Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1993

Isotach Behaviour of Organic Clays and Peats

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ABSTRACT: Accurate prediction of long-term settlement in soft soils is critical for the safe and cost-effective design of infrastructure, particularly in regions underlain by organic clay and peat. While isotach-based constitutive models are widely used to account for creep deformation in clays, their validity for organic soils such as organic clay and peat remains uncertain. This study presents a series of constant rate of strain (CRS) oedometer tests performed on Bleskensgraaf clay and Zegveld peat, including stepwise strain rate variations across a wide range (10^{-4} to 10^{-8} s^{-1}) of strain rates. The study emphasizes the need for constitutive models that are validated against a strain rate regime representative of field conditions.

Results confirm that both materials exhibit fixed isotachs when plotted on strain vs. the logarithm of effective stress. For clay, isotachs remain approximately linear and parallel in the normally consolidated range. Furthermore, the isotachs appear to be equidistant for log-cycle differences in strain rate, supporting the linear model within the tested strain rate regime. In contrast, peat shows an increased divergence of isotachs with decreasing strain rate resulting in increasing $C_{\alpha\varepsilon}$ / C_c ratios suggesting non-linear creep behaviour on a logarithmic time scale. These findings imply that the use of linear isotach models for organic soils, particularly peat, may lead to underestimation of long-term (creep) settlements.

KEYWORDS: Isotach, strain rate, creep, organic clay, peat.

1 INTRODUCTION

Building infrastructure on soft soils such as organic clay and peat presents unique geotechnical challenges due to their high compressibility and susceptibility to time-dependent deformation. The primary contributor to long-term settlement in these types of soils is creep: a continuous deformation that occurs under sustained loading. Accurate prediction of this long-term behaviour is essential for the design and maintenance of infrastructure, particularly in regions with extensive deposits of highly compressible organic soils.

Among existing constitutive models, isotach-based models are widely used to describe and predict the long-term deformation of soft soils. These models offer a theoretical framework which relates strain rate to effective stress and strain. These frameworks are embedded in many settlement prediction models commonly used to model the deformation of clay and peat. Most of the theoretical foundations and experimental validation of these models have been advanced using inorganic clays as described by Watabe & Leroueil (2012) and by Tanaka & Tsutsumi (2016).

However, large parts of the Netherlands are underlain by highly organic soils such as organic clay and peat. Important questions remain regarding the extent to which these models can be reliably extended to these types of soft soils.

2 OBJECTIVE

The study aims to clarify the validity and limitations of linear isotach theory to describe and model the deformation behaviour of organic rich soft soils by analysing the results of a series of Constant Rate of Strain (CRS) oedometer tests performed on both organic clay and peat from the Netherlands.

The tests include long-duration, low-strain-rate phases that are rarely captured in routine laboratory tests and that are closer to the very low strain rates of field conditions. The performed tests include stepwise changes in strain rate aimed to investigate the constitutive behaviour under varying loading conditions. Particular attention is paid to the response following a change in strain rate, as this behaviour is critical for assessing the robustness of isotach-based models.

The study is part of a broader effort to improve the theoretical foundation and practical application of settlement models in soft soil engineering, with particular relevance to infrastructure built on organic compressible subsoils.

3 STATE OF THE ART

3.1 *Oedometer tests*

In soft soil engineering, one-dimensional consolidation behaviour is typically investigated using either the Incremental Loading (IL) test or the Constant Rate of Strain (CRS) test. While the IL test has traditionally been the standard method, applying sequential load steps and allowing for dissipation of excess pore pressures and creep within each step, it produces segmented limited stress–strain data points and generally requires long test durations. The CRS test by contrast deforms the soil sample continuously at a controlled rate of displacement. This produces continuous stress–strain data and enables a more precise determination of settlement parameters.

3.2 *Rheological model*

Isotach models presume that the one-dimensional viscoplastic strain rate, or creep rate, is a function of the two state variables effective stress (σ') and strain (ε), as shown in equation 1. With this premise, the strain rate can be plotted in effective-stress-strain diagrams and contouring of strain rate yields lines of constant strain rate ($\dot{\varepsilon}$), called isotachs. In Greek 'iso' translates to 'equal' and 'tachy' to 'velocity'.

$$\dot{\varepsilon}_{vp} = f(\sigma', \varepsilon) \tag{1}$$

Šuklje (1957) was the first to draw isotachs based on IL oedometer-test data and coined the term 'isotach'. In another seminal work, Leroueil et al. (1985), provided key constraints on 'isotach behaviour' using CRS tests on Batiscan clay as shown in Figure 1. Their findings largely confirmed that the strain rate is a function of effective stress and strain. Leroueil et al. (1985) report isotach crossing corresponding to a strain rate of $\dot{\varepsilon} = 1.69 \cdot 10^{-8}$ s^{-1} as shown in Figure 1. This isotach crossing is attributed to thixotropic behaviour (Leroueil et al., 1985).

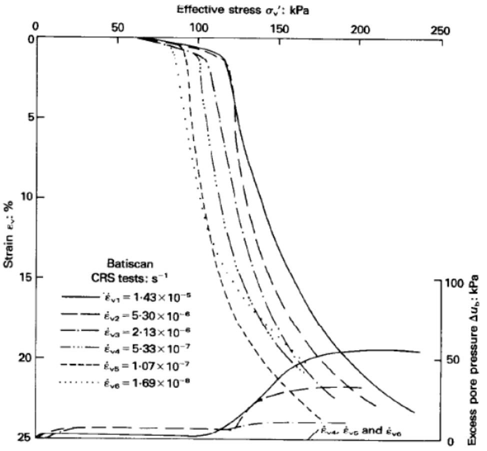

Figure 1. Results of CRS tests on Batiscan clay (Leroueil, 2006).

Postulated by Šuklje (1957) and later advanced by Bjerrum (1967), Leroueil (1985) and Den Haan (1994) among others, the isotach framework form the backbone of widely used settlement models for soft soil engineering.

3.3 *The linear isotach framework*

Different forms of isotach models are used in engineering practice. The isotach framework as implemented in the Netherlands is shown in Figure 2. It is referred to here as the linear isotach framework, and is built on three fundamental concepts:

- A unique relationship exists between strain (ε), effective stress (σ'), and strain rate ($\dot{\varepsilon}$).
- Isotachs are linear and parallel when plotted on strain vs. the logarithm of effective stress.
- The mutual distance between different isotachs remains constant for log-cycle differences in strain rate when plotted on strain vs. the logarithm of effective stress.

In this framework, the total accumulated (creep) strain is stress-independent as shown in Figure 2 where stress path A-B and C-D both result in the same amount of (creep)strain. Figure 2 shows void ratio *e* on the vertical axis. Linear or natural strain are more commonly used. Each choice is associated with distinct settlement parameters as shown in Table 1.

Table 1. Compression-stress definitions.

Compression axis	Reloading-swelling	Primary compression	Secondary compression
Void ratio	C_r	C_c	$C_{\alpha e}$
Linear strain	*RR*	CR	C_α
*Natural strain**	a	b	c

* Development of effective stress evaluated on natural logarithmic scale instead of logarithmic scale with base 10.

The primary compression parameter determines the steepness of the (IL or CRS) compression curve in the normally consolidated range and is thus a measure of the inclination of different isotachs. The secondary compression parameter describes the (vertical) spacing between isotachs with one log-cycle difference in strain rate. In the linear isotach framework, the primary compression index and the secondary compression index are constant and hence stress and strain rate independent, as shown in Figure 2. Constancy, therefore, also applies to the ratio of the secondary and the primary compression index $C_{\alpha e}$ / C_c.

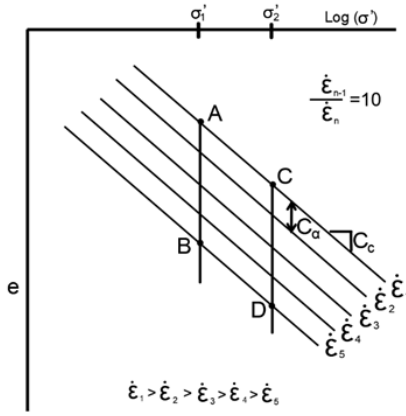

Figure 2. Definition of linear isotach framework.

3.4 *Existing challenges to the linear framework*

Several existing studies have provided indications/evidence that appear to limit the applicability range of the linear isotach framework.

Watabe & Leroueil (2012), for instance, have shown that $C_{\alpha e}$ / C_c tends to decrease with decreasing strain rate for the tested inorganic worldwide clays. This suggests that the spacing between different isotachs reduces with decreasing strain rate. Different researchers (Leroeuil, 2006; Kawabe & Tatsuoka, 2013; Watabe & Leroeuil, 2015) even hypothesize a limit timeline, an isotach beyond which further strain accumulation is absent (or negligible). In such models, $C_{\alpha e}$ / C_c gradually reduces to zero as the soil's state approaches the limit timeline, implying that secondary compression is finite at infinite time (Watabe & Leroueil, 2015).

In recent years, isotachs have also been shown to become distorted during unloading or in over-consolidated state due to mechanisms such as swelling and structural rearrangement of the soil matrix (Nash & Brown, 2015; Vergote et al., 2021). These effects alter the strain rate response and violate the assumptions of fixed parallel equidistant isotachs.

4 MATERIALS AND METHODOLOGY

4.1 *Samples and sample characteristics*

The IL- and CRS tests have been conducted at the Deltares Geotechnical Laboratory in Delft, the Netherlands. The clay samples were extracted from the Bleskensgraaf monitoring site, and the peat samples used for testing were extracted from the Zegveld polder. To retrieve high-quality undisturbed samples, the Deltares Large Diameter Sampler (DLDS) was used. The DLDS is a down-hole tube sampler designed to extract samples with a diameter of 0.4 m and a height of 0.5 to 1.0 m, enabling both conventional testing and large-scale laboratory experiments (Zwanenburg, 2017). Characteristics of the used clay and peat samples are shown in Tabel 2 and 3 respectively.

Table 2. Bleskensgraaf clay characteristics.

Parameter	Symbol	Value range	Unit
Depth	*d*	2.9 – 3.1	m - MSL
Water content	*w*	59 - 161	%
Natural density	*γ*	12.1 – 15.4	kN/m^3
Initial void ratio	e_0	1.6 – 4.0	-
Loss on ignition	*LOI*	3.6 – 15.9	%

Each of the 12 organic clay samples were prepared with an initial height of 20 mm and 62.5 mm in diameter, in accordance with standard CRS procedures. Two additional IL-tests were performed in order to assess the influence of unloading steps.

The 6 peat samples were prepared with an initial height of 30 mm and 62.5 mm in diameter to allow for larger displacements per phase. Computed tomography (CT) scans of the used peat samples confirm the dual-porosity structure of the peat where large roots, sedge, reeds and wooden branches are abundantly distributed throughout the peat layers. More details of the tested peat is described by Massop et al. (2024).

Table 3. Zegveld peat characteristics.

Parameter	Symbol	Value range	Unit
Depth	*d*	1.6 – 1.8	m - MSL
Water content	*w*	502 - 525	%
Natural density	*γ*	10.4 – 10.5	kN/m^3
Initial void ratio	e_0	8.1 – 8.3	-

4.2 *Strain rate range*

The CRS tests were performed both with a constant rate of displacement and with varying displacement rates during individual tests. The latter enables visualization of parts of different isotachs. Strain rates between 10^{-4} to 10^{-8} s^{-1} were used with a maximum duration of 56 days per individual test. The lower limit follows from device specifications and test duration, while for high strain rates, the generation of pore pressure restricts applicable strain rates. Variation of rates in individual tests is elucidated in the results chapter. In spite of the low strain rates used in the experiments, field strain rates still are commonly several orders of magnitude lower, often ranging from 10^{-9} to 10^{-12} s^{-1} (Leroueil, 2006).

4.3 *Use of natural strain*

Log(σ') – ε curves, such as isotachs, cannot be linear to very large strain when linear, or Cauchy strain, ε^C, is used as shown by the right panel of Figure 3. This follows from the fact that the test sample or soil thickness cannot reduce to zero, irrespective of the load level. Consequently, compression ratios, based on linear strain, are not constant to high stress or strain. To deal with the non-linearity the usage of natural strain as defined in equation 2 is preferable (Den Haan, 1994). Natural strain is therefore used to represent the change in sample height of the performed CRS tests.

$$\varepsilon^H = \int_{h-h_0}^{h-h_0-\Delta h} \frac{dh}{h} = -\ln\left(\frac{h_0-\Delta h}{h_0}\right) = -\ln(1-\varepsilon^c) \qquad (2)$$

5 RESULTS

5.1 *Bleskensgraaf clay*

The excess pore pressure profile which develops in a CRS test reflects the equilibrium between pressure dissipation by drainage and pressure enhancement by loading and compression. Higher strain rates induce larger pore pressures. This in turn may lead to inaccurate calculated effective stress in the sample due to a non-homogeneous stress distribution within the sample. Moreover, during the tests, permeability reduces due to a reduction in void ratio. This enhances pore pressure over the duration of the tests. The left panel of Figure 3 shows the typical results of one of the performed CRS tests on organic clay. The difference between the total- and effective stress throughout the test is minimal. The measured generated excess pore pressure is limited throughout the CRS test, thereby not compromising the development of calculated effective stress.

The CRS tests show that parts of the stress–strain curve with the same displacement rate fall on top of each other, both for constant and varying strain rate test, when no unloading steps are applied. For example, as shown in Figure 4, the acceleration at the end of the test, from a displacement rate of 0.00108 mm/h to 0.108 mm/h, brings the stress–strain curve back to the same isotach as was found at an earlier stage of the tests at the same displacement rate. From this it is concluded that the compression behaviour of the organic clay does not show stress-dependency when continuously loaded.

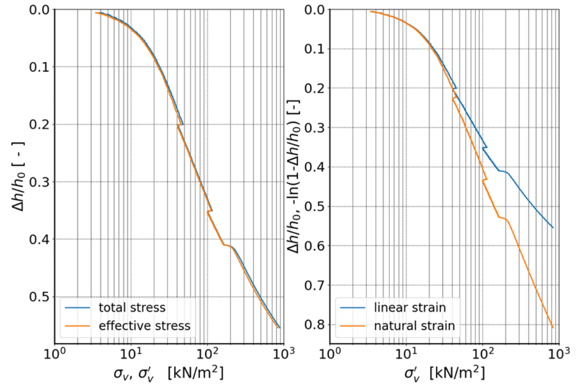

Figure 3. Left: CRS test curves on Bleskensgraaf clay plotted against total stress and effective stress. Right: Influence of different strain notation on the compression behaviour. Strain rate regime of both graphs $1.5\cdot10^{-8}$ s^{-1} - $1.5\cdot10^{-6}$ s^{-1}.

In contrast to the findings of Lerouel at al. (1985, 2006) all isotachs, in the strain rate range of the performed tests, run parallel in the normally consolidated range, even for the lowest displacement rate of $1.5\cdot10^{-8}$ s^{-1}. No evidence of isotach crossing or distortion was found. That is, the thixotropic behaviour observed in the test results on Batiscan clay, Leroueil et al. (1985), is not found in the test results of this study.

The CRS tests on Bleskensgraaf clay provide partial support for the second fundamental concept of the linear isotach framework. Isotachs show a high degree of parallelism in normally consolidated range during the first phase of testing when evaluated using natural strain or linear strain. However, at larger strain, parts of different isotach are only linear when evaluated using natural strain, as shown by the right panel of Figure 3. Isotachs plotted on linear strain start to bend when reaching a strain level around 50%. Accounting for the end of layer effect by visualizing the results using natural strain renders linear isotachs as shown in Figure 4.

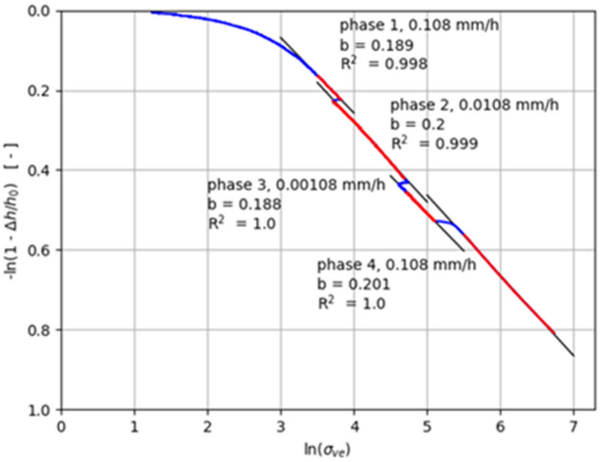

Figure 4. Typical stress-strain curve CRS test on Bleskensgraaf clay.

Additional IL tests confirm that non-linear isotachs are found after unloading steps are applied to the clay sample. This concurs with the findings of Vergote at al. (2021) who only reported isotach distortion after unloading. For increasing over consolidation ratio (OCR) an increasing difference is found between the observed and predicted displacement rate. Even for small unloading steps the difference might reach several orders in magnitude. When no unloading steps are applied however, the visualized isotachs from both constant and variable strain rate tests generally appear parallel in normally consolidated stress range.

The performed CRS tests on Bleskensgraaf clay largely support the third fundamental concept regarding the equidistant nature of the isotachs. Only at higher strain rates, mild deviations are noted. However, these deviations may also reflect a bias in pore pressure correction, which could lead to overestimated effective stresses and incorrectly increasing isotach spacing.

The test results do not provide evidence for a progressive decrease in isotach spacing with decreasing strain rate as reported in the literature discussed in section 3.4.

5.2 *Zegveld Peat*

Figure 5 shows a test result for Zegveld peat in a diagram using natural strain. The compression curve segments shift in a consistent manner in the diagram for the applied changes in strain rate. The test results, therefore, provide a strong indication that a unique relationship between strain rate, effective stress and strain exists, which supports the first fundamental concept of the linear isotach framework.

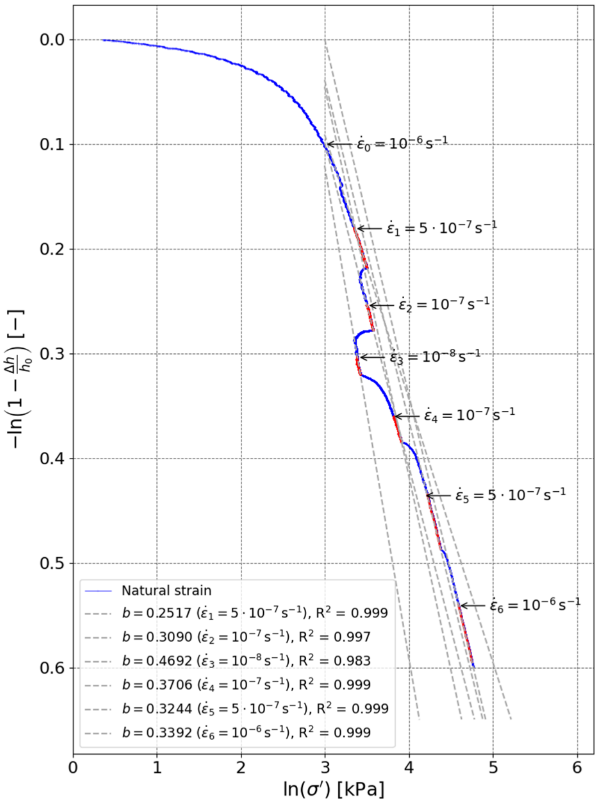

Figure 5. Typical stress-strain curve CRS test on Zegveld peat.

However, the second fundamental concept of the linear isotach framework clearly is not met below a strain rate $\dot{\varepsilon} < 10^{-7}$ s^{-1}. Only in the strain rate regime of 10^{-7} s^{-1} to 10^{-6} s^{-1} do the trajectories of parts of different isotachs show a decent degree of parallelism as indicated by the inclination (b) of the tangent lines through parts of different isotachs marked in red in Figure 5. The degree of parallelism is shown to decrease with a decrease in strain rate. This observation is made in all five long-term CRS tests.

The CRS tests on Zegveld peat also do not support the third fundamental concept of the linear isotach model. The mutual distance between different isotachs is shown to increase with decreasing strain rate. This observation is made in all five long-term tests and indicates a non-linear creep rate with the logarithm of time. This may be explained by tertiary compression which is known to occur in peat (Dhowian et al., 1980).

The deviation from the linear isotach framework was further documented in an additional creep test, results of which are displayed in Figure 6. In this test, the sample was loaded past the yield stress with $\dot{\varepsilon} = 10^{-6}$ s^{-1}. Subsequently, the CRS apparatus was switched to load controlled, keeping the effective stress constant for a total of 16 days. Then, the loading mechanism of the CRS apparatus was switched again to displacement controlled returning to the initial strain rate of $\dot{\varepsilon} = 10^{-6}$ s^{-1}.

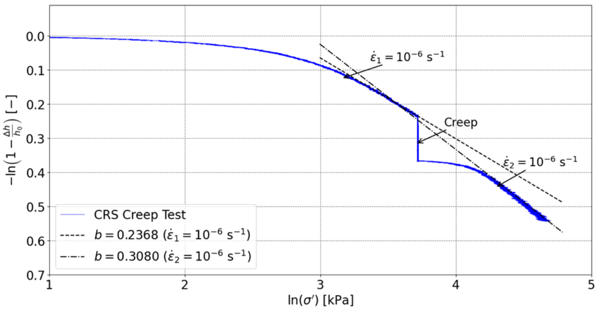

Figure 6. Stress-strain development of CRS test on Zegveld peat including creep phase showing non-constant isotach spacing.

Figure 6 shows how after completion of the creep phase, the compression curve does not return to the (linear) isotach inferred from the test prior to initiation of the creep phase. This is demonstrated in Figure 6 by the different slopes of tangent lines drawn through part of the CRS test prior and after the creep phase, both corresponding to a strain rate of $\dot{\varepsilon} = 10^{-6}$ s^{-1}. From this difference in slope, it is concluded that the second fundamental concept of the linear isotach model of parallel isotachs is not met. Note that the constant load phase was started after exceeding the initial yield stress.

At the start of the creep phase the sample is loaded with a displacement rate corresponding to $\dot{\varepsilon} = 10^{-6}$ s^{-1}. Analysis of the development of accumulated creep strain over time allows for the estimation of strain rates at different moments throughout the creep phase of the CRS test. As time progresses, and creep strain accumulates, isotachs corresponding to reducing strain rates are crossed. Figure 7 shows the visualisation of natural strain development with corresponding natural strain rate of the creep phase of the performed CRS test in blue. It shows that the strain rate at the start of the creep phase is equal to $\dot{\varepsilon} = 10^{-6}$ s^{-1}. A straight line is plotted through the datapoints indicated in Figure 7. If isotachs are equidistant for log-cycle difference in strain rate, the strain rate would decrease linearly with corresponding natural strain level. Figure 7 shows that this might be the case at the start of the creep phase. However, extrapolation of the initial trend shows that after some time the natural creep strain rate is larger than predicted. This demonstrates a non-constant isotach spacing for log-cycle difference strain rates. The third fundamental concept of the linear isotach model is therefor not met within the evaluated strain rate regime.

The inter-isotach distance is shown to increase with decreasing strain rate yielding similar results as the five CRS tests performed with varying strain rates. The CRS creep test thus reinforces the conclusion that Zegveld peat exhibits a non-constant secondary compression index resulting in non-linear creep behaviour on logarithmic timescale.

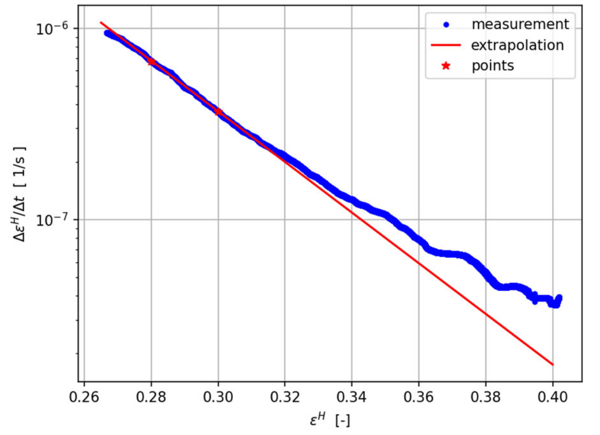

Figure 7. Visualisation of non-linear decrease in strain rate over natural strain during creep phase of the CRS test.

6 COMPARISON

The results of the compression behaviour of Bleskensgraaf clay and Zegveld peat reveal notable differences in how well the assumptions of the linear isotach framework hold across these two soft soils. Table 4 presents a concise overview of the different degrees of validity of the linear isotach assumptions for both materials.

Table 4. Comparative table linear isotach model assumptions.

Assumption	Bleskensgraaf clay	Zegveld peat
Fixed isotachs	Supported	Supported
Parallel isotachs	Partially supported	Unsupported
Equidistant isotachs	Largely supported	Unsupported

A hypothesis that explains the deviating peat behaviour is the bio – chemical aspects that play a role in the deterioration of organic material. Aerobic and anaerobic processes will contribute to the measured settlement, but are not explicitly incorporated in Eq. (1). Additional study should verify this hypothesis.

7 DISCUSSION

7.1 *Strain rates of field conditions and CRS testing*

The laboratory tests do not show full support for the core assumptions of the linear isotach framework. It is important to stress that these finding apply to a range of strain rates that could be applied by the used CRS apparatus. The lowest possible strain rate that could be achieved by the equipment is still orders in magnitude larger than those observed in the field.

Figure 8 shows different strain rates from field projects in peat areas in the Netherlands. Data from long-term monitoring of settlement plates in the Zegveld polder and a corner reflector in the Gaasp polder illustrate the lower bound of field strain rates of peat meadows unaffected by construction. Deformation analysis of the A2 highway, built on approximately 6 meters of peat, during construction and years after construction shows the estimated strain rate reducing over time. These field projects highlight the difference in order of magnitude of strain rates between field conditions in peat and those achievable in conventional CRS testing. The order of magnitude of these field strain rates in peat is comparable to the strain rate regime of in situ clays as described by Leroueil (2006).

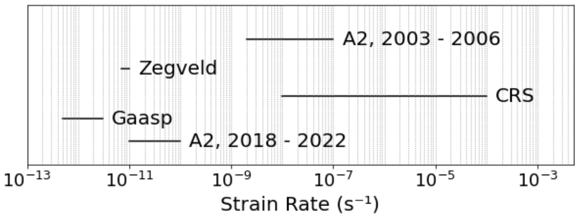

Figure 8. Difference in strain rate regime observed in laboratory testing and situ for different locations in The Netherlands.

7.2 *Potential underestimation of long-term settlement*

Recent publications on isotach modelling of clays include a reducing inter-isotach distance with decreasing strain rate including an end-of-creep isotach (Leroeuil, 2006; Kawabe & Tatsuoka, 2013; Watabe & Leroeuil, 2015). The CRS tests on organic clay don't comply to these findings and show relatively constant isotach spacing for log-cycle differences in strain rate. Consequently, given the difference in order of magnitude in strain rate between laboratory and field conditions, implementation of a reducing mutual distance between different isotachs could result in severe under-estimation of long-term (creep) settlement.

Moreover, the mutual distance between different isotachs in Zegveld peat is shown to increase with a decrease in strain rate resulting in a changing creep rate on logarithmic timescale. This is illustrated in Figure 9 where the primary compression index and the secondary compression index are stress- and strain rate dependent. Stress paths A-B and C-D both result in different amounts of accumulated (creep) strain. Not accounting for this divergence of isotachs could result in the underestimation of long-term settlement.

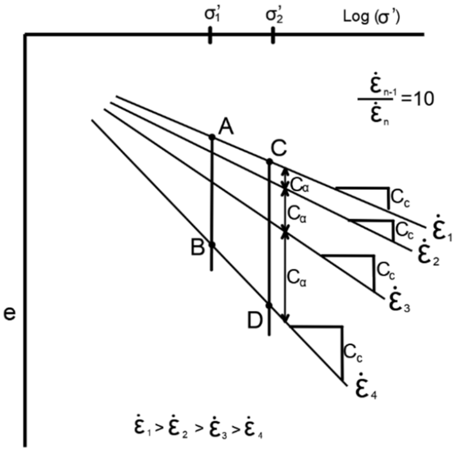

Figure 9. Diverging isotachs as observed in the CRS tests on Zegveld peat result in stress- and strain rate dependent settlement parameters.

8 CONCLUSIONS

This study aimed to investigate the validity of the linear isotach framework based on fixed parallel equidistant isotachs in describing the time-dependent compression behaviour of soft organic soils. Several important insights are gained regarding the applicability of this theoretical framework.

For Bleskensgraaf clay, the linear isotach framework is generally supported within the tested strain rate range (10^{-8} to

10^{-5} s^{-1}) under normally consolidated conditions. Isotachs are largely parallel and equidistant. The ratio of $C_{\alpha e}$ / C_c appears constant, consistent with the linear theoretical framework. However, deviations were observed following unloading, where isotachs are distorted and strain rates diverge from predictions, confirming the model's limitations under more complex stress paths.

In contrast, Zegveld peat does not conform to the assumptions of the linear isotach framework, particularly at strain rates below 10^{-7} s^{-1}. Isotachs are found to be non-linear and the mutual distance between different isotachs is shown to increase with decreasing strain rate. Subsequently, the $C_{\alpha e}$ / C_c ratio increases, indicating a non-linear creep response on a logarithmic time scale. This behaviour also contradicts the concept of a limit timeline and suggests that traditional isotach-based models may underestimate long-term settlement in peat.

Overall, the findings demonstrate that while the linear isotach framework may reasonably capture the behaviour of inorganic clay under continued loading, its assumptions do not generalize well to peat. The increasing isotach spacing and non-linear creep behaviour observed in peat indicate the need for more flexible constitutive models that allow for strain-rate-dependent settlement parameters. This becomes particularly important for field applications where strain rates are several orders of magnitude lower than those achievable in laboratory conditions.

Therefore, to further improve the applicability of the isotach framework for organic soils a further validation for strain rates representative of field conditions is required. Additional studies should include bio-chemical aspects resulting in volume reduction of organic material.

9 ACKNOWLEDGEMENTS

The authors wish to thank Rijkswaterstaat and the TKI-delta technology programme for providing support for the tests analysed in this study.

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