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## Triaxial behaviour of ballast and the role of confining pressure under cyclic loading

Joanne Lackenby  
*University of Wollongong*

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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**

2006

## 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 6<sup>th</sup> Australia New Zealand Young Geotechnical Professionals Conference*, July, Gold Coast, Australia, pp. 115-120.

Joanne Lackenby

5 June, 2006

## **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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## LIST OF NOTATION

|                           |   |
|---------------------------|---|
| $\theta$                  | bulk stress = $\sigma_1' + \sigma_2' + \sigma_3'$               |
| $\nu$                     | coefficient of lateral stress                                   |
| $\phi$                    | friction angle  |
| $\psi$                    | ratio of cyclic deviator stress to peak static deviator stress  |
| $\eta$                    | speed factor  |
| $\delta$                  | track condition descriptor                                      |
| $\beta$                   | train loading state   |
| $\alpha'$                 | coefficient   |
| $\beta'$                  | coefficient   |
| $\gamma'$                 | coefficient   |
| $\phi'$                   | dynamic impact factor   |
| $(\sigma_1'/\sigma_3')_p$ | peak stress ratio   |
| $\gamma_0$                | coefficient   |
| $\varepsilon_1$           | axial strain after first loading cycle                          |
| $\gamma_1$                | coefficient   |
| $\sigma_1'$               | major principal stress  |
| $\sigma_1' - \sigma_3'$   | deviator stress magnitude                                       |
| $\sigma_2'$               | intermediate effective stress                                   |
| $\sigma_3'$               | effective confining pressure                                    |
| $\varepsilon_a$           | axial strain  |
| $\varepsilon_{a,rec}$     | recoverable portion of axial strain                             |
| $\sigma_d$                | magnitude of deviator stress                                    |
| $\gamma_b$                | specimen unit weight  |
| $\Psi_{failure}$          | $\psi$ ratio at failure during a stepwise cyclic test           |
| $\Psi_{final}$            | $\psi$ ratio at 20% axial strain during a stepwise cyclic test  |
| $\varepsilon_N$           | axial strain after a particular number of cycles                |
| $\tau_{oct}$              | $= \sqrt{2/3}(\sigma_1' - \sigma_3')$ (axisymmetric conditions) |
| $\sigma_{oct}$            | $= 1/3(\theta)$   |
| $\Delta q_{cyc}$          | difference between the maximum and minimum cyclic load          |
| $\varepsilon_r$           | radial strain   |

|                     |  |
|---------------------|--|
| $\Delta S$          | change in total particle surface area  |
| $\varepsilon_s$     | shear strain   |
| $\varepsilon_v$     | volumetric strain  |
| $\Delta W_k$        | 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  |
| $N_{\text{int}}$         | 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  |
| $q_{\text{max,cyc}}/p'$  | stress ratio  |
| $q/p'_{\text{failure}}$  | stress ratio at failure during a stepwise cyclic test               |
| $q/p'_{\text{final}}$    | stress ratio at 20% axial strain during a stepwise cyclic test      |
| $q/p'_{\text{peak,sta}}$ | peak stress ratio during a static test                              |
| $q_{\text{max,cyc}}$     | maximum cyclic load   |
| $q_{\text{min,cyc}}$     | minimum cyclic load   |
| $q_{\text{peak,sta}}$    | 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  |