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Double-frequency ground penetrating radar for measurement of ice thickness and water depth in rivers and canals: Development, verification and application

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ABSTRACT

In situ measurement of the ice thickness and water depth distributions in a river, canal, or lake is one of the most important means of measuring and responding to an ice flood. In view of the shortcomings of the use of single-frequency ground penetrating radar (GPR) for simultaneous measurement of ice thickness and water depth, a double-frequency GPR with 100 and 1500 MHz antennas was developed in the present study. To avoid interference between the two antennas with different frequencies, there is a 15-ms time-sharing operation. Similarity analysis of neighboring GPR signals was used to obtain the accuracy value of two-way travel time. The proposed GPR system also enables the real-time determination of the longitude and latitude coordinates of the measurement site using a real-time kinematic (RTK) system. The system measured the ice thickness and water depth at 97 and 99 sites, respectively, in the Mohe section of the Heilongjiang River, and the Togtoh, Inner Mongolia section of the Yellow River; both in China. Comparison of the measurements to those obtained by traditional drill-hole methods, yielded a mean value of absolute errors of 0.12 m and 0.04 m for water depth and ice thickness, respectively. The system was further used to measure the distribution of the ice thickness and water depth over a distance of 0.5 km in the Longdao Wharf section of the Heilongjiang River, and over a distance of 67 km in the Mohe section of the river,between the entrance of the Luogu River and Beiji village. The measurement results indicate that the developed double-frequency GPR is suitable for in situ measurement of ice thickness and water depth in rivers during ice periods.

1. Introduction

In situ measurement of the ice conditions of rivers, lakes, canals, and reservoirs is important to understanding dynamic ice processes. It also provides basic data for preventing and mitigating ice floods. Ice thickness and water depth are important parameters of such observations and their measurement methods can be generally divided into two types: contact and non-contact measurements. Contact measurements include traditional drilling and the use of resistance heating line and pressure sensors (Li et al., 2005; Huang et al., 2016). These methods are considered to be the most reliable and have been in use for decades. However, in some cold areas, such as the Heilongjiang Province and the Inner Mongolia Autonomous Region in China, the minimum air temperatures during winter are generally about −30 °C or lower, and the ice thickness is often more than 1 m. In such areas, the traditional ice thickness and water depth measurement methods have the disadvantages of low efficiency, fewer sampling sites, and logistically complex work (Fu et al., 2010). Recently, Cui et al. (2015) used the differences between the electrical resistance and temperature characteristics of air, ice, and water to partly overcome the disadvantages of traditional contact measurement methods. The apparatus retrieved the ice thickness and temperature gradient inside an ice layer through detection of the electrical resistance and temperature.

The non-contact measurement methods include sonar; remote sensing by satellite, airborne and ground-based radar; and ground penetrating radar (GPR). The equipment used for sonar ice condition measurement is the Shallow Water Ice Profiler (SWIP) produced by ASL Environmental Sciences (Brown and Duguay, 2011). The system functions by transmitting and receiving ultrasonic pulse signals. It has the advantage of the ability to measure the ice thickness, water depth, and ice concentration (Marko and Jasek, 2008, 2010a, 2010b; Morse and Richard, 2009; Ghobrial et al., 2012, 2013). A satellite remote sensing survey is suitable for large-scale ice condition surveys, such as ice cover and ice thickness. Beckers et al. (2017) used a satellite altimeter to

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measure ice thickness for Great Slave Lake and Great Bear Lake in Northern Canada. Ground-based X and Ku band frequency-modulated continuous-wave (FMCW) radar has also been used to derive ice thickness of bubbled freshwater lake ice with heterogeneous snow cover (Gunn et al., 2015).

There has been continuous improvement of the GPR measurement method in recent years, with the technology offering the advantages of compactness, low cost, and high efficiency. The GPR can also be dragged over long distances for ice condition measurements. The GPR method is commonly used for research purposes. Arcone and Delaney (1987), Arcone, 1991 conducted ice thickness measurements using an airborne GPR system. Finlay et al. (2008) and Proskin et al. (2011) used a 500 MHz GPR to measure ice thickness, and a 120-MHz version to measure water depth. The dielectric constant of the ice cover was also summarized, from 2.13 to 4.44. Holt et al. (2009) used a 50–250 MHz variable-frequency GPR to measure sea ice with a thickness between 1 and 7 m, and a 300–1300 MHz mode to measure a thinner range of thickness between 0.3 and 1.0 m. The radar measurements showed a mean difference of 0.14 m and standard deviation of 0.03 m compared to in situ measurements that ranged from 0.5 to 4 m in thickness. Stevens et al. (2009) used a PulseEKKO 100 GPR with 50 MHz and 100 MHz antennas and a Noggin Plus GPR system with 250 MHz shield antennas. In order to void interference, fixed separations of 2 m, 1 m, and 0.26 m were maintained for 50 MHz, 100 MHz, and 250 MHz antennas, respectively. Zhang et al. (2017) used a 200 MHz GPR to measure the in situ ice thickness at the location of the Toudaoguai hydrological station along the Yellow River, and the ice thickness ranged from 0.29 to 0.8 m and the root-mean-square error (RMSE) was 0.03 m. Kämäri et al. (2017) used a GPR with a nominal frequency of 800 MHz and antenna separation of 10 cm to measure ice thickness. The measurement results showed a mean absolute error of 0.03 m, equivalent to 5% mean percentage error in the case of ice with 0.5 m thickness.

Jones et al. (2013) combined the use of GPR with frequencies of 1 GHz and 250 MHz and high-resolution (HR) spotlight TerraSAR-X (TSX) satellite data to identify and characterize floating ice and grounded ice. Gusmeroli and Grosse (2012) used a 1 GHz GPR to detect overflow and suggested that ice thickness measurements of GPR should not be conducted while slush was on the ice.

Commonly, the dielectric constant of air is 1, that of water is about 80, that of ice is 3–4, and that of sandstone (silt) is 5–30 (Davis and Annan, 1989). A high contrast in permittivities will cause reflections at a surface, and a low contrast will result in transmission of a large portion of the incident signal. Snow, ice, and water in situ are often mixed with air, sandstone, or other materials, so their physical and electrical properties are changeable, which will lead to lower measurement stability and accuracy. Ice jams have a complex structure, which alters the dielectric constant, resulting in the inapplicability of the dielectric constant of pure ice.

In addition to ice thickness, the corresponding water depth of the measuring site is also needed because ice thickness is only one of the causes of ice jams or ice dams. For example, if the water depth is high enough, the ice can be transported easily in the river, so thicker ice does not always cause an ice jam or dam. Although GPR systems are widely used for the measurement of ice thickness and water depth, the current single-frequency GPR is incapable of accurate simultaneous measurement of ice thickness and water depth. Of course, the water depth can be measured in the summer, but when you measure the ice thickness in the winter with a single-frequency GPR, it is hard to follow the same measurement route. This has prompted the development of a two-radar system that performs two measurements. However, such a system is not only subjected to a greater workload, there is also no guarantee that the measurement sites of the ice thickness and water depth will be exactly the same. The latter issue is a source of error in the ice condition measurements obtained by a two-radar system.

The objectives of this study were to 1) develop a double-frequency GPR for the simultaneous measurement of ice thickness and water depth, 2) analyze factors that affect ice thickness and water depth measurement accuracies of GPR, 3) explain reasons of ice jams in the Longdao Wharf section and Mohe County section of the Heilongjiang River in China based on measurement results.

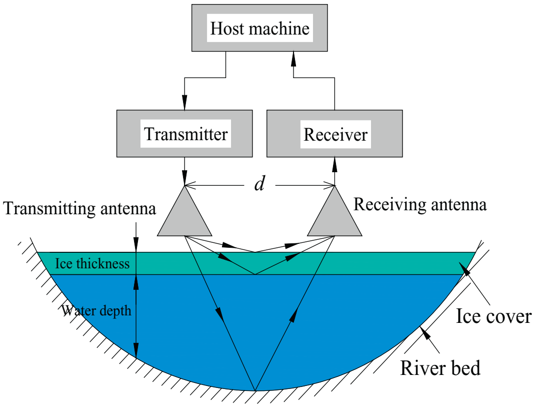

Fig. 1. Basic principle of the use of a GPR to measure ice thickness and water depth. Cyan and blue represent ice and water respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

The basic operating principle of a GPR system is illustrated in Fig. 1. High-frequency short-pulse electromagnetic waves are transmitted into the ice from the transmitting antenna of the radar system placed on the ground. The waves encounter underground formations or targets of differing electrical properties and are reflected back to the ground surface where they are received by the receiving antenna of the radar system. Two-way travel time (t) in the measured medium can be calculated as follows (Galley et al., 2009):

$$t = \frac{\sqrt{d^2 + 4H^2}}{v} \tag{1}$$

where H is the ice thickness or water depth, v is the propagation velocity of the electromagnetic waves in the measured medium, and d is the distance between the transmitting and receiving antennas of the radar system.

$$v = \frac{c}{\sqrt{\varepsilon}} \tag{2}$$

where $c = 30\ \mathrm{cm/ns}$, is the propagation velocity of the electromagnetic waves in a vacuum, and ε is the dielectric constant.

Then, the thickness of the measured medium, H, can be obtained as follows:

$$H = \sqrt{\frac{c^2t^2 - \varepsilon d^2}{4\varepsilon}} \tag{3}$$

The differences among the dielectric properties of air, ice, water, and sandstone were given above, and this enables detection of layers between two materials with different dielectric permittivities using a GPR. A double-frequency radar system was developed, thus enabling the simultaneous measurement of ice thickness and water depth. Following are some highlights of the development:

1. Based on the previous studies, ice thickness and water depth in the Heilongjiang River, a radar with frequencies of 100 and 1500 MHz for simultaneous measurement of water depth and ice thickness, respectively, was developed with an improved shape and layout of the antenna. The 1500 MHz antenna was placed at the center of the 100 MHz antenna so that the centers of the measurement sites of the