DATA PROCESSING METHOD OF SUBGRADE SAFETY

Road safety determination in operation period is based on monitoring and detecting data processing and analysis. As known, the accuracy of deformation prediction is often related to amount of information of the monitor. Applicability of various models and methods are not the same under the conditions of sample sizes. For large sample monitoring results, considering the timeliness of subgrade deformation and creep, creep model empirical formula can be used to predict large deformation. For samples with missing small sample size in terms of monitoring, empirical formula of foundation settlement prediction model commonly used in engineering include:

Fuzzy integration is expressed by membership function, so how to establish realistic membership function is the key of achieving fuzzy comprehensive evaluation. Fuzzy distribution function for quantitative evaluation factor common used include trapezoidal function, triangular function, normal function, bell-shaped function, k-degree parabolic function and so on. Membership degree of qualitative factors are commonly determined by empirical method. So membership degrees for the same fuzzy process determined by different people are also variable and thus more subjective. Common experience methods include fuzzy statistics, examples, expert experience and dual contrast sort. According to safety principles of the smaller the value based on the normalization ,the more favorable for road safety, expert rating method is commonly used to calculate the membership degree of qualitative factors.
hyperbolic, exponential, logarithmic curve, hoshino method, Asaoka method and Logistic curve. Different prediction models have different conditions and scope of application, the accuracy of prediction is different. Taking soft subgrade settlement forecasts of Chengdu to Nanchong highway for example, several prediction model accuracy differences were compared.

Table 1  0-118 days measured data regression equation and total settlement prediction results

<table>
<thead>
<tr>
<th>regression equation</th>
<th>correlation index</th>
<th>(S_\infty) (cm)</th>
<th>residual (cm)</th>
<th>error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exponential curve 1</td>
<td></td>
<td>0.973</td>
<td>1475.27</td>
<td>1047.27</td>
</tr>
<tr>
<td>exponential curve 2</td>
<td></td>
<td>0.950</td>
<td>615.35</td>
<td>187.35</td>
</tr>
<tr>
<td>hyperbolic curve</td>
<td></td>
<td>0.973</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>hoshino method</td>
<td></td>
<td>0.903</td>
<td>383.70</td>
<td>-44.30</td>
</tr>
</tbody>
</table>

monitoring time-interval 0 to 118 days, 5 values; initial point for hoshino method \(t_0=55\), \(s_0=47\) cm (2 effective values); calculated total settlement 428 cm.

Table 2  0-485 days measured data regression equation and total settlement prediction results

<table>
<thead>
<tr>
<th>regression equation</th>
<th>correlation index</th>
<th>(S_\infty) (cm)</th>
<th>residual (cm)</th>
<th>error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exponential curve 1</td>
<td></td>
<td>0.924</td>
<td>356.31</td>
<td>-71.69</td>
</tr>
<tr>
<td>exponential curve 2</td>
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<td>0.936</td>
<td>407.17</td>
<td>-20.83</td>
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<tr>
<td>hyperbolic curve</td>
<td></td>
<td>0.964</td>
<td>400.98</td>
<td>-27.02</td>
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<tr>
<td>hoshino method</td>
<td></td>
<td>0.999</td>
<td>370.18</td>
<td>-57.82</td>
</tr>
</tbody>
</table>

monitoring time-interval 0~485 days, 13 values; initial point for hoshino method \(t_0=55\), \(s_0=95\) cm; calculated total settlement 428 cm.

Seen from the above table, better empirical model for soft ground subgrade settlement prediction were exponential curve and inverse exponential curve model. Exponential curve model is suitable for settlement regression prediction of soft ground that long-term secondary consolidation settlement is not obvious which
requires regression data should include the dead load data and later. For obvious long-term secondary consolidation settlement conditions, reverse exponential regression curve is recommend and also data should include the dead load data and later.

Applicable conditions of exponential curve and reverse exponential curve as the preferred soft ground subgrade settlement prediction model mainly incarnates in two aspects: (1) Monitoring data for Regression must include data after a period of constant load, otherwise the prediction accuracy is poor; (2) Total settlement prediction shows small results, the larger of secondary consolidation, the greater of prediction error.

In fact, almost all of the empirical formula have two limitations above. In order to solve the problem by empirical formula, according to settlement curve characteristics of soft ground subgrade, correction Logistic model suitable for the whole process of subsidence monitoring data regression was proposed.

In logistic curve expression, a, b, and K are the three regression parameters, where K has a clear engineering significance, which value represents the size of settlement while a and b have no clear engineering significance. Now, take the curve inflection point abscissa substitution, so that, then, substitute into the original logistic model to obtain the transformed model as shown in formula(4).

\[
S_t = \frac{K}{1 + e^{b(T-t)}}
\]  

(4)

In which, K and b are regression parameters, T is inflection point correction parameters, inflection time in engineering can be measured in s-t curve.

Analysis of Logistic regression curve shows that adjusting time factor exponential can extend convergence process later while not affecting the level of the correlation curve fitting. Therefore, index of independent variable t in Logistic model index can be amended to m, the revised model expression is shown below.

(1) m amendment is

\[
S_t = \frac{k}{1 + ae^{-bm}}
\]  

(5)

(2) T and m amendment is

\[
S_t = \frac{K}{1 + e^{b(T-m)}}
\]  

(6)

Where m is Secondary consolidation Correction parameter. \((0 \leq m \leq 1)\)

Other parameters have the same meaning as above.

From the point of view of function, m amendment can adjust late convergence morphology of Logistic curve. The smaller the m, the longer the convergence process which is more suitable for the later large settlement case. For soft grounds, the better m value is effected by natural environment, traffic loads, and many other complex factors, it is difficult to directly establish analysis model to calculate. For the similar working condition sections, m can be defined as the same value. So repeated trials are good way to determine the better value of m. Figure 6 shows settlement by predicted and measured results comparison for soft ground subgrade of Chengdu to Nanchong expressway.
CONCLUSIONS

Fuzzy comprehensive evaluation method of subgrade safety determination is proposed through establishing different disease risk determination index and method of combination disease monitoring and disease detecting which can provide scientific basis for subgrade safety monitoring sections selection and safety risk level determination.

The Logistic curve correction and verification show that the inflection point T control method using the modified model can accurately determine the location of the actual settlement curve inflection point, compared with uncorrected model and it has a good correlation. Prediction accuracy has greatly improved. It is good solution to dependency problems of other empirical models inflection point after monitoring information. Adopting the time factor index m to modify Logistic model can obtain better accuracy compared with uncorrecting model which means that correction parameter m play a regulatory role for presence of inflection point which well adapted to the soft ground subgrade long-term settlement prediction.

REFERENCES:


