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TRIAXIAL BEHAVIOUR OF BALLAST AND THE ROLE OF CONFINING PRESSURE UNDER CYCLIC LOADING

A thesis submitted in fulfilment of the

requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

by

JOANNE LACKENBY

BE Engineering (Environmental)

FACULTY OF ENGINEERING

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CERTIFICATION

I, Joanne Lackenby, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil, Mining and Environmental Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

The following publications are related to the research work conducted in this study:

Indraratna, B., **Lackenby, J.**, and Christie, D., (2005). "Effect of Confining Pressure on the Degradation of Ballast under Cyclic Loading." *Géotechnique*, 55 (4), pp. 325–328.

Lackenby, J., Indraratna, B., McDowell, G., and Christie, D., (2006). "Triaxial Behaviour of Ballast and the Role of Confining Pressure under Cyclic Loading." Submitted to *Géotechnique* for review in September 2005.

Lackenby, J., and Premaratne, P., (2005). "Method of Noise Removal for the Calculation of Resilient Strain and Resilient Modulus." Chapter in "Mechanics of Ballasted Rail Tracks – A Geotechnical Prospective" by B. Indraratna and W. Salim, Taylor and Francis Group/ Balkema, The Netherlands.

Indraratna, B., Khabbaz, H., Salim, W., **Lackenby, J.**, and Christie, D., (2004). "Ballast Characteristics and the Effects of Geosynthetics on Rail Track

Deformation." *International Conference on Geosynthetics and Geoenvironmental Engineering*, *ICGGE,* Bombay, India, pp. 3-12.

Lackenby, J., and Indraratna, B. (2004). "The Effect of Confining Pressure on the Behaviour of Railway Ballast under Cyclic Loading." *Proceedings of the 6th Australia New Zealand Young Geotechnical Professionals Conference*, July, Gold Coast, Australia, pp. 115-120.

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ABSTRACT

Traditional railway foundations or substructures, consisting of one or two granular layers overlying a subgrade or natural formation, have become increasingly overloaded in recent years due to the utilisation of faster and heavier trains. During this period, there has been little, if any, re-engineering of the substructure in Australia, resulting in maintenance cycles becoming more frequent and increasingly expensive. Finding economical and practical techniques for enhancing the stability and safety of the substructure, thereby ensuring a capacity for supporting further increases in load, is vital in securing the long-term viability of the railway industry.

The load bearing ballast is located directly below the sleepers and is responsible for limiting the stresses projected onto the weaker subgrade and preventing train-induced sleeper movement. Two significant ballast problems arising from increasing axle loads are differential settlement and degradation. It is thought that substructure enhancement can be attained and these problems largely curtailed through the manipulation of the level of effective confining pressure supporting the ballast layer.

To investigate this possibility, a series of large-scale, high-frequency, drained, cyclic triaxial tests were conducted to examine the deformation (permanent and resilient) and degradation response of railway ballast. It was identified that the level of lateral confining pressure should be considered as an important design parameter. Two of the major benefits arising from increased confinement are reduced lateral movement (spreading) and vertical settlement resulting in improved line and level, and superior track stiffness and associated enhancements in ride comfort for passengers. The major drawback in the event of excessive confinement is unacceptable levels of particle breakage. The experimental results indicated, however, that insufficient confining pressure is as damaging in terms of particle breakdown as excessive pressure, and that minimal degradation will be achieved at some intermediate value. For maximum deviator stress magnitudes of 230, 500 and 750 kPa, ‘optimum’ breakage conditions were encountered within the confining pressure ranges 15 – 65, 25 – 95, and 50 – 140 kPa, respectively.

Practical methods of increasing the in-situ track confinement are suggested and evaluated in terms of ease of installation, effectiveness and cost. It is concluded that the more superior methods of achieving increased confining pressure are by reinforcing the ballast using geosynthetics, or by increasing the effective overburden pressure through increased shoulder and/or crib height or via the achievement of a higher initial ballast density (greater compaction).

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θ	bulk stress = $\sigma_1'+\sigma_2'+\sigma_3'$
ν	coefficient of lateral stress
ϕ	friction angle
ψ	ratio of cyclic deviator stress to peak static deviator stress
η	speed factor
δ	track condition descriptor
β	train loading state
α'	coefficient
β'	coefficient
γ'	coefficient
ϕ'	dynamic impact factor
$(\sigma_1'/\sigma_3')_p$	peak stress ratio
γ_0	coefficient
ε_1	axial strain after first loading cycle
γ_1	coefficient
σ_1'	major principal stress
$\sigma_1'-\sigma_3'$	deviator stress magnitude
σ_2'	intermediate effective stress
σ_3'	effective confining pressure
ε_a	axial strain
$\varepsilon_{a,rec}$	recoverable portion of axial strain
σ_d	magnitude of deviator stress
γ_b	specimen unit weight
$\psi_{failure}$	ψ ratio at failure during a stepwise cyclic test
ψ_{final}	ψ ratio at 20% axial strain during a stepwise cyclic test
ε_N	axial strain after a particular number of cycles
τ_{oct}	= $\sqrt{2}/3(\sigma_1'-\sigma_3')$ (axisymmetric conditions)
σ_{oct}	= $1/3(\theta)$
Δq_{cyc}	difference between the maximum and minimum cyclic load
ε_r	radial strain

ΔS	change in total particle surface area
ε_s	shear strain
ε_v	volumetric strain
ΔW_k	difference between W_{ki} and W_{kf}
A	area between particle size distribution curves before and after loading
a	asperity diameter
A	material constant
a	regression coefficient
a'	settlement after one cycle
a_0	coefficient
B	material constant
b	regression coefficient
B	area between final particle size distribution and the arbitrary boundary of maximum breakage
b'	sleeper breadth
b_0	coefficient
BBI	ballast breakage index
B_g	breakage index
b_p	breakage potential
B_p	total breakage potential
b_{pl}	values of b_p after loading
b_{po}	values of b_p before loading
B_r	relative breakage
B_t	total breakage
C	regression coefficient
c'	coefficient
CSDZ	compressive stable degradation zone
C_u	coefficient of uniformity
D	particle diameter
D	regression coefficient
$d\varepsilon_a/dN$	rate of axial strain
d_1	diameter of largest particle retained on a particular sieve
d_2	diameter of smallest particle retained on a particular sieve

d_{95}	95% of the maximum sieve aperture d_{max}
DFT	discrete Fourier transform
d_h	horizontal distance between rail centres
DIF	dynamic impact factor
d_m	mean particle diameter
d_{max}	maximum sieve aperture
d_{min}	minimum sieve aperture
d_s	superelevation deficiency
DUDZ	dilatant unstable degradation zone
E	regression coefficient
e_0	initial void ratio
E_r	rail modulus
F	axial force
F	regression coefficient
g	distance between rail centres
G	gap grading
g	regression coefficient
G	regression coefficient
G_s	specific gravity
H	regression coefficient
h	regression coefficient
h	vertical distance from rail top to vehicle centre of mass
I_r	rail moment of inertia
k	regression coefficient
K_0	coefficient of earth pressure at rest
k_0	initial permeability
k_1	material constant
k_2	material constant
k_3	material constant
l	total sleeper length
L	effective sleeper length
M	moderate grading
m	regression coefficient
M_R	resilient modulus

n	ballast porosity
N	number of loading cycles
n	regression coefficient
n_1	regression coefficient
N_{int}	number of loading cycles per interval
ODZ	optimum degradation zone
P	static wheel load
p	regression constant
p'	mean effective stress
PSD	particle size distribution
Q	wheel load
$q_{max,cyc}/p'$	stress ratio
$q/p'_{failure}$	stress ratio at failure during a stepwise cyclic test
q/p'_{final}	stress ratio at 20% axial strain during a stepwise cyclic test
$q/p'_{peak,sta}$	peak stress ratio during a static test
$q_{max,cyc}$	maximum cyclic load
$q_{min,cyc}$	minimum cyclic load
$q_{peak,sta}$	static peak deviator stress
q_r	actual load transmitted to sleeper from static wheel
R	constant
R	ratio of cyclic deviator stress to static failure deviator stress
R^2	coefficient of determination
S	surface area
s	regression coefficient
SA	surface area
S_N	settlement after a particular number of cycles
S_w	specific surface area
t	probability of maximum allowable rail deflection not being exceeded
t	regression coefficient
t'	sleeper thickness
u	material constant
U	uniform grading
u'	track modulus

v	material constant
V	train speed
V'	volume
VU	very uniform grading
W_{kf}	percentage by weight retained on each sieve after loading
W_{ki}	percentage by weight retained on each sieve before loading
x	empirical coefficient
Y	coefficient
y_r	rail deflection