Cold Regions Science and Technology 88 (2013) 17–36

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

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

Secondary creep approximations of ice-rich soils and ice using transient relaxation tests

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ARTICLE INFO

Article history:
Received 16 June 2012
Accepted 27 December 2012

Keywords:
Ice-rich frozen soil
Polycrystalline ice
Unfrozen water
Secondary creep
Relaxation test
Stepped creep tests

ABSTRACT

This paper serves two purposes: 1) it presents a simple empirical approach based on relaxation tests, from which secondary creep parameters can be approximated with significant practical time savings and 2) provides secondary creep observations and parameters for ice-rich soils as a function of cryostructure and massive ice facies. The form of test presented consists of a relaxation test in which the strain varies with time. Empirical evidence indicates that the onset of a secondary creep phase in ice-rich soils and ice is connected to the strain. Under increasing or decreasing stepped constant stress creep (CSC) tests, the initiation of secondary creep rates occurs very quickly upon a step change in the applied stress. The relaxation condition represents a continuously decreasing stepped creep tests. Once secondary creep conditions are initiated, the relaxation test can be used to approximate secondary creep. Secondary creep characteristics determined from relaxation tests agree well with CSC tests. Tests were conducted on ice-rich frozen silt from a Pleistocene age Yedoma permafrost composed of uniform windblown loess (Fairbanks silt). In addition to frozen soils, a number of samples of massive wedge ice and Matanuska glacial and basal ice were tested. Relaxation tests were conducted at temperature between −1 °C and −5 °C. Analysis of secondary creep parameters indicates that cryostructure has an influence on the secondary creep behavior of frozen soils. It is shown the volumetric unfrozen water has a significant impact on secondary creep parameters. With increasing unfrozen water content, parameters A and n approach the values observed for polycrystalline ice. It was shown for temperatures warmer than −2 °C and stresses between 200 kPa and 1000 kPa, ice-rich soils creep at a faster rate than polycrystalline ice facies. This relates to unfrozen water. For temperatures colder than −3 °C, the creep rates of polycrystalline ice are greater than undisturbed frozen soils for stresses less 200 kPa. The creep characteristics of remolded Fairbanks silt are not representative of undisturbed ice-rich samples and provide non-conservative creep estimates of undisturbed frozen soils.

1. Introduction

The structural distribution of ice in frozen soils is generally not considered when the creep properties of frozen soils are studied. Cryostructure reflects its cryogenic genesis (Katasonov, 1960). Due to the variability resulting from differing cryostructures, it is likely that the creep response of frozen soils also varies with cryostructure. A few works have looked at the influence of cryostructure on time dependent properties of frozen soils (Bray, 2012; Pekarskaya, 1965; Savigny and Morgenstern, 1986; Vialov, 1959; Vyalov et al., 1980). The influence of cryostructure on the creep behavior of ice-rich Fairbanks silt using conventional constant stress creep tests was discussed by Bray (2012).

Soils can be roughly grouped by volumetric ice content as ice-poor (0–20%) intermediate (20–60%), ice-rich (55–85%) and dirty ice (80–90%), with overlap existing (Arenson et al., 2007). Determination of secondary creep parameters for undisturbed soils is typically hindered by the significant time investments required for conventional creep testing and the normal variability of responses seen for undisturbed frozen soils. Remolded soils are commonly used to help reduce this inherent variability. However as a consequence, the secondary creep behavior may no longer represent the undisturbed soil response. There is a paucity of data regarding the creep properties of undisturbed ice-rich soils with notable works including Arenson and Springman (2005a, 2005b), McRoberts (1988), McRoberts et al. (1978), and Savigny and Morgenstern (1986).

Secondary creep behavior is of significant and practical importance for ice-rich soils and ice (Andersland and Ladanyi, 1994). Determination of secondary creep parameters are typically conducted under constant stress creep (CSC) and to a lesser extent, with constant strain rate (CSR) tests. In a CSC test, a sample is loaded to a prescribed stress state and the stress is held constant until the sample shows damped creep (stabilization) or either progresses to a secondary or tertiary creep mode. A family of creep curves is then produced from the

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http://dx.doi.org/10.1016/j.coldregions.2012.12.011

different stress levels. The data is then used to describe a creep law of interest. Ideally, seven to eight different stress levels are tested. At low stresses, it can take months or years to develop a family of creep curves for one soil type at one given temperature. Major constraints with conventional testing methods include the need for numerous samples, significant test times especially under low stress conditions, and the inherent variability of undisturbed soils.

The purpose of this paper is three fold: 1) This paper presents a new empirical approach to determine minimum strain rate or secondary creep approximations from relaxation tests. The approach is based on empirical observations regarding the strain influence on secondary creep and the dominant nature of secondary creep in CSC stepped creep tests for ice-rich soils and ice. Empirical evidence is then provided which shows the correlation between relaxation based secondary creep approximations and CSC derived secondary creep characteristics. This method has particular relevance to the frozen soil engineering community by which the determination of secondary creep parameters can be greatly accelerated. 2) This paper provides qualitative and quantitative secondary creep analysis of undisturbed ice-rich permafrost soils, remolded soils, and various forms of undisturbed polycrystalline ice. Ice-rich permafrost samples were obtained from a Pleistocene syngenetic Yedoma deposit in Interior Alaska. Special emphasis is placed on the creep response in relationship to soil cryostructure. In addition to permafrost soils, tests were run on massive wedge ice, Matanuska basal glacial ice, and Matanuska glacial ice. 3) Unfrozen water is shown to influence the creep response of frozen soils.

2. Soils and ice

A complete description of the soils and permafrost conditions can be found in Bray (2008b, 2012). In order for this paper to be complete, a brief summary of the various soils and ice is provided. A range of soil and ice samples were used in the course of the testing program. The bulk of the samples were obtained from the CRREL permafrost tunnel, Fox, Alaska. The tunnel is located within a permafrost deposit formed during the Pleistocene, which is referred to as Yedoma or the ice-complex, and is characterized by syngenetically formed ice-rich sediments and large ice wedges (Shur et al., 2004). The deposit has been impacted by fluvial thermal erosion that operated preferentially along ice wedges (Bray et al., 2006). An emphasis of this study is the comparison of the creep response in relation to soil cryostructure. Cryostructure is the pattern of ice inclusions within frozen soils and depends on the depositional and cryogenic genesis of the permafrost soils (Katasonov, 1960). Within the tunnel, cryostructures are a strong indicator of the original or modified permafrost deposits (Bray et al., 2006). The soil cryostructures tested include micro-lenticular, massive, and reticulate-chaotic. Samples include undisturbed and remolded Fairbanks silt from the permafrost tunnel, ice from massive ice wedges, and basal ice and englacial ice from the Matanuska Glacier, Alaska. A brief description of the various soils as grouped by cryostructure and ice types is provided below. Tables 1 and 2 list the basic gravimetric and volumetric properties for the samples used during the relaxation test phase of the testing program. All undisturbed samples were obtained with a SIPRE corer or continuous diamond coring bit and remained in a frozen state throughout sampling, transport, and storage.

The particle size and soil mineralogy remains nearly identical despite changes in cryostructure. The particle distribution for undisturbed soils with micro-lenticular and reticulate-chaotic cryostructure and remolded soils with massive cryostructure is shown in Fig. 1. The particle size distributions fall within a narrow zone with average particle distribution consisting of 6.9% sand, 85.5% silt, and 7.6% clay.

Soils with micro-lenticular cryostructure represent undisturbed samples and are diagnostic soils of the original Pleistocene syngenetic permafrost. The soils are very ice-rich, unconsolidated sediments with thaw strains averaging 0.4 to 0.6. Typical gravimetric water contents range from 90% to 180%, with water contents exceeding 200% not uncommon. Typical frozen bulk densities range from 1.25 $g\ cm^{-3}$ to 1.35 $g\ cm^{-3}$ and organic contents ranging from 2% to 10%. The soil contains small straight to wavy, lenticular shaped

Table 1
Summary of soil properties for undisturbed permafrost samples.

No.	Sample	Cryostructure	γ_{bf} ($g\ cm^{-3}$)	γ_{dry} ($g\ cm^{-3}$)	w_{grav} (%)	$w_{vol,ice}$ (%)
23	S_29.9 m RWH 3–17 cm	VML	1.28	0.57	123.1	76.6
24	S_29.9 m RWH 34–50 cm	VML	1.29	0.59	118.9	76.4
25	S_29.8 m RWH	VML	1.25	0.51	144.8	80.6
26	S_30.5 m block RWV core 3	HML	1.32	0.62	111.3	75.4
27	S_30.5 m block RWV core 4	HML	1.34	0.65	108.0	75.8
28	S_30.5 m block RWV core 5	HML	1.33	0.66	100.8	72.8
29	S_30.5 m block RWV core 6	HML	1.31	0.61	115.5	76.1
30	S_30.5 m RWH core a	VML	1.35	0.66	102.8	74.2
31	S_71.6 m RWH core a	RC	1.47	0.84	74.0	68.0
32	S_71.6 m RWH core b	RC	1.50	0.87	71.4	67.8
33	S_71.6 m RWH core c	RC	1.42	0.76	86.2	71.2
34	S_71.6 m RWH core e	RC	1.33	0.62	115.7	77.8
35	IW core a	IW	0.89	–	–	96.9
36	IW core 4	IW	0.90	–	–	97.0
37	IW core 5	IW	0.88	–	–	95.2
38	IW core 6	IW	0.92	0.03	–	95.9
39	IW core 9	IW	0.89	0.01	–	95.8
40	IW core 10	IW	0.89	0.02	–	94.9
41	IW core 11	IW	0.90	–	–	97.2
43	Matanuska basal ice core 2	BI	0.95	0.02	–	–
44	Matanuska basal ice core 3	BI-ML	1.40	0.76	83.1	69.0
45	Matanuska glacial ice core 3	GI	0.92	–	–	–
46	Matanuska glacial ice core 5	GI	0.93	–	–	–

γ_{bf} is frozen bulk density, γ_{dry} is dry density, w_{grav} is gravimetric water content, $w_{vol,ice}$ is the volumetric ice content. Sample designation: S_29.9 m RWH 3–17 cm indicates sampled was obtained at station 29.9 m, cored from the right wall horizontally at a depth of 3–17 cm.

Table 2
Summary of soil properties for remolded samples.

No.	Sample	Cryostructure	γ_{bf} ($g\ cm^{-3}$)	γ_{dry} ($g\ cm^{-3}$)	w_{grav} (%)	$w_{vol,ice}$ (%)
49	RM core 1	RM	1.59	1.05	52.5	59.7
50	RM core 5	RM	1.57	1.04	50.6	57.2
51	RM core 6	RM	1.59	1.06	50.2	58.0
52	RM core 8	RM	1.54	1.01	51.5	56.8
53	RM core 9	RM	1.53	1.03	48.2	54.1
54	RM core 10	RM	1.53	0.98	55.9	59.8
55	RM core 11	RM	1.55	1.01	52.4	57.8
56	RM core 12	RM	1.55	1.01	52.7	58.1
57	RM core 13	RM	1.56	0.99	57.0	61.6
58	RM core 14	RM	1.56	1.00	55.5	60.5
59	RM core 15	RM	1.53	0.98	55.7	59.5
60	RM core 17	RM	1.51	0.96	57.1	59.8
61	RM core 18	RM	1.52	0.96	58.6	61.3
62	RM core 19	RM	1.54	1.01	51.9	57.1
63	RM core 20	RM	1.55	1.00	55.1	59.9

RM refers to remolded soil with massive cryostructure, γ_{bf} is frozen bulk density, γ_{dry} is dry density, w_{grav} is gravimetric water content, $w_{vol,ice}$ is the volumetric ice content.