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# Characterization and evaluation of permafrost thawing using GPR attributes in the Qinghai-Tibet Plateau

Yupeng Shen[a,b,*], Ruifang Zuo[a], Jiankun Liu[a,b], Yahu Tian[a,b], Qing Wang[c]

[a] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, P.R. China
[b] Beijing Key Laboratory of Track Engineering, Beijing 100044, P.R. China
[c] School of Information and Communication Engineering, Beijing Information Science and Technology University, Beijing 100101, P.R. China

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ABSTRACT

Recognizing the status of permafrost thawing and providing information for permafrost treatment in the Tibetan Plateau is a key problem. In this paper, a GPR experiment is designed to explore effective geophysical attributes for characterizing and evaluating the impact of key factors on permafrost thawing. A new algorithm for the assessment of rapid relative water content is also presented. After processing the GPR data, the weighted average frequency attribute, sweetness attribute and relative wave impedance attribute, which better characterize the effect of different factors on permafrost thawing, are selected. The weighted average frequency attribute can distinguish the thawing front and evaluate the extent of thawing in addition to the completely thawed fringe; the sweetness attribute can help to characterize thawing in water ice mixed with permafrost and evaluate the impact of free water on permafrost below the thawing front. The relative wave impedance attribute highlights the completely thawed fringe and other smaller internal stratifications in the permafrost thawing zone. Using the rapid relative water content assessment algorithm, it is easy to evaluate the extent of thawing using only GPR data. In addition, a thermokarst lake strengthens the degree of permafrost thawing. Permafrost thawing accelerates on sunny slopes. This study shows that roadbeds inhibit permafrost thawing and that a thermosyphon significantly inhibits permafrost thawing.

## 1. Introduction

Permafrost is a significant feature of the Tibetan Plateau (TP) and is attributed to its cold climate. The TP permafrost has an area of approximately $1.50 \times 106\,\text{km}^2$ and was formed during rapid uplifting in the Quaternary period (Niu et al., 2011). During construction or operation of line engineering in the permafrost area, there are many changes, such as in topography, vegetation, surface reflection, permeability, snow cover and water distribution, which would cause the destruction of thermal equilibrium of the surface and atmosphere, increasing heat, permafrost recession, and the acceleration of the active layer or thawing speed (Treat et al., 2013; Favaro and Lamoureux, 2015; Zhang et al., 2015). The combined effects of global climate change and human activities would cause engineering problems to happen as the environment changed in the permafrost area over nearly 40 years (Nelson et al., 2002; Grosse et al., 2011). The bearing capacity would reduce, and excessive settlement would occur due to the recession or thawing of the permafrost where slope instability and surface cracks appear simultaneously (Jiang et al., 2014; Niu et al., 2014). Because seasonal permafrost thawing can lead to changes in the electromagnetic properties of the materials in the thawing zone, these changes will respond to the signals of wave fields in a geophysical field (Davis and Annan, 1989). Some researchers are using geological penetrating radar (GPR) data to study permafrost thawing (Steelman and Anthony, 2009).

Ground Penetrating Radar (GPR) is a non-invasive and efficient geophysical method for imaging and characterization of shallow subsurface targets (Zhao et al., 2013).This method is widely applied in many different areas, such as geotechnical engineering, archaeological prospecting, pipeline location and security detection, geological studies, glaciology, and other fields (Daniel and Joerg, 2015; Zelimkhan et al., 2014; Amir et al., 2013; Lech and Jacek, 2013; Ali et al., 2015; Ilaria et al., 2014; David et al., 2008, 2011; Antonio et al., 2015; Forte et al., 2012; Kruse et al., 2006; Forte and Pipan, 2008; Greg et al., 2013; Steven et al., 2002; Michael et al., 2012; Fukui et al., 2008; Wang et al., 2008; Achim et al., 2010).

To obtain more information from GPR data, GPR attributes are used to analyse and interpret GPR data (Young et al., 1997; Bradford et al., 2010). GPR attributes are similar to seismic attributes because they have the same wave theory and processing and interpretation

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[*] Corresponding author at: No.3 Shangyuancun, Haidian District, Beijing 100044, P.R. China.
*E-mail address:* ypshen@bjtu.edu.cn (Y. Shen).

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techniques (Ursin, 1983; Baker et al., 2001; Grasmueck, 1996). Attributes based on seismic or GPR data, such as polarity, phase, frequency, or velocity, are a quantitative measure of a geophysical characteristic of interest (Chopra and Marfurt, 2005). They can be analysed in order to enhance information that might be more subtle in a traditional data image, leading to a better geological or geophysical qualitative and quantitative interpretation of the data (Chopra and Marfurt, 2006). However, there are hundreds of types of GPR attributes from geometrical and physical features. The appropriate attributes need to be screened for different target detection and detection purposes. Zhao et al. used GPR attribute analysis for archaeological prospection in the river harbour area of the Aquileia Archaeological Park, NE Italy (Zhao et al., 2013). They calculated and critically evaluated several attributes to characterize targets in 2D and 3D. João et al. identified and delineated a subsurface collapsed paleocave system using selected GPR attributes in the western portion of the Potiguar Basin (north eastern Brazil) (João et al., 2014). Amir et al. used GPR attenuation attributes to monitor and assess a bridge deck (Amir et al., 2013).

A recent application of GPR is to image the near-surface thermal structure and profiles of permafrost because of the strong dielectric permittivity contacts between frozen and unfrozen wet materials (Hinkel et al., 2001; Moorman et al., 2003; Ma et al., 2015; Titov and Krylov, 2015; Xiao and Liu, 2016; Léger et al., 2017). Even though it is important to obtain the properties of the permafrost thawing medium and information for permafrost treatment projects using GPR attributes, it is undecided how to research the method of using the GPR data attributes to characterize the properties of the permafrost thawing medium and how to evaluate the impact of different factors on permafrost thawing.

Fast water content assessment is a key aspect of this process because engineers use it to predict and detect roadbed stability and hazardous locations. Because of the limitations of inefficient and expensive sampling measurements, some researchers propose methods to estimate water content by using GPR data. These methods are based on GPR direct ground wave and Rayleigh scattering (Ghose and Slob, 2006; Colby and Anthony, 2009; Christina and Andreas, 2013; Andrea, 2010). However, it is difficult to acquire these kinds of data in the Qinghai-Tibet Plateau because the survey acquisition mode for CMP gathering is time-consuming and laborious. How to quickly estimate the water content from vertical (zero offset) GPR profiles is a pivotal problem to be solved.

To solve these problems, we designed a serials of GPR experiments in the Qinghai-Tibet highway, which is close to the Chumaer River in the Hoh Xil plateau region in the center of the Tibetan Plateau, China (N35.32, E93.32) (Fig. 1). The experiment acquires GPR data to evaluate the impact of key factors on permafrost thawing. These factors are divided into four parts, which include lake, sunny slope or shady slope, subgrade and active protection of the permafrost (e.g. thermosiphon). Through various calculations, a set of types of GPR attributes and parameters, such as amplitude, phase, frequency and velocity, are obtained and may be used to characterize the permafrost. By comparisons and statistical analysis of different attributes, it was found that the weighted average frequency, sweetness attributes and relative wave impedance can better characterize the effect of different factors on permafrost thawing. By introducing an instantaneous quality factor into the Topp empirical relationship, the new rapid relative water content (RWC) assessment method is defined (Topp et al., 1980).

This research provides a direct method to use GPR attributes for the most effective permafrost thawing characterization and evaluates the impact of key factors on permafrost thawing. It also provides an algorithm for rapid relative water content assessment using GPR data.

## 2. Experiment description

### 2.1. Test site

The field site is located along the Qinghai-Tibet highway, which is close to the Chumaer River in the Hoh Xil plateau region in the center of the Tibetan Plateau, China (N35.32, E93.32). The Kunlun Mountains and Tanggula mountains are located on the north and south side of this region (Fig. 1). The range of temperature change with seasons is large, and a seasonal river develops in this region because of the mountains that block the continued cold current (Zhao et al., 2000). In addition, road construction in permafrost areas affects the thermal regime of frozen soils, which results in permafrost degradation and road damage (Niu et al., 2002). For these reasons, the phenomenon of degradation of permafrost. Extensive destruction and collapse are generated on the roadbed of the Qinghai-Tibet Highway. Core logs in the vicinity show that there are three layers. The first layer is subgrade filling with depth of 2.3 m to 3.0 m. The second layer is silt sand in wet state with depth of 6.5 m. The last layer is siltstone (10%–40% grade) and mudstone.

### 2.2. Test experiment and data acquisition

The SIR-20 GPR system equipped with 200 MHz and 80 MHz central frequency antennas was used to perform wheel survey acquisition in the test site. The GPR sections were acquired roughly parallel to the road shoulder (Fig. 2(a)) within a time window of 200 ns with a sampling of 512 samples per trace and 153 scans per second for the 200 MHz frequency antenna and within a time window of 400 ns with a sampling of 512 samples per trace and 153 scans per second for the 80 MHz frequency antenna.

Fig. 2 shows the test experiment and data acquisition where Fig. 2(a) represents the direction of survey and location of thermokarst lake or sump water and thermosyphon, Fig. 2(b) shows the different locations of the roadbed, road shoulder and original ground, Fig. 2(c)

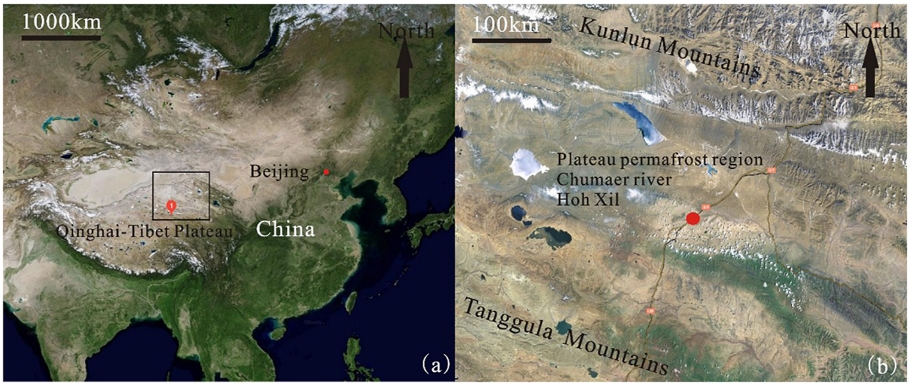

**Fig. 1.** (a) Location map of Tibetan Plateau, China; (b) location map of test site (red point). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)