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Triaxial creep testing on argillaceous weak rock for DSGSD movement prediction

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Abstract

Deep-Seated Gravitational Slope Deformations (DSGSDs), very slow-moving landslides, are widespread across Italy, from the Alps to the central Apennines. These slow movements, often associated with geological formations exhibiting viscous behaviour, can severely affect infrastructures. A significant example is the interaction between the Sparvo twin-tube motorway tunnel, located in central Italy, and a large DSGSD affecting the area. Such conditions require careful monitoring of the infrastructure and, when possible, the development of tools such as advanced numerical models to study and predict the time evolution of the interaction between the infrastructure and the complex landslide.This can be achieved using time-dependent constitutive models, whose most advanced formulations require the calibration of multiple parameters. The calibration process, in turn, relies on a detailed characterization of the time-dependent behaviour of the geological formations involved.This paper focuses on the characterization of the time-dependent behaviour of Palombini shale formation, anargillaceous weak rockresponsible for the DSGSD movement interacting with the Sparvo tunnel. For this purpose, several triaxial multistage creep tests were carried out on Palombini shales samples. The tests, performed on specimens collected both within the landslide shear band and outside it, revealed a marked tendency of the material to develop time-dependent deformations and allowed the definition of strain–time curves under different stresses. Moreover, the results showed clear behavioural differences between the highly deformed in-situ material sampled from the shear band and the intact material collected outside the shear band, allowing a more comprehensive characterization of the time-dependent behaviour of the argillaceous weak rock.

Keywords

Laboratory testing, soft rocks, time-dependent behaviour, creep, landslides

1 Introduction

Deep-seated gravitational slope deformations (DSGSDs) are large-scale rock mass movements affecting extensive slope sectors, involving depths of up to several hundred metres and exhibiting very slow displacement rates (Chigira 1992). Among the predisposing factors influencing the slow kinematics of these landslides, often associated with creep, is the presence of geological formations at depth exhibiting intrinsic viscous behaviour. Given their exceptional size, these slow-moving landslides may interact with existing infrastructure networks (Vassallo et al. 2019, Barla et al. 2025).

Dedicated studies are therefore required to evaluate the time-dependent evolution of landslide–infrastructure interactions and to ensure the long-term structural integrity and serviceability of the affected assets. On this context, time-dependent infrastructure-landslide interaction requires the development of reliable predictive tools, such as numerical models, and therefore the adoption of appropriate constitutive laws to simulate the landslide creep behaviour. Advanced viscoelastoplastic constitutive models, such as those based on Perzyna's overstress theory (Perzyna, 1966), require the calibration of multiple viscosity-related material parameters. In some cases, these parameters are directly linked to the intrinsic viscous behaviour of the material. To this end, laboratory creep testing (Aydan et al., 2014) provides a means to characterize the time-dependent behaviour of geomaterials involved in landslide movement.

This study presents the investigation and characterization of the Palombini Shale, an argillaceous soft rock responsible for the movement of the large slow-moving Sparvo landslide, in central Italy, which interacts with a recently constructed motorway tunnel. Particular attention is devoted to the results of triaxial creep tests, expressed in terms of strain–time curves, carried out to characterize the time-dependent behaviour of this material, as a prerequisite for more detailed studies on the evolution of tunnel-landslide interaction. The experimental programme included tests performed on both previously deformed material, sampled from the landslide shear zone, and intact material, collected outside the shear zone, in order to identify the main differences in creep behaviour.

2 The Sparvo landslide

In the Italian context, characterised by the widespread presence of slow-moving landslides, particular relevance is given to the interaction between the Sparvo twin-tube motorway tunnel (central Italy) and a large DSGSD affecting the area (Lunardi et al. 2017; Barla 2018).The recently constructed tunnel intersects the deep-seated movement over several hundred metres. Despite its relatively low average displacement rate (approximately 5 mm/year), the DSGSD exerts time-dependent and progressively increasing pressure on the tunnel lining.This long-term interaction led, within the first years following excavation completion, to significant damage to the tunnel lining, necessitating the installation of structural reinforcement measures to ensure its long-term integrity.Furthermore, the need to closely monitor the ongoing interaction between the landslide and the infrastructure required the implementation of a comprehensive monitoring system on the landslide, consisting of a dense network of both continuous and manual inclinometers, piezometers, topographical measurements, and satellite-based radar interferometry. The monitoring network enabled a detailed characterization of the landslide, including its spatial extent, the tunnel section directly affected, and the geological model of the slope, as depicted inFig. 1.

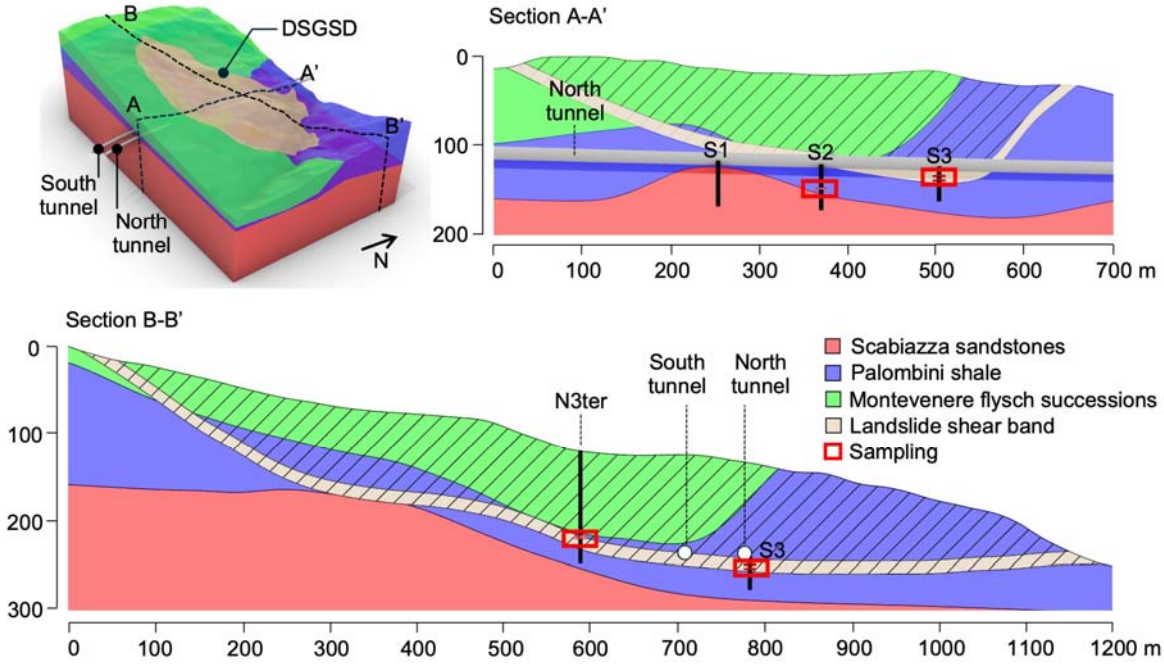


Fig. 1 3D geological model of the slope, spatial extent of the landslide and cross section of the tunnel-landslide interaction.

The landslide extends for approximately 1200 m downslope (Section B–B' in Fig. 1) and, as indicated by the extensive inclinometer network, develops along a shear band.The shear band is predominantly localized within the clayey Palombini Shales formation, composed of dark grey fissile claystones interbedded with calcilutites and tectonized ophiolitic masses.The slow kinematics of the landslide, only marginally affected by seasonal groundwater fluctuations, appear to be primarily governed by the intrinsic tendency of this argillaceous soft rock along the shear band to exhibit viscous deformation.To investigate the time-dependent behaviour of the Palombini Shale involved in the deep-seated landslide, a series of triaxial creep tests was performed on specimens sampled within the shear band (sampled in borehole S3 and N3ter in Fig. 1) and outside it (sampled in borehole S2 in Fig. 1)in order to compare the time-dependent deformational response. In particular, the tests aimed to distinguish between the behaviour of the highly deformed material and that of the intact argillaceous soft rock.

3 Laboratory creep testing on Palombini shale and interpretation

The investigation of the creep behaviour of the Palombini Shales involved triaxial creep tests under undrained conditions (TX-CIU). The tests were performed using the High Pressure Triaxial Apparatus (Barla et al. 2010) at the Geotechnical Laboratory of the Politecnico di Torino. The testing procedure can be summarized in the following stages: 1) specimen saturation, 2)isotropic consolidation of the specimen, 3) undrained shearing phaseto reach the prescribed deviatoric stress *q,* 4) creep phase maintaining constant the deviatoric stress *q*, 5) repetition of stages 3 and 4 until specimen failure.

Five tests were carried out on specimens collected within the landslide shear zone, representing material that has undergone cumulative deformation over time. In contrast, three tests were conducted on the same lithology but outside the shear band, which can therefore be regarded as intact material not previously deformed in situ.Table 1summarizes the main characteristics of the triaxial creep tests. Fig. 2shows, in the p'–q plane, the stress states corresponding to the creep stages compared with the material failure envelope. The failure envelope, derived from standard CID and CIU triaxial tests performed during the tunnel design phase, is defined by afriction angle $\varphi' = 14.9°$ and an effective cohesion $c' = 37.7$ kPa, according to the Mohr–Coulomb failure criterion.

Table 1. Summary of the main characteristics of the triaxial creep tests: consolidation pressures, stress states at the onset of each creep stage and the mobilized shear strengthratio during creep.

			Consolidation		**Creep**				**Failure**
	Test code	**Borehole**	**σ_r [kPa]**	**pp [kPa]**	**Creep stage**	**p'_{creep} [kPa]**	**q_{creep} [kPa]**	**Mobilized Shear Strength Ratio**	**$\varepsilon_{a,failure}$ [%]**
Creep tests on specimens within the shear band	TX - 01	N3ter	1984	800	Creep 1	962	466	0.80	5.49
	TX - 02	N3ter	1984	800	Creep 1	1119	323	0.52	5.47
					Creep 2	1246	514	0.72	
	TX - 03	S3	1984	800	Creep 1	1032	350	0.60	3.54
					Creep 2	1044	481	0.77	
	TX - 04	S3	1984	800	Creep 1	992	329	0.58	6.85
					Creep 2	995	539	0.87	
	TX - 05	S3	1984	800	Creep 1	1043	334	0.57	5.3
					Creep 2	1129	459	0.70	
Creep tests on specimens outside the shear band	TX - 06	S2	2800	1200	Creep 1	1424	706	0.84	9.06
					Creep 2	2016	1010	0.87	
					Creep 3	2562	1417	0.95	
	TX - 07	S2	2800	1200	Creep 1	1437	780	0.90	10.3
					Creep 2	2204	1076	0.85	
					Creep 3	2714	1600	1.00	
	TX - 08	S2	2000	800	Creep 1	1057	345	0.58	Test in progress
					Creep 2	1255	490	0.69	

Fig. 3presents the creep curves in terms of axial strain versus time under constant deviatoric stress, as obtained from the different tests performed. The results highlight a pronounced tendency of the material to develop viscous deformations, with both primary and secondary creep stages clearly identifiable in each loading phase.

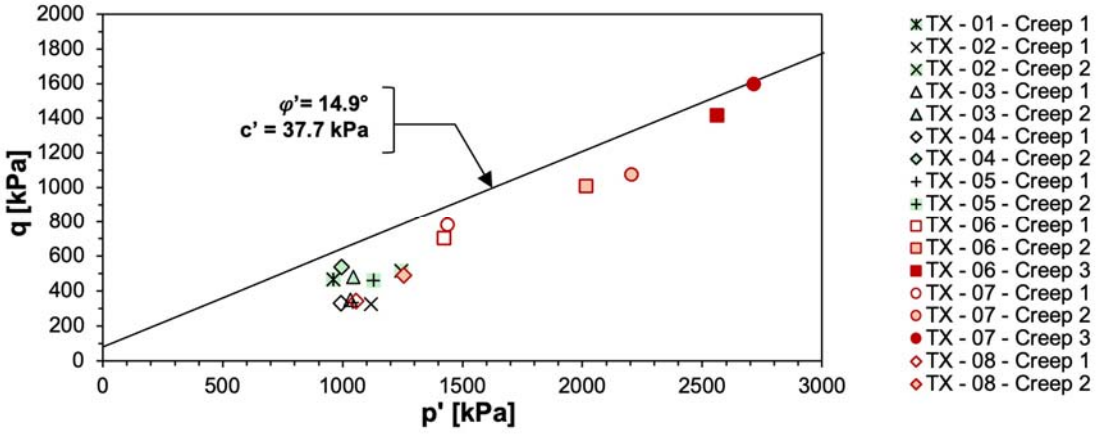


Fig. 2 Stress states corresponding to the creep stages of each test compared with the material failure envelope.

Tertiary creep leading to failure, associated with the localization of a shear surface within the specimen, was observed only in test TX-07, for which the applied stress state corresponded to a mobilized shear strength ratio equal to unity with respect to the theoretical failure envelope.Test TX-06 exhibited a strain rate that increased to such an extent that the response can be considered as approaching failure conditions. However, a distinct tertiary creep stage was not clearly identifiable; rather, a markedly accelerated secondary creep developed. In this case, deformation was more diffuse within the specimen, resulting in a barrel-shaped failure mode.All other tests were brought to failure during subsequent undrained shearing stages following two creep phases, with the exception of test TX-08, which is still ongoing at the time of writing this paper.

Axial strain rates during the secondary creep stage were derived from the creep curves obtained in the various tests. This stage, characterized by an approximately constant strain rate, is considered representative of the behaviour of slow-moving landslides. The observed response is consistent with previous studies (Cristescu and Gioda 1994), indicating that axial strain rate during secondary creep increases with increasing mobilized shear strength, i.e., as the stress state approaches failure.A marked difference in deformational behaviour is, however, evident between the intact argillaceous rock (sampled outside the shear band) and the material collected within the landslide shear zone. Fig. 4 a) illustrates the relationship between axial strain rate and mobilized shear strength at the onset of each creep stage for all tests. At comparable mobilized shear strength levels, the shear band material exhibits systematically higher axial strain rates than the intact material. This behaviour is attributed to the destructuration and cumulative deformation history of the shear zone material, likely associated with a shear-induced reorientation of the microstructure. In contrast, the intact material displays a comparatively stiffer viscous response. The cumulative in situ deformation of the shear band material due to long-term landslide movement also influences the axial strain at failure at the laboratory scale. As shown in Table 1, specimens from the shear zone failed at significantly lower axial strains than those obtained from outside the shear band.The axial strain at failure is higher in the intact material, which must undergo progressive structural degradation to reach the critical state. In contrast, shear band material is already partially destructured, exhibits an oriented shear-induced fabric, and is close to critical state. Consequently, failure occurs at lower axial strains. To further investigate the effect of cumulative in situ deformation within the shear band on the time-dependent behaviour of the Palombini Shales, a “Virtual Time ToFailure” (VTTF) is introduced.This parameter represents the time (in days) required for failure under secondary creep conditions, neglecting tertiary creep acceleration, and is defined as the ratio of axial strain at failure,$\varepsilon_{a,failure}$, to the secondary creep strain rate$\dot{\varepsilon}_a$:

$$VTTF = \frac{\varepsilon_{a,failure}}{\dot{\varepsilon}_{a,secondarycreep}} \tag{1}$$

Fig. 4 b) presents the VTTF values, computed for each creep stage of all tests, as a function of the axial strain rate, with reference to the axial strain at failure measured in each test. The data are well described by a power-law relationship.

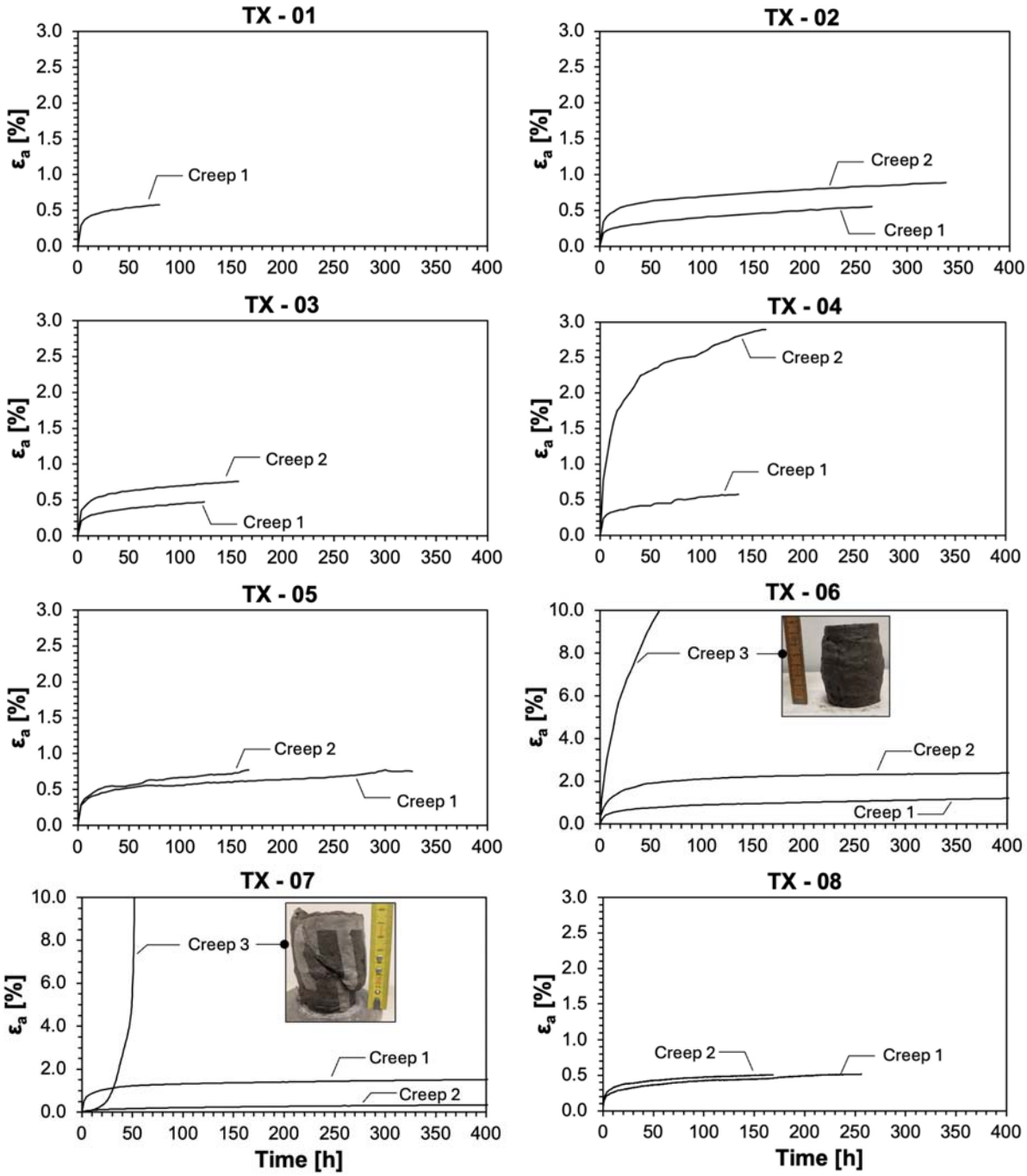


Fig. 3 Time- Axial strain curves of the creep stages of each test.

At the laboratory scale, for a given axial strain rate, the normalized difference between the VTTF of intact material (outside the shear band) and that of deformed material within the shear zone quantifies the degree of damage relative to the initial intact condition. For the Palombini Shales, the shear band material shows a damage level of approximately 46% compared to the intact state, highlighting the significantly shorter creep lifetime of the shear zone material compared to the intact rock.The observations presented herein may contribute to the calibration of numerical predictive models describing the evolution of creep-driven slow-moving landslides.A physically based time-dependent model for such unstable slopes should be capable of capturing not only deformation rate changes driven by variations in the stress state, but also potential failure associated with tertiary creep.This process is controlled not only by the stress conditions within the shear band relative to material strength, but also by the material deformation history, particularly the residual strain at failure. Given that the deformation history of large slow-moving landslides is typically unknown, experimental tests may be used to estimate the current degree of material damage, which can then serve as a starting point for further analysis, accounting the appropriate scale effects between laboratory and field conditions. Consequently, dedicated testing on both intact and in-situ deformed materials is essential in these contexts.

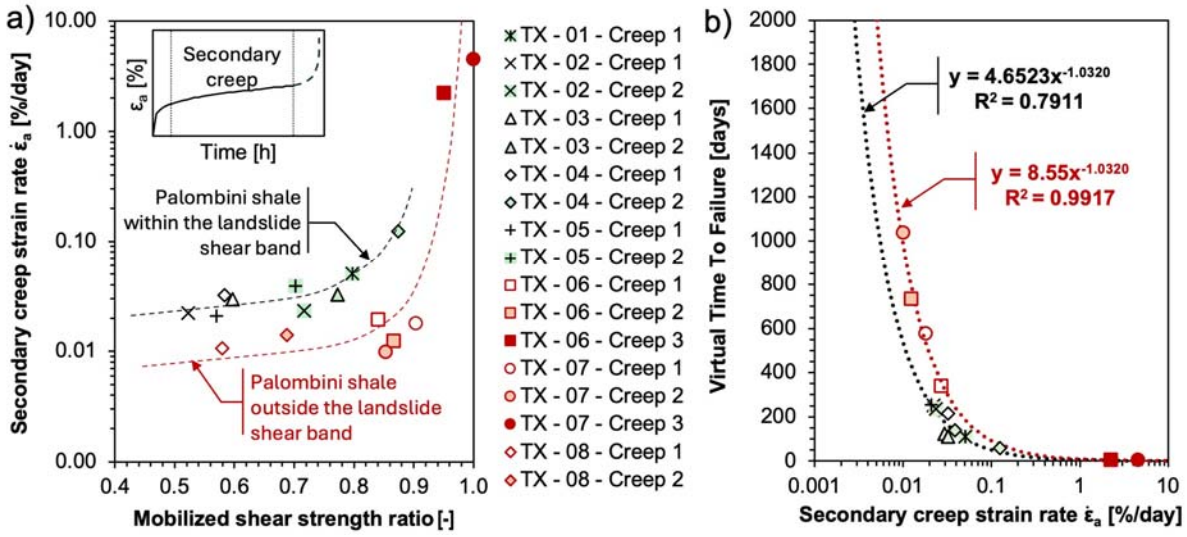


Fig. 4 Relationship between secondary creep strain rate and mobilized shear strength ratio for each creep stage across all tests a) and Virtual time to failure as a function of the secondary creep strain rate b).

4 Conclusions

This study investigates the time-dependent behaviour of the Palombini shale involved in the Sparvo slow-moving landslide through triaxial creep tests on intact and shear band material. The results highlight a pronounced viscous response, with well-defined primary and secondary creep stages and failure occurring only near the strength envelope. A clear difference in behaviour is observed, with shear band material exhibiting higher secondary creep strain rates and lower axial strain at failure due to cumulative deformation and destructuration. The proposed Virtual Time To Failure (VTTF) parameter quantifies this effect, indicating a significantly reduced creep lifetime for the shear zone material. These findings provide experimental support for the calibration of time-dependent constitutive models for creep-driven landslides.

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