



Type Classification and Engineering Stability Evaluation of Permafrost Wetlands on the Qinghai–Tibet Plateau

Xuesong Mao¹, Ying Zhao^{1*}, Qian Wu¹, Wanjun Huang¹ and Liangqing Han²

¹School of Highway, Chang'an University, Xi'an, China, ²Jiangsu Zhongsheng Group Co.,Ltd., Wuxi, China

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*Correspondence:

Ying Zhao
2017021007@chd.edu.cn

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On the Qinghai–Tibet Plateau area, the permafrost and the wetlands are interdependent to form a symbiotic system, called permafrost wetlands (PWs). Due to the extremely complex hydrothermal conditions, the PWs greatly impact road stability. Thus, it is necessary to classify PWs in terms of engineering characteristics and evaluate their engineering stability. In this study, the typical diseases of subgrade in permafrost wetland areas are analyzed based on field investigation. Then, the permafrost type, waterlogged area ratio, and meadow development degree are used as the main indicators for classifying PWs by a three-level division method. Finally, a scheme for the engineering stability evaluation of PWs was established based on the fuzzy comprehensive theory and used for the pre-evaluation of the engineering stability for the proposed Qinghai 224 highway. The results indicate that the longitudinal cracks and uneven deformation are the main road diseases in this area, caused by the combined effect of permafrost, waterlogged areas, and meadow development. The PWs are divided into 15 types according to the engineering characteristics. Waterlogged area ratio and meadow development degree are proven to represent the development of underlying permafrost. The influencing factors include climatic environment, permafrost property, and wetland conditions, which have decreased influence on the engineering stability of PWs. The engineering stability of k230 + 100 and k255 + 400 is evaluated as basically stable and less stable, and the corresponding measures are adopted. At present, no significant damage occurred on the two road sections. The results suggest that the evaluation model in this article can be used to pre-evaluate the engineering stability of PWs.

Keywords: permafrost wetlands, typical diseases, type classification, engineering stability, evaluation model

INTRODUCTION

The Qinghai–Tibet Plateau is a typical region of high-altitude permafrost distribution in China and even the world. Due to the water blocking effect of the permafrost layer, rainfall, snowmelt, and surface runoff cannot infiltrate into the permafrost, resulting in the accumulation of water on the surface to form wetlands. The natural environment, vegetation characteristics, and permafrost combine to create the environmental sensitivity of permafrost wetlands (Bai et al., 2004; Wang et al., 2015), which significantly affects the stability of roads (Wang et al., 2004; Chai et al., 2017). On the Qinghai–Tibet Plateau, the road pavement instead of the original vegetation has disrupted the original hydrothermal balance of the wetlands and blocked surface runoff, thus exacerbating the degradation of the permafrost, which has led to a series of road disease problems, especially uneven

settlement and longitudinal cracks (Wen et al., 2009; Mu et al., 2014; Li et al., 2015; Peng et al., 2015; Chang et al., 2016; Chai et al., 2017; Yang et al., 2019). Some scholars also pointed out that the thaw settlement of the permafrost beneath the roadway is one of the sources of the subgrade settlement (Qi et al., 2012; Yu et al., 2013). In addition, the wetlands features are also conducive to the development of road diseases. The accumulation of water in the soil layer leads to water migration to the subgrade, causing road diseases with seasonal freezing and thawing (Mao et al., 2010). Meantime, the low temperature of PWs promotes the formation of a peat layer with high compressibility. The settlement caused by the compression of the peat layer is also part of the subgrade settlement. It can be found that these road diseases are closely related to the type and stability of the permafrost and wetlands conditions. The permafrost state is not only influenced by road constructions but also closely related to the wetland conditions (Liu et al., 2009; Chang et al., 2012). It can be seen from the above analysis that the permafrost and wetlands both interact and contribute to each other, and together they affect road stability. Thus, the engineering characteristics of PWs on the Qinghai–Tibet Plateau require attention.

In order to better understand the characteristics of wetlands on the Qinghai–Tibet Plateau, many researchers proposed the classification system in terms of causes or features (Ni et al., 1998; Sun, 2003). Meantime, several scholars proposed classification systems at different spatial scales. Li et al. (1998) classified the wetlands in the Three-River Source region into moor, lake, river, and riverbed. Zhao (1999) classified the alpine wetlands into peat marshes and submerged marshes based on the presence or absence of peat accumulation and then divided them into 11 marsh subtypes based on geomorphological conditions and water recharge types. Sun (2003) classified the wetlands of the Qinghai–Tibet Plateau into grass wetlands, forested wetlands, river wetlands, and lake wetlands according to the Ramsar Convention. Chen et al. (2002) added artificial wetlands on the basis of 3 basic natural wetland types—lake wetland, swamp wetland, and river wetland—according to the basic hydrological, biological, and soil characteristics of plateau wetlands. Zhang et al. (2010) proposed a revised 4-class classification system of alpine wetlands based on remote sensing and classified the wetlands into 13 subcategories, such as river, weedy wet meadow, hippophae rhamnoides, beach gravel, lake, and *Phragmites australis* marsh. Although the classification systems considering the causes, features, and space of wetlands on the Qinghai–Tibet Plateau have been widely documented, little information exists paying attention to the engineering characteristics of wetlands.

The engineering characteristics of wetlands significantly affect the stability of permafrost wetlands. The traditional road safety assessment system mainly adopts the safety factor as the evaluation criterion. The evaluation results have great inaccuracy due to the uncertainty of geotechnical parameters. In order to overcome this problem, Qi et al. (2006) proposed a calculation method to calculate the reliability index and failure probability based on a genetic algorithm for the thawing settlement of the permafrost subgrade. However, road stability is related to geological and climatic conditions, regulation

measures, and so on. Huo et al. (2010) selected the annual ground temperature, permafrost type, artificial permafrost table, drainage condition of subgrade, and method of special adjustment as the key factors and established the linguistic variables and fuzzy membership function to describe the relationship between the factors and the road diseases. Meanwhile, Qi et al. (2007) and Miao et al. (2018) established a prediction model of subgrade deformation considering ground temperature, subgrade height, and permafrost table using a BP neural network. For the special engineering measures for subgrade in permafrost areas, the treatment effect was evaluated using fuzzy theory and catastrophe progression method considering the natural environment, frozen soil properties, and engineering measures (Cao et al., 2015; Zhao et al., 2019; Luo et al., 2021). It can be seen that the current research mostly focuses on the evaluation of subgrade stability in permafrost areas and rarely considers the impact of permafrost wetlands on road stability. Therefore, it is necessary to evaluate the engineering stability of the PWs in order to take appropriate treatment measures to strengthen the wetland foundation.

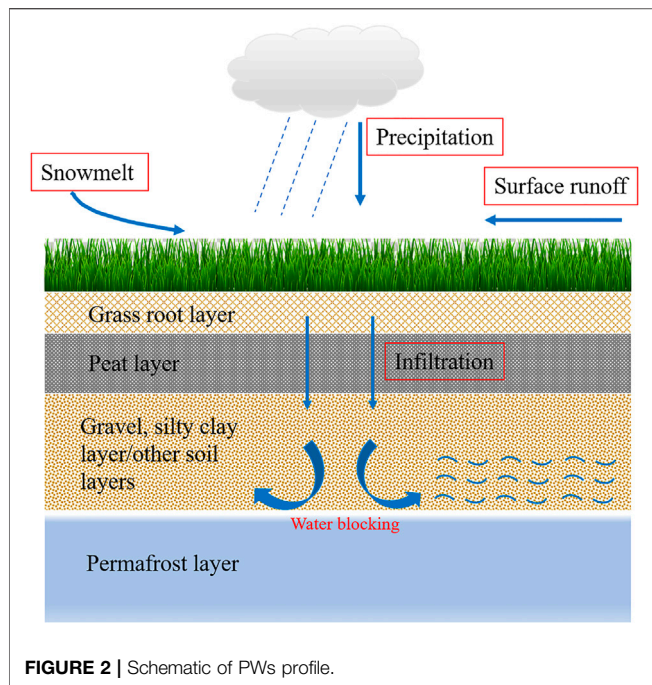
This study proposes the classification system of permafrost wetlands according to engineering characteristics. Furthermore, the engineering stability of permafrost wetlands is evaluated based on the fuzzy comprehensive evaluation model. The results provide an important reference to understanding the role of permafrost wetlands in engineering construction.

PERMAFROST WETLANDS AND TYPICAL DISEASES OF SUBGRADE IN STUDY AREA

The study area is located in the center of the Qinghai–Tibet Plateau and the Midwest of Yushu, with an average altitude of 4179.1 m, belonging to a typical alpine climate. The road traverses many wetlands with meadows covering the surface, waterlogged



FIGURE 1 | Permafrost wetlands on the Qinghai–Tibet Plateau.



areas, and permafrost existing underground, which can be called permafrost wetland (PWs), as shown in **Figure 1**. The developed modern glaciers and glacial landforms, dense rivers and lakes, abundant ice-snow meltwater, alpine climate, and the prevalence of the permafrost have contributed to the formation and development of wetlands on the Qinghai–Tibet Plateau.

Based on field investigation, the strata of PWs are composed of the grass layer with grass roots, peat layer with an inadequate decomposition of plant residues, powdered clay interspersed with gravel, and permafrost layer, as shown in **Figure 2**. The wetlands and the permafrost underneath constitute a symbiotic system (Sun, 2000; Sun et al., 2008), which is mainly manifested in two aspects: the protection and enhancement of peat and grass layer to permafrost and the promotion of permafrost to peat and grass layer. Vegetation has been found to strongly protect frozen soil from incoming radiation, thereby insulating the soil from ambient conditions (Kudelyacev et al., 1977; Kelly et al., 2004; Cannone and Guglielmin, 2009; Anderson et al., 2019; Fedorov et al., 2019). Moreover, the grass-root layer can reduce the surface heat transfer into a deep stratum due to the poor thermal conductivity. Meantime, the role of ground-hugging vegetation and plant roots in water absorption and retention enables the frozen soil to reach a material-energy balance and ecological equilibrium (Niu et al., 2019). When the temperature rises, the peat layer consumes heat by evaporating water to slow down the transmission of the cold storage of permafrost to the surface. When the temperature drops to negative temperature, the peat layer in a frozen state, due to its higher thermal conductivity, can transfer the cold energy deeper into the soil to promote cold storage of the permafrost (Sun, 2000). The permafrost layer can effectively block water infiltration, allowing snowmelt, precipitation, and river water to accumulate on the surface, forming a waterlogging area, which facilitates the continuity of

the soil swampy process. Instead, when the surface vegetation is destroyed, its functions of heat insulation, heat preservation, and water storage are weakened or disappear (Iwahana et al., 2003; Wang et al., 2008), causing heat and water to enter directly into the subsurface, which is manifested by enhanced vertical transport of water and heat. Eventually, the underlying permafrost degrades or disappears, which affects the existence of wetlands leading to the degradation or disappearance (He et al., 2009; Luo et al., 2012). The symbiotic mechanism existing between wetlands and permafrost is a key factor in forming the special geological environment of the Tibetan Plateau. It was found that permafrost on the Qinghai–Tibet Plateau is degrading year by year due to climate warming and construction of ground engineering (Luo et al., 2012; Han et al., 2018; Sheng et al., 2020), which in turn affects the development of wetlands (Wang et al., 2010; Liu et al., 2019).

Based on the above analysis, it is clear that the complex characteristics of permafrost wetlands are the main challenge to be overcome for road construction, which leads to a series of road disease problems. In this study area, the longitudinal cracks and the uneven deformation are the main forms of road diseases according to the field investigation (**Figure 3**). The black asphalt pavement breaks the original hydrothermal equilibrium of the wetlands, and the input of a large amount of heat energy makes the permafrost under the subgrade in a state of degradation. The thawing of the permafrost layer leads to the uneven compression deformation of the subgrade, which is the main internal cause of the uneven settlement and longitudinal cracks. In addition, the developed permafrost wetlands have lush grass, and the soil is wet or overwet all year-round, which leads to the active migration of moisture to the subgrade. The surface water infiltrated by the road shoulder and slope foot carries much heat, resulting in a relative decrease of the permafrost table. Furthermore, water gathers near the permafrost table to form a thick ice layer under the road shoulder (Mao et al., 2010). Finally, the longitudinal cracks and uneven settlement are generated in the subgrade under the coupling action of heat and water. It indicates that the combination of the permafrost, waterlogged area, and meadow development contributes to road diseases.

TYPE CLASSIFICATION OF PERMAFROST WETLANDS

Determination of Classification Index

For the actual engineering project, the classification of PWs should comprehensively consider and analyze the various elements that affect road stability. Based on a field investigation, the permafrost type, waterlogged area ratio, and meadow development degree were selected to be the classification indexes, which considered the effects of permafrost, meadow, and water on the project construction. The permafrost type was identified by the field drilling method. The waterlogged area ratio was obtained by the aerial survey and micro-geomorphology extraction technology. The thickness of the vegetation layer was determined by field measurement.

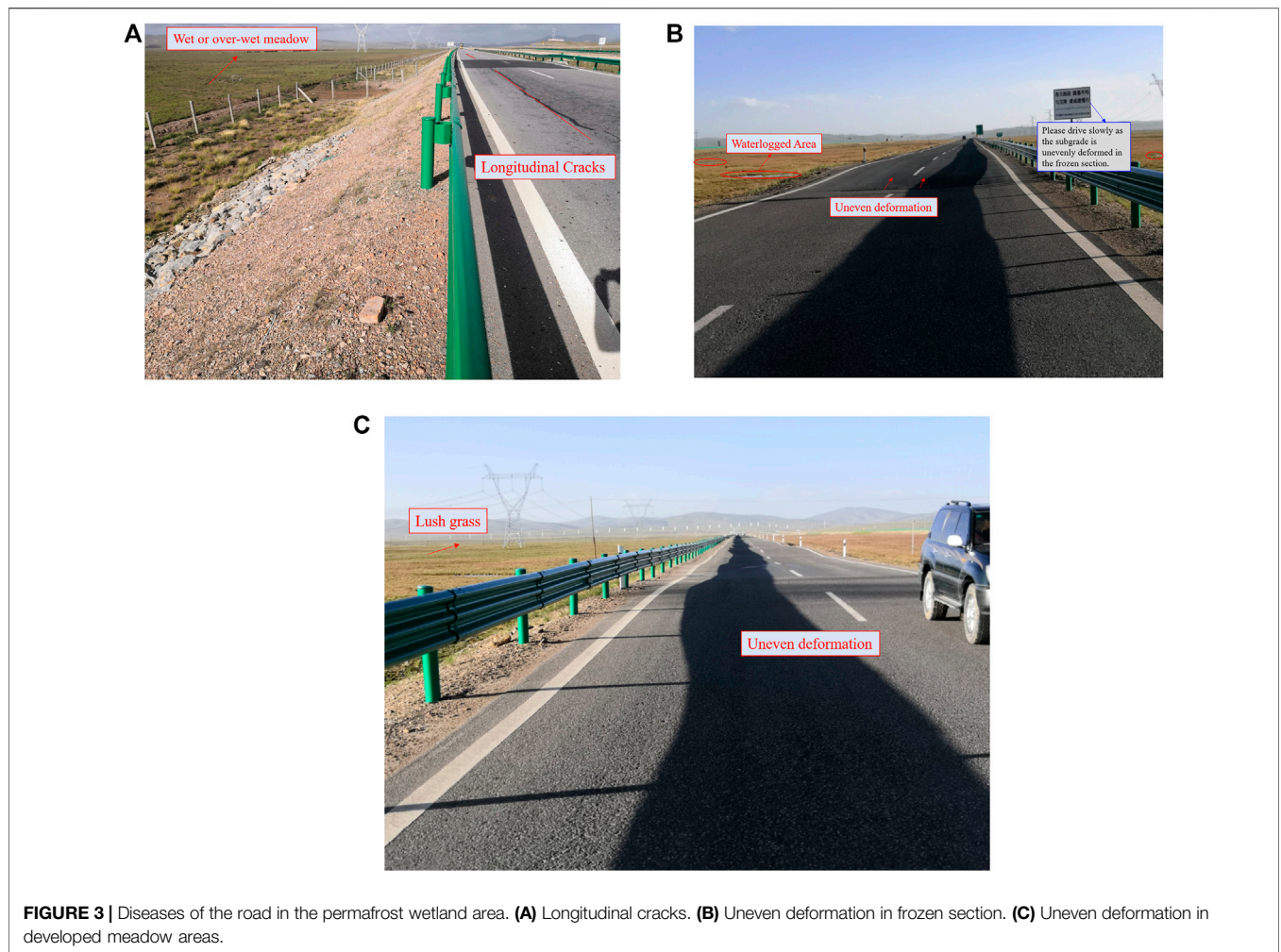


FIGURE 3 | Diseases of the road in the permafrost wetland area. **(A)** Longitudinal cracks. **(B)** Uneven deformation in frozen section. **(C)** Uneven deformation in developed meadow areas.

TABLE 1 | Classification of permafrost by volume ice content.

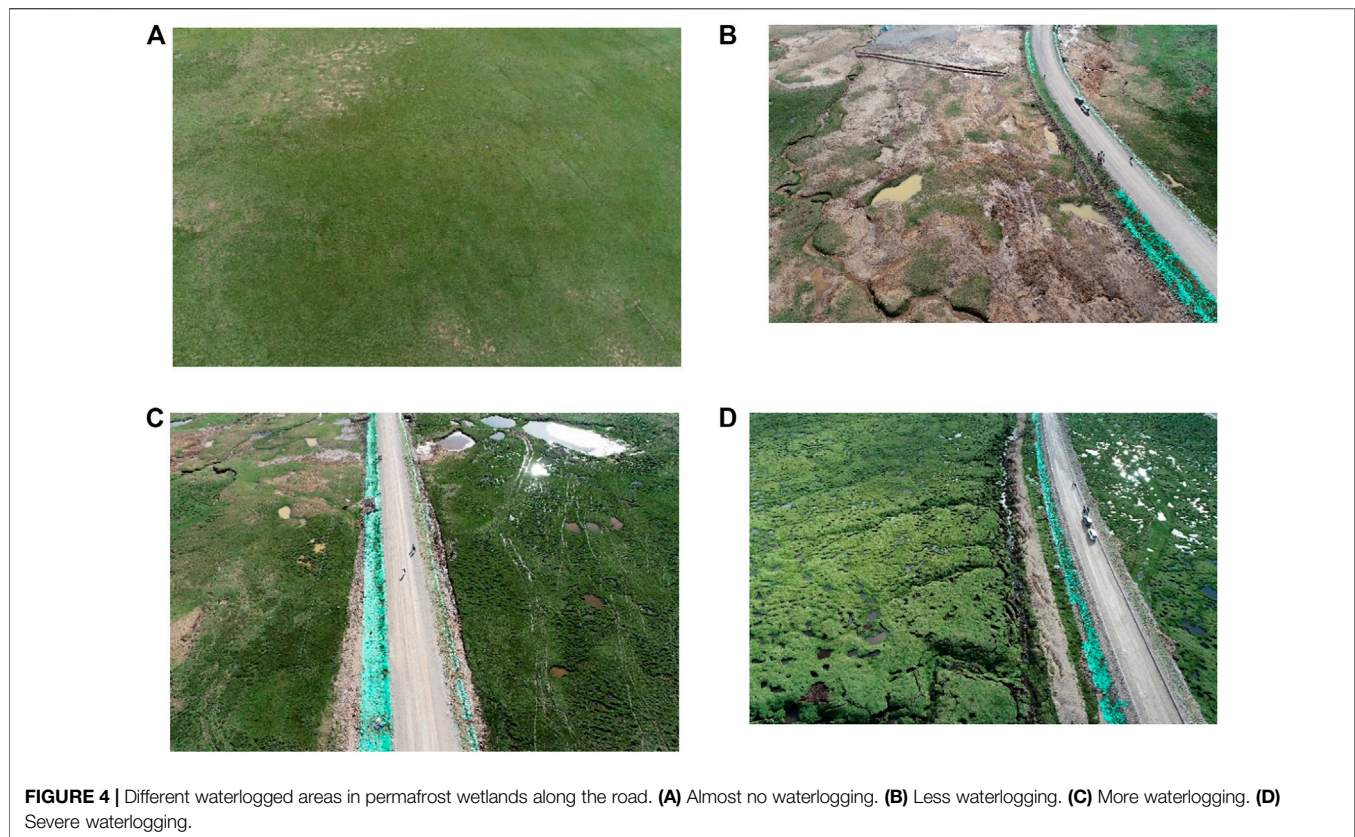
Permafrost type	Ice-poor soil	Icy soil	Ice-rich soil	Saturated frozen soil	Ice layer interspersed with soil
Ice content (%)	<0.1	0.1–0.2	0.2–0.3	0.3–0.5	>0.5

Permafrost Type

The types of permafrost are the products of the comprehensive action of various natural conditions, reflecting the characteristics of seasonal thaw layer and permafrost, which are the main factor for subgrade design in the permafrost area. Some scholars take permafrost type and ground temperature as the main zoning index (Cheng and Wang, 1982). In addition, the stability of the subgrade in the permafrost region depends on the ice content of the permafrost under the roadway (Wen et al., 2009; Xu, 2014). In China, “Specifications for Design of Highway Subgrades” classifies permafrost according to the volume ice content, which can be divided into ice-poor soil, icy soil, ice-rich soil, saturated frozen soil, and ice layer interspersed with soil, as shown in **Table 1**.

Waterlogged Area Ratio

In the permafrost area, the permafrost layer hinders the infiltration of surface water. Combined with the low-lying terrain and poor drainage conditions, this often increases the water in the soil and forms the waterlogged areas in severe cases. However, the water on both sides of the road infiltrates into the subgrade, and with the freeze-thaw process, it is easy to form a thick pure ice layer inside the subgrade leading to disease problems (Mao et al., 2010). Furthermore, the upper soil layer in the waterlogged area is in an oversaturated state, which can lead to a reduction in its bearing capacity. The consolidation of the upper soil layer is a key factor causing the subgrade settlement. Therefore, it is necessary to pay attention to water accumulation along the road during the road design,



construction, and operation and set up drainage facilities or intercept facilities in advance.

Figure 4 shows different waterlogging conditions of wetlands along the road in the study area. It can be seen that the road crosses PWs with different waterlogging conditions. Moreover, the percentage of waterlogged areas is positively correlated with vegetation development; that is, the larger the percentage, the more developed the vegetation. The reason is that water can promote vegetation growth, which shows that the occurrence and development of surface vegetation, water, and permafrost are interdependent and mutually influential relationships. The waterlogging condition of the PWs was evaluated according to the percentage of waterlogged area n_s : almost no waterlogging ($n_s < 5\%$), less waterlogging ($5\% \leq n_s < 25\%$), more waterlogging ($25\% \leq n_s < 55\%$), and severe waterlogging ($n_s \geq 55\%$).

Meadow Development Degree

Vegetation has a significant influence on the hydrothermal processes of permafrost (Wu et al., 2003; Kelly et al., 2004), although the permafrost restricts the growth of some plants owing to low temperature, water isolation, and other restricts. For a long time, an ecological balance has been established between vegetation and permafrost, and vegetation is often used as an indicator of underlying permafrost and thawing soil (Chang et al., 2012). In this study, the meadow development degree is expressed by the thickness of vegetation h , measured from the top of vegetation to the

bottom of grass root. According to the field survey findings, the meadow development degree can be divided into four cases: undeveloped ($h < 8$ cm), basically developed ($8 \text{ cm} \leq h < 15$ cm), developed ($15 \text{ cm} \leq h < 40$ cm), and fairly developed ($h \geq 40$ cm), as shown in **Figure 5**. It can be seen that the more developed the meadow, the higher the ice content of the permafrost. This result indicates that the meadow development degree can be used as an indicator of the permafrost type on the Qinghai-Tibet Plateau wetlands.

Extraction of Waterlogged Areas

Based on the field survey and exploration data, the typical road sections with different permafrost types and waterlogged areas were selected. Then, aerial surveys are conducted on typical road sections to extract the waterlogged areas of specific areas.

The unmanned aerial vehicle (UAV) used for this study is a DJI Genie 4 pro v2.0 with a 20-megapixel FC6310 digital camera. The topographic data of the wetlands along the road are collected by shooting at an altitude of 60 m above the study area. The aerial photography area was a rectangle of 150 m on each side perpendicular to the roadbed centerline and 300 m along the roadbed centerline. In the flight, the ground resolution (GSD) of 1.64 cm/pixel was applied according to the requirements of 1:500 mapping scale. In order to get better results during the flight, the fore-and-aft overlap was set to 80% and the side overlap was set to 70% to facilitate image stitching and generation of elevation points.

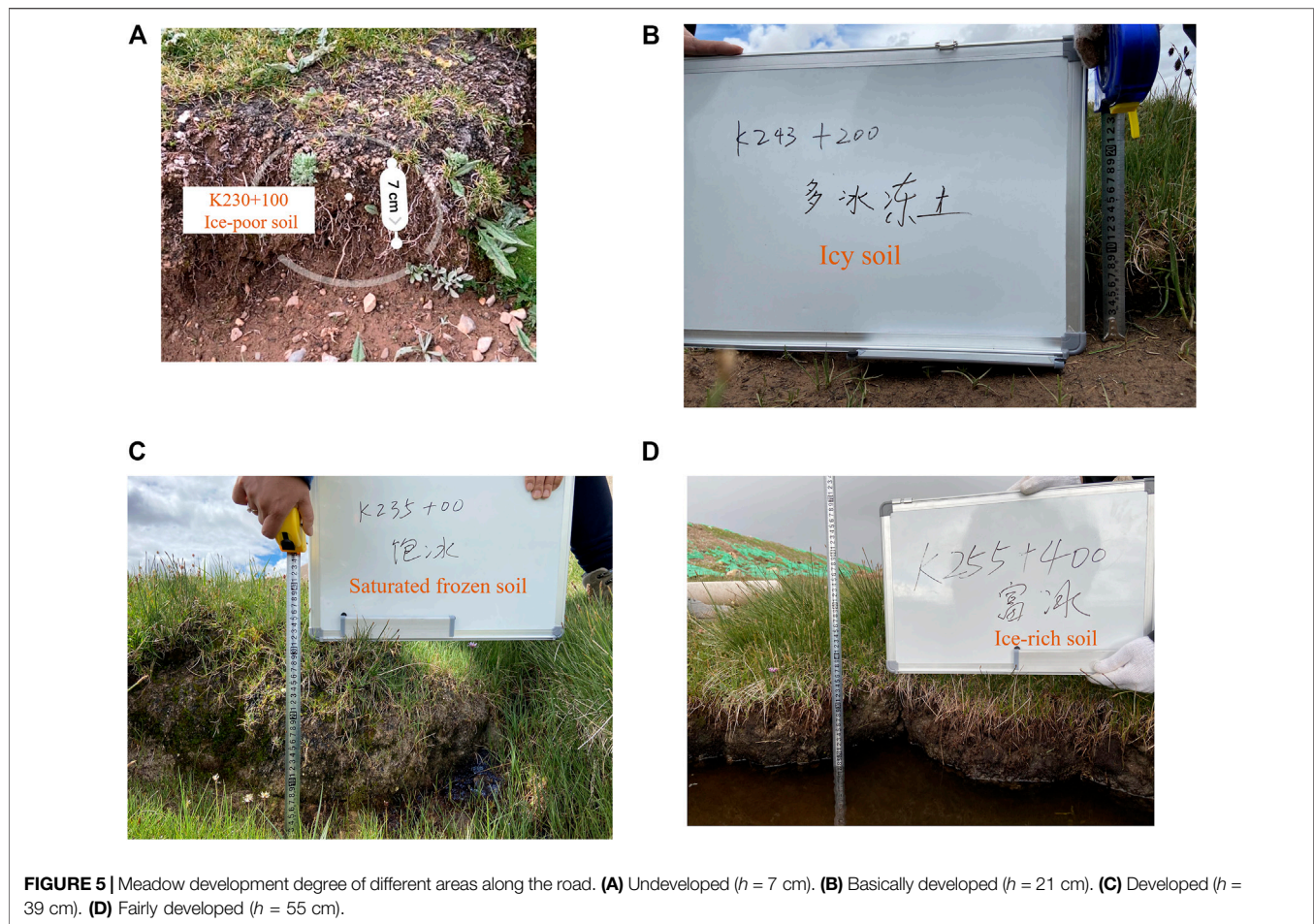


FIGURE 5 | Meadow development degree of different areas along the road. (A) Undeveloped ($h = 7$ cm). (B) Basically developed ($h = 21$ cm). (C) Developed ($h = 39$ cm). (D) Fairly developed ($h = 55$ cm).

The orthophotos taken by the UAV were calibrated by Global Mapper and then imported into Image-Pro Plus for micro-geomorphology extraction, as shown in **Figure 6**. The waterlogged area ratio n_s can be computed by the following equation:

$$n_s = \frac{\sum_{i=1}^n s_i}{s} = \frac{s_w}{s}, \quad (1)$$

where s_i is the area of a single waterlogged area, $i = 1, 2, \dots, n$; n is the number of identified waterlogged areas; s is the total area of the selected area, m^2 ; s_w is the waterlogged area of the selected area, m^2 .

The calculation of n_s is mainly done by extracting the micro-geomorphology from the actual captured 2D model images, identifying the waterlogged area in the specified area, and then counting the proportion of waterlogged area in the specific area. According to the image recognition results, the waterlogged area ratio near the typical road sections was calculated, as shown in **Table 2**. The analysis found a spatial correlation between the waterlogged area ratio and the type of permafrost. The larger the waterlogged area ratio, the higher the ice content of the underlying permafrost, which indicates that the waterlogged area ratio can be used as an indicator of different permafrost types.

Classification of Permafrost Wetlands

This classification system belonging to the small-scale classification model integrates the effect of permafrost, moisture, and vegetation on the engineering characteristics of permafrost wetlands. The permafrost wetlands are divided into 15 types using the three-level division, composed of the permafrost type, waterlogged area ratio, and meadow development degree, as shown in **Table 3**. The permafrost wetlands' characteristics are quantitatively reflected by a combination of letters and numbers. The first letter represents the classification index, such as W represents the waterlogged area ratio, P represents the permafrost type, and M represents the meadow development degree. The numbers represent the development degree of each index. For waterlogged area ratio, 1~4 represent $n_s < 5\%$, $5\% \leq n_s < 25\%$, $25\% \leq n_s < 55\%$ and $n_s \geq 55\%$, respectively. For permafrost type, 1~5 represent ice-poor soil, icy soil, ice-rich soil, saturated frozen soil, and ice layer interspersed with soils, respectively. For meadow development degree, 1~4 represent $h < 8$ cm, $8 \text{ cm} \leq h < 15$ cm, $15 \text{ cm} \leq h < 40$ cm, and $h \geq 40$ cm, respectively. For example, W3 means the proportion of the waterlogged area is 25~55%, P4 means the permafrost type is saturated frozen soil,

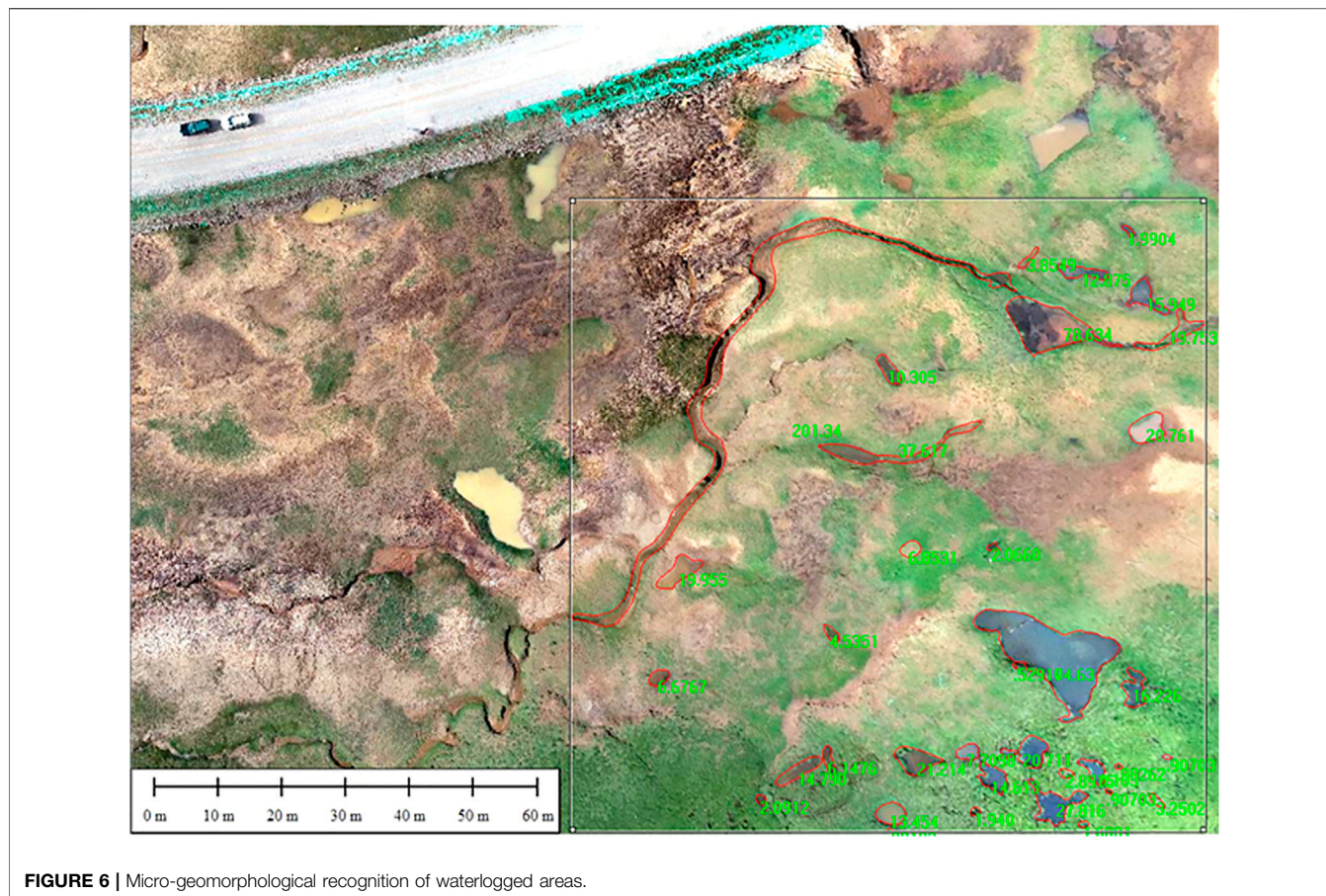


FIGURE 6 | Micro-geomorphological recognition of waterlogged areas.

TABLE 2 | Waterlogged area ratio of PWs near typical road sections.

Stake number	Permafrost type	Waterlogged area ratio n_s (%)	Evaluation results
K230 + 100	Ice-poor soil	2.34, 3.39	Almost no waterlogging
K227 + 400	Icy soil	4.15	Almost no waterlogging
K251 + 000	Icy soil	7.87	Less waterlogging
K251 + 185	Icy soil	18.45	Less waterlogging
K225 + 400	Ice-rich soil	30.13	More waterlogging
K255 + 400	Ice-rich soil	26.35	More waterlogging
K235 + 000	Saturated frozen soil	42.12, 56.35	More waterlogging/severe waterlogging
K228 + 400	Ice layer interspersed with soil	58.37	Severe waterlogging

and M3 means the degree of meadow development is 15~40 cm. Thus, W3-P4-M3 represents the permafrost wetlands having more waterlogging and the developed meadows, and the underlying permafrost is saturated frozen soil. The larger number indicates the greater degree of influence of a factor on the wetland's formation. Correspondingly, the more susceptible the permafrost wetlands are to weakness and less carrying capacity.

EVALUATION OF ENGINEERING STABILITY OF PERMAFROST WETLANDS BASED ON FUZZY THEORY

For evaluating the engineering stability of permafrost wetlands, the analytic hierarchy process (APH) and fuzzy comprehensive evaluation are applied to appropriately reduce the randomness of subjective judgment and improve the reliability of the evaluation results.

TABLE 3 | Classification of permafrost wetlands types.

Permafrost wetlands type	Waterlogged area ratio n_s (%)	Permafrost type	Meadow development degree h (cm)
W1-P1-M1	<5%	Ice-poor soil	<8
W1-P1-M2	<5%	Ice-poor soil	8–15
W1-P2-M1	<5%	Icy soil	<8
W1-P2-M2	<5%	Icy soil	8–15
W2-P1-M1	5–25%	Ice-poor soil	<8
W2-P1-M2	5–25%	Ice-poor soil	8–15
W2-P2-M1	5–25%	Icy soil	<8
W2-P2-M2	5–25%	Icy soil	8–15
W3-P3-M3	25–55%	Ice-rich soil	15–40
W3-P3-M4	25–55%	Ice-rich soil	>40
W3-P4-M3	25–55%	Saturated frozen soil	15–40
W3-P4-M4	25–55%	Saturated frozen soil	>40
W4-P4-M3	>55%	Saturated frozen soil	15–40
W4-P4-M4	>55%	Saturated frozen soil	>40
W4-P5-M4	>55%	Ice layer interspersed with soil	>40

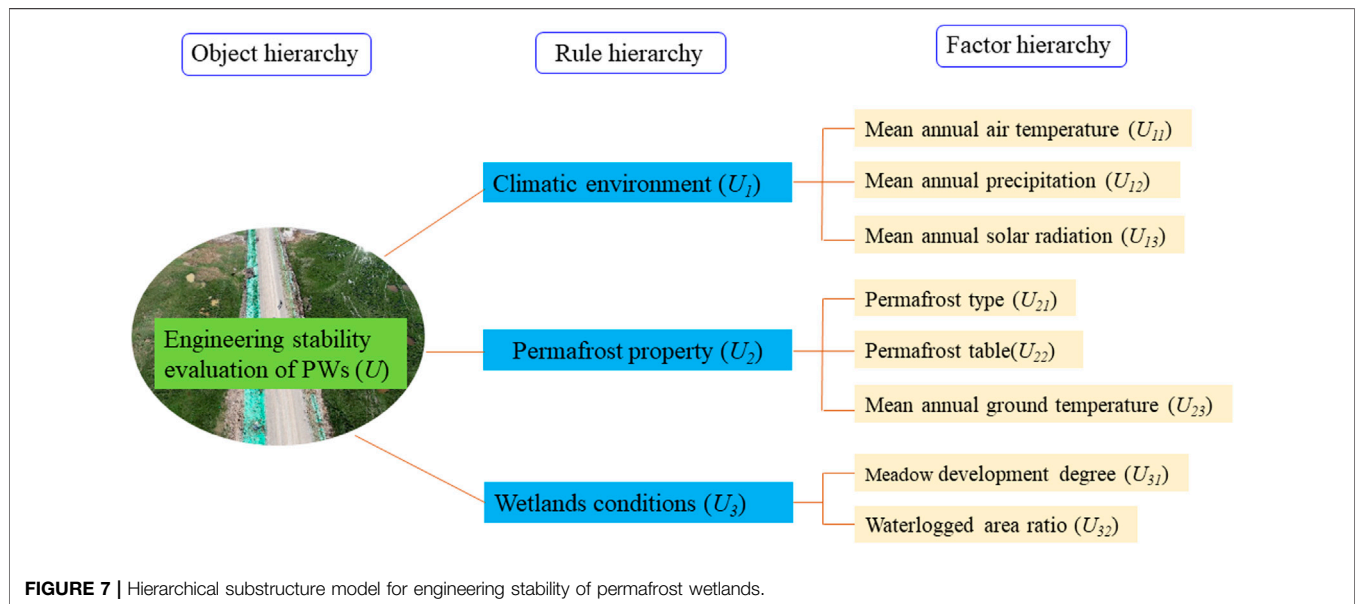


FIGURE 7 | Hierarchical substructure model for engineering stability of permafrost wetlands.

Construction of Index System of the Foundation Stability

The construction of the index system needs to meet the systematic, scientific, operable, and practical principles. Firstly, the index system can accurately and fully reflect the situation of the evaluation object through qualitative or quantitative methods. In addition, the difficulty of quantifying the indicators should be considered. It is required that the scoring methods and standards should be clear and easy to operate while ensuring that the evaluation results are as objective, comprehensive, and fair as possible. Based on the above analysis of factors affecting PWs formation, the hierarchical substructure model for PWs stability is established, as shown in **Figure 7**. This hierarchical substructure model consists of three levels: object hierarchy, rule hierarchy, and factor hierarchy. Rule hierarchy includes

climatic environment, permafrost property, and wetlands conditions, controlled by the elements in factor hierarchy. The elements in the factor hierarchy are the evaluation indexes of the engineering stability for PWs.

Establishment of Fuzzy Comprehensive Evaluation Model

Determination of Weight

The reasonableness of weight determination directly affects the accuracy and scientificity of the evaluation results. Firstly, the judgment matrix should be established, which is the evaluation for objective factors. Each value in the matrix was marked by a number from 1 to 9 or its reciprocal and characterized the relative importance of each element. The larger the number, the more

important this factor is relative to other factors. Assume that A_i denotes the k th element in the rule hierarchy ($i = 1, 2, \dots, n$), and the element in factor hierarchical is B_{ij} ($j = 1, 2, \dots, m$). The relative importance of elements $B_{i1}, B_{i2}, \dots, B_{im}$ is determined by pairwise comparison and is quantified as b_{lk} ($l = 1, 2, \dots, m; k = 1, 2, \dots, m$). The relative importance of each element is determined by an expert questionnaire survey. The judgment matrix can be expressed as

$$B_m = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mm} \end{bmatrix}_{m \times m}, \quad (2)$$

where b_{lk} represents the importance of factor B_{il} relative to B_{ik} and b_{lk} is determined as

$$b_{lk} = \begin{cases} 1, l = k \\ 1/b_{kl}, l \neq k \end{cases} \quad (3)$$

The judgment matrix is built to make the judgment process and conclusion mathematical and quantifiable. Then, the weight value of each factor is calculated based on the judgment matrix. The calculation steps are as follows:

First, the judgment matrix B_m is normalized to obtain matrix \bar{B}_m :

$$\bar{b}_{lk} = b_{lk} / \sum_{l=1}^m b_{lk}, l, k = 1, 2, \dots, m. \quad (4)$$

And then, each line of the normalized matrix \bar{B}_m is summed to obtain the vector $W = [W_1, W_2, \dots, W_m]$:

$$W_i = \sum_{k=1}^m \bar{b}_{ik}. \quad (5)$$

The vector W is normalized to obtain the eigenvector vector $\bar{W} = [\bar{W}_1, \bar{W}_2, \dots, \bar{W}_m]$:

$$\bar{W}_i = W_i / \sum_{i=1}^m W_i. \quad (6)$$

Finally, each value in the eigenvector vector \bar{W} is the weight value of each factor.

Consistency Checking of the Judgment Matrix

The consistency checking of the judgment matrix is performed to ensure the rationality of weight value. The consistency index of the judgment matrix can be written as

$$CI = \frac{\lambda_{max} - m}{m - 1}, \quad (7)$$

where λ_{max} is the maximum eigenvalue and $\lambda_{max} = \frac{1}{m} \sum_{i=1}^m \frac{(BW)_i}{W_i}$. m is the number of factors. Then, the consistence proportional factor CR is proposed for consistent checking, and the calculation formula is as follows:

$$CR = \frac{CI}{RI}, \quad (8)$$

where RI is the mean random consistency index, as shown in Table 4. When $CR < 0.1$, it indicates that the degree of

inconsistency of judgment matrix B_m is within the allowed range and the weight value is reasonable. Thus, the weight value of factors can be applied in the stability evaluation calculations.

Establishment of Multi-Level Fuzzy Comprehensive Evaluation Model

The fuzzy comprehensive evaluation method belongs to the category of fuzzy mathematics. Based on the principle of affiliation of fuzzy mathematics, the qualitative problem is transformed into a quantitative problem to make an overall evaluation of the complex system. The steps are as follows:

(1) Determine the influencing factor set and evaluation set.

Assume that $U = \{U_1, U_2, \dots, U_n\}$ is the influencing factors set of the object to be evaluated. $V = \{V_1, V_2, \dots, V_m\}$ is the m evaluation levels describing the state of each factor.

(2) Construct the single factor evaluation matrix R .

The membership degree r_{ij} ($0 \leq r_{ij} \leq 1$) of each factor U_i ($i = 1, 2, \dots, n$) to the evaluation level V_j ($j = 1, 2, \dots, m$) was solved by membership function to form a single-factor evaluation matrix R as follows:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}_{n \times m}. \quad (9)$$

In this study, the value limit of each factor evaluation can be uniformly expressed as $< v_1, v_1 \sim v_2, v_2 \sim v_3, > v_4$, and the membership functions are shown in the following equations:

$$r_{i1} = \begin{cases} 1 & x < v_1 \\ \frac{(v_1 + v_2) - 2x}{v_2 - v_1} & v_1 \leq x < \frac{v_1 + v_2}{2} \\ 0 & x \geq \frac{v_1 + v_2}{2} \end{cases}, \quad (10)$$

$$r_{i2} = \begin{cases} 0 & x < v_1, x \geq \frac{v_2 + v_3}{2} \\ \frac{(v_1 + v_2) - 2x}{v_2 - v_1} & v_1 \leq x < \frac{v_1 + v_2}{2} \\ \frac{(v_2 + v_3) - 2x}{v_3 - v_1} & \frac{v_1 + v_2}{2} \leq x < \frac{v_2 + v_3}{2} \end{cases}, \quad (11)$$

$$r_{i3} = \begin{cases} 0 & x \geq v_3, x < \frac{v_2 + v_3}{2} \\ \frac{2x - (v_1 + v_2)}{v_3 - v_1} & \frac{v_1 + v_2}{2} \leq x < \frac{v_2 + v_3}{2} \\ \frac{2(v_3 - x)}{v_3 - v_2} & x \geq \frac{v_2 + v_3}{2} \end{cases}, \quad (12)$$

TABLE 4 | Values of mean random consistency index *Rl*.

<i>m</i>	1	2	3	4	5	6	7	8	9	10	11
<i>Rl</i>	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

$$r_{i4} = \begin{cases} 0 & x < \frac{v_2 + v_3}{2} \\ \frac{2x - (v_2 + v_3)}{v_3 - v_2} & \frac{v_2 + v_3}{2} \leq x < v_3 \\ 1 & x \geq v_3 \end{cases} \quad (13)$$

TABLE 5 | Evaluation standard for swamp wetland.

Stable level	Stable	Basically stable	Less stable	Unstable
Stability index	(87.5, 100]	(62.5, 87.5]	(37.5, 62.5]	(0, 37.5]

(3) Determine the weight vector of evaluation factors.

In fuzzy evaluation, the weight vector $W = [w_1, w_2, \dots, w_n]$ can be used to express the relative importance among the factors $U_i (i = 1, 2, \dots, n)$ because

TABLE 6 | Evaluation standard for engineering stability of permafrost wetlands.

Rule hierarchy	Factor hierarchy	Stable	Basically stable	Less stable	Unstable
Climatic environment (U_1)	Mean annual air temperature/ $^{\circ}\text{C}$ (U_{11})	<-4.5	-4.5 ~ -3.5	-3.5 ~ -2.5	>-2.5
	Mean annual precipitation/mm (U_{12})	<50	50-150	150-300	>300
	Mean annual solar radiation/MJ/m ² (U_{13})	<5500	550-6,000	6,000-7,000	>7,000
Permafrost property (U_2)	Permafrost type (U_{21})	Ice-poor	Icy soil	Ice-rich soil	Saturated frozen soil
	Permafrost table/m (U_{22})	<1	1-3	3-5	>5
	Mean annual ground temperature/ $^{\circ}\text{C}$ (U_{23})	<-2	-2 ~ -1	-0.5 ~ -1	>-0.5
Wetlands conditions (U_3)	Meadow development degree/cm (U_{31})	<8	8-15	15-40	>40
	Waterlogged area ratio (U_{32})	<5%	5-25%	25-55%	>55%

TABLE 7 | PWs type and permafrost property.

Stake number	Type of PWs	Waterlogged area ratio $n_s/\%$	Meadow development degree h/cm	Permafrost type	Permafrost table/m	Mean annual air temperature/ $^{\circ}\text{C}$	Mean annual ground temperature/ $^{\circ}\text{C}$
k230 + 100	W1-M1-P1	3.39	7	Ice-poor soil (3.80%)	5.3	-4.1	-0.2
k255 + 400	W3-M4-P4	26.35	55	Ice-rich soil (16.41%)	1.5	-5.1	-0.4

TABLE 8 | Single factor evaluation matrix for factor set.

Rule set	Factor set	k230 + 100				k235 + 000			
		Stable	Basically stable	Less stable	Unstable	Stable	Basically stable	Less stable	Unstable
Climatic environment	Mean annual air temperature	0.2	0.8	0	0	1	0	0	0
	Mean annual precipitation	0	0	0	1	0	0	0	1
	Mean annual solar radiation	0	0.4	0.6	0	0	0.4	0.6	0
Permafrost property	Permafrost type	1	0	0	0	0.859	0.141	0	0
	Permafrost table	0	0	0	1	0.5	0.5	0	0
	Mean annual ground temperature	0	0	0	1	0	0	0	1
Wetlands conditions	Meadow development degree	1	0	0	0	0	0	0	1
	Waterlogged area ratio	1	0	0	0	0	0.55	0.45	0

TABLE 9 | Judgment matrix of evaluation index for rule set.

Index	Climatic environment	Permafrost property	Wetlands conditions
Climatic environment	1	2/3	1/2
Permafrost property	3/2	1	2/3
Wetlands conditions	2	3/2	1

Note: the consistency index for judgment matrix CR, 0.0008 < 0.1.

TABLE 10 | Judgment matrix of climatic environment.

Index	Mean annual air temperature	Mean annual precipitation	Mean annual solar radiation
Mean annual air temperature	1	1/2	3
Mean annual precipitation	2	1	4
Mean annual solar radiation	1/3	1/4	1

Note: the consistency index for judgment matrix CR, 0.0091 < 0.1.

TABLE 11 | Judgment matrix of permafrost property.

Index	Permafrost type	Permafrost table	Mean annual ground temperature
Permafrost type	1	2	1/2
Permafrost table	1/2	1	1/3
Mean annual ground temperature	2	3	1

Note: the consistency index for judgment matrix CR, 0.0046 < 0.1.

TABLE 12 | Judgment matrix of wetlands conditions.

Index	Permafrost type	Permafrost table
Meadow development degree	1	1/2
Waterlogged area ratio	2	1

Note: the consistency index for judgment matrix CR, 0.

different factors have different positions and different roles in the evaluation object. In this study, the weight of each factor is determined according to the AHP method described above.

(4) Single-level fuzzy comprehensive evaluation.

For the weight vector W and the single-factor judgment matrix R , the fuzzy operation $F = WR$ is performed:

$$F = WR = [w_1, w_2, \dots, w_n] \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \quad (14)$$

(5) Multi-level fuzzy comprehensive evaluation.

In this study, the index system has three levels: the object set U , the rule set U_i ($i = 1, 2, \dots, n$), and the factor set U_{ij} ($j = 1, 2, \dots, k$). Thus, a two-level fuzzy comprehensive evaluation is required to obtain the evaluation results of the object set U . The evaluation level $V = \{V_1, V_2, \dots, V_m\}$ consists of m evaluation levels. For rule set U_i , the weight factor $W_i = [w_{i1}, w_{i2}, \dots, w_{ik}]$ is introduced. For object set U , the weight factor $W = [w_1, w_2, \dots, w_n]$ is introduced. According to the single-level fuzzy comprehensive evaluation method, the weight factor W_i and the single-factor judgment matrix R_i are subject to fuzzy operation $F_i = W_i R_i$ to obtain the secondary fuzzy comprehensive evaluation matrix $F = [F_1, F_2, \dots, F_n]^T$. Then, the same fuzzy operation is applied on the weight factor W and the secondary fuzzy comprehensive evaluation matrix F :

$$P = WF = \{p_1, p_2, \dots, p_n\} \quad (15)$$

Evaluation of Engineering Stability of Permafrost Wetlands

The evaluation set $V = \{\text{stable, basically stable, less stable, unstable}\}$ is established based on the engineering stability of permafrost wetlands in alpine and high-altitude areas. Further, quantify the evaluation set and assign the value to $V = \{100, 75, 50, 25\}$. In order to make the evaluation results easy to understand, the wetlands' stability grades are divided

TABLE 13 | Weight value of engineering stability of PWs.

Rule set	Weight <i>W</i>	Factor set	Weight <i>W_i</i>	Relative weight
Climatic environment	0.1638	Mean annual air temperature	0.3202	0.0524
		Mean annual precipitation	0.5572	0.0913
		Mean annual solar radiation	0.1226	0.0201
Permafrost property	0.2973	Permafrost type	0.2973	0.0884
		Permafrost table	0.1638	0.0487
		Mean annual ground temperature	0.5389	0.1602
Wetlands conditions	0.5389	Meadow development degree	0.3333	0.1796
		Waterlogged area ratio	0.6667	0.3593

TABLE 14 | Evaluation results.

Stake number	Type of PWs	Stable level	Evaluation results				Stability index
			Stable	Basically stable	Less stable	Unstable	
k230 + 100	W1- M1-P1	Basically stable	0.6378	0.1141	0.1082	0.1400	81.27
k255 + 400	W3-M4-P4	Less stable	0.1527	0.2424	0.1737	0.4311	52.92

by the stability index. The stability index is obtained by $Q = PV^T$. The larger the stability index, the more stable the wetlands. The range of stability index values corresponding to each level is shown in **Table 5**. In order to ensure the long-term stability of road engineering built on the permafrost wetlands, the underlying permafrost should be protected from degeneration first. Then, some measures should be taken to strengthen the foundation of wetlands due to the existence of the peat layer, which is symbiotic with vegetation.

Based on the field investigation, many references, and experts' opinions, the evaluation standards for the grading of each evaluation index in engineering stability of PWs are given in **Table 6**.

Case Study

The k230 + 100 and k255 + 400 are selected from the study's road—the Qinghai 224 highway—for the engineering stability evaluation of the permafrost wetlands. In this area, precipitation is mainly concentrated from late May to late September, accounting for more than 80% of the total annual precipitation. The annual average precipitation is 409 mm, the annual average evaporation is 1401.8 mm, and the annual solar radiation is about 6200 MJ/m² (Wang et al., 2015; Bao et al., 2017). The engineering stability of the wetlands passed through by the selected sections is evaluated. Meantime, the corresponding treatment measures are proposed. The type of wetlands and the property of permafrost are shown in **Table 7**.

The fuzzy evaluation method is used to evaluate the factors affecting the engineering stability of PWs. According to the above survey results and the calculation method for membership degree, the single factor evaluation matrix for each factor set is determined, as shown in **Table 8**.

The judgment matrix for each set can be determined by expert questionnaire survey and reference; refer to **Tables 9–12**. The

weight value can be obtained by a judgment matrix to indicate the relative importance of each factor. The weight values are given in **Table 13**. According to the results obtained by the AHP method, the weight values of the climatic environment, permafrost property, and wetlands conditions are 0.1638, 0.2973, and 0.5389, respectively. In the factor set, the relative weights of waterlogged area ratio, meadow development degree, mean annual ground temperature, mean annual precipitation, and permafrost type are 0.3593, 0.1796, 0.1602, 0.0913, and 0.0884, respectively, and the impact on the engineering stability of PWs is reduced in turn.

Through the fuzzy comprehensive evaluation model, the evaluation results of PWs near the two stake numbers are obtained, as shown in **Table 14**. According to the stability index, the engineering stability of PWs near stake numbers k230 + 100 and k255 + 400 is basically stable and less stable, respectively. The area near stake number k230 + 100 belongs to the ice-poor soil area. Foundation soil has weak frost heaving and weak thawing characteristics. The surface was directly impacted by the impact compaction roller without removing the vegetation. Then, backfill the sand gravel to the original surface elevation. After settlement stabilization, fill the sand gravel to the bottom of the pavement layer. The area near stake number k255 + 400 belongs to the ice-rich soil area, with a wet and soft layer thickness of about 0.5 m. Due to its poor bearing characteristics, this layer was reinforced by riprap with a thickness of 0.5 m. Then, the impact compaction technology was applied to squeeze the silt out. Finally, the gravel with 1.0 m thickness was filled with heavy rolling. The engineering stability of the foundation has been enhanced after the treatments. Therefore, the fuzzy comprehensive evaluation model used to evaluate the engineering stability of permafrost wetlands has certain reliability.

CONCLUSION

In this study, the permafrost type, waterlogged area ratio, and meadow development degree were selected to quantify the engineering characteristics of permafrost wetlands. A three-level classification system was applied to classify the types of permafrost wetlands. Based on these analyses and field investigation, a fuzzy comprehensive evaluation model for engineering stability of permafrost wetlands was established, and a case study was conducted to verify the rationality of the evaluation model. The following conclusions can be drawn:

- (1) Field investigation indicates that the permafrost layer and the wetlands constitute a symbiotic system on the Qinghai–Tibet Plateau. The permafrost layer facilitates the formation and development of wetlands due to the water isolation effect of the permafrost layer. Under the combined effect of permafrost, waterlogged area, and meadow development, the longitudinal cracks and the uneven deformation are the main forms of road diseases.
- (2) The permafrost wetlands can be divided into 15 types using a three-level division considering the engineering characteristics. The permafrost type, meadow development degree, and waterlogged area ratio were selected as the classification indexes.
- (3) According to the results obtained by the AHP method, the degree of impact on wetland stability is wetlands conditions > permafrost property > climatic environment, and the waterlogged area ratio, meadow development degree, mean annual ground temperature, mean annual precipitation, and permafrost type are the main factors that affect wetland stability.

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- (4) The method of combining AHP and fuzzy comprehensive evaluation can effectively evaluate the engineering stability of the permafrost wetlands and can be used to pre-evaluate the engineering stability of permafrost wetlands.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

AUTHOR CONTRIBUTIONS

XM and QW conceived this research. XM and LH contributed to conception and field investigation. WH and YZ contributed to data analysis and methodology. YZ wrote the first draft of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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Conflict of Interest: LH was employed by the company Jiangsu Zhongsheng Group Co., Ltd.

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