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Effect of confining pressure and frequency on the deformation of ballast

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Abstract

Increasing the speed and frequency of trains with the same static axle weight imparts higher dynamic axle loads more frequently. When this occurs on existing track which has not been designed for such loading there can be increased rates of ballast degradation, characterised by unacceptable deformation and lateral spread, leading to more frequent requirements for track maintenance. Recent studies carried out at the University of Wollongong highlighted that confining pressure and frequency have a significant influence on the permanent deformation and degradation of ballast. However, confinement required to keep the deformation and degradation of the ballasted track to an acceptable limit will depend on the train speed (frequency). In this context, a series of cyclic triaxial tests was conducted on latite basalt samples having an initial confining pressure of 120 kPa. After every 25 000 cycles, the confining pressure was decreased in steps to simulate the drop of confining pressure during heavy traffic. This test procedure was adopted to replicate the influence of train speed on the stability of ballast. Test results indicated that both the frequency and confining pressure have a significant influence on the permanent deformation of ballast. Resilient modulus is found to increase with an increase in confining pressure and number of cycles, but to decrease with increasing frequency. The results also showed that the ballast layer requires a minimum level of confinement for preventing an excessive amount of track deformation. An empirical equation is formulated to determine the required confining pressure and resilient modulus of the ballast layer for an allowable limit of track deformation at a given train speed.

Keywords

frequency, confining, pressure, effect, ballast, deformation

Disciplines

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TECHNICAL NOTE

Effect of confining pressure and frequency on the deformation of ballast

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Increasing the speed and frequency of trains with the same static axle weight imparts higher dynamic axle loads more frequently. When this occurs on existing track which has not been designed for such loading there can be increased rates of ballast degradation, characterised by unacceptable deformation and lateral spread, leading to more frequent requirements for track maintenance. Recent studies carried out at the University of Wollongong highlighted that confining pressure and frequency have a significant influence on the permanent deformation and degradation of ballast. However, confinement required to keep the deformation and degradation of the ballasted track to an acceptable limit will depend on the train speed (frequency). In this context, a series of cyclic triaxial tests was conducted on latite basalt samples having an initial confining pressure of 120 kPa. After every 25 000 cycles, the confining pressure was decreased in steps to simulate the drop of confining pressure during heavy traffic. This test procedure was adopted to replicate the influence of train speed on the stability of ballast. Test results indicated that both the frequency and confining pressure have a significant influence on the permanent deformation of ballast. Resilient modulus is found to increase with an increase in confining pressure and number of cycles, but to decrease with increasing frequency. The results also showed that the ballast layer requires a minimum level of confinement for preventing an excessive amount of track deformation. An empirical equation is formulated to determine the required confining pressure and resilient modulus of the ballast layer for an allowable limit of track deformation at a given train speed.

KEYWORDS: deformation; laboratory tests; repeated loading

INTRODUCTION

The increased demand for high-speed trains is contributing to higher loads on the rail ballast and can cause excessive deformation and degradation. Undesired deformation and degradation of ballast affects the safety of the rail operation and ride comfort. Ballast is one of the major components of the rail track responsible for transferring loads to sub-strata, absorbing noise, draining water and so on (Selig & Waters, 1994). Moreover, owing to the increased traffic loads, the initial confining pressure of the ballast can decrease and can exhibit large vertical deformation and lateral spread. Therefore, these tracks require frequent maintenance for the safe operation of passenger and freight trains. Recently, Indraratna *et al.* (2005, 2010) and Lackenby *et al.* (2007) conducted laboratory experiments to understand the effect of confining pressure and frequency on the permanent deformation and degradation of ballast. Indraratna *et al.* (2005) highlighted that during cyclic loading, the pattern of particle breakage could be characterised by three distinct degradation zones

- (b) optimum degradation zone (ODZ)
- (c) compressive stable degradation zone (CSDZ).

(a) dilatant unstable degradation zone (DUDZ)

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These zones are defined by the level of effective confining pressure (σ'_3) acting on the specimen and also depend on the level of the applied maximum deviator stress $q_{\max}$. Lackenby *et al.* (2007) and Indraratna *et al.* (2010) revealed that the permanent deformation and degradation of railway ballast under cyclic loading is influenced by confining pressure and frequency. Lackenby *et al.* (2007) also investigated the densification and particle degradation response of railway ballast under cyclic loading; they determined that the extent of densification and particle breakage was significantly affected by the confining pressure. However, these conclusions were based on large-scale triaxial tests at constant frequency of 20 Hz even though the confining pressures were changed from 15 to 240 kPa. Therefore, this study could not capture the role of train speed (directly proportional to frequency) on the permanent deformation of ballast. Indraratna *et al.* (2009) concluded that the particle breakage has a significant influence on the resilient modulus of the railway ballast. However, none of these studies was able to capture the effect of decreasing confining pressure on the permanent deformation of ballast due to the increasing train speed. Therefore, the current paper presents investigations into the effect of varying confining pressure and frequency on the permanent deformation and resilient behaviour of ballast. A series of cyclic triaxial tests was conducted on latite basalt samples with an initial confining pressure of 120 kPa. After every 25 000 cycles, the confining pressure was decreased in steps and the frequency was changed from 10 to 40 Hz to represent different train speeds. This test procedure was adopted to replicate the influence of train speed on the

stability of ballast at various levels of ballast confining pressure that replicate realistic track conditions

LABORATORY INVESTIGATION

Laboratory tests were conducted using the large-scale cyclic triaxial apparatus, designed and built at the University of Wollongong. Specimens' dimensions were 300 mm in diameter and 600 mm high. Fig. 1 shows the particle size distribution (PSD) curve of ballast adopted for this study, which is representative of the current practice in Australia (Standards Australia, 1996). The ballast particles were first washed by water jet, so that they were free from dust, and then dried in the sun. They were then sieved through a set of sieves (53 mm, 45 mm, 37.5 mm, 31.5 mm, 26.5 mm and 19 mm) and stored separately. Particles from each sieve size were weighed and then mixed properly. The mixed particles were placed in four different layers into a 5 mm thick neoprene rubber membrane and compacted using a vibrator to a representative field density of 1530 kg/m³. A membrane correction of 15 kPa to a cyclic deviatoric stress (q_{cyc}) was applied for the 5 mm thick Neoprene rubber membrane (ASTM, 2002). A rubber pad was used on top of the ballast particles before placing a vibrator, in order to minimise breakage during compaction. The compaction was facilitated by a split cylindrical mould, which was removed before the specimen was placed within the cell pressure chamber. To study the effect of decrease in confining pressures with increase in train speed, the sample was given an initial confining pressure of 120 kPa (about 3–4 times the normal confining pressure that exists in typical tracks). The sample was left overnight for consolidation before applying the cyclic load. Each sample was loaded statically first at a rate of 1 mm/s to a stress equal to the average of the minimum and maximum cyclic deviatoric stress. Cyclic loading was then applied up to 25 000 cycles at a confining pressure of 120 kPa and a frequency of 10 Hz. Subsequently, the confining pressure was reduced gradually to 60 kPa and another 25 000 cycles were applied. Cyclic loading was continued, further reducing the confining pressure to 30 kPa and 15 kPa. It should be noted that 25 000 cycles of loading was maintained for each confining pressure. This was based on the earlier findings that the permanent deformations would remain constant around 10 000–25 000 cycles, irrespective of the applied confining pressure (Lackenby *et al.*, 2007). In total, cyclic loading was continued for 100 000 cycles or until the axial strain exceeded 25%. This whole procedure was repeated for 20 Hz and 40 Hz frequencies to replicate the effect of increasing train speed. Details of these tests are summarised in Table 1.

Fig. 1. Initial particle size distribution of ballast sample

Table 1. Summary of cyclic triaxial tests

Frequency, f : Hz	Confining pressure, σ'_3 : kPa	σ_d : kPa (Esveld, 2001)	Number of cycles, N
10	15, 30, 60, 120	374	100 000
20	15, 30, 60, 120	428	100 000
40*	15, 30, 60, 120	536	75 000

* $\epsilon_a > 25\%$ after 75 000 cycles.

A typical harmonic cyclic load (a sinusoidal waveform) was used during the testing programme. Detailed explanations of the testing equipment and experimental procedures can be found elsewhere (Indraratna *et al.*, 2005, 2010; Lackenby *et al.*, 2007). The minimum cyclic deviatoric stress (q_{min}) was kept at 45 kPa (Lackenby *et al.*, 2007) to take into account the weight of sleeper and rail. Shenton (1975) stated that higher train speeds may increase the dynamic forces and impart greater stresses to the ballast. Kempfert & Hu (1999) carried out in situ measurements of dynamic forces in the track induced by speeds up to 400 km/h and highlighted that the dynamic stress increased significantly as the speed increased from 150 km/h to 300 km/h. Therefore, cyclic deviatoric stresses (q_{cyc}) were calculated following Esveld (2001) for respective train speeds (frequency); these are presented in Table 1. Details of the Esveld's method to calculate contact pressure on ballast is given in the Appendix.

EXPERIMENTAL RESULTS AND DISCUSSION

Permanent deformation behaviour

Figure 2(a) illustrates the axial strain (ϵ_a) at various frequencies (f) and the effective confining pressure (σ'_3) with number of cycles (N). It is observed that ϵ_a increases with the increase in f and decrease in σ'_3 . Also, it increases with increase in N . ϵ_a increases rapidly in the initial cycles and stabilises after a few thousand cycles. Lackenby *et al.* (2007) reported that the ϵ_a stabilises or shakedown (insignificant rate of increase of ϵ_a with N) at around 10 000 cycles. In addition, Fig. 2(a) shows that when σ'_3 decreases to 60 kPa from 120 kPa, ϵ_a again increases rapidly in the initial few cycles. It stabilises again after application of an additional 10 000 cycles at lower frequency range ($f \leq 20$ Hz). Initial deformation is more rapid with decreasing confining pressure (e.g. initial deformation occurred around four times larger for reduction in σ'_3 from 30 kPa to 15 kPa, as compared to the change in σ'_3 from 120 kPa to 60 kPa). However, at high frequency such as at $f = 40$ Hz, when σ'_3 decreases from 60 kPa to 30 kPa, rapid deformation continued to occur and did not stabilise before reaching failure (i.e. $\epsilon_a = 25\%$). These results clearly indicate the requirement of a threshold value of σ'_3 in limiting track deformation. At very low σ'_3 , for example 15–30 kPa, excessive deformation of the track may occur even at low train speeds (i.e. $f \leq 20$ Hz) and the ballast requires $\sigma'_3 \geq 60$ kPa for operating high-speed trains ($f \geq 40$ Hz). Such type of ballast behaviour can be attributed to rapid particle rearrangement and breakage at high f . ϵ_a increases rapidly (at low values of N) followed by a stabilised state that occurs around an additional load application of 10 000 cycles. This can be seen from the results of $f = 10$ and 20 Hz where σ'_3 is adequately capable of providing stable ϵ_a . In case of high f , such as 40 Hz, σ'_3 below 60 kPa cannot provide enough support to the sample (Fig. 2(a)) and as a consequence, stable ϵ_a is hard to attain. This test results imply that higher confining pressure on tracks catering for higher speeds will be more appropriate, as conventional

Fig. 2. Effect of variation of confining pressure (σ'_3) on (a) axial strain (ϵ_a) and (b) volumetric strain (ϵ_v) at various frequencies (f) with number of cycles (N)

Australian tracks rarely have confining pressures exceeding 30 kPa (Lackenby *et al.*, 2007).

Figure 2(b) shows the volumetric strains (ϵ_v) (negative compression) behaviour at various f and σ'_3 with N . At $\sigma'_3 = 120$ kPa, ϵ_v is compressive for all f and it increases with increase in f and N . At all frequencies, when the sample experiences a decrease in confining pressure, it dilates rapidly during the initial 1000 cycles, followed by a stable ϵ_v .

Resilient behaviour

Lekarp *et al.* (2000) reported that the frequency and load duration has little or no significant effect on resilient modulus of granular materials. However, they also mentioned that the resilient modulus may decrease with increase of frequency in undrained conditions. In this study, the effect of f and σ'_3 on the resilient modulus (M_r) was assessed by recording the resilient (recoverable strain) $\epsilon_{a,rec}$ and deviator stress magnitude q_{cyc} ($q_{max} - q_{min}$) at various number of cycles N using the following expression

$$M_r = \frac{q_{cyc}}{\epsilon_{a,rec}} \quad (1)$$

Figure 3 illustrates the effect of f and σ'_3 on M_r with N . For a particular f and σ'_3 (such as 10 Hz and 120 kPa), M_r initially increased rapidly and became almost constant after

Fig. 3. Effect of variation of confining pressure (σ'_3) on resilient modulus (M_r) at various frequencies (f) with number of cycles (N)

application of a few thousand cycles (e.g. 10 000 cycles). This initial rapid increase in M_r can be attributed to cyclic densification (Figs 2(a) and 2(b)) where ballast particles rearrange and even break in order to achieve a stable configuration. M_r is found to decrease with increase in f . However, M_r increases as σ'_3 increases.

Selig & Alva-Hurtado (1982) reported that a reduction in recoverable axial strain ($\epsilon_{a,rec}$) with each successive cycle and subsequent increase in M_r can be attributed, at least partly, to densification from cumulative ϵ_v . This type of behaviour can be seen at all f and σ'_3 . Fig. 4 presents the variation of final value of resilient modulus (M_{rf}) at 25 000 cycles for various f plotted against σ'_3 . It is evident from the figure that M_{rf} increases linearly with confining pressure. Moreover, M_{rf} is found to decrease with f . An empirical relationship between M_{rf} and σ'_3 is developed and can be expressed as

$$M_{rf} = a\sigma'_3 + b \quad (2)$$

where a and b are material parameters tabulated in Fig. 4 for different values of f .

Figure 5 presents the variation of final axial strain, (ϵ_{af}) and final resilient modulus (M_{rf}) for different values of confining pressures and frequencies. It is evident that ϵ_{af} decreases with the increase of M_{rf} irrespective of σ'_3 and f . In other words, a higher resilient modulus results in less

Fig. 4. Trend of variation of final resilient modulus (M_{rf}) at various frequencies (f) with confining pressure (σ'_3)

Fig. 5. Relation between final resilient modulus (M_{rf}) and final axial strain (ϵ_{af})

track deformation. Moreover, a unique relationship between ϵ_{af} and M_{rf} is observed irrespective of σ'_3 and f , and the relationship can be expressed by

$$\epsilon_{af} (\%) = \alpha M_{rf} + \beta \quad (3)$$

where α and β are empirical constants determined from laboratory data. In this case, the values of α and β are -0.19 and 48.20 respectively.

Equation (3) can be used to estimate the required resilient modulus of the track for a given track deformation level. For example, for an allowable limit of track deformation, say 10% of the ballast layer thickness, it is necessary to have the track resilient modulus around 200 MPa (Fig. 5). To achieve $M_r = 200$ MPa, minimum lateral confinement should be around 40 kPa, 75 kPa and 110 kPa at 10 Hz, 20 Hz and 40 Hz frequencies, respectively, as illustrated in Fig. 4. If appropriate σ'_3 is not applied to the ballast layer and the train speed increases, the track would be anticipated to suffer severe and undesirable deformation. Equation (3) describes the whole of track deformation, and the current results from the laboratory experiments can be influenced by the sub-ballast and subgrade layer. Moreover, equation (3) is derived under conditions where the major track deformation is contributed to the ballast layer under a given track confinement. Therefore, proper caution should be taken while using equation (3), where track deformation is largely affected by the subgrade soil. Further research/analyses of field data would be helpful to validate the equation for the field cases.

Various methods of increasing track confinement have been discussed by Lackenby *et al.* (2007), such as preventing lateral ballast flow using containing sheets at the shoulders or geosynthetics at the ballast/capping interface and redesigning the sleeper shape to reduce ballast flow (winged precast concrete sleepers).

CONCLUSIONS

This paper presents the results of large-scale cyclic triaxial tests conducted on latite basalt at different frequencies and confining pressures. It has been concluded that both frequency and confining pressure have considerable influence on the permanent deformation of ballast. Axial and volumetric strains are found to increase with an increase in frequency and number of cycles. Volumetric strains are observed to increase with the confining pressure irrespective

of frequency. Resilient modulus increases with an increase in confining pressure and the number of cycles, but it decreases with increasing frequency. The results confirmed that a minimum lateral confinement was necessary to maintain acceptable deformation. A unique relationship was observed between the final axial strain and resilient modulus, irrespective of the confining pressure and frequency. An empirical relationship is also proposed to estimate the minimum confining pressure and resilient modulus required for a given level of permanent deformation at various frequencies (train speeds). The application of equation (3) is limited to similar track confining pressures and frequencies (speeds) as tested in the laboratory conditions.

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APPENDIX

Esveld's method to calculate vertical stress on ballast

Esveld (2001) proposed the following expression to estimate vertical stress on ballast based on Zimmermann's theory

$$\sigma_{\max} = \sigma_{\text{mean}}(1 + t\bar{s}) \leq \bar{\sigma} \quad (4)$$

$$\sigma_{\text{mean}} = \frac{Qa}{2LA} \quad (5)$$

where $\sigma_{\max}$ is the maximum compressive stress exerted on the ballast bed (N/mm^2); σ_{mean} is the mean value of compressive stress exerted on the ballast bed (N/mm^2); Q is the effective wheel load (N); a is the sleeper spacing (m); L is the characteristic length (m); A is the contact area between sleeper and ballast bed for half sleeper (m^2); t is the increment factor; $\bar{s}$ is the variation coefficients; and $\bar{\sigma}$ is the permissible stress on the ballast bed directly beneath the sleeper.

Effective wheel load (Q), characteristic length (L) and velocity factor (ϕ) are given by the following expressions

$$Q = k_1 Q_0 \quad (6)$$

$$L = \sqrt[4]{\frac{4EI}{k_2}} \quad (7)$$

$$k_2 = \frac{CA}{a} \quad (8)$$

$$\phi = 1 + \frac{V - 60}{140} \quad \text{for } V > 60 \text{ km/h} \quad (9)$$

where Q_0 is the nominal wheel load (N); k_1 is 1.1–1.3 and takes account of increase in wheel load in curves because of cant deficiency or excess; k_2 is the foundation coefficient (N/m^3); E is the modulus of elasticity of steel rail (N/m^2); I is the moment of inertia of steel rail (m^4); and V is the train velocity (km/h).

NOTATION

- A contact area between sleeper and ballast bed for half sleeper (m^2)
- a sleeper spacing (m)
- α, β empirical material constants
- C foundation modulus (N/m^3)
- E modulus of elasticity of steel rail (N/m^2)
- f frequency of cyclic loading
- I moment of inertia of steel rail (m^4)
- k_1 1.1–1.3, accounts for increase in wheel load in curves because of cant deficiency or excess
- k_2 foundation coefficient (N/m^3)
- L characteristic length (m)
- M_r resilient modulus

M_{rf}	final resilient modulus
N	number of cycles of loading
Q	effective wheel load (N)
Q_o	nominal wheel load (N)
q_{cyc}	cyclic deviatoric stress
q_{max}	maximum cyclic deviatoric stress
q_{min}	minimum cyclic deviatoric stress
$\bar{s}$	variation coefficients
t	increment factor
V	train velocity (km/h)
α and β	empirical material constants
ϵ_a	axial strain
$\epsilon_{a,rec}$	recoverable axial strain
ϵ_{af}	final axial strain
ϵ_v	volumetric strain
σ_{max}	maximum compressive stress exerted on the ballast bed (N/mm ²)
σ_{mean}	mean value of compressive stress exerted on the ballast bed (N/mm ²)
$\bar{\sigma}$	permissible stress on the ballast bed directly beneath the sleeper
σ'_3	effective confining pressure
ϕ	velocity factor

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