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An attempt to correct strain data measured with vault-housed extensometers under variations in temperature

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ABSTRACT

Strain data obtained by vault-housed extensometers have precisions on the order of nanostrains, but they are distorted by variations in temperature, which cause two types of noise: "actual variations" due to the thermo-elastic effect of the Earth's crust, and "false variations" due to the thermal expansion of extensometer, which occurs when the extensometers themselves are subjected to variations in temperature. Here, I explore a method of removing false variations, which are severe when the vault is located at shallow depths. If variations in temperature at arbitrary points inside a vault are estimated, false variations can be removed from the recorded variations in strain. I derive formulae that enable variations in temperature to be estimated at various points in a vault, based on measured variations at reference points. The formulation is valid if some simplification is allowed. I examined whether variations in temperature inside a vault can be estimated in terms of the derived formulae, and obtained the following results. When the reference temperature data are obtained from adequate points in the vault, variations in temperature at another point can be estimated with an accuracy of 0.1 °C. However, when the reference temperature data are obtained from outside the vault, estimated variations in temperature are rather inaccurate, which means that the false variations in strain cannot be removed accurately. Moreover, the data indicate that the thermal diffusivity of the ground is temporally variable, and this introduces another difficulty in correcting false variations in strain data. These results indicate that correcting the distortions in strain data due to variations in temperature is much more difficult than anticipated.

1. Introduction

Following on from studies of crustal deformation in the 1960s (e.g., Hagiwara and Rikitake, 1967), observations of crustal deformation using extensometers (i.e. rods with a length of several tens of meters) housed in vaults (i.e. long tunnels) have been considered to be one of the important ways of measuring deformation of the Earth's crust. The advantage of extensometers in vaults over other modern geodetic techniques, such as Global Positioning Systems (GPS), Interferometric Synthetic Aperture Radar (InSAR), and bore-hole type strain meters and tiltmeters, is their ability to detect small signals. This is particularly the case for detecting events in the period range of seconds to hours. Extensometers in vaults installed under excellent conditions can detect subtle changes in strain of the order of 10^{-9}, such as those caused by the Earth's free oscillation (e.g., Park et al., 2008), the pre-eruption processes of volcanoes (e.g., Ishihara, 1990; Yamazaki et al., submitted for publication), and the steps in strain due to remote earthquakes (Yamazaki et al., 2011). These subtle changes are barely detectable by other means. Crustal strain data measured with vault-housed extensometers can also be used for studying events in the pre-GPS era, because of their rather long history. For these reasons, attempts to re-examine crustal strain data have been started, and data exchange systems are under construction (Yamaguchi et al., 2010).

However, strain data obtained with vault-housed extensometers have several drawbacks when they are used for studies of long-term (i.e., > days) events. One of the major drawbacks is the distortion of data due to temporal variations in temperature, which give rise to two types of noise in strain data measured by extensometers: actual deformation of the crust caused by changes in temperature (e.g. Berger, 1975; Harrison and Herbst, 1977) and false variations in strain caused by the thermal expansion of sensor rods (e.g., Furuzawa et al., 1993). Hereafter, I refer to these noises as the "thermo-elastic effect" and "false variation in strain (due to variations in temperature)", respectively. Strategies to avoid the thermo-elastic effect have been proposed (e.g., Ben-Zion and Leary, 1986), although this task is generally difficult because the effect represents the integrated effect of thermal expansion of the ground, and is therefore inevitable even if we refer to temperature data at a point.

False variations in strain due to variations in temperature arise by the following mechanism. Extensometers are composed of a rod, one end of which is fixed and the other (the free end) unfixed (Fig. 1). Sensors of extensometers measure the displacement of the ground

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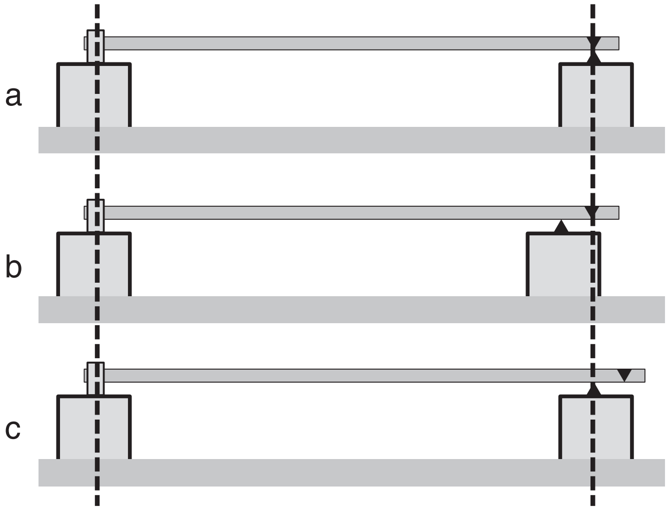

Fig. 1. Schematic of an extensometer, showing the mechanism by which false variations in strain are generated due to variations in temperature. (a) Original location of free end of the extensometer and sensor mounted on the ground. (b) The case where the ground contracts because of tectonic phenomena. (c) The case where the ground does not contract, but the rod of the extensometer is extended due to thermal expansion. The sensor only records the relative displacements between the two triangles in each panel, and it therefore cannot distinguish b from c.

relative to the free-end of the rod. Although the sensor records the ground strain, it also records changes in sensor length. The length of a rod changes with temperature; thus, false changes in strain may be recorded. In contrast to the thermo-elastic effect, false variations in strain have not been investigated in detail because they are easily avoided by installing the sensor at great depth in a long tunnel, where temperature variations are negligible. Nevertheless, some extensometers used for geodetic purposes are installed in shallow vaults (e.g. Teraishi et al., 2009).

Establishing a method for the reliable correction of strain data is indispensable if data from shallow vaults are to be used. In general, the main drawbacks in using extensometer strain data are considered not to be the false variation in strain due to variations in temperature, but to be the loadings that result from precipitation and groundwater (e.g., Kasahara et al., 1983). Accurate corrections for the effects of ground water are obviously difficult because the relevant relationships are highly non-linear (e.g., Hashimoto, 2007). The thermo-elastic effect is also difficult to remove, as mentioned above. Compared with these complex effects, one might anticipate that corrections for false variations in strain due to variations in temperature would be relatively easy to make because the spatio-temporal variations in temperature can be described by a linear equation. If such corrections for temperature are possible, we can choose the option of a shallow vault for an extensometer because a shallow vault, even though strongly affected by temperature variations, is relatively unaffected by groundwater. However, few studies have attempted to quantify the effects of temperature variations on extensometers, or to clarify the validity of the data corrections used.

The purpose of this paper is to determine whether data corrections can be reliably made for strain data obtained from vault-housed extensometers where there are significant variations in temperature. Although the thermo-elastic effect is generally dominant as a source of distorted strain data due to variations in temperature, false variations in strain due to variations in temperature are considered to be larger in the case of extremely shallow vaults. For this reason, the present study focuses on false variations in strain; the thermo-elastic effect is only briefly discussed. To this end, the remainder of this paper is organized as follows. In Section 2, we consider theoretically how and when we can remove the false variations in strain due to variations in temperature. In Section 3, we present a set of temperature and strain data used for numerical testing, obtained at a tectonically active location but which were probably distorted by temperature variations. In Section 4, the procedure of estimating variations in temperature inside vaults is applied to correct strain data, and determine whether the procedure works successfully. In Section 5, we discuss the usefulness of the strain data measured in shallow vaults, based on the results presented in Section 4. Finally, the main conclusions are summarized in Section 6.

2. Strategies and the actual procedure of data correction

Given that false variations in strain data (ΔE) arise from variations in temperature (ΔT), a necessary condition for ΔE being removable is that ΔT can be estimated by some reference time series. Therefore, we should consider the problem of estimating ΔT at one location ($\mathbf{x}$; referred to as the target point) by using ΔT at another location ($\mathbf{x}_{\mathrm{ref}}$; referred to as the reference point). If $\Delta T(\mathbf{x},t)$, where t denotes time, can be estimated by $\Delta T(\mathbf{x}_{\mathrm{ref}},t)$, the following relationship should be satisfied:

$$\Delta T(\mathbf{x},t) = \int_0^\infty A(\mathbf{x},\mathbf{x}_{\mathrm{ref}};s)\Delta T(\mathbf{x}_{\mathrm{ref}},t-s)ds, \tag{1}$$

either in a time domain, or equivalently,

$$\Delta T(\mathbf{x},\omega) = A(\mathbf{x},\mathbf{x}_{\mathrm{ref}};\omega)\Delta T(\mathbf{x}_{\mathrm{ref}},\omega) \tag{2}$$

in a Fourier domain. The function A describes a predictive filter of temperature.

To estimate ΔT at an arbitrary point $\mathbf{x}$, it is necessary to find the optimum form of A for a given set of $\mathbf{x}$ and $\mathbf{x}_{\mathrm{ref}}$. A straightforward procedure to determine A is an empirical method using Eq. (1) or (2). Using actual data of temperature at $\mathbf{x}$ and $\mathbf{x}_{\mathrm{ref}}$, the filter function A in Eq. (1) or (2) can be determined in principle. However, in practice, it is difficult to determine A correctly by empirical methods. Temporal variations in temperature generally involve a large range of frequency (i.e., daily to decadal), and this means that A cannot be determined unless T data are available for a period of several decades. Given that T is usually available only for a restricted period of time, the empirical determination becomes difficult.

Accurate determination of A in Eq. (1) is feasible only if A is expressed by a known function characterized by a small number of parameters. In such a case, we need to determine only the relevant parameters. The existence of such a function is uncertain, but if it exists, the explicit form of the function should be determined by a theoretical consideration of heat conduction in the ground surrounding the vault under observation. If such a function does not exist, or if the function involves a large number of parameters, determination of A becomes difficult.

Heat conduction in the ground is expressed as

$$\frac{\partial}{\partial t}T(\mathbf{x},t) = k(\mathbf{x},t)\nabla^2 T(\mathbf{x},t), \tag{3}$$

where k is thermal diffusivity. We need to express the solution of Eq. (3) in a form of Eq. (1). Since k has three-dimensional heterogeneity, and because the explicit distribution of k is difficult to estimate, finding a solution for T is generally difficult. An exceptional case is that where the heat conduction equation is reduced to the form

$$\frac{\partial}{\partial t'}T(x',t) = k(x')\frac{\partial^2}{\partial x^2}T(x',t), \tag{4}$$

where x' is a scalar function of $\mathbf{x}$. This simplification applies to situations where k has a one-dimensional (1-D) distribution. For this reason, herein we refer to the simplification in Eq. (4) as a 1-D approximation. Note that Eq. (4) may be valid only within a restricted region of the ground (e.g., Fig. 2).