Soft Soil Improvement by Geosynthetics for Enhanced Performance of Transport Infrastructure

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ABSTRACT: Increasing demand for transportation has forced new infrastructure to be built on weak subgrade soils such as estuarine or marine clays. The application of heavy and high-frequency cyclic loads due to vehicular movement during the operational (post-construction) stage of tracks can cause (i) cyclic undrained failure, (ii) mud pumping or subgrade fluidisation, and (iii) differential and excessive settlement. This keynote paper presents the use of prefabricated vertical drains (PVDs) to enhance the performance of tracks. A series of laboratory experiments were carried out to investigate the cyclic response of remoulded soil specimens collected from a railway site near Wollongong, NSW, Australia. The results of the laboratory tests showed that beyond the critical cyclic stress ratio (CSRc), there is an internal redistribution of moisture within the specimen which causes the top portion of the specimen to soften and fluidise. The role that geosynthetics play in controlling and preventing mud pumping was analysed by assessing the development of excess pore water pressure (EPWP), the change in particle size distribution, and the water content of subgrade soil. The experimental data showed that PVDs can prevent the EPWP from building up to critical levels. PVDs provide shorter-radial drainage for EPWP to dissipate during cyclic loading, resulting in less accumulation of EPWP. Moreover, PVDs cause soil to behave in a partially drained rather than an undrained condition, while geotextiles can provide adequate surficial drainage and effective confinement at the ballast/subgrade interface. Partially drained cyclic models were developed by adopting the modified Cam clay theory to predict the behaviour of soil under cyclic loadings. The Sandgate Rail Grade Separation project case study presents a design of short PVDs to minimise the settlement and associated lateral displacement due to heavy-haul train loadings.

KEYWORDS: Case history, Cyclic loads, Prefabricated Vertical Drains, and Subgrade.

1. INTRODUCTION

Many regions in Australia and Southeast Asia are characterized by soft soils with unfavourable engineering properties. While it is better to avoid such geological conditions when developing new railway corridors, the growing demand for transportation necessitates the construction of transport infrastructure in these challenging geological settings (Indraratna et al., 2010). Various techniques have previously been used to improve this soft subgrade to enable new railway lines to be constructed. These techniques include surcharge preloading with prefabricated vertical drains (PVDs), vacuum preloading, stone columns, deep soil mixing (cement columns), and piled embankments. Extensive research has been carried out in this field and design guidelines are readily available (Arulrajah et al., 2009; Basack et al., 2016; Indraratna et al., 2005; Rujikiatkamjorn & Indraratna, 2007; Zhu et al., 2020).

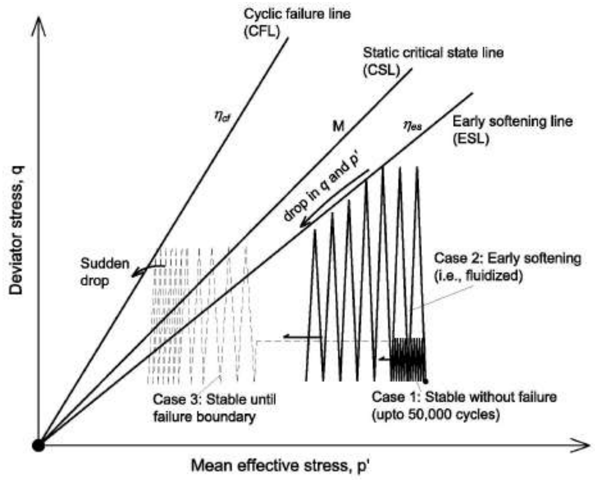
During their operational stage, tracks laid on subgrade which impedes drainage when subjected to cyclic loads can lead to increased excess pore water pressure (EPWP) (Ansal & Erken, 1989; Brown et al., 1975; Diaz-Rodriguez, 1989), which ultimately reduces the effective load-bearing capacity of the track formation (Sakai et al., 2003). Under high EPWP, the stress within the soil mass decreases until it reaches a stage of instability, excessive deformation, and shear failure (Li & Selig, 1998). With regards to the failure mechanism, the stress path reaches a failure line which is followed by unacceptably large axial strains (Figure 1 – Case 3).

According to Nguyen et al. (2019), saturated subgrade soil in low-lying areas becomes internally unstable under high dynamic axle loads. It then begins to pump fine particles into the overlying ballast layer due to an excessive upward hydraulic gradient induced by an increase in EPWP at shallow depths. This phenomenon is commonly referred to as mud pumping or subgrade fluidisation. The failure mechanism in p-q space indicates a sharp drop in the cyclic deviator stress due to strain-softening that is accompanied by non-zero effective stress towards the failure line (Figure 1 – Case 2). In Australia, where a considerable portion of railway tracks has been constructed on saturated subgrade soil with high water contents, soil fluidisation has been a significant issue for many years (Indraratna et al., 2011). The photographic records of soil fluidisation in ballasted tracks in Australia are presented by Indraratna et al. (2020c). Pumped slurry can be observed on the top of the ballast. This phenomenon not only reduces the overall bearing capacity of the track but also significantly diminishes the drainage capacity of the ballast due to the clogging of fine particles.

The traffic-induced permanent deformation of subgrade is a critical aspect of track design. Within railway tracks, settlements can be attributed to three distinct types of deformation: (i) permanent deformation of the railway ballast (i.e., deformation in the superstructure), (ii) undrained shear deformation of the subgrade, and (iii) consolidation settlement of the subgrade. In the p-q space, subgrade stress can remain stable and may not reach the failure envelope (Figure 1 – Case 1). However, excessive permanent deformation can cause undesirable differential settlement which can result in costly maintenance requirements. In order to predict this deformation accurately, the strength and deformation of the ballast, subballast, and subgrade, as well as the magnitude and duration of the traffic load (Chai & Miura, 2002) must be considered. In places consisting of soft, thick clay, track deformation due to consolidation settlement can be significant compared to the deformation of superstructure and undrained yielding (Indraratna et al., 2010).

In many instances, issues with subgrade occur due to poor drainage within the subgrade, which is why subgrade drainage must be improved. A prominent study in literature showcased how PVDs minimise the accumulation of EPWP by establishing shorter radial drainage paths (Hansbo, 1979; Holtz et al., 1991). Radial drainage paths facilitated by vertical drains not only enhance the stability of clayey foundations, they also help to solve the drainage problems that are often encountered in soft soils with low permeability (Ni et al., 2013).

While the use of PVDs to improve the pre-consolidation stress of road and railway embankments is well-documented, their application during the operational stage of tracks remains relatively unknown. According to the available literature, when a heavy-haul train travels at a speeds of 45-225 km/h, the loading frequency in subgrade varies between 1 – 5 Hz (Mamou et al., 2017; Powrie et al., 2007). The performance of PVDs under these cyclic loading conditions has thus far received limited attention. Therefore, the primary objective of this keynote paper is to present the significant research contributions on the utilization of PVDs in transport infrastructure, with a specific focus on undrained cyclic failure, soil fluidization, and cyclic consolidation settlement during track operations.



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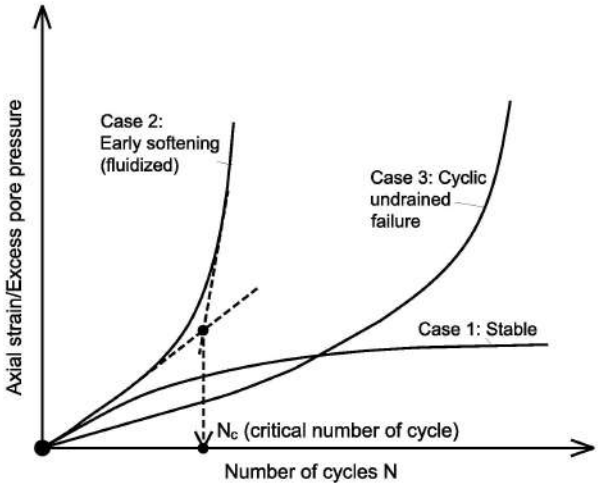

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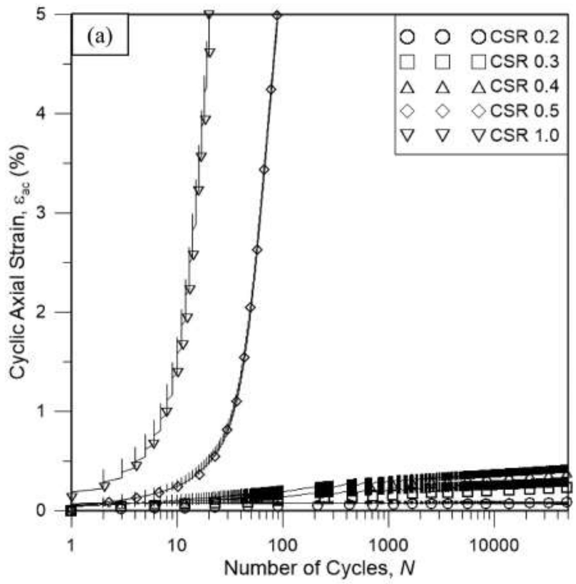
Figure 1 Response of subgrade soil due to cyclic loadings: (a) stress path; (b) axial strain or excess pore water pressure (after Indraratna et al. 2020b, with permission from Elsevier)

2. USE OF PVDS TO PREVENT CYCLIC UNDRAINED FAILURE

2.1 Effects of Cyclic Stress Ratio (CSR) on EPWP Development

In undrained conditions the development of EPWPs reduces the effective stress of soil and shifts the stress path towards the failure line. Using a series of triaxial tests on normally consolidated saturated clayey soils, Sangrey et al. (1969) reported a critical stress level beyond which cyclic failure occurs. When the cyclic stress applied is 0.5 times the maximum static deviator stress, the axial strain and EPWP stabilises after a specific number of loading cycles. However, when the cyclic stress was 0.8 times higher than the maximum static deviator stress, the axial strain and EPWP increased dramatically, indicating cyclic undrained failure. Therefore, the cyclic stress ratio (CSR) was used instead of the actual cyclic stress. In a cyclic triaxial test the CSR is usually defined as 0.5 σ_d/σ'_c ; where σ_d is the applied cyclic deviator stress and σ'_c is the effective confining pressure. When the CSR is low, which means a smaller load, the rate of PWP and axial strain can also be low, which means undrained failure will occur after many loading cycles or when it reaches equilibrium under a lower CSR.



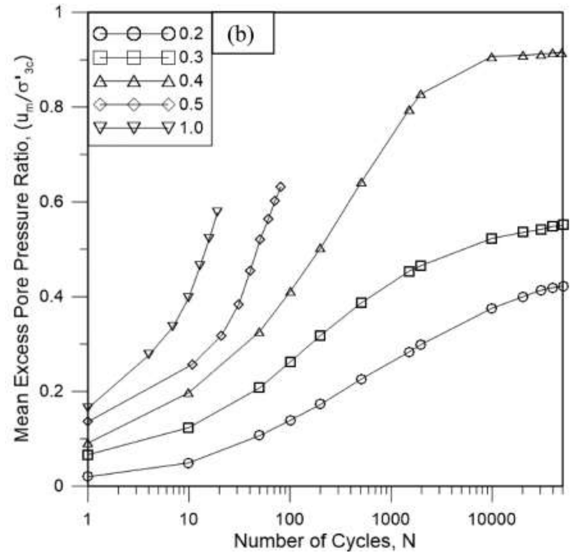


Figure 2 Effect of CSR on axial strains and mean excess pore water pressure ratio (after Indraratna et al. 2020a, with permission from Canadian Science Publishing)

The cyclic stress applied to subgrade soil varies with the axle load. For example, railway tracks in NSW usually experience 15-35 tonnes. However, the stress from the railway only reaches a shallow depth, which is why the effective confining pressure of subgrade soil can be as low as 15 – 30 kPa. Indraratna et al. (2020a) conducted a comprehensive study to investigate the effect of CSR on soil fluidisation. The CSR was varied between 0.2 to 1.0 (loading frequency = 0.1 Hz), and the cyclic axial strain and EPWPs were monitored. Figure 2 shows that the axial strain and mean EPWP increased with the increasing CSR values.

2.2 Effect of the Loading Frequency

Through a series of undrained cyclic triaxial tests, Zhou & Gong (2001) and Indraratna et al. (2020a) showed that the loading frequency had a significant effect on the development of EPWP and associated cyclic loading response of soil. Yasuhara et al. (1982) 's test results suggest that this frequency can delay the development of the peak excess pore pressure under undrained loading, where low frequencies induce a faster peak pore pressure than higher loading frequencies. Moreover, Thevakumar et al. (2021) conducted cyclic hollow cylinder test on reconstituted kaolin samples and showed that when the loading frequency changed from 0.1 Hz to 1 Hz, the resulting axial strains and EPWP differed significantly due to the effect of principal stress rotation.

2.2 Large-Scale Cyclic Testing Programme to Determine the Effectiveness of PVD under Cyclic Loading

To examine the ability of PVDs to prevent cyclic undrained failure, Indraratna et al. (2009) carried out large-scale cyclic triaxial testing on samples of kaolinite. This apparatus can accommodate samples that are 300 mm in diameter by 600 mm high (Figure 3). A type of hydraulic dynamic actuator was used to apply load cycles to the soil specimens (Indraratna et al., 1998). Each specimen had a vertical drain at the centre, and miniature pore pressure sensors were positioned at radial distances to monitor the EPWP. The width and thickness (and length) of the vertical drain were scaled down to 32 mm x 4 mm using the unit cell theory described in Indraratna & Redana (2000).

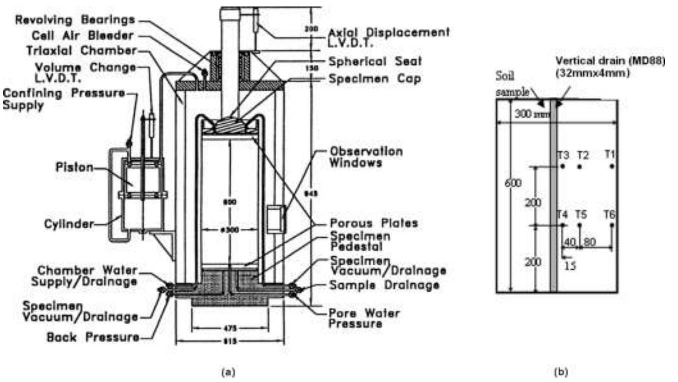


Figure 3 E(a) Schematic diagram of large-scale triaxial apparatus ; (b) locations of miniature pore pressure sensors (after Indraratna et al., 2009, with permission from ASCE)

A cyclic load equivalent to a CSR of 0.65 was applied to the sample having top drainage and radial drainage. An undrained test was also carried out under the same loading conditions to compare the effects. The results in Figure 4 demonstrate that PVDs effectively reduced the development of EPWP, while the undrained sample reached critical values of EPWP ratio (R_u). Here, R_u is defined as the EPWP normalized to the initial effective stress. Also, the development of EPWP near the drain is much smaller than at locations further away from the drain, showing how the length of the drainage path influences the development of EPWP. The data confirms how effectively PVDs can reduce the EPWP that is rapidly induced under cyclic loads, thus mitigating the potential for undrained failure.

Figure 5 shows substantial axial strains developing in undrained tests, and failure was detected when the curve started to concave downward in the log N plot. However, in tests carried out with PVDs the axial strains increased gradually until they reached a constant level, with no sample failure observed. These test results provide further confirmation that PVDs effectively mitigate cyclic undrained failure.

3. ABILITY OF PVDS AND GEOSYNTHETICS TO PREVENT SUBGRADE FLUIDISATION

3.1 Subgrade Fluidisation under Cyclic Triaxial Loading

Subgrade fluidisation is a complex geo-hydraulic phenomenon which involves the upward migration of finer particles towards the subgrade surface under adverse hydraulic conditions. The primary factor contributing to subgrade fluidisation is the generation of high EPWP. Cyclic triaxial tests carried out by Indraratna et al. (2020a) reported that the subsoil experienced higher axial strains and EPWP when the axle load increased, this led to soil softening and associated mud pumping. There was an exponential increase in axial strains and mean EPWP inside the subgrade soil when the test specimen was subjected to a critical cyclic stress ratio (CSRc). Furthermore, the specimen was also subjected to a considerable loss in stiffness when the cyclic stress exceeded the CSRc. As Figure 6 shows, the water content of the top soil increased until it approached the liquid limit of the soil (Fluid-like state). Subsequently, the particle size distribution (PSD) curves plotted at various heights along the fluidised sample proved there was an increment in the volume of fines in the upper layers (loss of fines observed at the middle layers) due to the internal redistribution of moisture under repetitive cyclic loads.

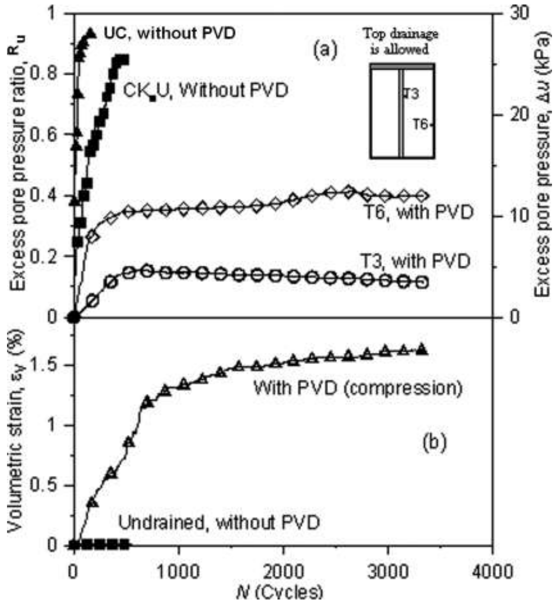


Figure 4 Measured EPWP in undrained (without PVD) and with PVD samples; (a) Ru versus the number of loading cycles (N) ; (b) volumetric strains (Indraratna et al., 2009)

3.2 Key Factors Affecting Subgrade Fluidisation

The characteristics of subgrade soil play an important role in dislocating fines from the soil matrix and pumping them up into the ballast/subballast layer. Nguyen et al. (2019) reviewed subgrade soils where soil fluidization had previously been reported. They found that most samples fell above the A line on the plasticity chart, indicating they consist of inorganic clay soils. For instance, subgrade soil consists of inorganic clays with low-medium plasticity that are vulnerable to subgrade fluidisation (Indraratna et al., 2020a, Nguyen et al., 2019); the liquid limit (LL) of these soft soils generally varies from 20-50 and the plasticity index (PI) remains less than 3.

Previous studies reported that higher cyclic stress can induce a rapid generation of EPWPs and diminish the stability of track foundations (Indraratna et al., 2020b). Dong et al. (2014) indicated that the generation of EPWPs under 50 kPa cyclic loading was almost double that which developed under monotonic loading. The cyclic frequency of subgrade soil depends primarily on the train speed, the carriage length, the bogies, and the distance between axles. Although larger axial strains and EPWP can develop at lower frequencies with increasing loading cycles (Indraratna et al., 2020a), the influence of frequency varies widely on different soils. Therefore, predictions can only be made by undertaking a series of laboratory and field tests. According to Alobaidi & Hoare (1996), the pumping of fines/slurry particles depends mainly on the surficial drainage and EPWPs that is generated at the subgrade/subbase interface. Furthermore, a significant hydraulic gradient generated during the dissipation of EPWP could separate the fines and pump the fine particles into the top layers. The inclusion of geosynthetics significantly reduced the generation of EPWPs and controlled the pumping of fines in both highway and railway embankments (Attya et al., 2007, Kermani et al., 2018; Palmeira et al., 1997).

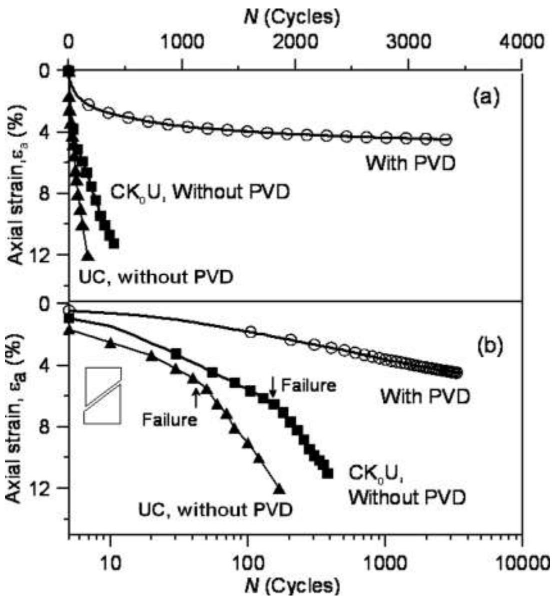
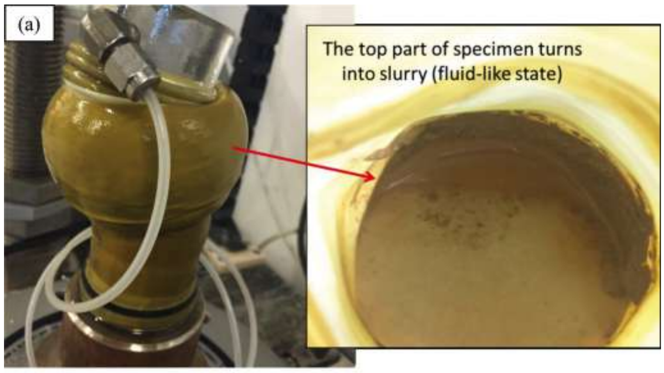


Figure 5 Measured axial strains in undrained (without PVD) and with PVD samples; (a) Number of loading cycles (N) in arithmetic scale; (b) N in log scale (after Indraratna et al. 2009, with permission from ASCE)

3.3 The Role of Geosynthetics at Preventing Subgrade Instability

Dynamic filtration tests were undertaken by Arivalagan et al. (2021) to measure the key factors that contribute to subgrade fluidisation and identify how effectively geosynthetics can reduce the risk of mud pumping. The dynamic filtration apparatus had miniature pressure transducers installed in the middle of the specimen to capture the accumulation of EPWP under cyclic loads. The EPWP measured by body transducers installed on the opposite faces of the polycarbonate cell could also measure the time-dependent excess pore pressure gradients (EPPGs) by considering the two adjacent layers of soil. The effectiveness of PVDs (Test P), Geocomposite/geotextile with a filter membrane (Test G), and PVDs combined with geocomposite (Test P+G) were assessed and then the laboratory results were compared to the undrained cyclic tests (Test U).

Figure 7 shows that the EPWP generated in Test P (PVD) is much lower than Test G (geocomposite), and was even from the start of the cyclic test. For instance, the rapid accumulation of EPWP with geocomposite is more than 35 kPa at MP2 (@40 mm) after only 500 cycles, but it was less than 20 kPa while using PVDs (Test P). However, the geocomposite could not alleviate the EPWPs in the middle of the sample (i.e., at 40 and 80 mm from the interface) below 15 kPa until after 30,000 cycles. This indicates that when only using a geocomposite, the rate at which excess pore water was dissipated in Test G was higher closer to the ballast/subgrade interface (MP1) than the middle/shallow part of the subgrade (MP2 and MP3), whereas the PVD dissipated the EPWP that developed at greater depths. For instance, the EPWP at MP3 was less than 4 kPa after 75,000 cycles. Although PVD (Test P) could dissipate the EPWP to less than 15 kPa at all three depths after 2000 loading cycles, the residual EPWPs at the subgrade interface are higher than those beneath because there is no more confinement or capping at the ballast/subgrade interface in Test P. The values of EPWPs that developed with the geocomposite are more than 30 kPa at the middle or lower regions (before 500 cycles); however, the PVD (Test P) certainly controlled the EPWPs, especially in the layers of deeper soil (80-120 mm). Therefore, the magnitude of EPWPs from Test P+G (PVD-Geocomposite system) is less than from the beginning of the test and remained less than 5 kPa at all depths after 75,000 cycles.



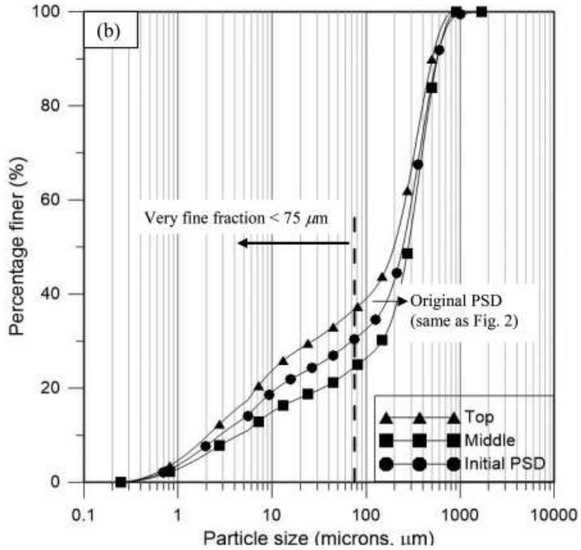


Figure 6 (a) Prepared triaxial specimen (b) Fludised specimen (c) Top part of specimen (Fluid-like state), and (d) Particle Size Distribution (after Indraratna et al., 2020a, with permission from Canadian Science Publishing)

The EPWPs that developed inside the specimen were measured under undrained conditions because they are the main cause of instability in subgrade under continuous cyclic loading. The generation of EPWPs under undrained cyclic tests is shown in Figure 7. On one hand there was a rapid development of EPWP up to 500 cycles, where all the miniature pressure readings remained above 25 kPa as the number of cycles increased. These results reveal that the middle or lower region of subgrade soil can develop higher EPWPs and is more vulnerable to subgrade failure under critical hydrodynamic conditions. On the other hand, there was an approximately 88% reduction in EPWPs 80 mm from the interface due to the PVD-geocomposite system shown in Figure 8. This proves that a combined PVD and geocomposite (P+G) system could minimise the potential for subgrade fluidisation during cyclic loading due to the continuous dissipation of EPWPs, unlike in the undrained tests (i.e., there was no significant reduction in Test U).

The PSD of soil collected at three different locations and at 0, 100, and 200 mm deep was determined using the Malvern particle analyser. Figure 9 shows a high particle migration from the middle of the soil towards the top in undrained tests. However, particle migration is significantly controlled in the Test P+G (PVD-Geocomposite system). The PSD of the top and middle regions remained the same in the test with a PVD-geocomposite system, and there was no sign of particle migration during cyclic loading. This indicates that geocomposite and PVDs could effectively prevent particles from migrating towards the upper layers.

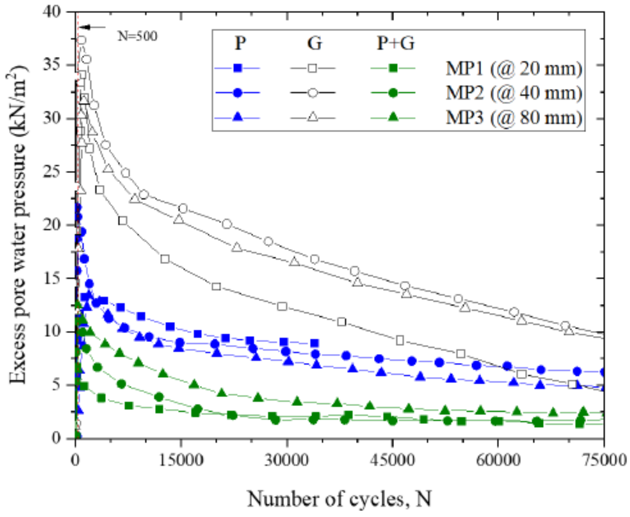


Figure 7 Development of excess pore water pressure – Tests with PVDs (P), Geocomposites (G) and PVD-Geocomposite system (P+G) (Arivalagan et al., 2022, with permission from Geotextiles and Geomembranes)

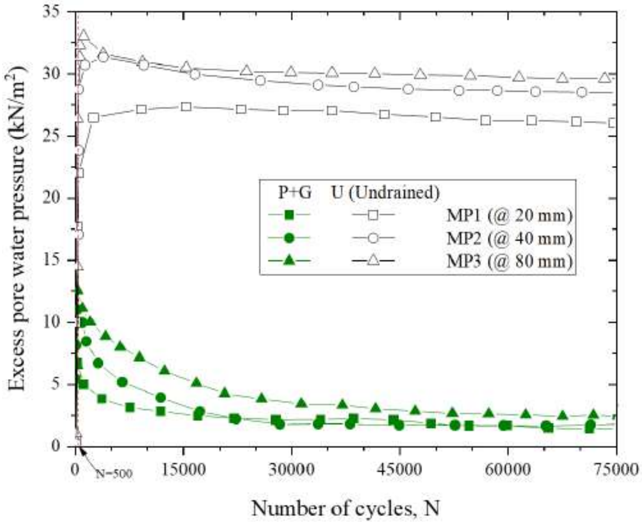


Figure 8 Generation of EPWPs – Undrained (U) and cyclic tests with PVD-Geocomposite system (P+G) (Arivalagan et al., 2022, with permission from Geotextiles and Geomembranes)

The moisture content of the specimen was measured at the end of each cyclic test. As Figure 10 shows, Test P (a sole PVD) could not reduce the water content near the top surface; the water content in Test P was almost 35% at the interface (top surface). Under repetitive cyclic loads, fine particles with increased moisture accumulated near the interface because ballast penetrated the subgrade surface. However, the inclusion of geocomposite (Test G or Test P+G) significantly reduced the water content and prevented fines from accumulating at the subgrade interface. In addition, the variations in the water content in Tests G and P+G are similar because the geocomposite on the topsoil mitigated any rapid increase in the water content by providing adequate confinement and drainage at the subgrade interface. This further confirms that geocomposites with PVD could reduce the accumulation of EPWPs at the subgrade surface and deeper layers of soil and also prevent the migration of fines and the formation of slurry under train load.

4. CONSOLIDATION SETTLEMENT OF SUBGRADES DUE TO CYCLIC LOADING

4.1 Flow Characteristics during Cyclic Consolidation

Consolidation settlement occurs due to the dissipation of EPWP from the soil (Mamou et al., 2017). Thick layers of estuarine clay from the Holocene era are commonly found along the eastern coast of Australia, which means that consolidation settlement in these areas can be excessive (Kelly et al., 2018). Hyodo & Yasuhara (1988) described the EPWP behaviour of soil under partially-drained loading after long-term cyclic loading (Figure 11). During cyclic loading the EPWP increases rapidly until it reaches a peak value and then decreases to a residual value (Hyodo & Yasuhara, 1988; Ni et al., 2015; Sakai et al., 2003). Where $du = du_G - du_D$; du = Total increase of excess pore water pressure during dt time interval; du_G = Amount of excess pore water pressure generated during dt time interval; du_D = Amount of excess pore water pressure dissipated during dt time interval. Before peak pore water pressure $du > 0$ as $du_G > du_D$. After peak pore water pressure $du < 0$ as $du_G < du_D$.

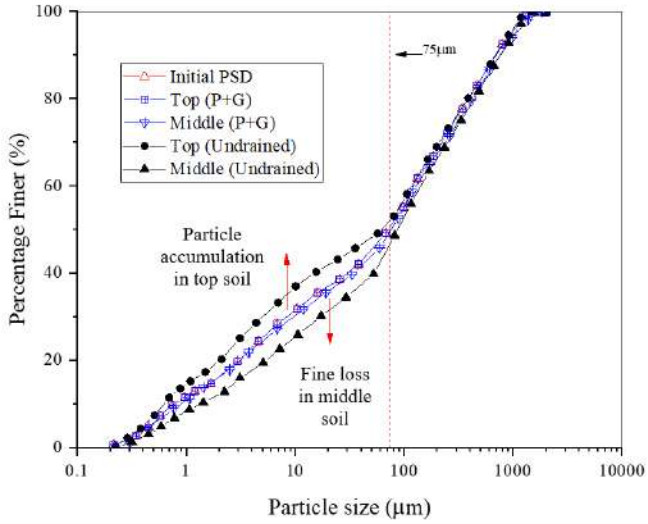


Figure 9 Particle size distribution – Undrained (U) and cyclic tests with PVD-Geocomposite system (P+G) (Arivalagan et al., 2022, with permission from Geotextiles and Geomembranes)

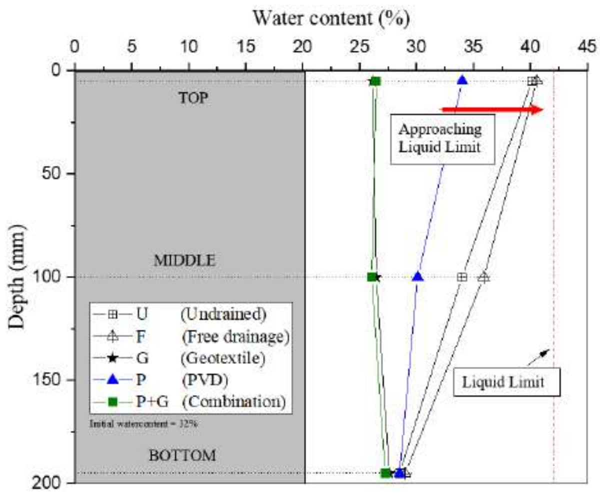


Figure 10 Water content at 100,000 cycles – Test with and without geosynthetics (Arivalagan et al. 2022, with permission from Geotextiles and Geomembranes)

This behaviour of EPWP in cyclic consolidation differs from that in static consolidation theories. When constructing a static embankment it is often assumed that EPWP develops instantaneously and consolidation settlement occurs afterwards, and therefore the hydraulic gradient is proportional to the flow rate (Hansbo, 1960; Kianfar et al., 2013). However, during cyclic consolidation the EPWP increases with the number of cycles and dissipation occurs simultaneously. Atapattu et al. (2023) carried out one-dimensional cyclic consolidation tests at 1 Hz loading frequency for five consecutive days (CL1 to CL5). Drainage was allowed in the vertical direction and the excess pore water pressure (EPWP) at mid-depth and the top surface was measured. As Figure 12 shows, the hydraulic gradient increased up to 30,000 loading cycles and then decreased after reaching the peak gradient. Therefore, the relationship between the hydraulic gradient and the flow rate is inversely proportional, as indicated during the initial stage of loading. However, when the dissipation rate dominates (i.e., $du_D > du_G$ after the peak hydraulic gradient), the hydraulic gradient becomes proportional to the flow rate, similar to static consolidation.

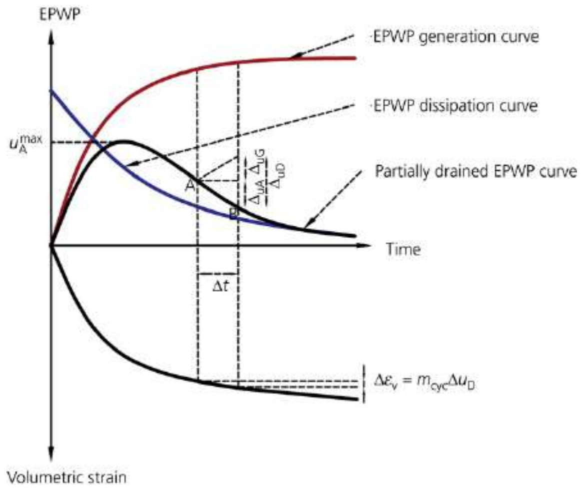


Figure 11 EPWP behaviour under partially-drained loading (adopted from Atapattu et al., 2023, with permission from Emerald Publishing Ltd.)

These test results indicate that cyclic consolidation depends on the number of cycles required to reach the maximum EPWP. Undrained cyclic loading tests by Korkitsuntornsan et al. (2022) on Ballina clay showed that the EPWP only stabilized after 15,000 loading cycles, whereas the radial consolidation test carried out on samples of reconstituted kaolinite took only 1000 cycles to reach the peak EPWP (Indraratna et al., 2014). Similarly, Sakai et al. (2003), observed a peak EPWP after 50 loading cycles. Therefore, the number of loading cycles required to reach peak EPWP and to obtain a residual EPWP value will depend on the properties of the soil. The end of consolidation settlement is usually determined when there is no remaining EPWP in the soil and the load has been fully transferred to the soil skeleton. Therefore, to determine the time it takes to reach the end of cyclic consolidation in a particular layer, it is important to determine the number of loading cycles required to obtain the peak EPWP and residual EPWP.

4.2 Influence of Periodic Loading on Cyclic Consolidation

Railways often undergo cyclic loading followed by periods of rest. Experimental research by Indraratna et al. (2009) indicated that during rest periods the EPWP that accumulated during cyclic loading would dissipate to a residual level with the presence of PVDs. Measurements closer to the drain (T3) showed much lower EPWP than those taken away from the drain (T6) (Figure 13). While the EPWP at T3 dissipated fully during the rest period, only about 50% of the EPWP at T6 had dissipated. This shows the importance of drainage in dissipating EPWP even during rest periods. Note also that the rate of EPWP dissipation during rest periods is slower than the rate at which EPWP accumulates during cyclic loading.

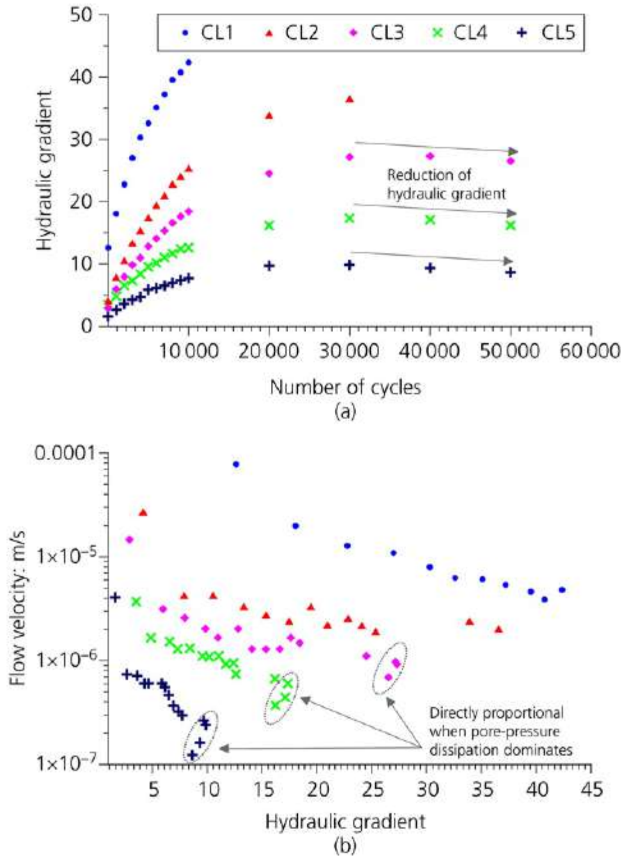


Figure 12 (a) Measured hydraulic gradient during cyclic consolidation test; (b) Relationship between flow rate and hydraulic gradient (after Atapattu et al., 2023, with permission from Emerald Publishing Ltd.)

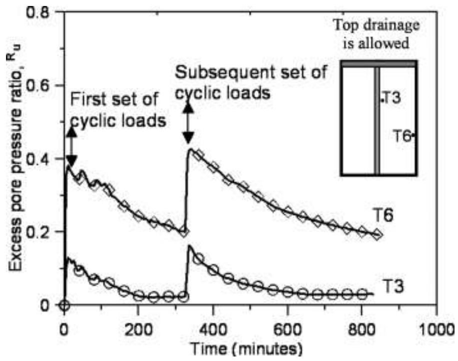


Figure 13 EPWP dissipation during the rest period (after Indraratna et al., 2009, with permission from ASCE)

Moreover, Atapattu et al. (2023) conducted a one-dimensional large-scale cyclic consolidation test with two-way drainage which yielded similar findings. Figure 14 shows a reduction in peak EPWP after each intermittent loading cycle. This is due to the inevitable increase in soil stiffness (resulting in decreased pore space or void ratio) during cyclic consolidation. As cyclic consolidation progresses the observed settlement is much less in later loading cycles than in the initial cycles. The EPWP generated at the end of cyclic loading dissipated during the rest period without causing any consolidation settlements. Moreover, there was no volumetric discharge of water from the drain. These observations indicate that in railway tracks, consolidation settlement of the subgrade only occurs during train passage but does not undergo further settlements during the rest period, despite the dissipation of EPWP. A similar pattern was observed at a railway site in Sandgate, NSW, where the EPWP increased when a train passed over, but then quickly returned to its normal hydrostatic level during the rest period.

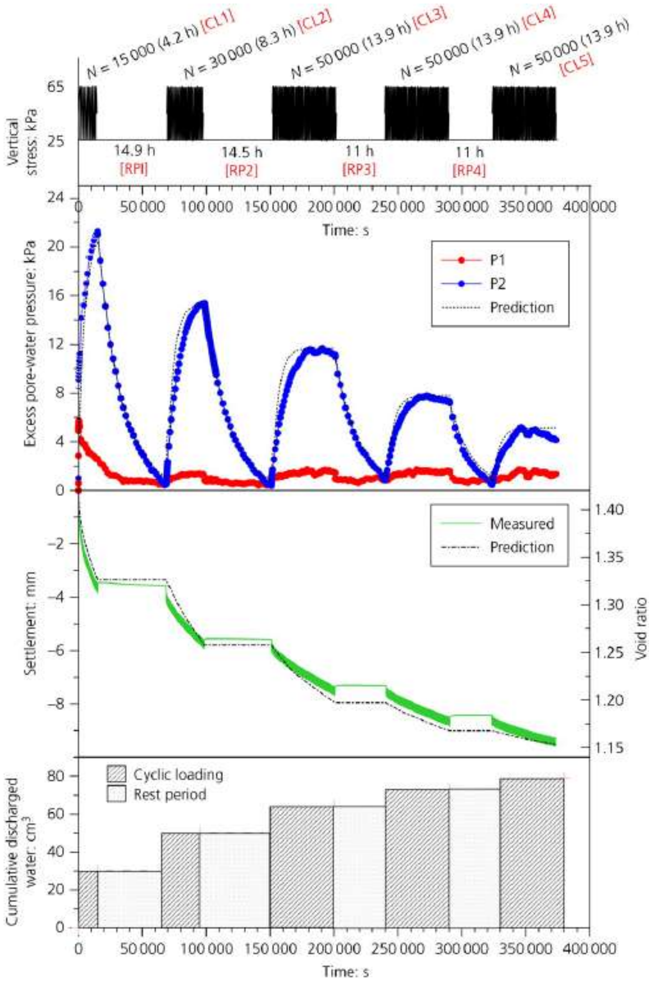


Figure 14 (a) applied stress; (b) EPWP; (c) settlement or void ratio; (d) volume of water discharged (CL – cyclic loading stages; RP – rest periods) (after Atapattu et al., 2023, with permission from Emerald Publishing Ltd.)

5. CONSTITUTIVE MODELS FOR SOFT CLAY UNDER CYCLIC LOADING

The accumulation of EPWP with an increasing number of loading cycles cannot be modelled from conventional soft soil models such as modified Cam Clay and PLAXIS soft soil models. To address this limitation, Carter et al. (1980) proposed a constitutive model based on a modified Cam Clay framework that considered changes to the yield surface during the unloading and reloading process. In this model the rate at which the yield surface shrinks during unloading was defined using a degradation parameter that is a function of the number of loading cycles. With this model the changes to the yield surface were captured during each unloading cycle. However, with this model the degradation parameter is constant and does not change with the increasing number of loading cycles, and therefore the rate of plastic strains will increase until failure. Ni et al. (2015) addressed the limitations of Carter et al. (1980) 's model by introducing a modified degradation parameter that considers the number of loading cycles; on this basis the EPWP rate will decrease with the increasing number of cycles. The yield surface response to cyclic loading in this model is shown in Figure 15(a).

- A' to A (1st loading cycle) = EPWP increases and the effective stress decreases. Normally consolidated soil is considered and therefore, during first cyclic loading the yield surface expands to $p'_{c1,1}$
- A to A* (1st unloading cycle) = Elastically unloading, the effective mean stress (P'A) remains constant and the deviatoric stress decreases to zero. However, the yield surface shrinks to $p'_{cu,1}$ from $p'_{c1,1}$
- A* to B' to B (2nd loading cycle) = soil elastically reloading until $q < q_{yield}$. Once $q_{yield} < q < q_{cyc}$, soil behaves plastically and the yield surface expands to $p'_{c1,2}$

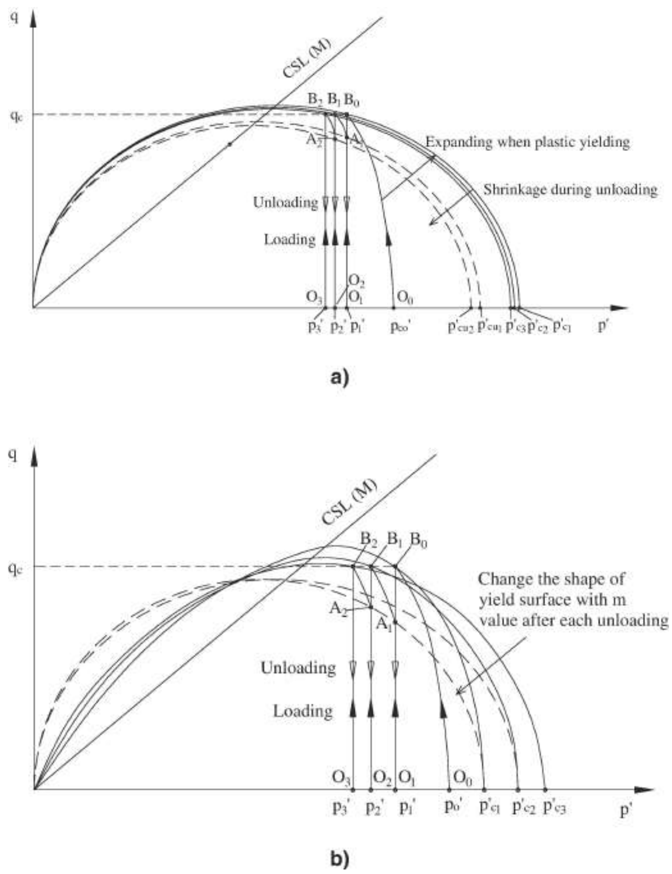


Figure 15 (a) Illustration of Ni et al. (2015) model; (b) Illustration of Truong et al. (2021) model (adopted from Indraratna et al., 2021, with permission from Elsevier)

Although Ni et al. (2015) model can accurately predict the permanent strains and EPWP during cyclic loadings, one of its limitations was the hardening parameter (pre-consolidation stress) which changes with the loading cycles under undrained loading. Ideally, under undrained cyclic loading the pre-consolidation stress will remain constant because there is no change in the void ratio. To address this limitation, Truong et al. (2021) proposed a new model which considers a shape change of the yield surface during each loading cycle while the size remains the same. No change in the size of the yield surface means that the hardening parameter does not change during unloading. Truong et al. (2021) introduced a shape parameter as a function of the number of loading cycles. An illustration of this model in p-q space is shown in Figure 15(b).

- $O_0 – B_0$ (1st loading cycle) = The yield surface expands to p'_{c1}
- B_0 - O_1 (1st unloading cycle) = Yield surface changes it shape while maintaining its size, i.e., p'_{c1} (dotted line)
- O_1 - A_1 (2nd loading cycle) = The yield surface reforms following the stress path $O_1A_1B_1$ to reach the desired level of q, resulting in a new shape and size of the yield surface (p'_{c2}).
- A_1 - B_1 = Plastic yielding occurs and expansion of the yield surface to (p'_{c2}).
- Therefore, size of the yield surface does not change during unloading.

6. APPLICATION TO A CASE STUDY

For subgrade under railways where the load distribution from heavy haul trains is typically contained within 6-7 m from the ballast layer, relatively short PVDs can be used to dissipate the accumulated pore pressures and curtail any lateral movement under cyclic load. Any excessive vertical deformation of estuarine deposits below the tips of the PVDs during the initial consolidation stage can be compensated for by continuous ballast packing. However, the rate and magnitude of consolidation settlement can still be optimised by the spacing and pattern of PVDs. This section presents a case history where a rail track built on soft formation was stabilised by short PVDs accompanied by a finite element analysis (Indraratna et al., 2010). The numerical analysis by the Authors was a typical Class A prediction for a field performance verification because it was analysed before the track was constructed.

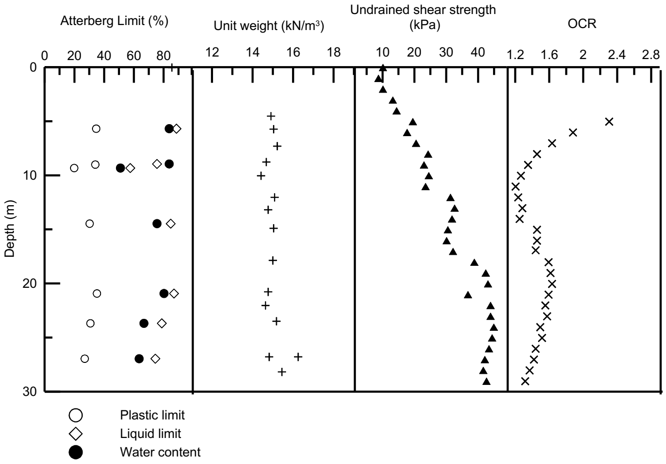


Figure 16 Soil properties at Sandgate Rail Grade Separation Project (adopted from Indraratna et al., 2010, with permission from ASCE)

To enhance the capacity of rail traffic along the Sandgate route, Kooragang Island, Australia, where there are major coal mines nearby, new railway lines were built close to the existing track. Site investigations including in-situ and laboratory tests, were reported by GHD Longmac (Chan, 2005) to obtain the important soil parameters needed for this design. It consisted of boreholes, piezocone tests, in-situ vane shear tests, test pits, and laboratory tests (e.g., the soil index property, standard oedometer testing, and vane shear testing).

The existing embankment fill was on top of soft estuarine clay soil located between 4 and 30 m deep over a shale bedrock. The profiles of soil strata and their properties, with depth, are shown in Figure 16. The groundwater level was located at the surface. Short PVDs were installed up to 8 m deep to dissipate excess pore pressure and control lateral displacement. In the absence of a surcharge embankment as preloading due to limited construction time, the PVDs were applied strategically to consolidate a relatively shallow depth within the influence zone and the depth affected by the train load. An equivalent static method using the dynamic impact factor was used to simulate field conditions. At this site, a vertical load of 80 kPa with an impact factor of 1.3 represented a train speed of 40 km/hr and a 25-tonne axle load. The Soft Soil and Mohr-Coulomb models were adopted via the finite element code PLAXIS, (Brinkgreve, 2002). Figure 17 shows a mesh discretisation of the cross-section of the rail track formation with short PVDs.

Based on the analysis, 8 m long PVDs were installed at 1.5 m spacings in the actual construction. Figure 18 shows the predicted and measured settlement at the centre line of the rail track and the lateral displacement after 6 months, The predicted settlement agreed with the field data, with the maximum displacement being presented within the shallow depth of clay. The "Class A" prediction of lateral displacement agreed with what occurred in the field.

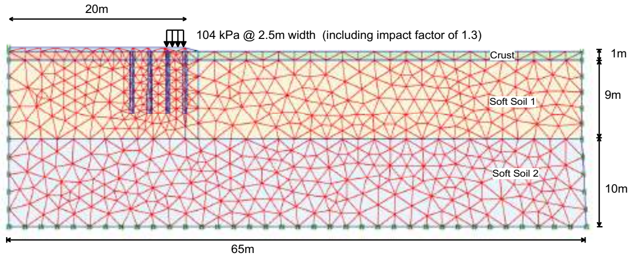


Figure 17 Vertical cross section of rail track foundation (after Indraratna et al., 2010, with permission from ASCE)

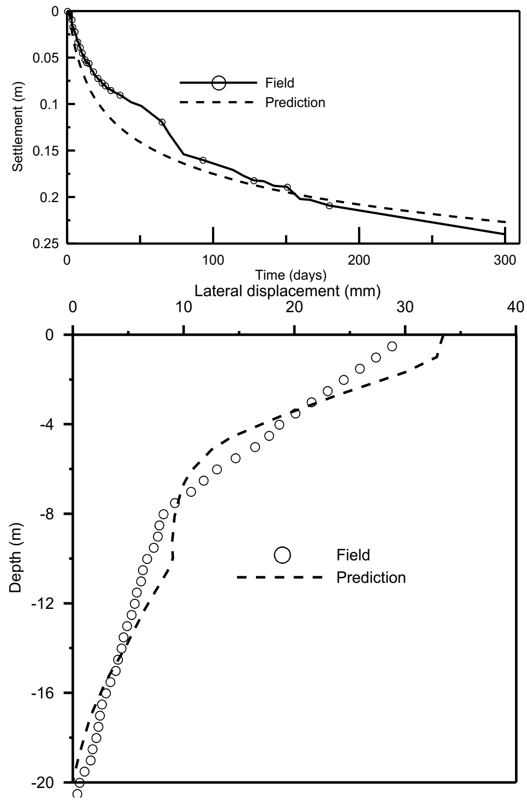


Figure 18 (a) Predicted and measured at the centre line of rail tracks; (b) Measured and predicted lateral displacement profiles near the rail embankment toe at 180 days (after Indraratna et al., 2010, with permission from ASCE)

7. CONCLUSIONS

This paper presents the results from laboratory tests of soft railway subgrades soils under cyclic loads with PVDs and geosynthetics. The key findings from this study are as follows:

- During the application of cyclic loads, the PVDs significantly reduced the build-up of EPWP, mitigating the risk of cyclic undrained failure. For example, the R_u measured near the PVD was about 0.1 compared to 0.9 in the undrained test without PVD.
- The plasticity of the soil, the volume of fines, and the hydraulic gradient resulting from EPWP affected the potential of subgrade soil pumping. Soils with low-to-medium plasticity are generally more prone to mud pumping. Experimental results proved that the water content of soil in the upper layer approaches its liquid limit due to an internal redistribution of moisture during soil fluidisation.
- The inclusion of geocomposite at the ballast-subgrade interface effectively prevents particle migration by dissipating the EPWP at the subgrade interface. Moreover, the implementation of the combined PVD-Geocomposite system demonstrated a substantial reduction in the risk of

track instability, as it further decreased the development of EPWP in the deeper layers of soil. The PVD-Geocomposite system reduced the development of EPWP by 53% compared to the geocomposite system used alone.

- These experiments demonstrated that EPWP generated during cyclic loading can be dissipated during rest periods without causing consolidation settlement. This implies that railway tracks undergo consolidation settlement only during the passage of trains, they do not experience any further settlement during the rest period, despite the dissipation of EPWP. Moreover, the dissipation of EPWP during the rest period leads to increased stability for subsequent train passages because the EPWP that develops during subsequent loading cycles is significantly reduced.

- The proposed cyclic constitutive soil models can be utilized to accurately predict the development of EPWP with an increasing number of cycles. These models address the limitations of traditional modified cam clay models which cannot capture the accumulation of permanent strains and EPWP under an increasing number of loading cycles.

- The Sandgate Rail Grade Separation project case study demonstrated the effectiveness of using short PVDs to enhance the stability of rail tracks. These PVDs helped to dissipate the EPWP, limit lateral displacement, and mitigate the occurrence of mud pumping.

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