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The effect of degree of saturation and cyclic stress ratio on the resilient response of railway formation material during principal stress rotation

L'effet du degré de saturation et du rapport de contrainte cyclique sur la réponse élastique du matériau de la formation ferroviaire pendant la rotation de contrainte principale

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ABSTRACT: This paper investigates degrees of saturation and magnitudes of cyclic shear stress for which principal stress rotation may have a significant effect on the resilient response of a railway formation material. Advanced cyclic triaxial and hollow cylinder soil element tests in apparatus equipped with high accuracy local instrumentation were carried out on a clay (11%) sand mixture. The results show that the resilient stiffnesses measured in the cyclic triaxial apparatus (without principal stress rotation) and the HCA (with principal stress rotation) increased by a factor of about 6 as the degree of saturation decreased to about 45%. In saturated conditions, increases in the magnitude of cyclic shear stress were found not to have a major effect below a certain cyclic shear stress threshold, but when the cyclic shear stress threshold was exceeded significant stiffness degradation occurred. The cyclic shear stress threshold in free-to-drain conditions was similar to the cyclic shear stress in the soil immediately below a ~ 0.3m deep ballast bed, but comfortably greater than the cyclic stress at a depth of ~1m below the sleeper base. In undrained conditions, the cyclic shear threshold was generally similar to the cyclic shear stress at a depth of ~1m below the sleeper base.

RÉSUMÉ : Cet article étudie les degrés de saturation et les amplitudes de la contrainte de cisaillement cyclique pour lesquelles la rotation de contrainte principale peut avoir un effet significatif sur la réponse élastique d'un matériau de formation ferroviaire. Une série d'essais cycliques avancés d'éléments de sol triaxiaux et cylindriques creux dans des appareils équipés d'une instrumentation locale de haute précision a été réalisée sur un mélange de sable argileux à 11%. Les résultats montrent que les raideurs élastiques mesurées dans l'appareil triaxial cyclique (sans rotation de contrainte principale) et le HCA (avec rotation de contrainte principale) ont augmenté d'un facteur d'environ 6 lorsque le degré de saturation diminuait à environ 45%. Dans des conditions saturées, les augmentations de l'amplitude de la contrainte de cisaillement cyclique ne se sont pas avérées avoir un effet significatif en dessous d'un certain seuil de contrainte de cisaillement cyclique, mais lorsque le seuil de contrainte de cisaillement cyclique était dépassé, une dégradation significative de la rigidité s'est produite. Le seuil de contrainte de cisaillement cyclique dans des conditions de drainage libre était similaire à la contrainte de cisaillement cyclique dans le sol immédiatement en dessous d'un lit de ballast d'environ 0,3 m de profondeur, mais confortablement supérieur à la contrainte cyclique à une profondeur d'environ 1 m sous la base de la traverse. Dans des conditions non drainées, le seuil de cisaillement cyclique était généralement similaire à la contrainte de cisaillement cyclique à une profondeur d'environ 1 m sous la base de la traverse.

KEYWORDS: Degree of saturation; suction; principal stress rotation; cyclic stability; resilient stiffness.

1 INTRODUCTION.

Seasonal variations in the water content of railway formations are likely to lower the water table, resulting in unsaturated zones and the development of suction in the soil (Fredlund, 2006). The influence of suction on the stiffness of soils is regulated by bulk water or menisci water effects. Bulk water regulated behaviour prevails for suctions less than the air-entry value; and with increasing suction the soil response shifts to menisci-water regulated behavior (Mancuso et al., 2002).

It has been shown that increases in suction generally increase the soil stiffness, resulting in a reduction in the magnitude of strains that occur (Hoyos et al., 2015, Han and Vanapalli, 2016).However, the influence of suction on the resilient stiffness of railway formation materials during cyclic shear stress changes representative of the stress paths of railway formation material is not fully quantitatively understood (Brown, 1996). This paper investigates degrees of saturation and magnitudes of cyclic shear stress for which principal stress rotation may have a significant effect on the resilient response of a railway formation material.

2 MATERIALS AND METHOD

2.1 *Materials*

The investigated material, an 11% clay content sand clay mix, was selected so as to replicate the average particle size distribution within the grading envelope of the South African Coal Line railway track foundation (Gräbe and Clayton, 2009; 2014). The particle size distribution of the 11% clay content mix, along with the grading envelope of the South African Coal Line railway track foundation material, is shown in Fig.1. The 11% clay content material was obtained by mixing specific amounts of Leighton Buzzard Sand Fractions B (LBSFB), C (LBSFC) and D (LBSFD); Hymod Prima Clay (HPC); and Oakamoor HPF5 silica flour silt (Mamou et al., 2017, 2018 Blackmore et al., 2020).

The modified Proctor compaction technique was used for specimen preparation, modelling the in situ material placement process. Specimens were prepared by compaction to a dry density of ~2.10Mg/m3, at a range of water contents.

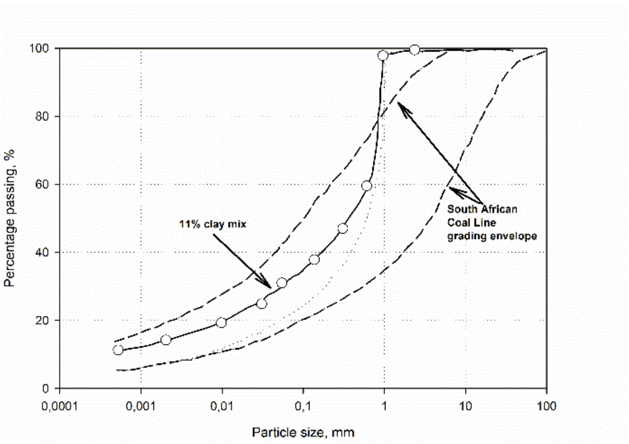

Figure 1. Particle size distribution of the 11% clay content mix along with the grading envelope of the South African Coal Line railway track foundation material redrawn from Gräbe and Clayton (2009).

2.2 *Apparatus*

The cyclic principal stress rotation tests for both unsaturated and saturated conditions were carried out using a hollow cylinder apparatus (HCA); data were interpreted using the Hight et al. (1983) framework of average stresses and strains. To obtain realistic stiffness values, axial strains were measured locally on the specimen to exclude errors associated with the misalignment of specimen ends, bedding, and apparatus compliance (Jardine et al.,1984; Clayton & Khatrush, 1986; Cuccovillo & Coop, 1997; Clayton, 2011). In the saturated cyclic principal stress rotation tests; drainage was from the bottom of the specimen only. Pore water pressures were measured independently at the top and bottom of the specimen using Druck PDCR810 pressure transducers (Mamou et al., 2017, 2018, 2019, 2020). In unsaturated conditions, cyclic tests without principal stress rotation were carried out using a cyclic triaxial apparatus (CTX). In the unsaturated CTX and HCA tests, no pore water or air pressure measurements were made; specimens were tested drained and the back-pressure connection was vented to the atmosphere (Blackmore et al., 2020).

2.3 *Testing*

In the saturated cyclic principal stress rotation tests, specimens were isotropically consolidated to an effective stress of 30kPa, then subjected to cycles of axial stress of 0 to 30kPa, together with cycles of shear stress of gradually increasing magnitude. The peak magnitude of the applied cyclic change in shear stress Δτθz was initially set to the value indicated by the numerical analyses presented by Powrie et al. (2007) for a soil element near the bottom of a railway track foundation extending to a depth of 1 m below the sleeper base (|Δτθz| = 8.5 kPa). The saturated cyclic principal stress rotation tests were carried out under both undrained and free-to-drain conditions, to explore the range of drainage conditions that might occur in the field. Table 1 summarizes the stress cycles applied in all of the saturated cyclic principal stress rotation tests. The first letter identifies the drainage condition; U for undrained and F for free-to-drain tests. The number that follows is the magnitude of cyclic shear stress imposed on the specimen. Before each undrained test, the specimen was subjected to a free-to-drain cyclic PSR preloading stage to reduce the effects of specimen preparation on the subsequent results. The free-to-drain preloading stages of undrained tests are denoted by the letter P.

Table 1: Summary of the saturated cyclic principal stress rotation tests

(s) Undrained tests

Cyclic preloading stage

Test	$\Delta\tau_{\theta z}$	Number of cycles
FB8.5P	$\Delta\tau_{\theta z}$ =+8.5 → −8.5kPa	708
FB11.5P	$\Delta\tau_{\theta z}$ =+11.5 → −11.5kPa	700

Undrained stage

Test	Test stage	$\Delta\tau_{\theta z}$	Number of cycles
U8.5	a	$\Delta\tau_{\theta z}$ =+8.5 → −8.5kPa	710[i]
U11.5	b	$\Delta\tau_{\theta z}$ =+11.5 → −11.5kPa	321

[1]Halfway through UB8.5P, owing to a fault in the control system, the axial stress $\Delta\sigma_z$ remained constant and equal to 15kPa rather than being cycled between 0 and 30 kPa, while the shear stress continued to be cycled between the desired values.

(b) Free to drain tests

Test	Test stage	$\Delta\tau_{\theta z}$	Number of cycles
F8.5	a	$\Delta\tau_{\theta z}$ =+8.5 → −8.5kPa	705
F11.5	b	$\Delta\tau_{\theta z}$ =+11.5 → −11.5kPa	715
F14.5	c	$\Delta\tau_{\theta z}$ =+14.5 → −14.5kPa	721
F17.5	d	$\Delta\tau_{\theta z}$ =+17.5 → −17.5kPa	708
F20.5	e	$\Delta\tau_{\theta z}$ =+20.5 → −20.5kPa	707
F23.5	f	$\Delta\tau_{\theta z}$ =+23.5 → −23.5kPa	713
F26.5	g	$\Delta\tau_{\theta z}$ =+26.5 → −26.5kPa	57

In the unsaturated HCA tests, specimens were subjected to an average confining pressure of 30 kPa. This was followed by three cyclic loading phases (Table 2). Phases 1 and 3 applied 500 cycles of SP2 (no PSR). Phase 2 applied 1000 cycles of SP1 (with PSR), except in test HCA+ 0v2 for which the stress path order was changed. This approach was adopted to allow an assessment of the effects of staging sequence. The first part of each test name (e.g. 'HCA' or 'CTX') denotes the apparatus used to obtain the data. This is followed by a number (e.g. '-3') denoting the specimen's water content relative to optimum. The stress path adopted for the majority of testing was termed 'variant 1' (or 'v1'), leading to a test name such as HCA-1·7v1. Other test variants (v0 and v2) examined, for example, the effect of test stage sequences. In unsaturated CTX tests, each specimen was compacted to a target water content and then subjected to a test sequence consisting of 20 loading stages (Table 3). Each loading stage was carried out at one of five confining (cell) pressures (po = 15, 30, 40, 55 or 85 kPa), and for each confining pressure, deviator stress ratios (qcyc/po) of 0.5, 1.0, 2.0 or 3.0 were applied, giving 20 stages in all.

Table 2: Summary of the unsaturated CHA tests (with principal stress rotation)

Test name	HCA loading sequence		
	Cyclic test phase	Cyclic stress path	Number of cycles
HCA+0v1	1	SP2	500
	2	SP1	1000
	3	SP2	500
HCA+0v2	1	SP2	500
	2	SP1	1000
	3	SP2	500
HCA-1v1	1	SP2	500
	2	SP1	1000
	3	SP2	500
HCA-1.7v1	1	SP2	500
	2	SP1	540*
HCA-2v1	1	SP2	500
	2	SP1	1000
	3	SP2	120*
HCA-3iv1	1	SP2	500
	2	SP1	1000
	3	SP2	500
HCA-3iiv1	1	SP2	500
	2	SP1	1000
	3	SP2	500
HCA+1v1	1	SP2	500
	2	SP1	1000
	3	SP2	500

Note: During PSR, confining stress =30 kPa, deviatoric stress amplitude = 7 kPa, datum =0 kPa, phase angle = 90°.
*Test interrupted.

Table 3: Summary of the unsaturated CTX tests (no principal stress rotation)

CTX loading sequence	Confining pressure p_o: kPa	Cyclic stress ratio (q_{cyc}/p_o)
1	15	0.5
2	30	0.5
3	40	0.5
4	55	0.5
5	85	0.5
6	15	1.0
7	30	1.0
8	40	1.0
9	55	1.0
10	85	1.0
11	15	2.0
12	30	2.0
13	40	2.0
14	55	2.0
15	85	2.0
16	15	3.0
17	30	3.0
18	40	3.0
19	55	3.0
20	85	3.0

The cyclic loading frequency in the triaxial tests (without principal stress rotation) was 0.50Hz. The cyclic loading frequencies in the saturated (0.0083Hz) and unsaturated (0·017Hz) principal stress rotation tests were dictated by the limitations of the HCA in achieving a consistent response at higher loading frequencies. Testing at higher loading frequencies might also have resulted in a non-uniform distribution of excess pore pressures within the specimen, and complications in the interpretation of data. The loading frequency in the free to drain tests is generally considered to represent a best case field scenario, assuming the same value of the dimensionless group $c_v/f.d^2$ and the same consolidation coefficient c_v in the laboratory and in the field; however, it is difficult to relate laboratory and in situ loading frequencies generally, not least because of a degree of ambiguity in what constitutes a loading event.

3 RESULTS AND DISCUSSION

The Resilient Young's moduli of the unsaturated 11% clay content mix measured in the CTX (with no principal rotation) and in the HCA (with principal stress rotation), at various post-test gravimetric water contents and hence suctions are shown in Fig. 2. The results in Fig.2 show that the resilient stiffness of the 11% clay content mix increased by a factor of about 6 as the degree of saturation decreased to about 45%, independent of whether principal stress rotation was applied. The average resilient stiffness measured at optimum moisture content (w=7%) was approximately 1.7 times the near saturated value (at w=8%). This suggests that even small deviations from the optimum water content to which materials are compacted in the field may significantly affect the resilient stiffness of railway foundation materials.

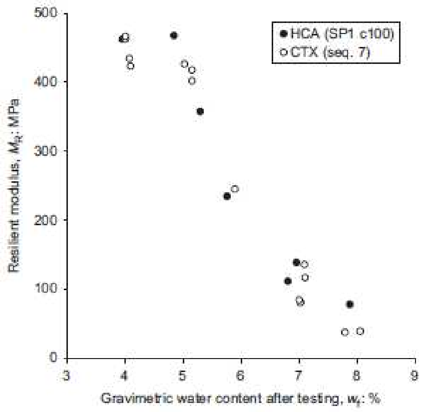

Figure 2. Resilient Young's modulus of the unsaturated 11% clay content mix as measured in the CTX (no principal rotation) and in the HCA (with principal stress rotation) at various gravimetric water contents after testing (Blackmore et al., 2020)

The effect of cyclic shear stress increases on the Resilient Young's modulus under saturated conditions and variable drainage conditions is shown in Figs. 3-4. Under saturated conditions and depending on the drainage conditions, cyclic shear stress increases below the cyclic shear stress threshold did not significantly affect the cyclic stability of railway track foundations. However, cyclic shear stress increases beyond the cyclic shear stress threshold, led to a significant reduction in resilient stiffness. The cyclic shear threshold was higher in free-to-drain than in undrained conditions. In free-to-drain conditions, the cyclic shear stress threshold was similar to the cyclic shear stress in the soil immediately below~0.3m deep ballast bed, but comfortably greater than the cyclic stress at a depth of ~1m below the sleeper base. In undrained conditions, the cyclic shear threshold was generally similar to the cyclic shear stress at a depth of ~1m below the sleeper base.

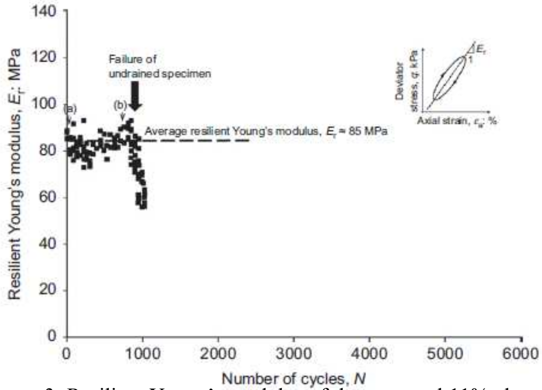

Figure 3. Resilient Young's modulus of the saturated 11% clay content specimen compacted to an initial 8.31% water content during undrained cyclic shear stress increases (Mamou et al., 2017, 2018)

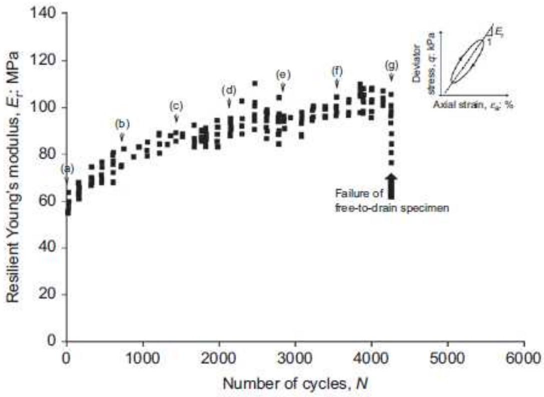

Figure 4. Resilient Young's modulus of the saturated 11% clay mix compacted to an initial 8.39% water content during free-to-drain cyclic shear stress increases (Mamou et al., 2017)

4 CONCLUSIONS

This paper has investigated degrees of saturation and magnitudes of cyclic shear stress for which principal stress rotation may have a significant effect on the resilient response of a railway formation material

- The resilient stiffnesses measured in the cyclic triaxial apparatus (without principal stress rotation) and the HCA (with principal stress rotation) both increased by a factor of about 6 as the degree of saturation decreased to about 45%
- In saturated conditions, increases in the magnitude of cyclic shear stress were found not to have a significant effect below a certain cyclic shear stress threshold, but when the cyclic shear stress threshold was exceeded significant stiffness degradation occurred.
- The cyclic shear stress threshold in free-to drain conditions was similar to the cyclic shear stress in the soil immediately below a ~0.3m deep ballast bed, but comfortably greater than the cyclic stress at a depth of ~1m below the sleeper base. In undrained conditions, the cyclic shear threshold was generally similar to the cyclic shear stress at a depth of ~1m below the sleeper base.

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