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2

Time-Dependency in Rock Mechanics and Rock Engineering

Ömer Aydan

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About the author

Born in 1955, Professor Aydan studied Mining Engineering at the Technical University of Istanbul, Turkey (B.Sc., 1979), Rock Mechanics and Excavation Engineering at the University of Newcastle upon Tyne, UK (M.Sc., 1982), and finally received his Ph.D. in Geotechnical Engineering from Nagoya University, Japan in 1989. Prof. Aydan worked at Nagoya University as a research associate (1987–1991), and then at the Department of Marine Civil Engineering at Tokai University, first as Assistant Professor (1991–1993), then as Associate Professor (1993–2001), and finally as Professor (2001–2010). He then became Professor of the Institute of Oceanic Research and Development at Tokai University, and is currently Professor at the University of Ryukyus, Department of Civil Engineering & Architecture, Nishihara, Okinawa, Japan. He has furthermore played an active role on numerous ISRM, JSCE, JGS, SRI and Rock Mech. National Group of Japan committees, and has organized several national and international symposia and conferences. Professor Aydan has received the 1998 Matsumae Scientific Contribution Award, the 2007 Erguvanlı Engineering Geology Best Paper Award, the 2011 Excellent Contributions Award from the International Association for Computer Methods in Geomechanics and Advances, the 2011 Best Paper Award from the Indian Society for Rock Mechanics and Tunnelling Technology and was awarded the 2013 Best Paper Award at the 13th Japan Symposium on Rock Mechanics and 6th Japan-Korea Joint Symposium on Rock Engineering. He was also made Honorary Professor in Earth Science by Pamukkale University in 2008 and received the 2005 Technology Award, the 2012 Frontier Award and the 2015 Best Paper Award from the Japan National Group for Rock Mechanics.

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Chapter 1

Introduction

Long term response and stability of rock engineering structures such as tunnels, underground openings, slopes and stone-made cultural assets have been receiving great attention since early times. Furthermore, the stability of the room and pillar mines during exploitation and after abandoning is also of great concern (Figure 1.1). There are many causes affecting their long term response and stability, such as sustained loading with or without additional loads resulting from various sources of blasting, machine vibration and earthquakes, freezing and thawing, and weathering due to physical and chemical actions of the percolating fluids.

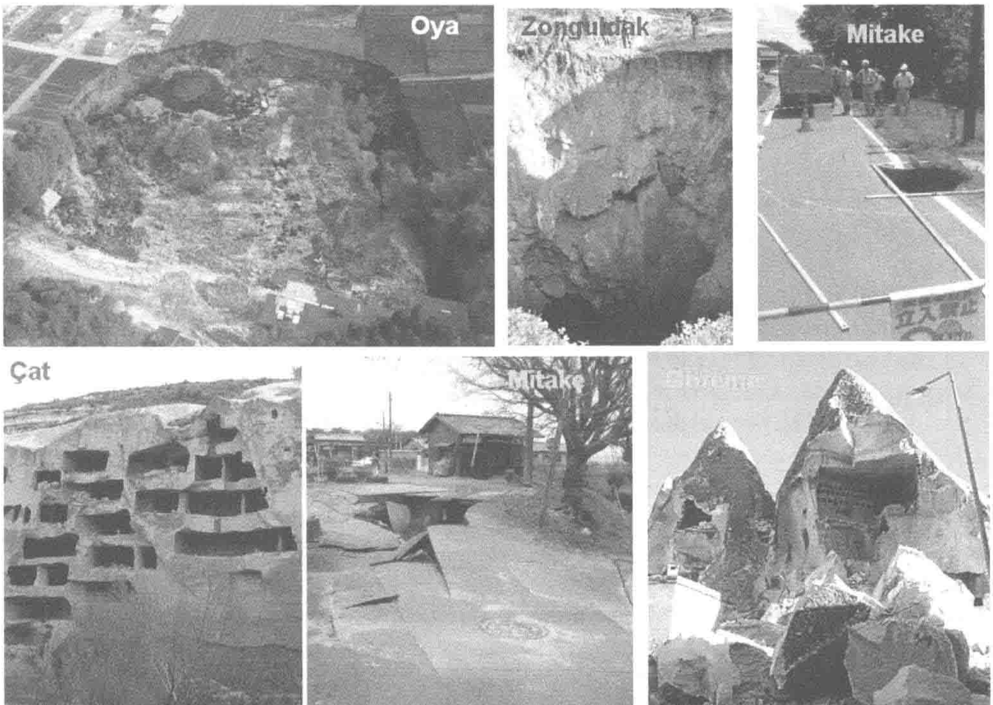

Figure 1.1 Collapse of some underground openings involving time-dependent characteristics of rocks.

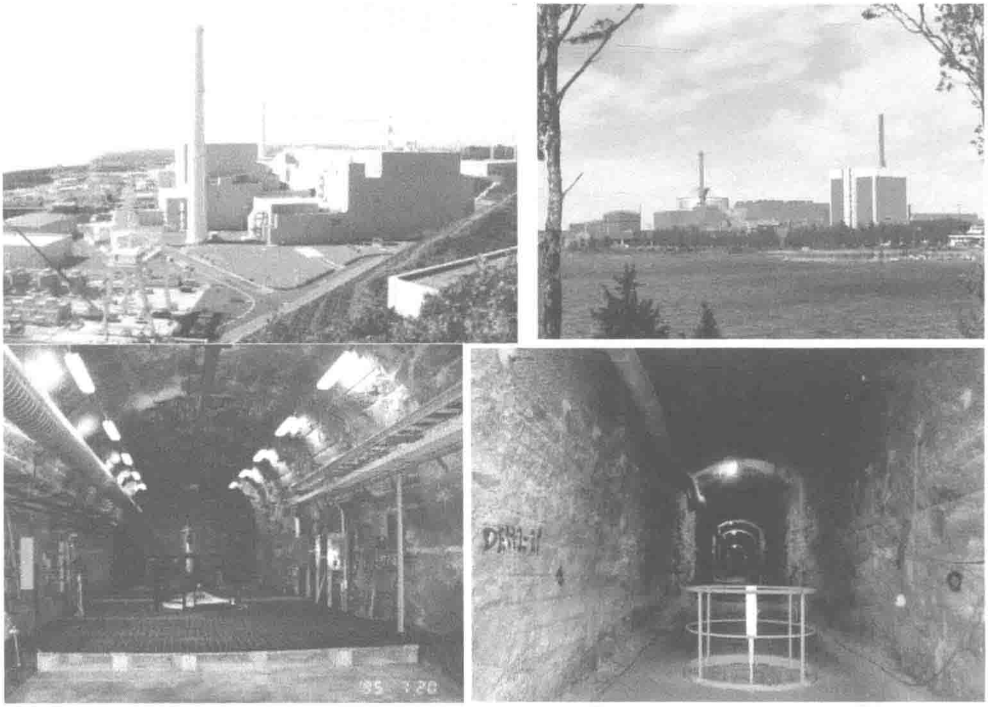

Figure 1.2 Some nuclear power plants and underground nuclear waste disposal caverns.

The nuclear waste disposal projects in countries utilizing nuclear energy and/or nuclear weapons require the consideration of a very long time span of at least 10,000 years for the assessment of response and stability of underground disposal facilities in rock. Particularly, the nuclear waste disposal projects involve very complex interactions of thermal, hydrological, diffusive and mechanical phenomena (Figure 1.2).

In Geo-science, it is well known that faults and the earth's crust show creep-like responses. Some case histories from San Andreas and North Anatolian fault are well documented. The crustal deformation response before the 2003 Miyagi-Hokubu earthquake in Japan was very similar to what is observed in creep experiments (Figure 1.3). There are also many experimental studies on the creep and relaxation behaviour of crustal rocks under different temperature regimes. The creep test is an experiment carried out under sustained loading condition. The load is generally applied in a step-like fashion. For time dependent or rate-dependent characteristics of rocks, there are different methods such as rate-dependent experiments besides creep tests. In actual sense, there are some correlations between these two different types of experiments.

This book is concerned with time-dependency in rock mechanics and rock engineering, whose spectrum is very wide as mentioned above. While the term "time-dependency" involves time-dependent behaviour/rate-dependent behaviour of rocks in a conventional sense, this book attempts to cover the spectrum as much as possible

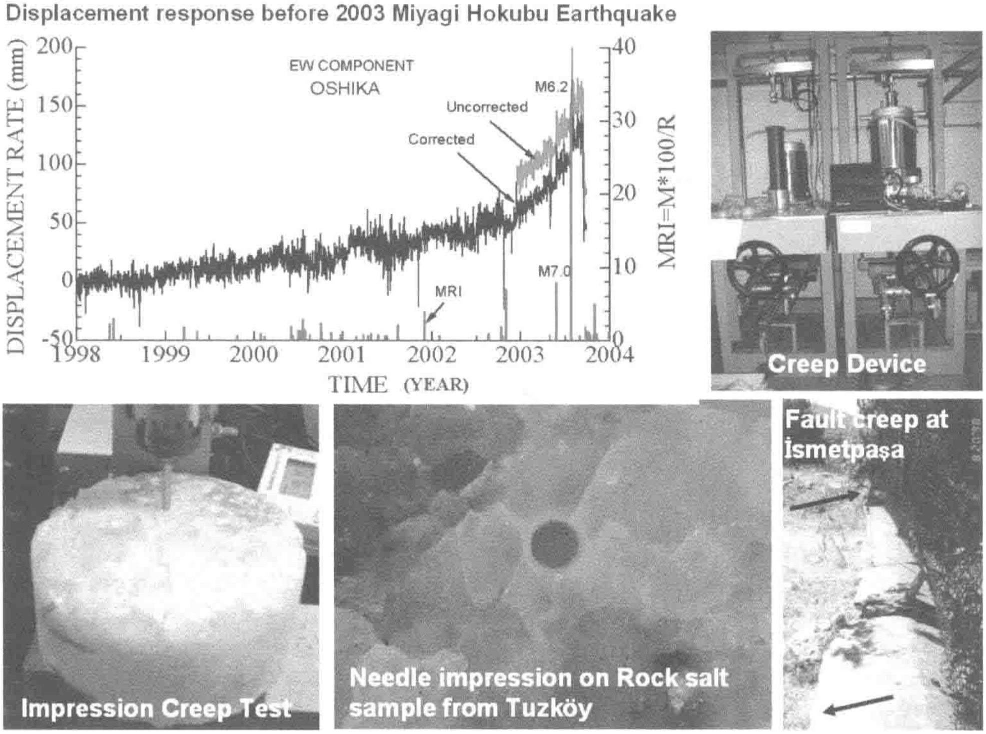

Figure 1.3 Examples of creep of rocks and faults and testing devices.

including coupled processes of thermal, hydrological and diffusions in rocks. This book specifically deals with the following topics.

Chapter 2: As all rocks exhibit time-dependent behavior, the long term response and stability of rock engineering structures are of great importance and the engineers must know how to deal with this issue. This chapter covers many aspects of time/rate dependency of rocks and associated engineering issues.

Chapter 3: Degradation of mechanical properties of soft rocks due to absorption and desorption of water as a result of cyclic drying-saturation process is another important issue in rock mechanics and rock engineering in the long term. This process involves moisture variation, which results in volumetric changes, causing their cracking and decomposition. The scientists and engineers involved with rocks must know this process and how to assess the performance of structures in such rocks in the long term. This chapter describes the fundamentals of this phenomenon, its mechanical modeling and some specific applications to actual problems.

Chapter 4: Heat transport in rocks is another important issue for dealing with the long term performance of structures of great importance as well as geothermal field exploitation. Furthermore, the understanding of mechanical property variations in relation to temperature fluctuations and their effect on rock engineering structures are also of great significance for rock engineers and scientists. This chapter is intended to cover the fundamental aspects of heat transport and its effect on the mechanical field. There are different techniques to evaluate thermal properties of rocks. A very practical procedure is proposed to evaluate thermal properties such as specific heat, thermal conductivity and thermal diffusivity. Some specific examples of practical applications are also presented.

Chapter 5: Seepage and cyclic variations of groundwater as free percolating fluid in rock mass may eventually result in the failure of some rock engineering structures in the short and long term. This requires an approach to couple the fundamental governing equations of thermal and mechanical fields. The understanding of this process should be of great value for engineers how to assess and monitor their structures in the long term. Besides the derivations of the fundamental governing equation, the theoretical background of Darcy law for porous rocks and discontinuities is presented. The theoretical background of transient pulse technique and its numerical representation are presented for longitudinal and radial flow conditions. Several practical applications of seepage in rock mass in relation to some specific rock engineering structures are presented.

Chapter 6: The nuclear-waste disposal issue in rock engineering is a very challenging problem for scientists and engineers of rocks and it involves very sophisticated interaction of fundamental governing equations. Particularly the studies dealing with radioactive waste disposal have been concerned with thermo-hydro-mechanical aspects of the phenomenon as well as the diffusion phenomenon of the radioactive substances. Since the diffusion phenomenon is quite important in the long term, a mechanical model based on the mixture theory is described to couple thermal, hydrological and diffusion fields in this chapter. In the presented model, Duffour and Soret effects, which are mostly neglected in previous studies, are also considered to couple the thermal and diffusion fields. Then a finite element formulation of the derived theoretical model is given and a series of numerical analyses carried out for the simulation of laboratory tests is presented. Furthermore, some parametric studies are performed to investigate the coupling effects of Duffour and Soret effects on thermal and diffusion fields.

Chapter 7: The near-field disposal of nuclear wastes in rock is associated with thermo-hydro-mechanical aspects of the phenomenon. While the heat is emitted from the nuclear waste contained in canisters, the in-situ stress in rock mass and seepage of ground water is of great significance for the stability of the waste disposal sites. This chapter describes a thermo-hydro-mechanical model based on the mixture theory to couple thermal, hydrological and mechanical fields. Then a finite element formulation of the derived theoretical model is presented and a series of numerical analyses was carried out for simulating some laboratory experiments of this phenomenon.

This book presents theoretical formulations, some experimental techniques, numerical formulations and examples of applications. If this book is used as a textbook for educational purposes, Chapters 2 to 5 may be used for both undergraduate and graduate courses. Chapters 6 and 7 would be for graduate courses, particularly.

Chapter 2

Time-dependent (rate-dependent) behaviour of rocks

2.1 INTRODUCTION

Long term response and stability of rock engineering structures such as tunnels, underground openings, slopes and stone-made cultural assets have been receiving great attention since early times. Furthermore, the stability of the room and pillar mines during exploitation and after abandoning is also of great concern (Mottahed & Szeky, 1982; Doktan, 1983). There are many causes affecting their long term response and stability such as sustained loading with or without additional loads resulting from various sources of blasting, machine vibration and earthquakes, freezing and thawing, weathering due to physical and chemical actions of the percolating fluids.

The nuclear waste disposal projects in countries utilizing nuclear energy and/or nuclear weapons require the consideration of very long time span of at least 10,000 years for the assessment of response and stability of underground disposal facilities in rock. Particularly, the nuclear waste disposal projects involve very complex interactions of thermal, hydrological, diffusive and mechanical phenomena.

Most of cultural assets from previous civilizations are structures made of various stones. The deterioration of these cultural assets due to natural causes is a serious problem to be dealt with. In addition to atmospheric agents and percolating fluids, long term sustained loading causes deformation and instability of those cultural assets.

In Geo-science, it is well known that faults and the earth's crust show creep-like responses. Some case histories from San Andreas and North Anatolian fault are well documented. The crustal deformation response before the 2003 Miyagi-Hokubu earthquake in Japan was very similar to what is observed in creep experiments. There are also many experimental studies on the creep and relaxation behaviour of crustal rocks under different temperature regimes.

Time-dependent behaviour of rocks has been experimentally studied since early times (see the textbook by Jaeger & Cook (1979) and Cristescu & Hunsche (1998) for details). The extensive experimental studies were performed on halides (rocksalt or halite and potash) as they have been considered good sealing rocks for the containment and disposal of nuclear wastes. The experiments were mainly carried on rock salts subjected to creep loading conditions under different constant temperature regimes (i.e. Wawersik, 1983; Hunsche, 1992). Almost all experiments were carried out under compressive uniaxial and/or triaxial loading conditions. In some of experiments, the healing process of rock salts was also studied.

Creep characteristics of rocks are very important for assessing the long term stability of rock engineering structures. A series of experiments for the creep characteristics of soft rocks was undertaken by the author at Tokai University and Toyota National College of Technology using uniaxial compression, Brazilian creep and impression creep testing methods. The author reports the results of experiments carried out on Oya tuff. Then a series of numerical studies were carried out to investigate the stress-strain fields induced in each type of experimental technique and their possible correlations. In the final part of the report, several examples of the utilization of creep characteristics of soft rocks for assessing the long term performance and stability of rock engineering structures are presented and discussed.

For time dependent or rate-dependent characteristics of rocks, there are different methods such as rate-dependent experiments besides creep tests. In actual sense, there are some correlations between these two different types of experiments as discussed in the work of Aydan & Nawrocki (1998).

2.2 CREEP BEHAVIOUR AND TESTING TECHNIQUES

The creep experiments are often used to determine the time-dependent strength and/or time-dependent deformation modulus of rocks. It has often been stated that the creep of rocks does not occur unless the load/stress level exceeds a certain threshold value, which is sometimes defined as the long term strength of rocks (Ladanyi, 1974; Bieniawski, 1970). However, experiments carried on igneous rock (i.e. granite, gabbro etc.) beams by Ito (1991) for three decades show that a creep response definitely occurs even under very low stress levels. The threshold value suggested by Ladanyi (1993) may be associated with the initiation of dilatancy of volumetric strain as illustrated in Figure 2.1. The initiation of dilatancy generally corresponds to 40–60% of the stress

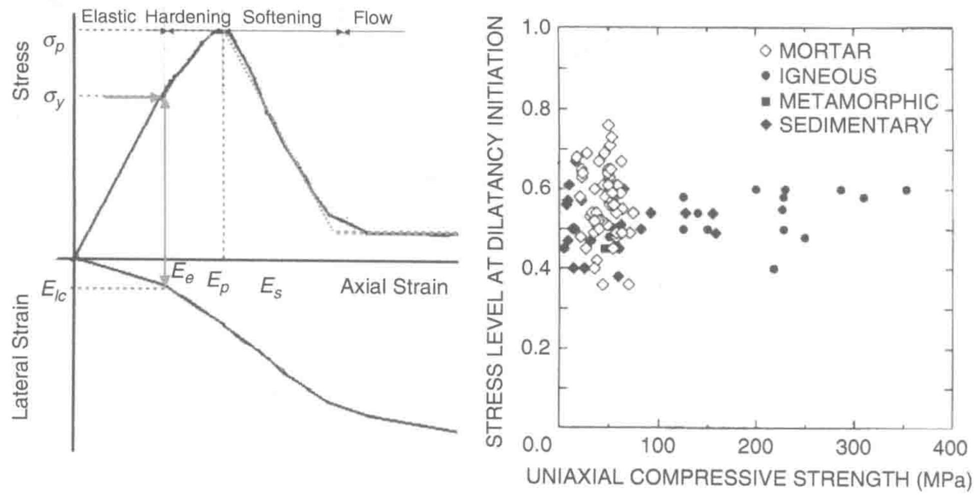

Figure 2.1 Illustration of threshold value for dilation and experimental results for different rocks (arranged from Aydan *et al.*, 1993, 1994).