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Estimation of long-term behavior of rock from short-term creep tests

K. Hashiba & K. Fukui
The University of Tokyo, Tokyo, Japan
hashiba@sys.t.u-tokyo.ac.jp

Abstract

Creep tests under constant stress are essential for investigating the time-dependent deformation and failure of rock. At a high stress level, creep strain increases, while the strain rate gradually decreases, reaches a minimum, and increases until failure occurs. Here, the stress level means the ratio of creep stress to short-term strength, and the creep strain is total strain minus elastic strain. That is to say, the creep of rock is composed of decelerating and accelerating portions. In contrast, the strain rate ata low stress level gradually decreases and approaches nearly zero, and hence it is quite difficult to complete the creep test until failure occurs.

To estimate the temporal change in creep strain from the beginning of a test to the final failure at low stress levels, the authors developed a new test method in which axial stress is increased, kept constant for a while at a predetermined stress level, increased again, decreased in the post-peak region, and kept constant at the same stress level until failure occurs. This test method provides both the beginning portion of decelerating creep and the ending portion of accelerating creep.

In this study, this test method was applied to two types of Japanese rocks, tuff and andesite, in uniaxial compression. The relations between creep strain and time in the decelerating portion and between creep strain and residual time in the accelerating portion at low stress levels were in a similar manner to those obtained from conventional creep tests at high stress levels. By interpolating the decelerating and accelerating creep curves, the complete creep curves and hence creep lifetimes were estimated at stress levels of between 20% and 80%.

Keywords

Time-dependent behavior, Creep, Strain rate, Lifetime.

1 Introduction

Understanding the time-dependent behavior of rock is essential for the long-term stability assessment of underground structures, such as tunnels, mines, and high-level radioactive waste repositories (Wagner 2019; Zhang et al. 2025). Creep tests in which time-dependent deformation is observed under constant stress have been widely applied to various rock types (Aydan et al. 2014; Innocente et al. 2021). At a high stress level, creep strain increases, while the strain rate graduallydecreases, reaches a minimum, and increases until failure occurs (Okubo et al. 1991; Bruntut et al. 2014; Imani et al. 2025), as shown in Fig. 1 (a). Here, the stress level means the ratio of creep stress to short-term strength, and the creep strain is total strain minus elastic strain. That is to say, the creep of rock is composed of decelerating and accelerating portions.Figures 1 (b) and 1 (c) are schematic illustrations of the creep strain with the logarithm of time and with the logarithm of residual time (i.e., creep lifetime minus elapsed time), which emphasize the deceleratingand accelerating creeps, respectively (Okubo et al. 1991).

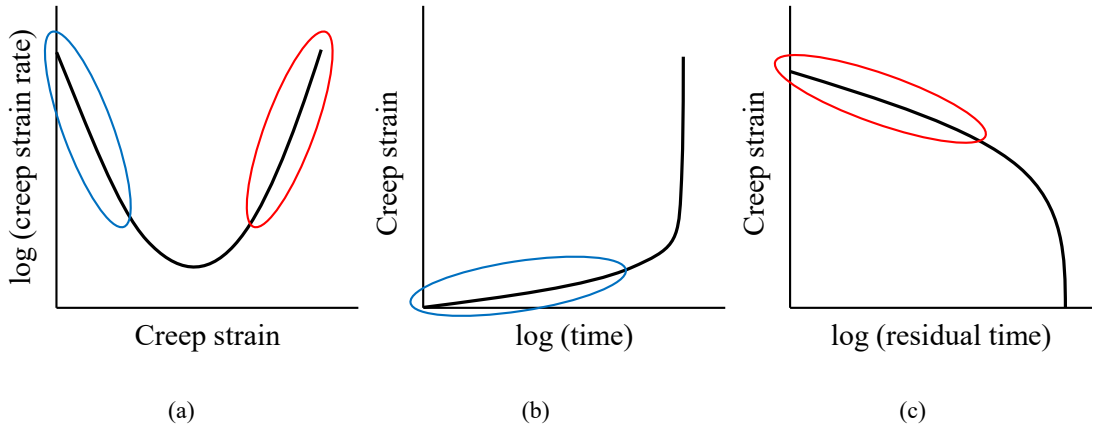


Fig. 1 Schematic illustrations of creep test results ata high stress level. The blue and red ovals indicate the decelerating and accelerating creeps, respectively. (a) log (creep strain rate) versus creep strain, (c) creep strain versus log (time), and (c) creep strain versus log (residual time).

These creep test results can be obtained in a relatively short period of time at high stress levels. In contrast, the strain rate ata low stress level gradually decreases and approaches nearly zero, and hence it is quite difficult to complete the creep test until failure occurs (Itôand Sasajima 1987; Hashiba and Fukui 2020). In previous studies, a multi-stage creep test in which creep stressis increased in stages has been conducted; however, this test method provides decelerating creep in each of the stages and accelerating creep only in the final stage at a high stress level (Bruntut et al. 2013). Hence, there is still little knowledge about the long-term creep behavior at low stress levels. Recently, the authors developed a new test method to estimate the temporal change in creep strain from the beginning of a test to the final failure at low stress levels (Hashiba and Fukui 2025). This paper presents the results of two types of Japanese rocks obtained with the new test method at low stress levels and compares them with short-term creep test results at high stress levels.

2 Test method

Sample rocks are Tage tuff and Sanjome andesite obtained in Japan of which the uniaxial compressive strengths are 22 MPa and 100 MPa, respectively. The specimens are cylindrical with a diameter of 25 mm and a height of 50 mm and were dried in a laboratory for more than two weeks. The tests were conducted in uniaxial compression using a 500 kN servo-controlled testing machine. The axial load and displacement were measured with a strain-gauge-type load cell and a linear variable differential transformer, respectively.

Figure 2 shows a schematic illustration of a stress-strain curve obtained with the test method developed by Hashiba and Fukui (2025). In this test method, a specimen is loaded from O to A, and the stress is kept constant to record the decelerating creep from A to B. The specimen is reloaded from B to C and unloaded from C to D, and the stress is kept constant to record the accelerating creep from D to E at the same stress level as that at A and B. In conventional creep tests, the position of stress and strain moves from A to Evia B and D. In contrast, this test method omits the section between B and D and provides both the beginning portion of decelerating creep and the ending portion of accelerating creep, as the curves enclosed by the blue and red ovals in Fig. 1 (a). By interpolating the separated

decelerating and accelerating creep curves, we can estimate a complete creep curve and hence creep lifetimefrom a single specimen in a short period of time. In this study, the strain rate was set to 10^{-4} /s from O to A, alternated between 10^{-5} /s and 10^{-4} /s at a strain interval of 5×10^{-4} from B to C, and set to -10^{-5} /s from C to D, in a similar way to that in Hashiba and Fukui (2025). Theduration between A and B was set to 1000 seconds. The stress at C was set to 1.1 and 1.15 times higher than that at D for Tage tuff and Sanjome andesite, respectively. This study focused on the creep test results and hence omitted the results about the strain-rate dependence of strength obtained from the strain-rate alternationbetween B and C. The results of Tage tuff obtained by Hashiba and Fukui (2025) were reorganized, and the results of Sanjome andesite were newly obtained in this study.

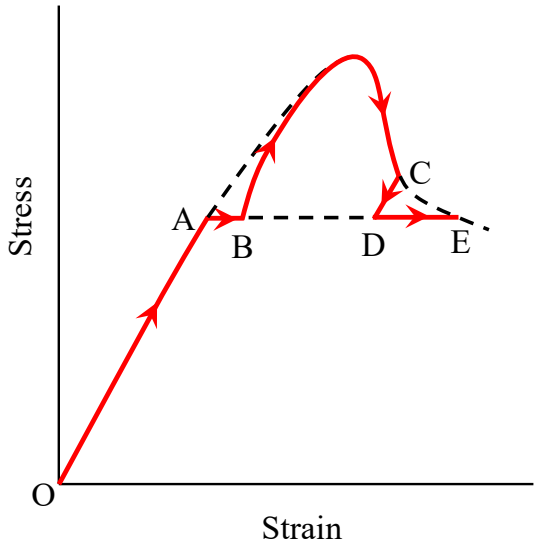


Fig. 2 Schematic illustration of astress-strain curve obtained with the test method developed by Hashiba and Fukui (2025).

3 Test results

Figure 3 shows the relation between creep strain and time obtained for 1000 seconds between A and B in Fig. 2 with the numbers indicating creep stress levels as percentages. The strain at one second after the start of the creep test was set to the origin. The creep strain monotonically increased, and the curves for both rocks are linear or slightly convex downward in a similar manner to the curve enclosed by the blue oval in Fig. 1 (b).

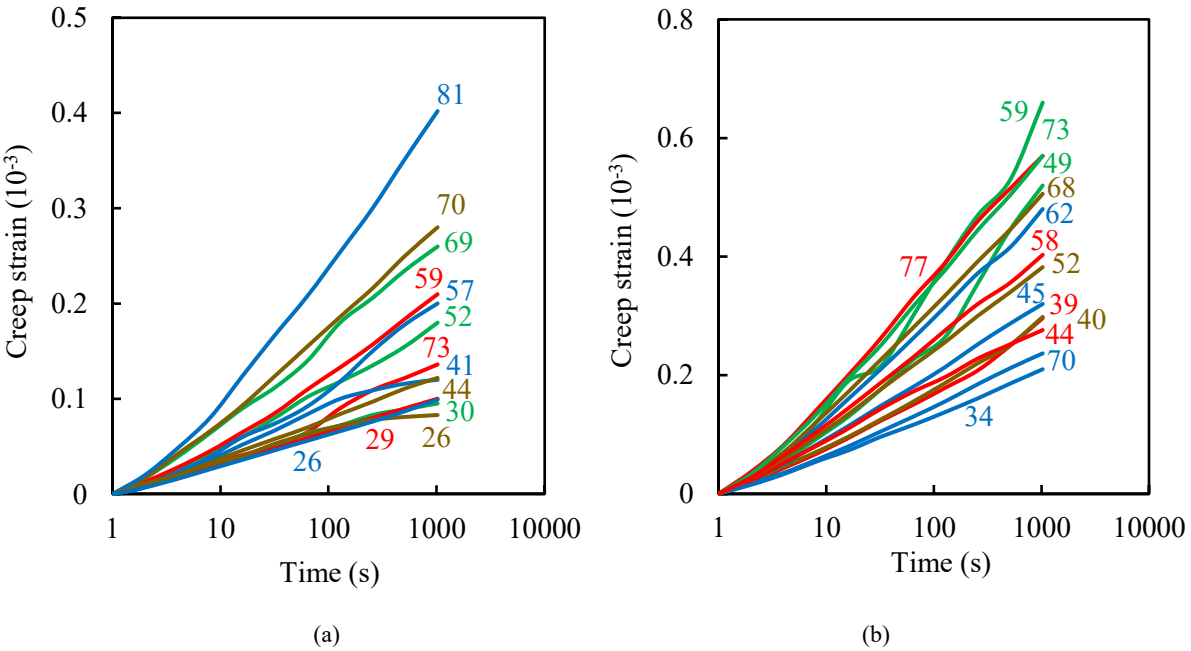


Fig. 3 Relation between creep strain and time in the decelerating creep obtained between A and B in Fig. 2.The numbers indicate creep stress levels. (a) Tage tuff and (b) Sanjome andesite.

Figure 4 shows the relation between creep strain and residual time obtained between D and E in Fig. 2; the time elapsed from right to left in Fig. 4. The curve with the same number and color as that in Fig. 3 was obtained from the same specimen. The curves for both rocks are linear or slightly convex upward in a similar manner to the curve enclosed by the red oval in Fig. 1 (c). The curves are located from bottom to top in an almost descending order of stress levels, and creep failure occurred within a few thousand seconds at not only high but also low stress levels.

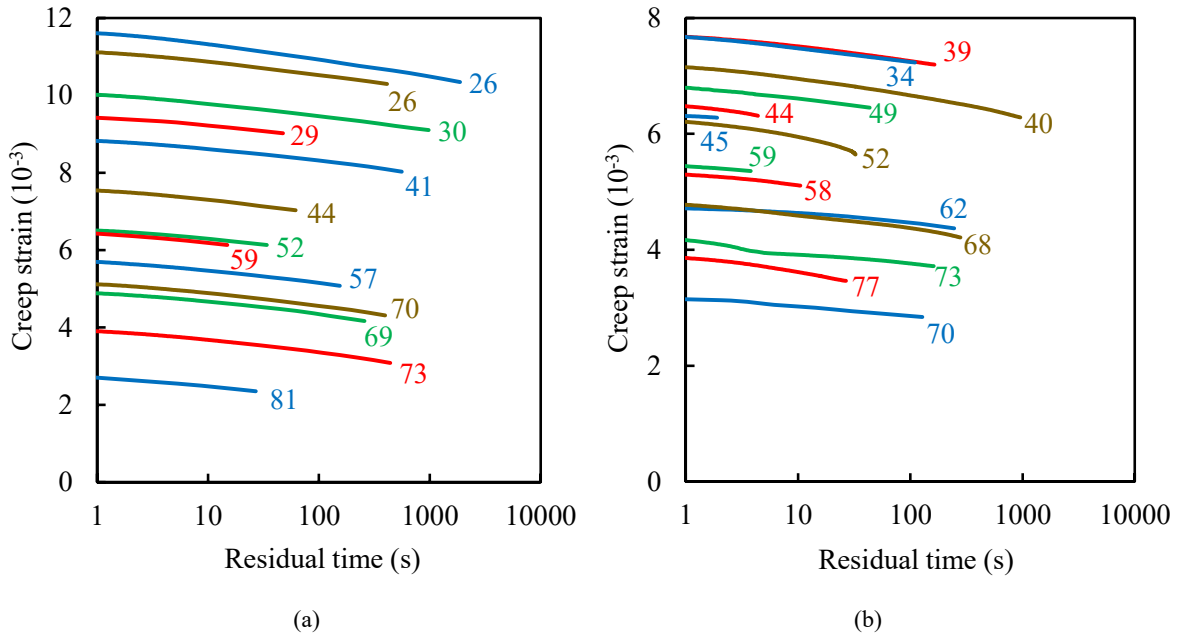


Fig. 4 Relation between creep strain and residual time in the accelerating creep obtained between D and E in Fig. 2. The numbers indicate creep stress levels. (a) Tage tuff and (b) Sanjome andesite.

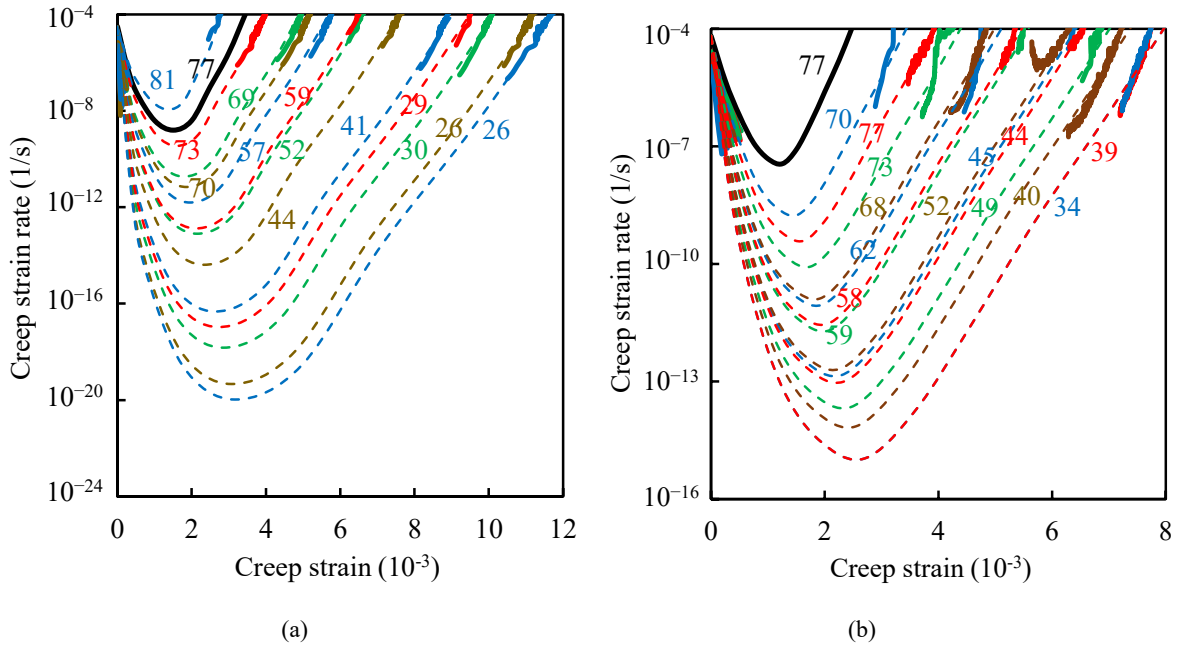


Fig. 5 Relation between creep strain rate and creep strain. The solid lines with colors were obtained in this study. The solidblack lines were obtained by Chu (1995) for Tage tuff and by Fukui (1990) for Sanjome andesite. The dashed lines were calculated from the solid black lines using Eq. (1) and (2). The numbers indicate creep stress levels. (a) Tage tuff and (b) Sanjome andesite.

Figure 5 shows the relation between creep strain rate and creep strain by solid lines with the same colors as those in Figs. 3 and 4. The decelerating and accelerating creep curves are observed at the left and right sides of the figures, respectively, in a similar manner to the curvesenclosed by the blue and red ovals in Fig. 1 (a). The results at high stress levels obtained in previous studies are shown in black, indicating that the strain rate decreases, reaches a minimum, and increases until failure occurs. To interpolate the decelerating and accelerating creep curves atthe low stress levels, the black line for

each rock was enlarged or reduced along both the horizontal and vertical axes using thefollowing equations.

$$\varepsilon_c' = \varepsilon_c \left\{ 1 + (r-1)\frac{\varepsilon_c}{\varepsilon_{cf}} \right\} \tag{1}$$

$$log\frac{d\varepsilon_c'}{dt} = log\frac{d\varepsilon_{c0}}{dt} - r\left(log\frac{d\varepsilon_{c0}}{dt} - log\frac{d\varepsilon_c}{dt} \right) \tag{2}$$

Where r Conversion ratio
ε_c Original creep strain on the black line
ε'_c Converted creep strain
ε_{cf} Final creep strain on the black line
$d\varepsilon_c/dt$ Original creep strain rate on the black line
$d\varepsilon'_c/dt$ Converted creep strain rate
$d\varepsilon_{c0}/dt$ Initial creep strain rate on the black line

Figure 5 shows the relation between the converted creep strain rate and creep strain by dashed lines with the same colors as those of the corresponding solid lines. Here, the conversion ratio r was set such that each of the dashed lines coincides with the decelerating and accelerating creep curves of the same color. This figure shows that the decelerating and accelerating creep curves are appropriately interpolated by the dashed lines and that the strain rate decreases, reaches a minimum, and increases until failure occurs at all the low stress levels.

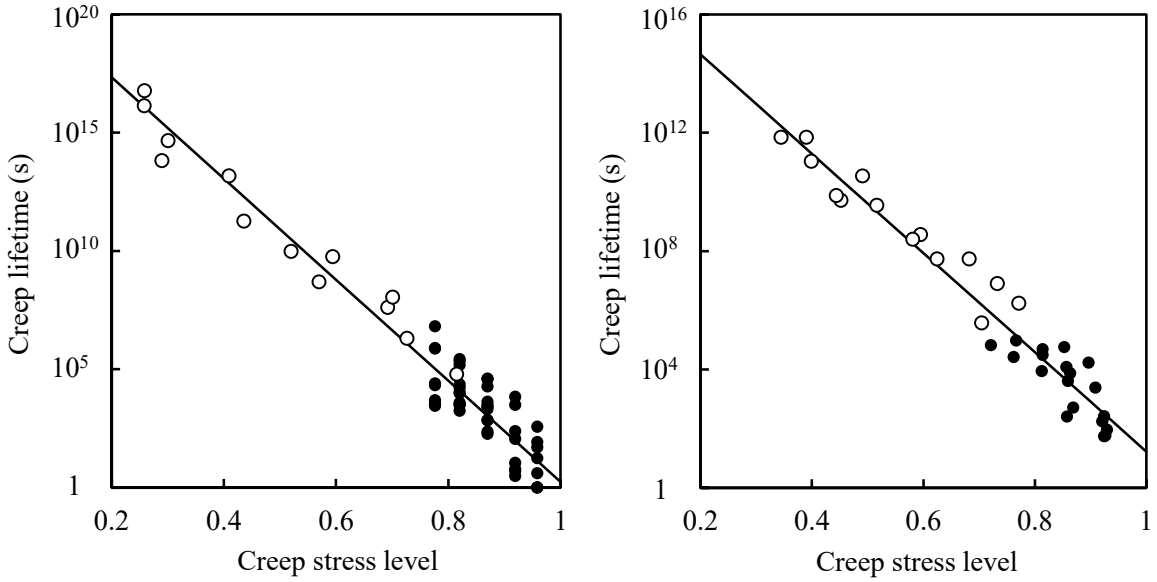


Fig. 6 Relation between creep lifetime and creep stress level. The open symbols were estimated in this study, and the closed symbols were obtained by Chu (1995) for Tage tuff and by Yamaguchi (1980) for Sanjome andesite. The black lines were calculated using Eq. (3). (a) Tage tuff and (b) Sanjome andesite.

The creep lifetime for each specimen was estimated by integrating the reciprocal of creep strain rate with respect to creep strain in Fig. 5 and shown by open symbols in Fig. 6. The closed symbols indicate the results obtained from conventional creep tests at high stress levels in previous studies. The test results at high stress levels as well as the estimated resultsatlow stress levels are located near the straight lines represented by the following equation with a and b of 21 and 22 for Tage tuff and 17 and 18 for Sanjome andesite.

$$\log t_c = -a\sigma_c + b \tag{3}$$

Where a, b Constants
t_c Creep lifetime
σ_c Creep stress level

4 Conclusions

The decelerating and accelerating creep curves were separately obtained for the two Japanese rocks, tuff and andesite, at low stress levels, using the test method in which axial stress is increased, kept constant for a while at a predetermined stress level, increased again, decreased in the post-peak region, and kept constant until failure occurs. The relations between creep strain and time in the decelerating portion and between creep strain and residual time in the accelerating portion were in a similar manner to those obtained from conventional creep tests at high stress levels. By interpolating the decelerating and accelerating creep curves using the results previously obtained at high stress levels, the complete creep curves and hence creep lifetimes were estimated at stress levels of between 20% and 80%. The relation between creep lifetime and creep stress level for the two rocks was found to be almost linear on a single logarithmic chart at not only high but also low stress levels. The applicability of this study to other rocks under various stress states and test environments will be examined in future studies.

The test method to obtain decelerating and accelerating creep curves is promising for investigating the long-term creep behavior of rock at low stress levels. However, the stress history in this test method is much more complicated than that in conventional creep tests, and hence its influence on creep behavior needs to be investigated in future studies.

References

Aydan Ö, Ito T, Özbay U, Kwasniewski M, Shariar K, Okuno T, Özgenoğlu A, Malan DF, Okada T (2014) ISRM suggested methods for determining the creep characteristics of rock. Rock Mech. Rock Eng. (47): 275–290. https://doi.org/10.1007/s00603-013-0520-6

Brantut N, Heap MJ, Meredith PG, Baud P (2013) Time-dependent cracking and brittle creep in crustal rocks: A review. J. Struct. Geol. (52): 17–43. https://doi.org/10.1016/j.jsg.2013.03.007

Brantut N, Heap MJ, Baud P, Meredith PG (2014) Rate- and strain-dependent brittle deformation of rocks. J. Geophys. Res. Solid Earth (119): 1818–1836. https://doi.org/10.1002/2013JB010448

ChuSY (1995) The time dependency of rocks under water-saturated condition. Dissertation at the University of Tokyo

Fukui K (1990) Creep and delayed failure of rocks under various loading conditions. Dissertation at the University of Tokyo

Hashiba K, Fukui K (2020) Twenty-year creep test with tuff under uniaxial compression. Geotech. Test. J. (43): 800–808. https://doi.org/10.1520/GTJ20180358

Hashiba K, Fukui K (2025) Innovative test methods for investigating the time-dependent behavior of rock: Review and new insights. Rock Mech. Rock Eng. (58): 12913–12927. https://doi.org/10.1007/s00603-025-04796-y

Imani M, Hedayat A, Walton G (2025) Critical state of damage at the onset of acceleration creep in Stanstead granite evaluated using 2D-DIC and percolation theory approach. Rock Mech. Rock Eng. https://doi.org/10.1007/s00603-025-05114-2

Innocente JC, Paraskevopoulou C, Diederichs MS (2021) Estimating the long-term strength and time-to-failure of brittle rocks fromlaboratory testing. Int. J. Rock Mech. Min. Sci. (147): 104900. https://doi.org/10.1016/j.ijrmms.2021.104900

ItôH, Sasajima S (1987) A ten year creep experiment on small rock specimens. Int. J. Rock Mech. Min. Sci. &Geomech. Abstr. (24): 113–121. https://doi.org/10.1016/0148-9062(87)91930-9

Okubo S, Nishimatsu Y, Fukui K (1991) Complete creep curves under uniaxial compression. Int. J. Rock Mech. Min. Sci. &Geomech. Abstr. (28): 77–82. https://doi.org/10.1016/0148-9062(91)93235-X

Wagner H (2019) Deep mining: A rock engineering challenge. Rock Mech. Rock Eng. (52): 1417–1446.https://doi.org/10.1007/s00603-019-01799-4

Yamaguchi T (1980) The time-dependent mechanical behavior of rock. Dissertation at the University of Tokyo

Zhang T, Zheng X, Wang S, Yang J, Chen X (2025): Discrimination, mechanical mechanisms, and control technologies for largedeformation in tunnel surrounding rock: A state-of-the-art review. Tunn. Undergr. Space Technol. (163): 106712.https://doi.org/10.1016/j.tust.2025.106712