Tunnelling and Underground Space Technology 82 (2018) 148–155

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Tangent modulus method – An original method to measure in-situ rock stress

Y. Fujii[a,*], M. Makasi[b], J. Kodama[a], D. Fukuda[a], K. Goto[c], S. Kumakura[c], M. Kanaoka[d], A.B.N. Dassanayake[e]

[a] Rock Mechanics Laboratory, Hokkaido Univ., N13W8 Sapporo, Japan
[b] Glencore Mount Isa Mines, Mount Isa, Queensland, Australia
[c] Docon, 1-5-4-1, Chuo, Atsubetsu, Sapporo, Japan
[d] Underground Space Department, Civil Engineering Technology Division, Shimizu Corporation, No.16-1, Kyobashi 2-chome, Chuo-ku, Tokyo 104-8370, Japan
[e] Department of Earth Resources Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka

ARTICLE INFO

Keywords:
Tangent modulus method
In-situ rock stress
Strain rate
Temperature
Confining pressure

ABSTRACT

This paper proposed Tangent Modulus Method (TMM) which is an improved oriented core method to determine in-situ rock stresses. In this approach, the cylindrical specimens prepared along different directions from thick core samples were uniaxially compressed twice to a given stress level. The stress value of the bending point in the first loading cycle of the stress-tangent modulus curve is considered as the normal component of the in-situ rock stress along the drilled direction of the specimen. Four types of rocks from soft porous tuff and sandstone to hard crystalline granite was investigated to evaluate the potential of this method. The effects of changes in strain rate, temperature, water content, confining and pore pressure, and stresses larger than the preload on the stress value of the bending point were experimentally investigated on preload specimens to investigate their influence on TMM. Comparison of the stress measurement results by TMM and an overcoring method at AK tunnel in Hokkaido, Japan was also performed to validate the TMM.

1. Introduction

As shown in extant studies including Fairhurst (2003) and Ljunggren et al. (2003), numerous methods for in-situ rock stress measurement have been developed to date. They are divided into in-situ methods, oriented core methods, and other methods. Oriented core methods can be applied to rock cores from great underground depth and are cheaper and less time consuming than other methods. However, various factors affect the results from oriented core methods, and they are recognized as less reliable than in-situ methods (Ljunggren et al., 2003).

In order to increase the reliability of oriented core methods, previous studies, such as Lavrov (2003), examined the impact of various conditions in the Kaiser effect, and this utilizes acoustic emission (AE) due to the initiation and propagation of microcracks. Experiments indicate that the stress level at the beginning of AE occurrence during uniaxial compression on a triaxially preloaded specimen is equal to the preloaded differential stress value minus 0.5–0.7 times the preloaded confining pressure value. This does not entirely preclude any estimation of in-situ stress, and instead presented a serious problem because the lateral stress is not known in advance. Results also indicate that heating of a saturated diorite or liporite specimen up to 80–100 °C completely eliminates the Kaiser effect. It should also be noted that the Kaiser effect requires a significantly expensive AE measurement system and excellent experimental skills.

Specifically, in the present study, the Tangent Modulus Method (TMM) is presented as a potentially better original oriented core method for stress measurement. The TMM does not require either an AE measurement system or excellent experimental skills. The effect of lateral stress on the result was 1/5th of that from the Kaiser effect (see Section 3.5). The reason is potentially because TMM utilizes the irrecoverable closure of voids as opposed to the initiation and propagation of microcracks (see Section 2). The effect of a change in the surrounding water temperature is not significant (see Section 3.2) although it is not possible to perform a quantitative comparison with the aforementioned results for the Kaiser effect because there are differences in the tested rock types.

The procedure for stress measurement using TMM is described first. Subsequently, the effects of changes in strain rate, temperature, water content, confining and pore pressures, and short duration loading of

* Corresponding author.
E-mail address: fujii6299@frontier.hokudai.ac.jp (Y. Fujii).

https://doi.org/10.1016/j.tust.2018.08.005
Received 21 November 2017; Received in revised form 10 July 2018; Accepted 13 August 2018

higher stresses (simulating the stress concentration at rock sampling) on the TMM are investigated using laboratory tests. Finally, a comparison between results using the TMM and a stress relief method in the AK tunnel, Japan, is discussed.

2. Tangent modulus method

The following procedure was used to determine in-situ rock stress in the study:

(1) Oriented thick rock cores were sampled from a drilling hole.
(2) Cylindrical rock specimens in various directions were prepared by re-drilling the thick rock core from a drilling hole.
(3) The specimens were uniaxially or triaxially compressed twice to a certain stress level.
(4) The stress value of the bending point in the stress-tangent modulus curve in the first loading cycle or the point where the first and the second stress-tangent modulus curves begin to separate (the point is also subsequently termed as the bending point for the purpose of convenience) was considered as the normal component of the in-situ rock stress in the direction of the specimen.
(5) The three-dimensional stress state was calculated from the normal stress components in more than six independent directions.

In order to demonstrate the potential of the tangent modulus method, the following experiments were performed (Fig. 1):

(1) 30 mmϕ × 60 mm long cylindrical rock specimens were compressed to a given preloading stress level, and the stress was maintained for a set time to simulate in-situ rock stress.
(2) The specimens were unloaded and subsequently cyclically compressed to a higher stress level twice after a delay time.
(3) The stress value at the bending point was compared to the preloading stress value.

As an outline, uniaxial preloading at approximately 30% uniaxial compressive strength (UCS) was applied for 1 h at 295 K, and cyclic loading was performed to approximately 50% UCS at a strain rate of $10^{-4}\,s^{-1}$ at 295 K unless other conditions were specified. A time delay was not incorporated although removal and re-installment of end-pieces and clip gages from the specimen were undertaken over one to several minutes. This was performed to ensure that stress memory did not arise due to deformation of the boundary between end-pieces and the specimen or from the clip gage and that measured stresses arose

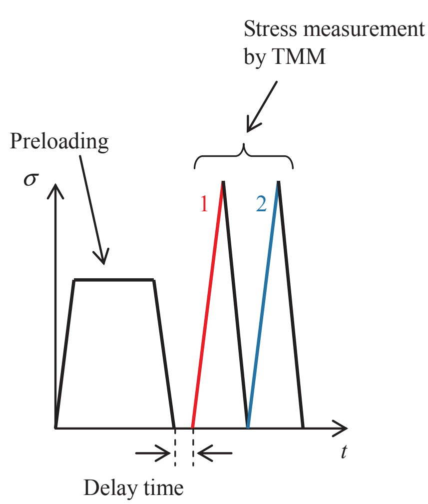

Fig. 1. Preloading and cyclic loading. 1 and 2 mean the first and the second loading cycle, respectively.

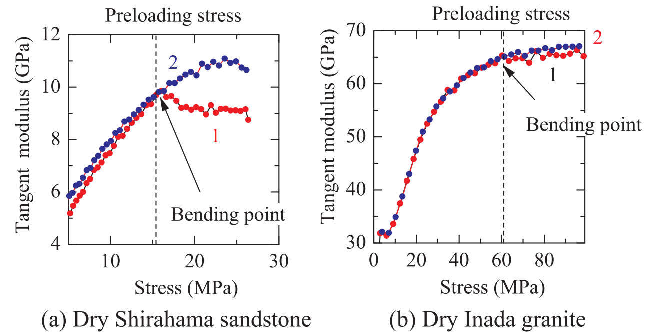

Fig. 2. Examples of stress-tangent modulus curve in cyclic loading. 1 and 2 mean the first and the second loading cycle, respectively. Strain rate and preloading duration were $10^{-5}\,s^{-1}$ and 60 min. for Shirahama sandstone. They were $10^{-4}\,s^{-1}$ and 100 min. for Inada granite.

solely from the rock specimen itself. It was assumed that rock specimens did not retain any memory of in-situ rock stress because they were sampled several years prior to performing the experiments and experienced changes in water contents during storage, cutting and grinding using water, and oven-drying for 24 h at 353 K. As shown later in Section 3.3, rock specimens lost their stress memory quickly due to changes in the water content.

The results confirmed that the bending point appeared at the preloading stress level in porous rocks, such as Shirahama sandstone (Fig. 2a) and Kimachi sandstone that both date to the Miocene age, and in a Pleistocene Shikotsu welded tuff under dry conditions (Fujii et al., 2006, 2008). The bending point was discernible although not quite distinctive in a hard and crystalline Inada granite (Fig. 2b; Fujii et al., 2008). The strengths of these rocks are shown in Table 1. Bending points became more indistinct with increases in the delay time due to relaxation. However, bending points were observed at the preloading stress level even after a delay time of 6 weeks when samples were preloaded for 17 h (Fig. 3). A significantly longer delay time was expected for rocks that were subjected to in-situ stress for geologically long periods.

The mechanism of TMM was explained by nearly irrecoverable closures of rock voids such as microcracks and pores. We assume that A in Fig. 4a denotes the in-situ stress condition under which a rock exhibits a few voids that are tabular and sufficiently large such that they are partly closed, and the rock is stiff during the first cyclic loading up to the in-situ stress level (B to C) because practically none of the voids closed. However, the stiffness decreased under further compression (C to D) due to the closure of the partly closed voids and closure of other open voids. Hence, a bending point appeared at C (Fig. 4b). Further closures did not occur in the second loading cycle, thereby resulting in high stiffness throughout the second loading cycle (E to F). The aforementioned mechanism also correlated well with the principle of Deformation Rate Analysis (DRA), (Yamamoto, 2009), which corresponds to another in-situ rock stress measurement method using oriented cores. In the study, TMM was performed by plotting the tangent modulus

Table 1
UCS (uniaxial compressive strength) in dry condition, preloading stress level and maximum stress in cyclic loading. UCS is the average value for 3 or 4 specimens at strain rate of $10^{-4}\,s^{-1}$.

	UCS (MPa)	Preloading stress (MPa)	Maximum stress in cyclic loading (MPa)
Shirahama Sandstone	52.8	15.4	26.4
Shikotsu Welded Tuff	15.2	4.6	7.6
Inada Granite	203.4	61.0	101.7
Kimachi Sandstone	41.0	12.3	20.5