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Development of a multi-interval displacement sensor using Fiber Bragg Grating technology

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ABSTRACT

We have developed a multi-interval displacement sensor using Fiber Bragg Grating (FBG) technology, which has potential for the long-term durability, high accuracy and ability to transmit data over long distances. Field trials in the Horonobe Underground Research Laboratory (URL) of the multi-interval displacement sensor developed using FBG technology are described. Laboratory tests were carried out to obtain the relational expression computed from the interrelationship of the variation in the Bragg wavelength, temperature and displacement. From the results of laboratory tests, accuracy of the sensor was evaluated to be better than $\pm 0.5\%$ of the measurement range. In situ monitoring at the Horonobe URL using the developed sensor was carried out in parallel with nearby monitoring using a conventional extensometer, which is an electrical signal system type, for verification of the developed sensor. The results of the in situ test indicate that the displacement values from both the sensor developed and the conventional extensometer are almost equivalent. One of the advantages of the developed sensor is the absence of noise in the monitoring data, in contrast to the data from a conventional extensometer.

1. Introduction

In Japan, high-level radioactive waste (HLW) separated from spent nuclear fuel during reprocessing will be disposed at depth in a stable geological formation [1]. A fundamental understanding of the short- and long-term deformation behavior of the rock mass surrounding a repository will be required to optimize the design and construction of underground excavations for an HLW repository [2–11].

The potential for displacement and damage in the rock mass surrounding excavations constructed for underground disposal facilities is increased due to stress concentration and creep. Therefore, the long-term monitoring of rock behavior for construction of a rock cavern is important to assess stability of the geological structures. In the endeavor to monitor safety of the excavations, the recent development and application of sensors that use fiber-optic technology has expanded in the fields of civil engineering and in rock and soil mechanics etc. [12–15].

From the standpoint of the application of fiber-optic technology to geotechnical engineering, aggressive application has been conducted in various fields such as strain monitoring of tunnels [16–19], rock slope stability [20–22], measurement of transmission line tower subsidence [23], pore pressure measurement [24], temperature measurement [25,26], streamflow observations [27], material transport measurements in the ground [28] and stress measurement [29]. Amongst these, with respect to displacement measurements, systems whereby the surface behavior of a tunnel or rock slopes are measured have predominated so far, therefore there has been little in the way of examples of the development of multi-interval displacement sensors.

Optical fiber has the potential of long-term durability compared to electrical cable. The reason is that in case of optical fiber, silica glass is used as the signal transmission medium, whereas, in the case of electrical cable, metallic wire is used. In addition, the cross-sectional area of optical fiber cable is much smaller than electrical cable so that borehole diameter can be reduced and still obtain a high density of data and at a large number of measuring sections in a borehole. When borehole diameters are small, disturbance around a borehole may be minimized. Measurements can be carried out in an inflammable gas environment such as in the presence of methane because optical fiber sensors do not provide an ignition source because they do not require electric power at the monitoring points. The optical fiber sensor is able to monitor directly from a distant location due to very small transmission loss and without interference from electric noise, so it does not required a relay system to boost signals. Therefore, a simple, space-saving system can be constructed compared to an electrical system. Therefore, for these reasons, the authors have been proceeding with the development

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of a multi-interval displacement sensor using FBG technology embedded in optical fiber core.

As part of the research and development program on geological disposal of HLW, Japan Atomic Energy Agency (JAEA) has been implementing the Horonobe Underground Research Laboratory (URL) Project investigating sedimentary rock formations in the Horonobe area of Hokkaido, Japan (Fig. 1) [30]. The objective of the Horonobe URL is to study the geological environment in this area and confirm the reliability of technologies being developed for application in the geological disposal of HLW in sedimentary rock. In the Horonobe URL project, one task is the development of a multi-interval displacement sensor using FBG technology embedded in optical fiber core. The sensor is needed for rock mechanics studies of the long-term behavior of the rock mass surrounding excavations [33]. Field trials of a multi-interval displacement sensor using FBG technology in the Horonobe URL are described in this paper.

The objective of this work is to confirm the applicability of the sensor in an actual geological environment and assess its workability. Laboratory tests were also carried out to obtain the relational expression computed from the relationship of the variation in the Bragg wavelength, temperature and displacement. The feasibility study at the Horonobe URL was conducted to confirm the workability and applicability of a multi-interval displacement sensor using FBG technology. The results of in situ tests comparing the multi-interval displacement sensor using FBG technology and a nearby extensometer are discussed.

2. Measurement principle of the FBG sensor

Optical fiber cable is composed of core and cladding (Fig. 2). Optical fiber core is made of silica glass that has high transmissivity to light. Fiber Bragg Grating is printed to the core by laser beam irradiation as shown in Fig. 2. As the index of refraction of the optic fiber core changes due to strain, light of different wavelengths are either reflected or transmitted.

At the moment, optical fiber instruments, techniques and systems that are of practical use in the field of civil engineering include: Fiber Bragg Grating (FBG) sensors, Brillouin Optical Time Domain Reflectometer (B-OTDR), Raman-Optical Time Domain Reflectometer (R-OTDR), Optical Time Domain Reflectometer (OTDR), Optical Strand Monitoring System (OSMOS), Surveillance d'Ouvrages par Fibers Optiques (SOFO) and the Extrinsic Fabry-Perot Interfero meters. B-OTDR, R-OTDR and OTDR can measure continuity of fibers but accuracy is unsatisfactory for measurement of displacement in a rock mass. OSMOS, SOFO and Extrinsic Fabry-Perot Interfero meters can measure a point or an interval for a single, optic fiber cable but multi-interval monitoring cannot be carried out easily. When multi-interval monitoring in a rock mass is to be carried out, a number of cables are required, thus this is a disadvantage. An advantage of FBG cable is that accuracy is high, almost 1×10^{-6} strain when used as a substitute for a strain gage. Another advantage is that multi-interval monitoring and continuous measurements are possible with a single fiber optic cable.

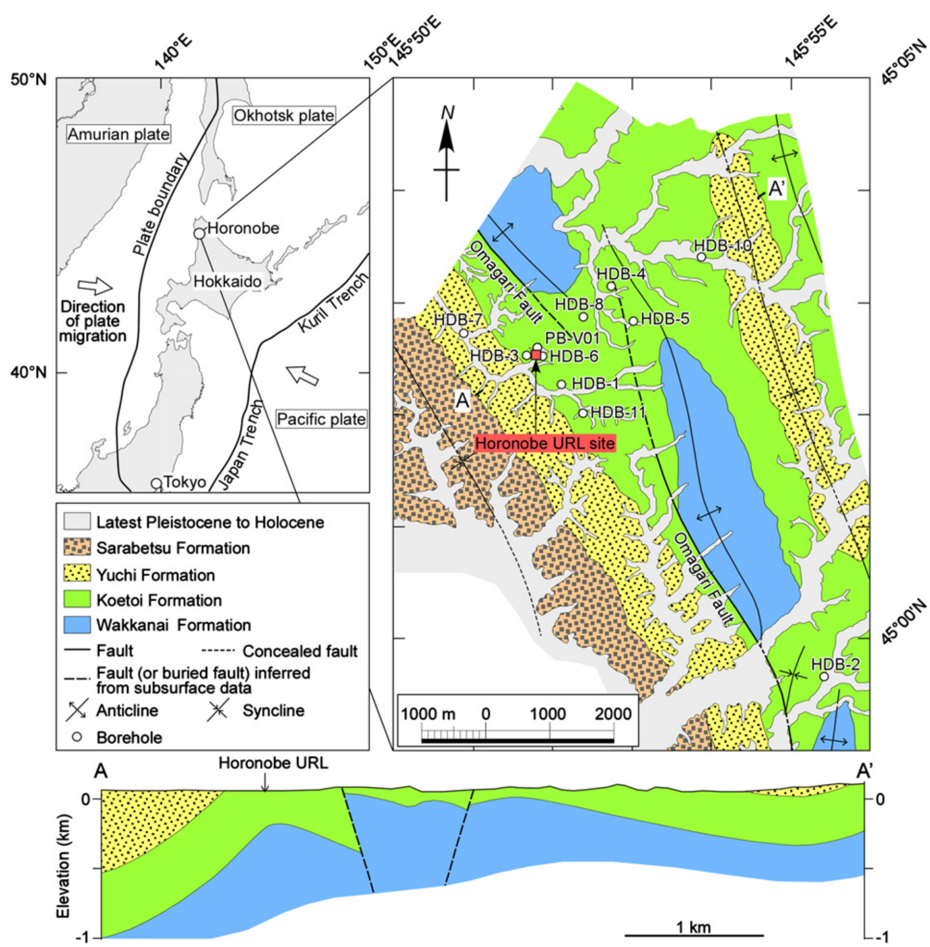

Fig. 1. Geological map with borehole locations and a geological cross-section of the Horonobe area (after [31]). Plate boundaries and the directions of plate movement, as shown in the inset map, are from [32].