The Effect of Confining Pressure on the Behaviour of Railway Ballast Under Cyclic Loading

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During train loading, the railway substructure is subjected to loading amplitudes that can, over time, cause serious track alignment and stability problems. Railway substructure problems have become more serious and widespread in recent years due to the employment of faster and heavier trains. Railway authorities throughout Australia are faced with shortening maintenance cycles, and substantial increases in maintenance costs. With train speeds, loads and frequency expected to continue to increase, finding new and innovative ways to strengthen the substructure, in particular the ballast layer, is vital for the continued safe and economical use of both passenger and freight trains. This project investigates three possible ways in which the substructure can be strengthened; by a) altering the magnitude of confining pressure on the load bearing ballast, b) optimising the ballast particle size distribution, and c) employing the use of geosynthetics within the substructure as a form of reinforcement. In this paper, a large-scale triaxial apparatus is used to examine the effect of confining pressure on the degradation and settlement characteristics of ballast. It was found that increasing the confining pressure leads to a significant reduction in settlement but increased ballast breakage.

INTRODUCTION

The four most frequently encountered substructure problems on railway lines are ballast degradation (breakage), differential track settlement, subgrade pumping and ballast fouling. If any of these problems occur on a particular line, then it is usually the ballast layer that is most affected. The layout of the railway substructure is shown in Figure 1. The main roles of the ballast are to support the sleeper and prevent sleeper movement, distribute stresses at a reduced level to the subgrade, provide resiliency to the track structure, and facilitate drainage away from the track. If the ballast is unable to fulfill any of these roles, maintenance is usually the outcome. One such maintenance technique used to correct line and level is tamping. During tamping, a machine lifts the track to the required level and positions it laterally. The ballast under the sleepers is then squeezed into position using the tamping tines. Tamping is thought to be a main cause of ballast ageing [2], and as Figure 2 indicates, it is not very effective in the long term. Therefore, minimising the need for maintenance will save railway authorities financially and also lengthen the life of the track.

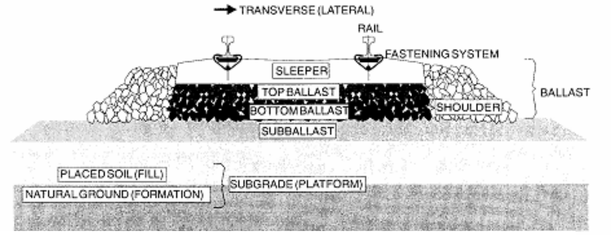

Figure 1 The Railway Substructure [1]

With these problems in mind, this paper presents the results from a series of triaxial experiments aimed at finding ways to improve the settlement response of the ballast layer, but at the same time ensuring that drainage and ride comfort are not compromised. The project is comprised of three main areas of study, but only the first is presented in this paper:

- The effect of the confining pressure on the degradation and deformation characteristics of the load bearing ballast (the ballast beneath the sleepers);
- The effect of ballast particle size distribution on track stability; and
- The potential use of geosynthetics within the substructure to prevent degradation, settlement and lateral spread.

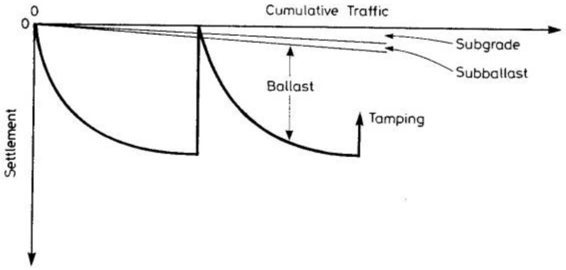

Figure 2 Track Settlement and the Influence of Tamping [3]

BEHAVIOUR OF GRANULAR MATERIALS UNDER CYCLIC LOADING

Settlement

Figure 2 shows that most settlement on a railway line is due to the accumulation of plastic strains within the ballast layer. Permanent deformation within the ballast is the result of three phenomena, shear strain, volumetric strain accumulation, and ballast degradation. The ballast layer is prone to settlement for two reasons, a) it is loosened during maintenance (unlike the subballast and subgrade layers), and b) it is subjected to the highest stress ratios. Stewart [4] identifies that cumulative permanent strain is dependent on the permanent strain during the first cycle, the loading amplitude, and the number of cycles. Using variable amplitude triaxial tests, Stewart found that the maximum load determines the ultimate magnitude of plastic deformation.

A large number of researchers who have investigated the cyclic loading of granular materials (e.g. [5,6]) have found that the overall settlement response is governed by what is known as the "shakedown load". Granular materials will either shakedown (the behaviour becomes purely elastic or reversible after a certain number of cycles), or will incrementally collapse (permanent strains increase rapidly, and the response is always plastic or irreversible). The shakedown load is the load below which behaviour becomes elastic. Ballast life is related to its resistance against incremental failure [7]. In a study by Brown [8], it was found that permanent and resilient strains reached equilibrium by 10^4 cycles.

Confining Pressure

The effect of confining pressure on the behaviour of granular materials under static loading is well understood. Figure 3 illustrates the relationships between volumetric strain and deviator stress in relation to axial strain under different confining stresses. For ballast and other granular materials, the peak deviator stress $(\sigma_1' - \sigma_3')_p$ increases with confining stress, but the peak principal stress ratio $(\sigma_1'/\sigma_3')_p$ decreases. As the confining pressure (σ_3') increases, the volumetric strain decreases and changes from dilation towards compression. Because dilation is suppressed, the breakage of particles is larger at high confining pressures [10].

Most papers investigating the effect of confining pressure on the cyclic behaviour of granular materials deal with undrained behaviour and liquefaction under earthquake loading. There are few studies that examine behaviour under drained conditions. Uzan [11] and Brown [8] found that under cyclic loading, axial strain decreases with increasing confining pressure. Raymond and Williams [12] conducted saturated drained repeated loading tests on ballast and found that the volumetric strain increases with confining pressure, although results were based on only two confining stresses. They indicated that the rates of strain during extension tests at σ_3'=100 kPa were approximately twice those at σ_3'=50 kPa.

Breakage

It has been reported that the primary cause of ballast contamination is from the breakdown of the aggregates themselves [13], and that this breakdown accounts for 40% of fouling material [1]. Ballast crushing not only leads to decreased track drainage due to the occupation of voids by fines, but also contributes to differential track settlement, lateral deformation and decreased shear resistance. Breakage is a common occurrence despite the fact that in-situ stresses are significantly smaller than the unconfined compressive strength of the parent aggregate.

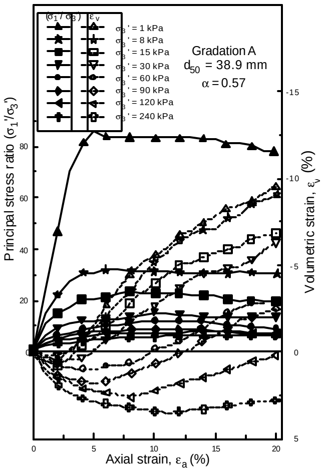

Figure 3 Behaviour of Railway Ballast under Static Loading Conditions [9]

It has been identified that the degradation of ballast particles can occur in three ways (Raymond and Diyaljee, 1979ab; Lees and Kennedy, 1975):

- The fracture of particles into approximately equal parts (this affects the long-term stability and safety of the track)
- The breakage of angular projections (influences the early settlement and track strength)
- The grinding off of small-scale asperities (introduces fines and causes fouling and reduced drainage)

Indraratna *et al.* [9] provide details on the steps involved in the deformation and degradation of ballast under cyclic loading. The first phase (initial 20000 cycles), often referred to as the stabilisation stage, involves the dynamic packing and sliding of particles relative to each other to form a compact aggregate. A consolidation stage occurs for the next 100000 cycles, during which the further rearrangement and packing of particles results in only minor ballast settlement. After this period, sharp edges and irregularities on the surface of the particles begin to break off at the contact points. Upon additional load increases and cycles, the relatively weak particles within the matrix, usually the large angular particles, start to break. Particle packing and settlement during this stage is much less than that corresponding to the stabilisation stage. Local crushing at one point causes a local redistribution of stress and a movement of particles which results in crushing at a new location [16, 17]. This in turn produces differential settlement [18]. According to Jeffs [19], any further long-term breakage can be attributed to the additional deformation of larger particles and interparticle grinding processes.

Breakage Quantification

Several methods are available in the literature to quantify the degradation of granular materials. Two methods have been found to be suitable for the analysis of railway ballast, namely those proposed by {Marsal 1967 #1190} for rockfill and {Hardin 1985 #490} for sands. Hardin defines breakage using three parameters, the breakage potential B_p (Equation 1), the total breakage B_t (Equation 3) and the relative breakage B_r (Equation 4). All breakage is referenced to the largest silt size, 0.074 mm. However, in the current study, all breakage is referenced to 1 mm due to the large size of the ballast particles, and breakage is quantified in terms of B_r.

$$B_p = \int_0^1 b_p \, df \qquad (1)$$

where b_p is the potential for breakage of a particle of size D given by Equation 2.

$$b_p = \log_{10}\left[\frac{D\,(mm)}{reference\ size\ (mm)}\right] \qquad (2)$$

$$B_t = \int_0^1 \left(b_{po} - b_{pl}\right) df \qquad (3)$$

where b_{po} and b_{pl} are the values of b_p before and after testing, respectively.

$$B_r = \frac{B_t}{B_p} \qquad (4)$$

PREDICTION OF THE RELATIONSHIPS BETWEEN SETTLEMENT, CONFINING PRESSURE AND BREAKAGE

It is hypothesised that the confining pressure will be related to the breakage and settlement by the relationships shown in Figure 4. Figure 4 shows that at low confining pressures, breakage is significant. This is because at small confining pressures, ballast particles have a low coordination number, resulting in large stress distributions at the contact points. Particles are also free to move and slide over one another resulting in the weak corners sustaining the deviator stresses. As the confining pressure is increased, it is thought that breakage will decrease to a minimum value. This decrease in breakage will be due to an increase in the coordination number, and a reduction in particle rearrangement. Behaviour in this region is characterised by a stabilisation zone where further increases in breakage will be due to the continued shearing of corners and weak points. Both settlement and breakage remain approximately constant within this zone. Breakage is more pronounced at high confining pressures and this is largely due to the suppression of dilation. Particles will no longer be able to slide past one another due to the high lateral restraint. This process will continue until the point A is reached which signifies the onset of severe breakage.

It is well known that settlement decreases as the confining pressure increases due to the inability of particles to rearrange and change position. However, in Figure 4, once point A is reached, the magnitude of particle crushing significantly influences the settlement characteristics. The breakage corresponding to point A is characterised not only by the breaking of corners, but also the fracture of particles.

It is quite clear from Figure 4 that high confining pressures restrict settlement but result in increased breakage. Therefore, one of the aims of this study is to identify the range of confining stresses that define the stabilisation zone, so that both breakage and settlement criteria can be satisfactorily met.

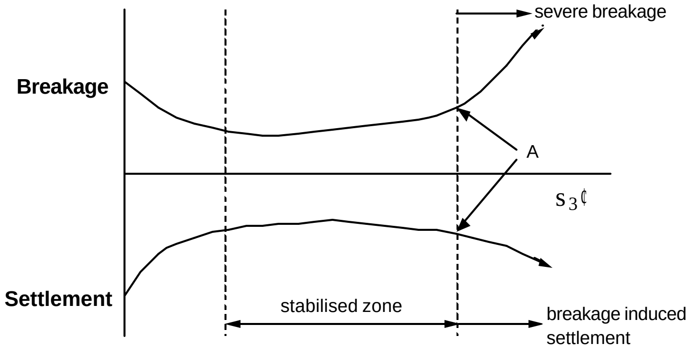

Figure 4 Hypothesised Effect of Confining Pressure on Breakage and Settlement

TESTING PROCEDURE

When studying the behaviour of railway ballast, scaled down aggregates do not give an accurate indication of the behaviour of full sized particles. For this reason, the use of large-scale equipment is necessary. A large-scale cylindrical triaxial apparatus (Figure 5) that can incorporate samples of size 300 mm diameter and 600 mm height has been utilised for ballast testing. A newly installed hydraulic dynamic actuator capable of applying loads up to 150 kN and frequencies of 60 Hz is used to simulate the train loading.

Tests were carried out on latite basalt, a quarried aggregate from Bombo in NSW. The basalt was prepared according to the particle size distribution shown in Figure 6. Also shown in Figure 6 is the distribution specified in the Australian Standard for Railway Ballast [22]. Triaxial specimens were compacted inside a 6 mm rubber membrane using a vibratory hammer, with a final achieved bulk density of approximately 15.3 kN/m^3 (G_s=2.7 and $e_0 \approx 0.82$). Following this, samples were saturated under a back pressure (B>0.96) and consolidated overnight.

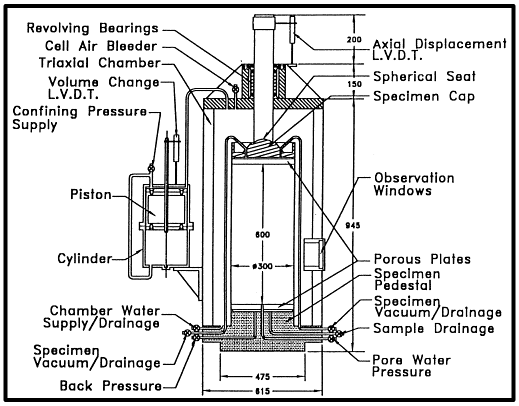

Figure 5 Large Scale Cylindrical Triaxial

Following consolidation, the appropriate confining pressure was applied, and an initial static load equivalent to the mean deviator stress was applied. The first 20 cycles were applied at a frequency of 1 Hz, and the remaining cycles at 20 Hz. A total of 500000 cycles were employed. Data in relation to settlement and volume change was recorded at regular intervals for the entire test. The ballast was resieved after the test to quantify the amount of particle breakage.

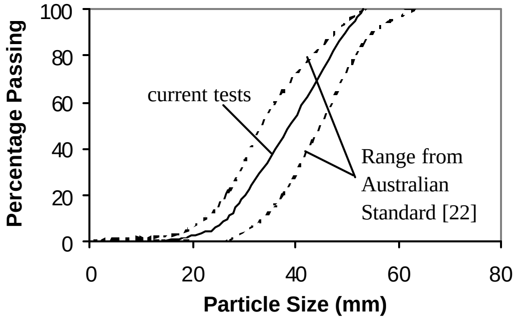

Figure 6 Particle Size Distribution used in Tests

Loading Characteristics

Six triaxial compression tests were conducted at effective confining pressures ranging from 1–240 kPa. The confining pressures supplied to the load bearing ballast are usually within the range 21-83 kPa [23]. The load was cyclically varied between two compressive stresses of 45–245 kPa. The 245 kPa pressure corresponds to the contact pressure between sleeper and ballast that would result from a static 25 tonne axle load, assuming 50% of the wheel load passes through the rail seat, and the effective contact area outlined in Jeffs and Tew [24] for concrete sleepers is utilised. Traditionally, this static load is multiplied by a dynamic impact factor to take into account dynamic forces due to train speed, and track and wheel irregularities (for example, see [25]). No dynamic impact factor was applied in this case, so the loading scheme represents the lower bound stresses that would be applied by a 100 tonne freight wagon. The upper bound case will be examined in future testing. However, the load scheme applied in the present study is also equivalent to an average passenger train (50 tonne carriage) multiplied by a dynamic impact factor of 2. The lower pressure (45 kPa) was chosen to represent the effective weights of the rail and sleepers. The testing frequency (20 Hz) corresponds to different train speeds depending on the assumed distance between train axles. For instance, in the case of the NSW Millennium train with axle spacing 2.3 m, the simulated train speed is 165 km/hr.

RESULTS AND DISCUSSION

The axial strain results for the cyclic triaxial tests are shown in Figure 7, and, as expected, the axial strain decreased with an increase in confining pressure. The settlement characteristics are best described by Equation 5, where ε_a is the axial strain, N is the number of cycles, and A and B are regression coefficients. After approximately 25000 cycles all samples have reached the maximum axial strain values, and following this point behaviour is essentially elastic (shakedown has occurred for all specimens, and settlement is within the stable zone shown in Figure 4). Further increases in axial strain can only occur with increases in the deviator load or frequency.

$$\varepsilon_a = A + B\ln(N) \tag{5}$$

Figure 8 shows the relationships between the confining pressure and the maximum values of axial, volumetric and radial strains achieved at the end of 500000 cycles. The change in axial strain with effective confining pressure can be described by Equation 6, where C is a coefficient (equal to 30 kPa in this case) and $R^2 = 0.95$.

$$e_a = \frac{C}{\sqrt{s_3'}} \tag{6}$$

Comparing the axial strain curve in Figure 8 to Figure 4, it is clear that in the experiments, point A was not reached i.e. there was no large scale crushing of particles. This signifies that the deviator stress will need to be increased in future tests (to the upper bound case detailed previously) so that larger levels of breakage will be attained and point A can be determined.

Figure 8 also shows that for confining pressures greater than 30 kPa, the volumetric strain increased with increasing confining pressure. The volumetric strain for the 1 and 8 kPa samples were both highly dilative, but the 1 kPa result has not been shown due to difficulties encountered in measuring the volume change at such a low confining pressure. Radial strains were strongly expansive at small confining pressures, and at 240 kPa the radial expansion due to the cyclic loading was virtually cancelled out by the compression caused by the large confining pressure.

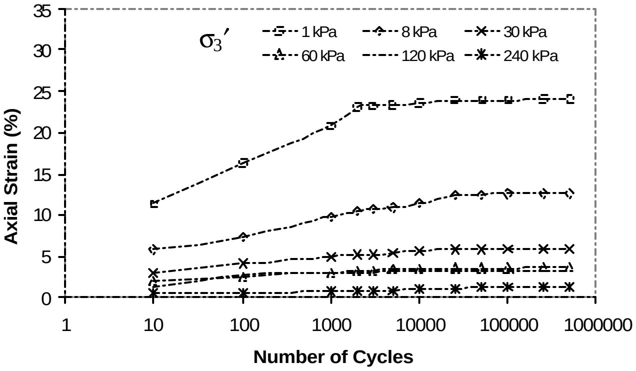

Figure 7 Axial Strains at Different Confining Pressures

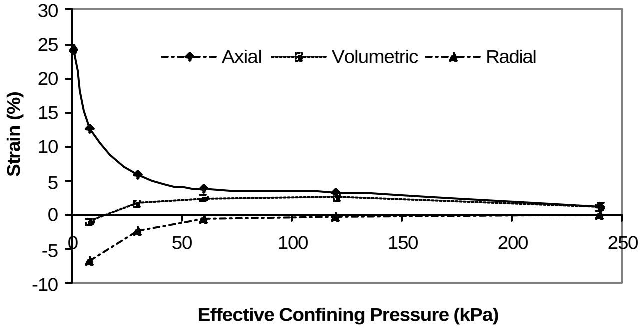

Figure 8 Relationships Between Confining Pressure and Maximum Values of Axial, Volumetric and Radial Strains

Ballast Degradation

The degradation results expressed in terms of the relative breakage B_r (Equation 4) are shown in Figure 9. Breakage is significant at low confining pressures (as predicted in Figure 4), and there appears to be an optimum confining pressure at around 30 kPa. Once again, however, particle breakage was too low for the critical point A to be reached. For this reason, these results need to be verified under a larger deviatoric loading scheme. Rapid axial strains were achieved for the 8 kPa and 1 kPa tests (Figure 7), which is largely responsible for the increased breakage at these confining pressures.

APPLICATIONS TO THE RAILWAY INDUSTRY

The main conclusion to be drawn from the current test series in relation of train loading is that passenger trains, or freight trains travelling under steady state conditions, do not cause significant ballast degradation. Even though normal pressures as high as 480 kPa were applied to the ballast, only the breakage of angular corners was achieved. There was no sign of particle fracture into approximately equal parts. It may be concluded that there can only be two possible causes of ballast degradation on a railway line, breakage caused by heavy freight trains with impact loading, or breakage caused by maintenance procedures, in particular tamping.

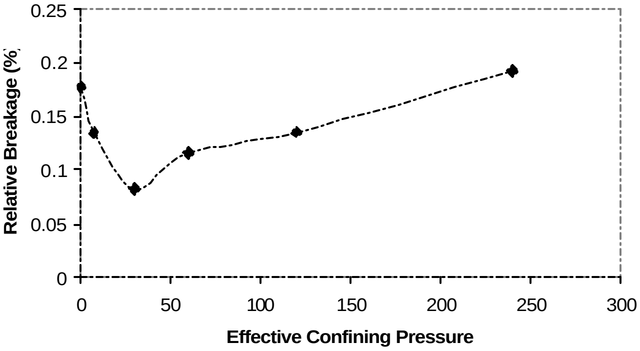

Figure 9 Effect of Confining Pressure on Relative Breakage

FUTURE TESTING

This research has shown conclusively that a maximum dynamic deviator stress of 245 kPa is insufficient to cause large-scale ballast damage. Several railway authorities provide values for the maximum contact pressures that are allowed between the sleeper and ballast. According to FIP [26], most railway authorities allow pressures of 400–500 kPa on the ballast layer. Pressures larger than this cause excessive ballast degradation and unsatisfactory track settlement. The Australian Standard for Prestressed Concrete Sleepers [27] states that ballast pressure should not exceed 750 kPa for high-quality, abrasion-resistant ballast. For this reason, the next set of experiments conducted on the cylindrical triaxial will apply double the current deviator stress (490 kPa) and the same range of confining stresses (1-240 kPa).

Following an increase in deviator stress, layer/s of geosynthetics will be placed within the ballast sample to investigate the effectiveness of geosynthetics in reducing breaking and settlement. Using another piece of large-scale equipment (cubical triaxial rig, samples 600×600×800 mm), previous studies at the University of Wollongong have shown that when geogrid-geotextile composites are placed at the subballast-ballast interface, reductions in settlement and lateral strain are observed. It is thought that by placing such geosynthetics within the cylindrical ballast sample, the lateral confinement will be increased, and this will affect settlement and breakage characteristics.

Testing is also continuing on the large-scale cubical triaxial. The effect of altering the lateral confinement (whilst maintaining plane strain conditions in the longitudinal direction) is under examination. A quantification of the effect of geosynthetics incorporation on the degree of confinement is also under consideration.

CONCLUSIONS

According to the results of experiments on ballast using a large-scale triaxial rig, it can be concluded that:
- the axial strain decreases with increasing confining pressure under cyclic loading
- the deviator stress applied was below the shakedown limit and did not cause the fracture of particles
- the volumetric strain was dilative below 10 kPa, and at higher confining pressures increased with confining pressure
- minimum ballast breakage was achieved at around 30 kPa
- higher values of deviator stress are required to determine the value of the critical point A (see Figure 4).

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