Quantitative settlement hazard assessment for a permafrost embankment based on distributed optical fiber monitoring

Zhen Li 1,2*, Shuangjie Wang2, Juan Zhang2,3 and Kun Yuan2

1 School of Highway, Chang’an University, Xi’an, Shaanxi Province, 710064, China
2 State Key Laboratory of Road Engineering Safety and Health in Cold and High-Altitude Regions, CCCC First Highway Consultants Co., LTD, Xi’an, Shaanxi Province, 710075, China
3 China Communications Construction Co., Ltd, Beijing, 100088, China

*Corresponding author’s e-mail: lizhen@ccroad.com.cn

Abstract. Quantitative assessment of the highway settlement hazard in permafrost regions is urgently needed for maintaining the performance of highway service. This study firstly conducted a field monitoring of an embankment located in the permafrost region by performing the distributed fiber optic monitoring. Subsequently, a novel indicator named embankment disease indicator (EDI) was developed based on strain gradient calculated through the monitoring results to build a permafrost embankment settlement hazard quantitative assessment framework. The results indicate that, (1) the distributed fiber optic monitoring can reflect the uneven settlement distribution of permafrost embankment over a wide range and long distance; (2) 0.152% is suggested as the strain gradient criterion to calculate EDI, EDI can quantitatively indicate differential settlement disease rate in permafrost embankment; (3) the model implementation results have a dynamic quantity consistent with the actual situation, the assessment framework is particularly useful for large regional uneven settlement assessment of permafrost embankment.

1. Introduction
Countries around the world have built many road projects in permafrost areas such as the Trans-Siberian railway in Russia, the Qinghai–Tibet highway and Qinghai–Tibet railway in China, and the Norman Wells–Alaska highway and Hudson Bay railway in the United States[1–2]. Thawing, sinking, and frost heaving are typical factors involved in highway embankment diseases, which are responsible for costly damages to pavement structures[3–6]. A reliable tool for the evaluation of embankment settlement hazards is of utmost importance in maintaining the service performance of highways prone to thawing, sinking, and frost heaving in permafrost regions[7].

Fuzzy mathematical methods have been widely proposed to evaluate embankment hazards. An analytic hierarchy process (AHP) was used to determine the weight of different identified safety factors[8]. Fuzzy probability theory established the fuzzy reasoning system of permafrost embankment disease, which gives an evaluation index of permafrost embankment disease[9–11]. Fuzzy expert systems obtain each factor’s evaluation set and determine the type of freezing–thawing disaster based on the membership principle of maximum factor[12]. Neural net prediction takes a series of settlement-related factors as influencing variables and learns how to predict settlement through examples, this method does not need to know an object’s mathematical model and has a strong fault...
tolerance[13–15]. Gray system theory fits a known data sequence in an exponential form and extends the curve into the future to make predictions regarding unknown data[16–17]. Combined with AHP and fuzzy mathematics theory, Ma[18] proposed a fuzzy comprehensive evaluation method to give quantitative evaluation results. All of these methods ignore the uncertainty related to the evaluation object, regional limitations and subjective statistics make the methods difficult to quantitatively evaluate and popularize effectively.

The disease distribution of permafrost embankment is regional and random[19], to conduct quantitative regional assessment, the assessment based on monitoring data is suggested as a more reliable method. Regional monitoring methods such as interferometric synthetic aperture radar(InSAR)[20–22] have been used in permafrost region, but affected by weather and constrained by economical efficiency, these methods cannot get long-term and reliable data. Measurement methods based on surface sensors are more common methods, especially in general packet radio data service(GPRS) remote automatic monitoring systems used in highway engineering status monitoring[23–24]. However, most of the data obtained are scattered and limited, which may lead to missing detection, regional assessments cannot be conducted on a large scale or for long distance infrastructure. The distributed optic fiber sensor can achieve hundreds of thousands of monitoring points with hundreds of kilometers of ultra-long distance measurements, and the rapid development of Brillouin Optical Time Domain Analysis (BOTDA) makes it possible to realize continuous spatial measurements with long measuring distances and high positioning accuracy[25], the acquisition of large volumes of monitoring data can effectively support engineering disaster evaluation and provide convenient regional disaster assessment of large linear structures such as highways in permafrost areas, which have been used in geotechnical structure engineering in recent years[26–27].

This paper aims to assess permafrost embankment settlement hazards, a field distributed optic fiber monitoring is conducted in Gonghe-Yushu Expressway (GYE) in the Qinghai-Tibet Plateau (QTP), quantitative regional highway settlement hazard assessment is conducted based on monitoring results, a novel embankment disease indicator (EDI) has been developed to build an assessment framework for permafrost embankment, model implementation is presented in Section 4, and concluding remarks can be found in Section 5.

2. Introduction

2.1. Field monitoring design

A field monitoring is conducted to observe the longitudinal uneven settlement of embankment. The field site is located on the GYE in the QTP(Figure.1), the average elevation of the site is greater than 4500m, the mean annual geotemperature of permafrost is nearly -0.27~−1.7℃, this site is a warm and ice-rich permafrost region and has strong representativeness and typicality to carry out monitoring of permafrost embankment hazard evaluation.

The monitored embankment is 100m long and 3m high with 12.25m wide pavement. To evaluate the longitudinal uneven settlement hazard, distributed optical fiber sensors are arranged along the right shoulder, left shoulder and road centerlines, the layout diagram is shown in Figure.2. The selection of key components of distributed optical fiber sensor and monitoring system is shown in the Figure.3, the optical fiber is metal-based strain sensing fiber NZS-DSS-C02, the fiber is outfitted with high-strength metal reinforcement, which greatly improves the tensile strength of the sensor fiber. Meanwhile, the surface screw structure of the sensor makes it have good coupling property with the soil. All the optical fibers are spliced by a Muti-core optical fiber cable in the wire connector and lead into the ODF optical distributing frame.

During construction, when the embankment fill layer reached the top surface design height, excavated 0.3m deep and 0.5m wide groove longitudinally along the embankment to lay distributed optical fiber sensors, after the installation was completed, the integrity of the sensors were detected to ensure that they were intact and alive, the sensors were summarized at the monitor room, then backfilled and paved the embankment.
Figure 1. The field site in the QTP.

Figure 2. Layout of distributed optical fiber sensors: a) Longitudinal layout; b) Lateral layout.

Figure 3. Distributed optical fiber sensor and accessories: a) 5mm metal-based optical fiber; b) Multi-core optical fiber; c) Wire connector; d) ODF optical distributing frame.

2.2. Monitoring results and analyses

Data collection and analysis was carried out in July 2018, October 2018, June 2019, November 2019, July 2020 respectively, the high spatial resolution distributed Brillouin fiber strain analyzer was adopted, and the measurement spatial resolution was 20cm, and the sampling resolution was 5cm. Take the monitoring results of July 2018 as the initial value, Figure.4 shows the longitudinal strain distribution at the three different positions.

The strain distribution at the three positions is extremely uneven longitudinally along the embankment, the uneven distribution is concentrated on different position of the embankment, along the left shoulder, it is concentrated between 20m~60m; along the road centerlines, it is 20m~40m and
60m~80m; while along the right shoulder, it is 30m~60m, the uneven strain distribution along the embankment easily leads to the phenomenon of “vehicle-jumping”.

The strain change obviously from 2018 to 2019 and change slightly from 2019 to 2020. Along the left shoulder, the maximum differential strain can reach 1717.5×10^-6 at July 2020, while along the road centerlines and the right shoulder is 1854.5×10^-6 and 2826.3×10^-6, although the maximum differential strain along the right shoulder is larger than the other positions, the hazard along the left shoulder is more serious than other positions from the aspect of uniformity of strain distribution. The results reveal that the strain distribution is not only uneven along longitudinal direction of the embankment, but also along the lateral direction, it is necessary to carry out quantitative regional hazard assessment to master the overall condition of permafrost embankment hazard.

Figure 4. Monitoring results during different periods at different positions: a) Left shoulder; b) Road centerlines; c) Right shoulder. (I: October 2018; II: June 2019; III: November 2019; IV: July 2020).

3. Embankment hazard assessment model

3.1. EDIε model

The longitudinal strain distribution along the embankment is considered as a two-dimensional plane(as shown in Figure.4, assuming that the longitudinal direction is y and lateral direction is x), to evaluate the uneven settlement, the gradient of strain distribution is used. Since the monitored strain distribution is discontinuous, the strain gradient at each discrete point can be calculated through difference algorithm and expressed by the following function:

\[
\begin{align*}
\Delta f_x(x, y) &= f(x, y) - f(x - 1, y) \\
\Delta f_y(x, y) &= f(x, y) - f(x, y - 1)
\end{align*}
\]  

(1)

where \( f(x, y) \) is monitored strain at each discrete point, \( \Delta f_x(x, y) \) is lateral strain gradient, \( \Delta f_y(x, y) \) is the longitudinal strain gradient.

Based on equation (1), discrete point where the strain gradient exceeds the allowable strain gradient standard can be counted:

\[
\begin{align*}
\Delta f_x(x, y) &\geq \nabla \\
\Delta f_y(x, y) &\geq \nabla
\end{align*}
\]  

(2)

where \( \nabla \) is allowable strain gradient standard.

For further evaluation, a novel indicator named embankment disease indicator (EDIε) is developed, the monitored strain at each discrete point represents an average value over a given area, thus the EDIε can be described as:
\[
EDI_e = \frac{\Delta S_e}{S_e} = \frac{\sum_{j=1}^{m} S_j \cdot e_j}{S \cdot \frac{1}{n} \sum_{i=1}^{n} e_i}
\]  

where \( e_i \) is the monitored strain at each discrete point, \( e_j \) is the strain which exceeds the allowable strain gradient standard, \( S_j \) is the area which exceeds the allowable strain gradient standard determined by equation (2), \( S \) is the total area of the assessed area, \( S_e \) is the strain weighted area, \( \Delta S_e \) is the strain weighted area which exceeds the allowable strain gradient standard.

\( EDI_e \) means differential settlement disease rate in permafrost embankment and \( EDI_e \in [0,1] \). Larger \( EDI_e \) indicates greater severity of the embankment hazard, when \( EDI_e \) reach 1, the entire permafrost embankment will be affected by abnormal differential subsidence diseases. According to equation (3), computing the overall \( EDI_e \) of the embankment includes two basic steps: (1) strain gradient at each discrete point; and (2) the strain weighted area which exceeds the allowable strain gradient standard.

### 3.2. Evaluation standard

The allowable strain gradient standard \( \nabla \) is served as the basis in determining permafrost embankment uneven settlement hazard. Deformation gradient index has been proposed, but no strain gradient index has been found, here we employed the ultimate tensile strength \( \sigma_s \) of the pavement structure to determine \( \nabla \) by finite element analysis[28].

The pavement structure and the finite element model is shown in Figure.5, the right sides of the model were subjected to lateral constraints, whereas the bottom sides were subjected to lateral displacement. Each pavement structure layer was assumed to be a continuous, homogeneous, and isotropic linear elastic structure, and each layer of pavement structure was completely continuous, with no interlayer stripping between layers. The density of each layer of the structural materials \( \rho \), the elastic modulus \( E \), the Poisson ratio \( \mu \), and the ultimate tensile strength \( \sigma_s \) are shown in Table 1.

| Material Name                  | \( E / \text{MPa} \) | \( \mu \)  | \( \sigma_s / \text{MPa} \) | \( \rho / \text{kg.m}^{-3} \) |
|-------------------------------|---------------------|---------|-----------------|-----------------|
| AC-13 bituminous concrete     | 1400                | 0.3     | 1.1             | 2410            |
| AC-16C bituminous concrete    | 1200                | 0.3     | 1.0             | 2420            |
| 6% Cement crushed gravel      | 1500                | 0.25    | 0.5             | 2350            |
| 4% Cement stabilized gravel   | 1300                | 0.25    | 0.5             | 2350            |
| Graded gravel                 | 220                 | 0.35    | /               | 2360            |

**Table 1. Pavement structural material calculation parameters.**

![Figure 5. Pavement composition and numerical simulation: a) Pavement layers; b) Finite element model.](image)

The relationship between tensile stress and differential settlement or differential strain is obtained, as shown in Figure.6~Figure.7. The base course cracks is prone to cause reflective cracks in the surface layer, if the ultimate tensile strength of materials is taken as the standard, the tensile stress on
the bottom surface of the base course reaches 0.5MPa faster than the base, the differential settlement at the bottom of base should be controlled at 2.52cm, and the corresponding allowable settlement gradient should be 0.511%. The differential strain should be controlled at $155.9 \times 10^{-6}$, and the corresponding allowable strain gradient should be $0.152\%\text{m}^{-1}$.

![Figure 6. The relationship between tensile stress and differential settlement or differential strain: a) Differential settlement; b) Differential strain.](image)

![Figure 7. The relationship between tensile stress and allowable settlement gradient or allowable strain gradient: a) Allowable settlement gradient; b) Allowable strain gradient.](image)

4. Model implementation

In addition to an assessment for different position of the highway, the proposed model is particularly useful for large regional assessment based on the $EDI_e$. This approach has merits over the single section or point approach and provide convenience to maintain the hazard of the permafrost embankment. On the basis of the hazard assessment framework proposed in Section 3, an application coded using Visual Basic Application script in the environment of Microsoft Excel has been developed to conduct model implementation.

As shown in Figure 8, the results show that along the left shoulder, the $EDI_e$ during July 2018 to July 2020 is 0.05%, 10.5%, 7.79%, 9.58%, there is a sharp change from July 2018 to June 2019 and then the hazard basically developed into a stable state.

The results show that the hazard development along the road centerlines and right shoulder is as same as the left shoulder, the difference is that the damage is relatively slight, the $EDI_e$ along road centerlines during July 2018 to July 2020 is 0.05%, 6.92%, 6.35%, 5.74%, while along the right shoulder, it is 0.05%, 5.07%, 5.69%, 5.48%. The difference between different positions reflects the unevenness and randomness of hazard distribution of permafrost embankment, the assessment of permafrost embankment urgently need economic and regional monitoring instruments to realize wide area monitoring.
Figure 8. The $EDI_e$ during different periods at different positions.

Figure 9 is the actual condition for field investigation from July 2018 to July 2020, the assessment results are consistent with the field investigation, part of the pavement surface appears subsidence and uplift, that make the road longitudinal appear slight undulation, the photos of pavement surface from June 2019 to July 2020 show that the trend of undulating waves is relatively stable.

![Photos of pavement hazard](image)

Figure 9. Photos of pavement hazard during different periods: a) July 2018; b) June 2019; c) July 2020.

Figure 10. The $EDI_e$ during different periods of the the whole embankment.

For large regional assessment of the whole embankment, the assessment results of the three different position are accumulative calculate, as shown in Figure 10, the $EDI_e$ of the whole embankment is 0.05%, 7.50%, 6.61%, 6.93%, the results reveal that $EDI_e$ is a dynamic quantity as thawing and frost heaving of the permafrost embankment occur yearly, the $EDI_e$ will keep changing.
constantly. Here the hazard development is summarized as the production stage (Class I), the rapid development stage (Class II) and slow development stage (Class III), suppose each stage has a corresponding $EDI_\varepsilon$ value, the road warning indicator of permafrost embankment can be suggested as Table 2.

| Road warning indicator | Class I  | Class II | Class III |
|------------------------|----------|----------|-----------|
| $EDI_\varepsilon$      | [0,10%]  | [10%,70%]| [70%,100%]|

5. Conclusions
To assess permafrost embankment settlement hazard, field monitoring was performed and a novel indicator named embankment disease indicator ($EDI_\varepsilon$) was developed to build a quantitative assessment framework. Based on the study, the following conclusions can be drawn:

(1) The distributed fiber optic sensor is especially suitable for monitoring over a wide range and long distance with the merit of high durability and high economy, and the monitoring results can reflect the uneven settlement distribution of permafrost embankment.

(2) The embankment disease indicator $EDI_\varepsilon$ is developed based on strain gradient, 0.152% is suggested as the strain gradient criterion to calculate the $EDI_\varepsilon$, the $EDI_\varepsilon$ can quantitatively indicate differential settlement disease rate in permafrost embankment.

(3) The model implementation results have a dynamic quantity consistent with the actual situation, the assessment framework based on embankment disease indicator $EDI_\varepsilon$ is particularly useful for large regional uneven settlement assessment of permafrost embankment.

Due to the limited data, this assessment framework needs to be validated with more data, the proposed model is also applicable to the monitoring results obtained by other regional monitoring methods, based on more regional monitoring results, the assessment framework for permafrost embankment settlement hazard will be more worth promoting.

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