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## **Stabilization of Ballasted Rail Tracks and Underlying Soft Formation Soils with Geosynthetic Grids and Drains**

Buddhima Indraratna<sup>1</sup>, Mohamed A. Shahin<sup>2</sup>, Cholachat Rujikiatkamjiorn<sup>3</sup>, and David Christie<sup>4</sup>

### **Abstract**

Railway ballast deforms and degrades progressively under heavy cyclic loading. Ballast degradation is influenced by several factors including the amplitude and number of load cycles, gradation of aggregates, track confining pressure, angularity and fracture strength of individual grains. The degraded ballast is usually cleaned on track, otherwise, fully or partially replaced by fresh ballast, depending on the track settlement and current density. The use of composite geosynthetics at the bottom of recycled ballast layer is highly desirable to serve the functions of both drainage and separation of ballast from subballast. Construction of the rail track also requires appropriate improvement of the subgrade soils to achieve an adequately stiff surface layer prior to placing the ballast and subballast. Based on extensive research at University of Wollongong, it is found that the gradation of ballast plays a significant role in the strength, deformation, degradation, stability and drainage of rail tracks. Results from large-scale triaxial testing indicate that a small increase in confining pressure improves track stability with less ballast degradation. Bonded geogrids-geotextiles also decrease differential settlements of tracks, ballast degradation and lateral movement, and the risk of subgrade pumping. Stabilization of soft subgrade soils is also essential for improving the overall stability of track and to reduce the differential settlement during the operation of trains. This paper also highlights the

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effectiveness of using prefabricated vertical drains (PVDs) for improving the behavior of soft formations underlying rail tracks.

## **Introduction**

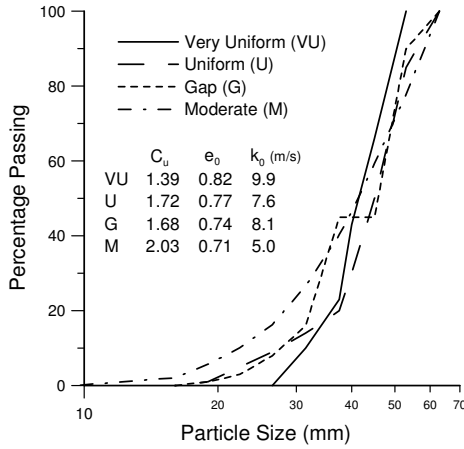
Railway tracks are conventionally founded on compacted ballast platforms, which are laid on natural or improved subgrade (formation soil). Ballast is a free draining granular material used as a load bearing material in railway tracks. It is composed of medium to coarse gravel sized aggregates (10 – 60 mm) with a small percentage of cobble-sized particles. The main functions of ballast are (Selig and Waters 1994): distributing and damping the loads received from sleepers, producing lateral resistance and providing rapid drainage. It could be argued that for high load bearing characteristics and maximum track stability, ballast needs to be angular, well-graded and compact, which in turn reduces the drainage of rail track. Therefore, a balance between the bearing capacity and drainage needs to be achieved. It will be shown later in this paper that the use of geosynthetics with special characteristics in track will improve the various functions that ballast is expected to perform.

The deviation of track alignment and vertical profile from the design geometry due to progressive degradation of ballast and consolidation of soft formation often invokes costly track maintenance. In case of ballasted railway tracks, the cost of track maintenance can be significantly reduced if better understanding of the geotechnical behavior of rail substructure, in particular the ballast layer, is achieved. Accordingly, a major research program has been launched at University of Wollongong to study the effect of parameters such as particle size distribution and confining pressure on the geotechnical behavior of ballast, and to investigate the role of geosynthetics in improving the performance of rail tracks, thereby, reducing track maintenance costs. In addition, the need for ensuring a stable formation soil underneath busy rail tracks is highlighted. In this context, the effectiveness of using prefabricated vertical drains (PVDs) for stabilizing soft formation soils underlying rail tracks is discussed. The role of PVDs in the dissipation of cyclic excess pore water pressure is elucidated.

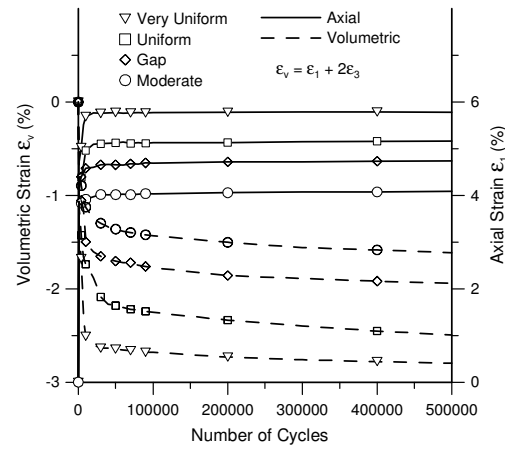
## **Effect of Particle Size Distribution on Ballast Behavior**

The gradation of ballast is a prime consideration for track performance. To evaluate the effects of particle size distribution on deformation and degradation behavior of ballast, large-scale cyclic triaxial tests were conducted on four different distributions of latite basalt at University of Wollongong. Details of the testing apparatus can be found in Indraratna et al. (2003). The gradation and void ratio characteristics of the test specimens are shown in Figure 1. Samples were subjected to an effective confining pressure of approximately 45 kPa, and cyclic loading having a maximum deviator stress of 300 kPa was applied on the ballast specimens at a frequency of 20 Hz. Figure 2 shows the effect of grain size distribution on the axial and volumetric strains of ballast under cyclic loading. The test results reveal that most uniform to moderately uniform samples give higher axial and volumetric strains. This is attributed to the looser states of the specimens prior to cyclic loading. In contrast, gap-graded and moderately graded distributions provided denser packing with a

higher co-ordination number (increased surface contact). Therefore, these gradations provided a higher shear strength as well as reduced settlement.

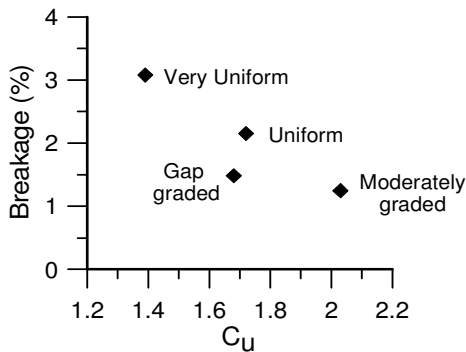


**Figure 1.** Particle size distributions used in the triaxial tests (Indraratna et al., 2004)

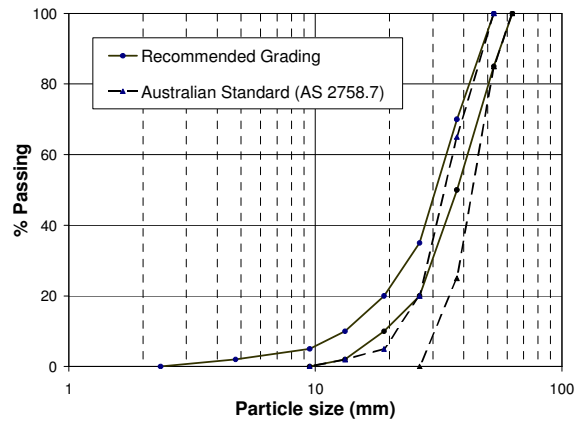


**Figure 2.** Axial and volumetric strain response of different distributions under cyclic loading (Indraratna et al., 2004)

In terms of deformation and resistance to particle breakage (Figure 3), the test results indicate that moderately graded ballast is far superior to uniform gradations, which is now acknowledged in the current ballast specifications of some countries including Australia. The test results also indicate that moderately graded ballast is still porous enough to maintain sufficient track drainage. Based on these findings, Indraratna et al. (2004) recommended a ballast gradation with a uniformity coefficient exceeding 2.2, but not more than 2.6, in comparison to very uniform (conventional) gradings with  $C_u = 1.4$ -1.5. This recommended gradation, which is relatively more well-graded than the current Australian Standards (AS 2758.7 1996) is presented in Figure 4.



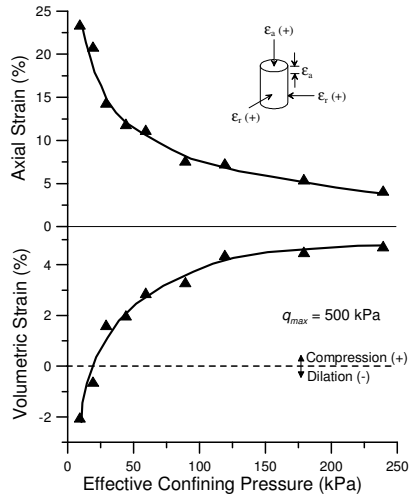
**Figure 3.** Effect of grading on particle breakage (Indraratna et al., 2004)



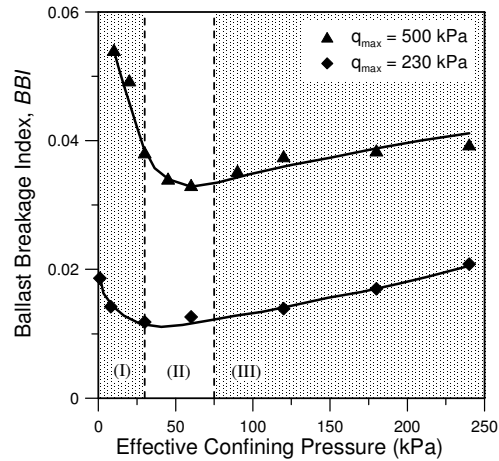
**Figure 4.** Recommended railway ballast grading in comparison with the current Australian Standard (Indraratna et al., 2004)

## Effect of Confining Pressure on Ballast Behavior

The role of confining pressure on ballast performance under cyclic loading has been investigated by Indraratna et al. (2005a). Figure 5 illustrates the effect of confining pressure ( $\sigma_3'$ ) on the axial and volumetric strains of ballast achieved at the end of 500,000 cycles for a maximum deviator stress of 500 kPa. As expected, the axial strains decreased with the increasing confining pressure. Ballast specimens exhibited dilation at small confining pressure ( $\sigma_3' < 30$  kPa), but became progressively more compressive as the confining pressure increased from 30 to 240 kPa. The effect of confining pressure on particle degradation is shown in Figure 6. It was found that there is an optimum confining pressure (30-75 kPa) in which the amount of ballast breakage was reduced to its minimum value. Some measures for increasing track confinement include: reducing sleeper spacing, increasing height of shoulder ballast, inclusion of a geosynthetic layer at the ballast-subballast layer interface, widening the of sleepers at both ends (Figure 7), and using intermittent lateral restraints at various parts of the track (Figure 8).



**Figure 5.** Variation of axial and volumetric strains with confining pressure (Indraratna et al., 2005)

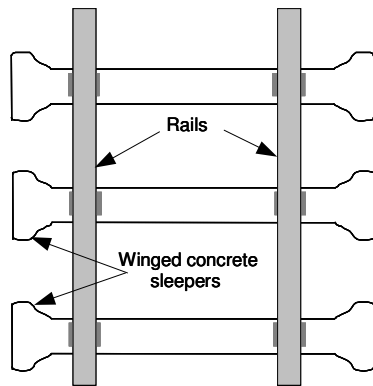


**Figure 6.** Effect of confining pressure on particle degradation (Indraratna et al., 2005)

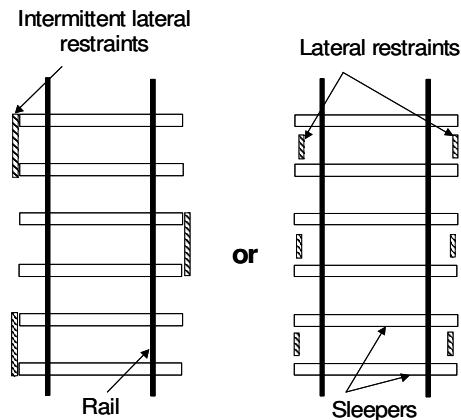
## Improvement of Recycled Ballast Using Geosynthetics

The deformation and degradation behavior of fresh and recycled ballast was investigated in a large-scale prismoidal triaxial chamber (Figures 9 and 10) simulating a small track section. Details of the large-scale rig can be found in Indraratna et al. (2003). The effectiveness of various geosynthetics in stabilizing recycled ballast was investigated through laboratory model test results. Three types of geosynthetics were used including woven geotextiles, geogrids and geocomposites. The tests were conducted in both dry and wet conditions to study the effects of saturation. The testing procedures together with complete findings and discussions have been reported by Indraratna et al. (2004).

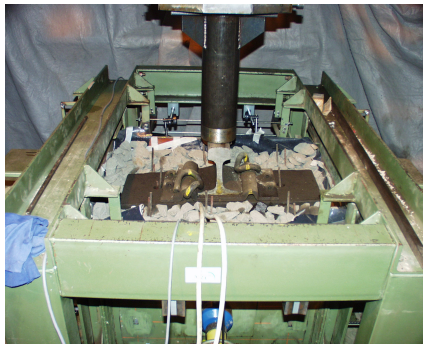
Figures 11 to 13 show the effect of geosynthetics on settlement, vertical strain and lateral strain of ballast in dry and wet status. It can be seen that, as expected, fresh ballast gives less deformation (i.e. settlement, vertical strain and lateral strain) than recycled ballast. It is believed that the higher angularity of fresh ballast contributes to much better particle interlock and therefore, causes less deformation. The test results reveal that wet recycled ballast (without any geosynthetic inclusion) generates significant deformation, because, water acts as a lubricant thereby reducing the frictional resistance and promoting particle slippage. Although geogrids and woven geotextiles decrease the deformation of recycled ballast considerably, the geocomposite (geogrid bonded with non-woven geotextile) stabilises recycled ballast remarkably well. As described by Rowe and Jones (2000), geocomposites can provide reinforcement to the ballast layer, as well as filtration and separation functions simultaneously. The combination of reinforcement by the geogrid and the filtration and separation functions provided by the bonded non-woven geotextile reduce the lateral spreading and fouling of ballast as well as ballast degradation, especially in wet conditions. The non-woven geotextile also prevents the fines moving up from the capping and subgrade layers (subgrade pumping), thereby keeping the recycled ballast relatively clean.



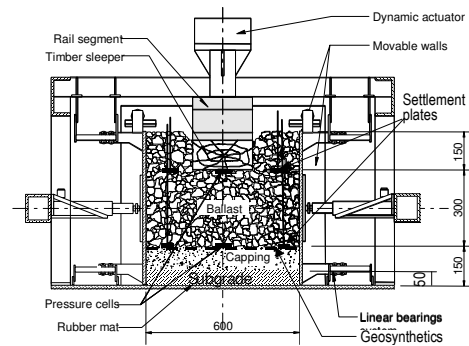
**Figure 7.** Sleepers with enlarged ends to increase the confining pressures



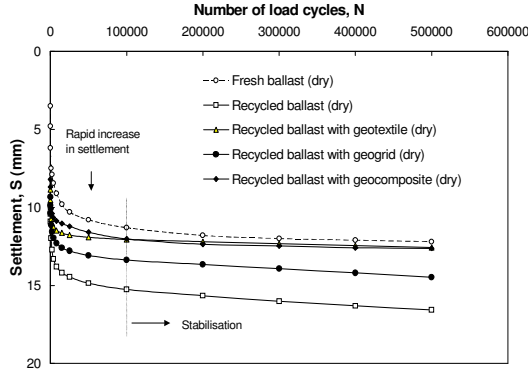
**Figure 8.** Increasing confining pressure using intermittent lateral restraints



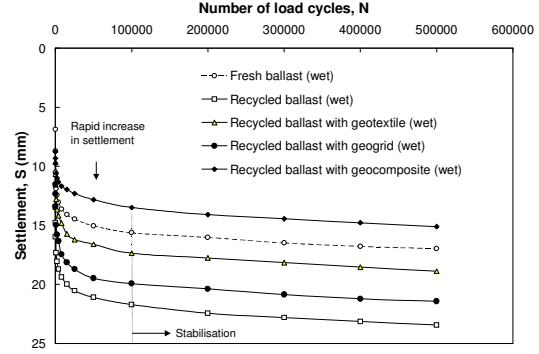
**Figure 9.** Large-scale prismoidal triaxial equipment designed at the UoW



**Figure 10.** Schematic view of the large-scale prismoidal triaxial apparatus (Indraratna and Salim 2003)

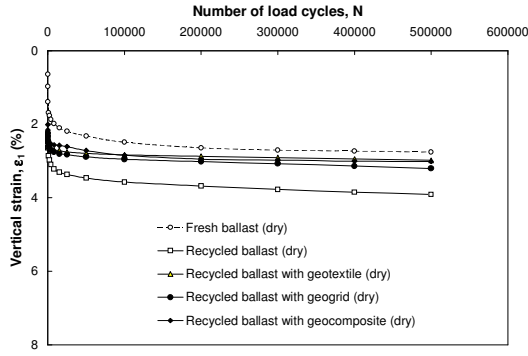


(a) dry samples

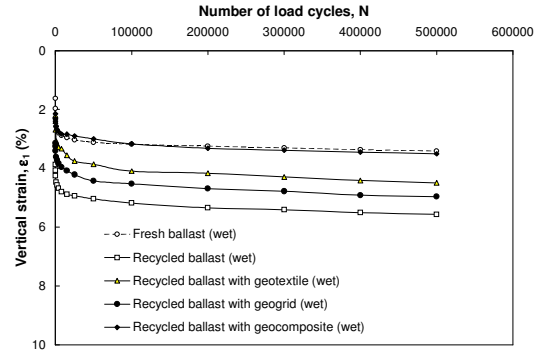


(b) wet samples

**Figure 11.** Effect of geosynthetics on the settlement of ballast  
(Indraratna et al., 2004)

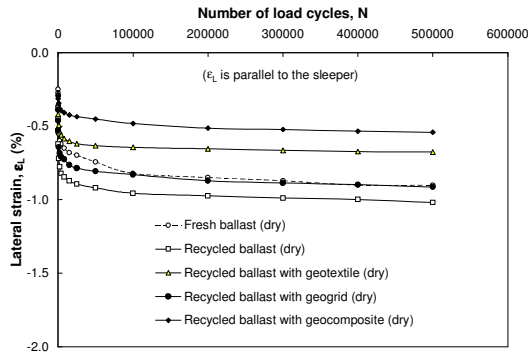


(a) dry samples

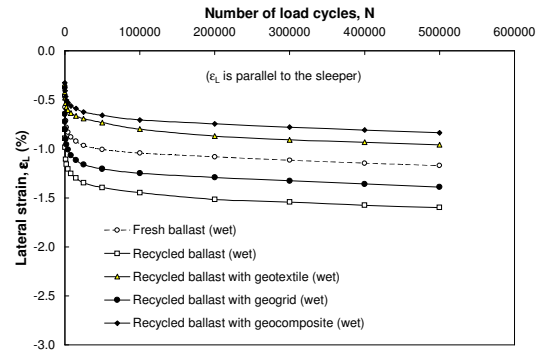


(b) wet samples

**Figure 12.** Effect of geosynthetics on the vertical strain of ballast  
(Indraratna et al., 2004)



(a) dry samples

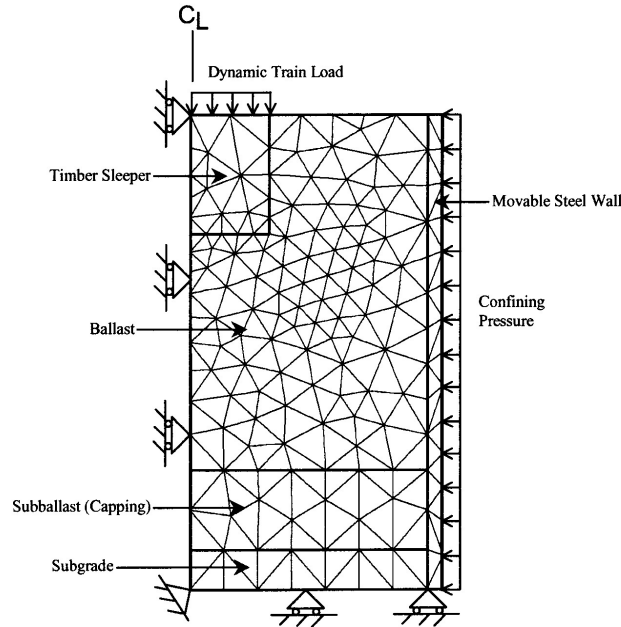


(b) wet samples

**Figure 13.** Effect of geosynthetics on the lateral strain of ballast  
(Indraratna et al., 2004)

To quantify ballast breakage based on Marsal's method (1967), each ballast specimen was sieved before and after testing, and the changes in percentage retained on each sieve size were recorded. The breakage index values of recycled ballast stabilized with geocomposites in dry and wet conditions were almost the same as

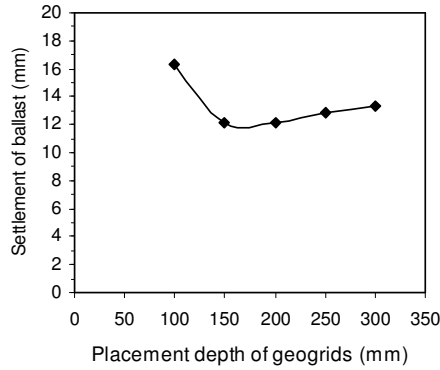
fresh ballast (without geocomposites), and approximately 50 % lower than those of recycled ballast without geosynthetics. This indicates clearly the benefits of using geosynthetics in the reduction of recycled ballast breakage in both dry and saturated conditions.



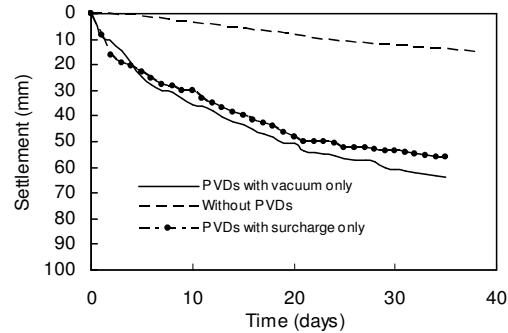
**Figure 14.** Finite element mesh used in PLAXIS for the prismoidal triaxial apparatus (Indraratna et al. 2005b)

Inclusion of geosynthetics for improving the deformation characteristics of ballast could be anywhere beneath the sleeper and within the ballast layer. However, to allow for tamping and subsequent maintenance of track (i.e. removal of used ballast and replacing with fresh aggregates), geosynthetics must not be placed at a depth less than 250-300 mm below the sleeper on new tracks, the geosynthetics are installed directly on the formation or subballast layer (Raymond 2002), whereas in track rehabilitation, they are installed on top of the old ballast, which has either been trimmed or embedded in the original subgrade formation (Ashpiz et al. 2002). In order to obtain the optimum location of geosynthetics for improving the deformation characteristics of recycled ballast, a finite element analysis (PLAXIS) was used. The large-scale prismoidal triaxial rig shown in Figure 10 was numerically discretised using the mesh shown in Figure 14. Due to symmetry, only one half of rig was considered in the numerical model. Full details of the finite element analysis conducted can be found in Indraratna et al. (2005b). The placement of geosynthetics beneath the sleeper was initially made at 300 mm depth (i.e. at the ballast capping interface) and then decreased at intervals of 50 mm so that the placement of geosynthetics could be examined at 250, 200, 150 and 100 mm, respectively. The results are plotted in Figure 15, which demonstrate that there is a threshold depth (between 150 to 200 mm) below which the geosynthetics do not contribute any further, but in fact, provides less assistance to settlement reduction. According to Figure 15, the optimum location of geosynthetics for improving the deformation

characteristics of recycled ballast may be taken as 200 mm. Nevertheless, for a conventional ballast thickness of 300 mm, placement of geosynthetics at the optimum location (i.e. at 200 mm) may not be feasible for maintenance reasons as mentioned earlier. Consequently, in such cases, the layer of geosynthetics may still be located conveniently at the bottom of the ballast bed (i.e. ballast/capping interface).



**Figure 15.** Optimum location of geosynthetics by the finite elements (Indraratna et al. 2005b)



**Figure 16.** Pre-consolidation settlements

### Improvement of Soft Formation Soils by Prefabricated Vertical Drains (PVDs)

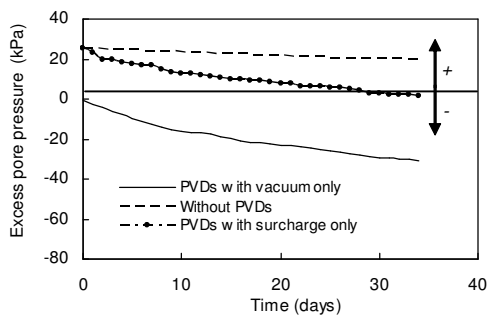
The quality of a robust rail track construction is defeated, if the underlying soft soil is weak and compressible, thereby leading to unacceptable differential settlement or pumping of slurried soil (under heavy axle loads) causing ballast fouling. In this context, the improvement of soft formation clays beneath rail tracks is imperative, and the use of PVDs prior to track construction is now encouraged in many coastal areas in Australia. Pre-construction consolidation of the formation soil will eliminate excessive post-construction settlement of the track as well as increasing the shear strength of the soil. Moreover, the PVDs will continue to function in the long-term to provide rapid pore pressure dissipation interfaces under cyclic load, especially in low-lying central areas subjected to high annual rainfall.

Pre-consolidation of soft formation soil by applying a surcharge load alone will take too long for urgent track construction. Installation of vertical drains can reduce the preloading period significantly by decreasing the drainage path length in the radial direction. When a higher surcharge load is required to meet the expected settlement and the cost of surcharge becomes expensive, the application of vacuum pressure with reduced surcharge loading can be used. In this method, an external negative load is applied to the soil surface in the form of vacuum pressure through a sealed membrane system. A higher effective stress is achieved by rapidly decreasing the pore water pressure, while the total stress remains the same, thus, any risk of potential shear failure due to excess pore pressure can be eliminated.

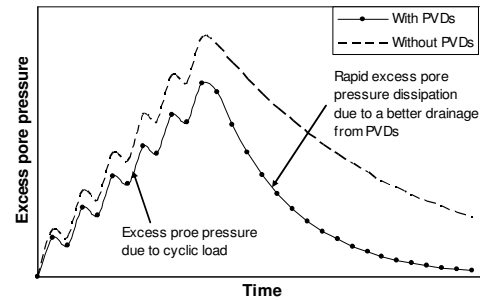
Figure 16 shows the results of the large-scale consolidometer which represent the typical time-settlement curves for soft soil formation improved by three different methods: (a) surcharge alone, (b) PVDs with surcharge and (c) PVDs with vacuum preloading. It can be seen that the required consolidation time is shorter when the rail

tracks are improved by PVDs, whereas consolidation behavior occurs more gradually in the case of surcharge alone (without PVDs). In terms of pore pressure dissipation, the initial excess pore pressure generated by vacuum application is smaller than that generated by conventional surcharge pressure (Figure 17). When vacuum pressure is applied, the ultimate excess pore pressure is always negative, significantly increasing the effective stress inducing consolidation. In the case of vacuum application, it is important to ensure that the site is totally sealed and isolated from any surrounding permeable soils to avoid air leakage that adversely affects the vacuum efficiency.

After track construction, the substructure including the underlying soil formation may be subjected to cyclic load from heavy freight trains. Ballast fouling by local subgrade pumping occurs where drainage is poor. Where PVDs have been installed, it is expected that they will speed up the dissipation of the excess pore pressure build up due to cyclic load. This is depicted in the illustrative example shown in Figure 18.



**Figure 17.** Time-dependent excess pore water pressure dissipation



**Figure 18.** Excess pore pressure generation due to cyclic load

## Conclusions

The results of this study illustrate that the particle size distribution of ballast plays a significant role on the behavior of rail tracks. Test results indicate that most uniform samples give higher axial and volumetric strains compared to more well-graded samples. The more well-graded ballast is less vulnerable to deformation and breakage than the uniform gradations. As long as the uniformity coefficient is less than 2.6, “free draining” conditions can still be ensured. Findings based on large-scale triaxial testing indicate that there is an optimum confining pressure (30-75 kPa) that can be applied on track at which ballast breakage is minimum.

Testing of recycled ballast indicates that the use of bonded geogrid-geotextile increases the bearing capacity of waste ballast and improves the overall resilient modulus of the layered stratum. The test results also demonstrate that the bonded grids decrease lateral movement and ballast degradation, apart from preventing ballast fouling by subgrade pumping. The finite element analysis of the cubical triaxial rig indicates that there is a threshold depth at which the effectiveness of geosynthetics is optimum. This threshold depth was found to be between 150 to 200 mm underneath the sleeper, even though for practical maintenance reasons, the grid may still be conveniently located at the bottom of the ballast bed of 300 mm.

Prefabricated vertical drains (PVDs) improve the geotechnical properties of soft formation clays underneath the track, and vacuum preloading further accelerates the pre-construction consolidation of formation clays significantly, thereby enhancing the stability of tracks during operation. PVDs also assist in rapid dissipation of excess pore pressure generated during cyclic loading.

## Acknowledgments

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