Effectiveness of Geosynthetics at Preventing Subgrade Instability under Cyclic Loading

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ABSTRACT

Recent laboratory investigations indicate that low-to-medium plasticity subgrade is vulnerable to subgrade fluidisation due to excessive local hydraulic gradients that develop under cyclic loading. This study primarily investigates the role of geosynthetics to dissipate accumulated excess pore water pressure (EPWP), and minimise particle migration and subgrade fluidisation in typical railway track environments using the Dynamic Filtration Apparatus (DFA). The experiments indicate there is an upward migration of moisture and fine particles towards the ballast-subgrade interface which cause the soil specimen to soften (slurry) under undrained cyclic tests. The combined prefabricated vertical drains (PVDs) and geocomposite system can dissipate the rapid accumulation of EPWPs due to the reduction in drainage path lengths and additional confinement at the ballast and subgrade interface. The excess pore pressure gradients (EPPG) that developed at different depths of the soil specimens were measured to assess the potential for the upward migration of fine particles.

Keywords:
Subgrade fluidisation, Excess pore water pressure, Geosynthetics, Mud pumping

1. INTRODUCTION

The stability of railway tracks constructed on soft and saturated ground is greatly affected by increased speeds and axle loads. This can lead to a significant drop in the stiffness of subgrade soil, as well as differential settlement and mud pumping under adverse hydro-dynamic conditions that substantially increase the cost of track maintenance. This is why innovative and cost-effective solutions are needed to enhance track performance over the operational design period.

A dynamic load significantly reduces track stability by inducing high excess pore water pressure (EPWP) that separates the fine particles from the coarser fraction of soil matrix and induces particle migration (Alobaidi & Hoare 1996). Most recent studies reported that fine particles can migrate upwards (Indraratna et al. 2020a; Indraratna et al. 2020b; Nguyen et al. 2019), and when they accumulate at the top they can turn into slurry (i.e., mud pumping) during the passage of trains. Subsequently, fines that are pumped-up into the ballast can hinder the drainage capacity of the track and inhibit the ballast from inter-particle friction, as shown in

Figure 1. The solutions used to prevent mud pumping and restore the strength and drainage capacity of tracks are important because although conventional methods such as renewing fouled ballast, maintaining ballast shoulders, side ditches, and the drainage system can improve the overall drainage capacity of the track, they can become ineffective under adverse hydraulic conditions and cannot prevent the infiltration of fines and subgrade fluidisation over the long term (Mamou et al. 2017; Selig & Waters 1994).

Figure 1: Subgrade mud pumping at Kembla Grange, NSW, Australia (Korkitsuntornsan 2020)

The installation of geosynthetics is an alternative way to provide adequate drainage and maintain the structural stability of tracks. Indraratna et al. (2010) reported that short wick drains can help to stabilise tracks and also mitigate the potential fluidisation of soft soils by continually alleviating EPWPs, even after the passage of trains. Past classical literature clearly explains how radial drainage paths are facilitated by vertical drains (Hansbo 1979; Hansbo 1997; Holtz et al. 1991), and how PVDs increase the stability of railway foundations. This explains why this mechanism is used to assist soil consolidation under cyclic loading (Indraratna et al. 2011). Moreover, less EPWPs would develop for the next train loading and potential fluidisation or infiltration of the subgrade could not be triggered (Indraratna et al. 2009; Singh et al. 2020).

Although various geotextiles and geocomposites have been tested in the field and undergone large-scale laboratory testing, their ability to prevent particle migration and fluidisation varies widely. While some studies reported that geosynthetics have limited efficiency and their performance could diminish rapidly after installation (Ayres 1986; Faure et al. 2006; Selig & Waters 1994; Sharpe 1988), more recent studies indicate that geosynthetics could prevent particle migration and potential track failures under dynamic loading (Arivalagan et al. 2021; Kermani et al. 2019). Geotextiles can also be combined with a capping layer and/or geogrids to enhance drainage and accelerate the rate at which EPWP dissipates under cyclic loading(Alobaidi 1991; Sharpe et al. 2014).

This study primarily examines how geotextiles, geocomposites and a combined PVD-Geocomposite system alleviate the occurrence of soil fluidisation. To achieve this goal, a series of dynamic filtration tests were carried out to assess fluidisation potential at the ballast/subgrade interface by measuring the excess pore water pressure (EPWP), axial deformation, moisture content, particle size distribution and time-dependent seepage.

2. LABORATORY INVESTIGATION

2.1 Dynamic Filtration Tests

To carry out dynamic filtration tests, samples of disturbed soil that had experienced mud pumping were collected from the South Coast Rail line at Wollongong, NSW, Australia. The test material consisted of more than 200 kg of subgrade soil that had been sieved through a 2.36 mm sieve and then stockpiled. Particle size distribution (PSD) and basic geotechnical tests were carried out as described in Figure 2(a) and 2(b). Nonwoven geotextiles (G2, G3) with pore opening sizes that varied from 60 to 80 μm were used for these laboratory experiments. Geocomposite G1 had a filter membrane sandwiched between two nonwoven geotextile layers with an aperture opening size (O_{95}) of <10 μm. The average permeability of G1, G2 and G3 were 0.03, 45, 40, 30 and 0.35 mm/s, respectively. The PVD had an assembled drain width of 100 mm, a thickness of 3.4 mm and a drain filter pore size of 75 μm. The assembled drain flow at 200 kPa discharge was 2800 m^3/yr. All the properties of the geosynthetics are listed in Table 1.

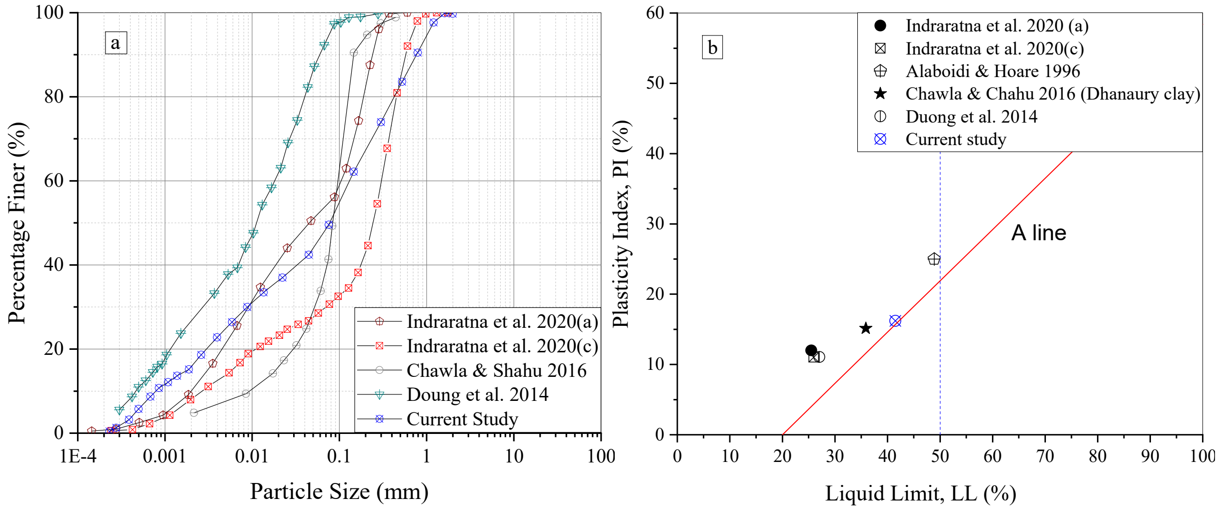

Figure 2: (a) Particle size distribution and (b) Plasticity Index of soils prone to mud pumping

Figure *3* shows that the dynamic filtration apparatus (DFA) had four major components: (1) a servo-hydraulic actuator system, (2) a test chamber, (3) lab controllers, and (4) computer programs. The test chamber had a 13 mm thick transparent polycarbonate cell where a suite of instruments were connected at various locations to measure the EPWPs, temporal variations in soil porosity, and the cyclic deformation of the test specimen. Geotextiles were laid at the interface between the ballast and subgrade specimens. A horizontal drainage path was created by the inclusion of PVD within the soil specimen, and PVD with a modified size was adopted in this study (Abeywickrama et al. 2021). As Figure 3 shows, there were four miniature pore pressure transducers (1 kPa accuracy) installed on the centreline of the specimen at depths of 20, 40, 80, and 120 mm, and at the edge, six body transducers (0.5 kPa accuracy) were placed at 25, 55, 85, 115, 145, and 175 mm below the ballast/subgrade interface. The rigid loading plate could induce uniform stress on the subgrade soil and have minimal effects on the rigid wall boundary (Mohammadinia et al. 2019; Trani & Indraratna 2010). In this study, a uniform normal stress was applied as a minimum vertical stress, and the sinusoidal vertical cyclic stress ($\sigma_{min} = 30$ kPa and $\sigma_{max} = 70 - 140$ kPa) which simulates a maximum axle load of 35-40 tonnes.

The frequency varied between 1.0 and 5.0 Hz, corresponding to train speeds of 45-225 km/h (Indraratna et al. 2020b).

Table 1: Properties of Geosynthetics used for cyclic tests

Geotextiles	G1*	G2	G3	PVD	P
Mean Peak Tensile strength (kN/m)	50	52.5	30	Assembled Drain grab strength (N)	2500
Aperture Opening Size AOS (µm)	<10	60	75	Drain filter pore size (µm)	75
CBR Puncture Resistance (kN)	10	9	5	Assembled Drain flow Discharge at 200kPa (m^3/yr)	2800
Thickness (mm)	4.5	2.5	3.5	Assembled Drain width and thickness (mm)	100x3.4

* Geocomposite

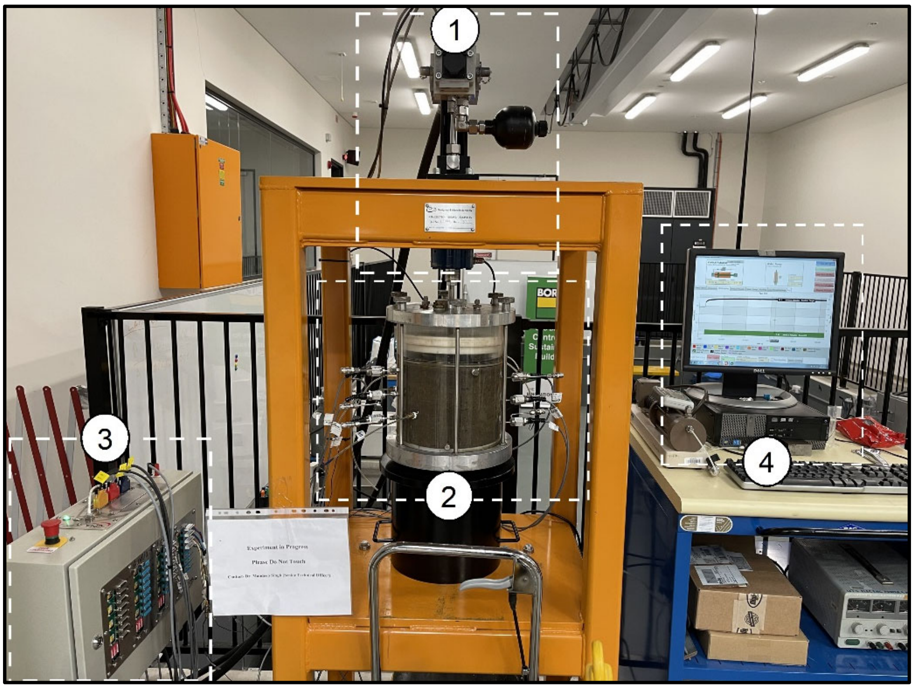

Figure 3: Dynamic Filtration Apparatus (DFA)

2.2 Testing Procedures

The detailed methodology has been provided elsewhere by Arivalagan et al. (2022), so only a brief summary is given here. Compaction was carried out in eight layers with 17% water content to achieve the desired density (1600 kg/m^3), and the 'nonlinear under-compaction' criterion proposed by Jiang et al. (2003) was utilised to ensure each test specimen had a uniform density. All the specimens had the same initial dry density, and their uniformity was assessed by testing two additional samples. The saturation of this specimen was monitored continuously by three ADR probes installed at different depths (Israr et al. 2016; Trani & Indraratna 2010). The prefabricated vertical drains were scaled down to mimic field conditions. The miniature pore pressure transducers, body pore pressure transducers, and the linear variable differential transformer (LVDT) were calibrated and then installed after saturating the soil specimen, and then a total vertical pressure of 30 kPa was applied for 48 hours to consolidate the specimen. The geosynthetics were saturated before being placed onto the subgrade soil and a sinusoidal load was applied through a servo-controlled actuator. Visual observations were made of the 'interlayer creation', the pumping of fines, and variations in the soil density. During testing, the temporal variations in porosity, the generation of pore pressure at different depths, and the overall axial deformation were monitored continuously.

3. RESULTS AND DISCUSSION

3.1 Subgrade fluidisation under undrained conditions

The EPWPs that developed inside the specimen were measured under undrained conditions because they are the main cause of instability in soft soils under continuous cyclic loading. Figure 4(a) shows the rapid development of EPWP within 500 cycles, where all the miniature pressure readings remained above 24 kPa and the transducer MP3 (at 80 mm) measured a maximum EPWP of 27 kPa at 75,000 cycles. The maximum EPWP at MP1 (20 mm from the interface) was less than 25 kPa until 75,000 cycles, which was approximately 15% less than the EPWP developed at MP3. These results confirm that the middle and lower layers can develop higher EPWPs, and they have more potential for subgrade failure under critical hydro-dynamic conditions. Subsequently, the time-dependent EPPG that developed at different depths (Figure 4(b)) could induce enough hydraulic force to dislocate the fine particles from the original soil matrix. EPPG can be defined as the ratio between changes in the excess pore water pressure head (dU_e) and the corresponding distance between two specified locations (dL). The EPWPs measured at different locations by body transducers are used to calculate the EPPGs. As Figure 4(b) shows, the EPPGs that developed in the top and middle layers (Layer (2-1), Layer (3-2) and Layer (4-3)) were above 35 up to 15,000 cycles, but then they decreased further as the number of cycles increased.

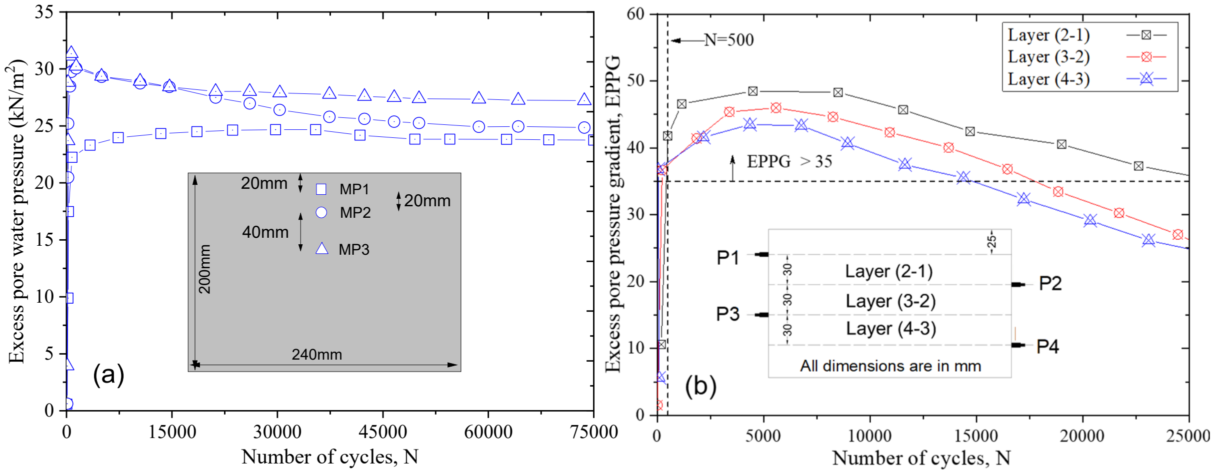

Figure 4: Generation of (a) EPWPs and (b) EPPGs under undrained conditions (modified after Arivalagan et al. (2021))

The PSDs of the soil at the top and middle are shown in Figure 5(a). Under undrained conditions, a lot of fine particles of less than 75 μm had accumulated on the top surface during repeated cyclic loading, but there was a significant loss of fines in the middle layers. During the test, the movement of fluidised soil towards the interface could also be seen through the transparent polycarbonate cell.

As Figure 5(b) shows, the water content of topsoil approached the liquid limit (LL). Subgrade soil can become fluidic if the water content approaches its liquid limit. The 30 mm of subgrade soil near the interface became slurry after just 500 cycles, and fines migrated upwards as the moisture increased in the middle layer. In other words, the undrained tests experienced an abrupt change in the water content along the height of the specimen (Figure 5(b)), and a finer fraction of less than 75 μm was pumped up at the interface. These results imply that the migration of fine particles with a substantially increased water content can induce soil fluidisation under cyclic loading.

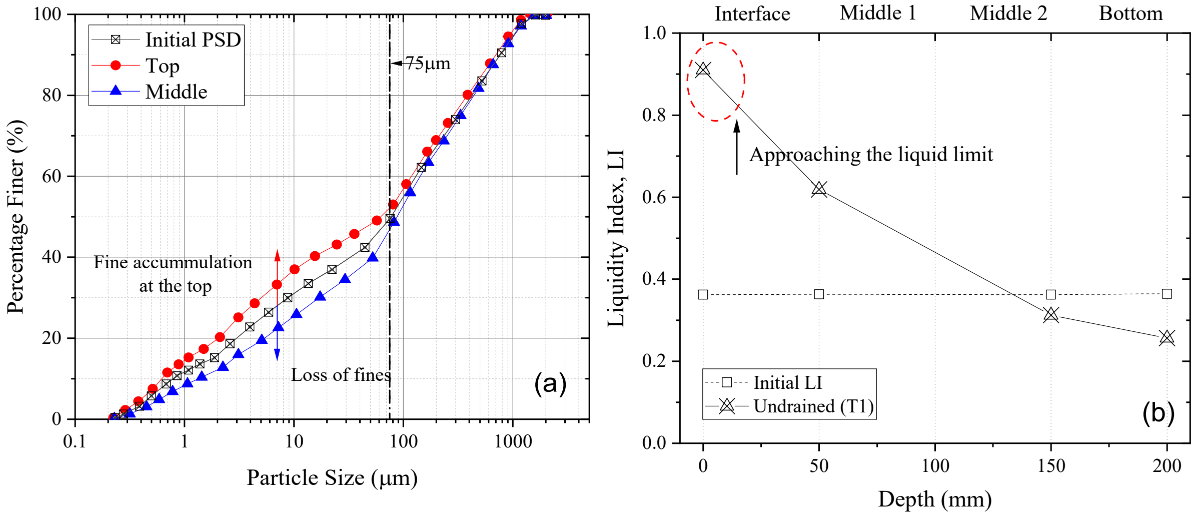

Figure 5: Variations in (a) PSD and (b) Liquidity Index of tested soil specimen at the end of cyclic load (modified after Arivalagan et al. (2021))

3.2 Effectiveness of Geosynthetics

As Figure 6(a) shows, geocomposite G1 dissipated EPWPs by more than 62% at 20 and 40 mm below the interface, unlike geotextile G3 (at 100,000 cycles). Until the test reached 65,000 cycles, the values from MP2 measured 40 mm below the interface were more than 22 kPa for G3 (Figure 6(a)), and there was a very low rate of dissipation compared to geocomposite G1. The miniature pressure transducer readings (MP2 and MP3) were more than 15 kPa over 50,000 cycles and without any significant reduction during Tests G2 and G3. Therefore, the geocomposite (G1) inclusion dissipated the EPWP better when compared to other geotextiles and undrained tests.

The ability of different geotextiles to curtail the water content of subgrade soil by providing adequate drainage is shown in Figure 6(b). The water content for the undrained test was close to the liquid limit at the top surface, and subsequently, it caused softening and fluidisation as finer particles accumulate below 500 cycles. However, geotextiles did help to reduce the water content of the soil specimen compared to the undrained tests. G2 and G3 had a maximum water content of above 30% near the interface and the penetration of ballast into the fibres observed in Test G3, which aggravated softening under cyclic loading. The inclusion of G1 could further reduce the water content by approximately 5%, unlike the other geotextiles. Moreover, the inclusion of G1 prevented particles from migrating from the middle and lower regions. There were no significant variations in the particle size distribution, especially at the top and middle layers, unlike the undrained tests (Figure 5(a)).

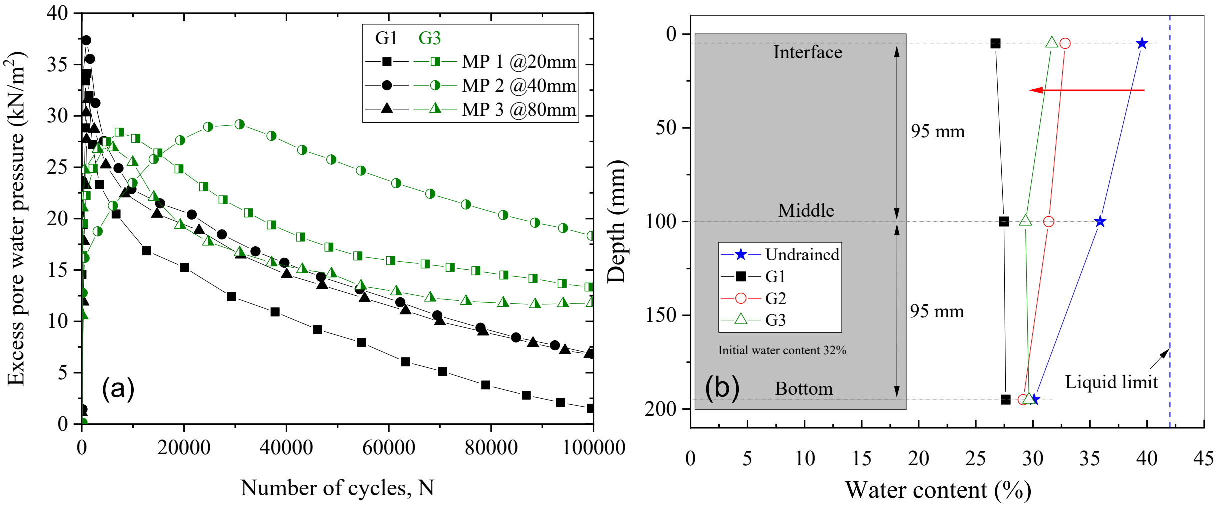

Figure 6: (a) Excess pore water pressure (G1 and G3), and (b) water content at 100,000 cycles (modified after Arivalagan et al. (2021))

3.3 Radial drainage paths due to the installation of PVDs

As Figure 7(a) shows, the EPWP measured at T1 (i.e., the shortest drainage path) is lower than at T2. Although the EPWP at location T2 may take much longer to dissipate than T1, the PVDs successfully dissipated them before reaching their critical values. Previous studies reported that soft clays with PVDs could not experience undrained failure even if the cyclic stress levels were higher than the critical cyclic stress levels (Indraratna et al. 2011). In this study, miniature pressure transducers (P1 - P6) installed at various locations were also used to determine the time-dependent EPPGs in vertical and horizontal directions. Figure 7(b) shows the disparity between vertical (i_V) and horizontal (i_H) EPPGs that developed with geosynthetic inclusions (i.e., a PVD-geocomposite system). In this case, radial drainage became predominant because the lateral EPPGs rapidly increased to more than 20 within 5 minutes of cyclic loading. The horizontal EPPGs remained above 30 until the end of testing and they were approximately ten to twelve times greater than the vertical EPPGs (at 240 minutes of cyclic loading).

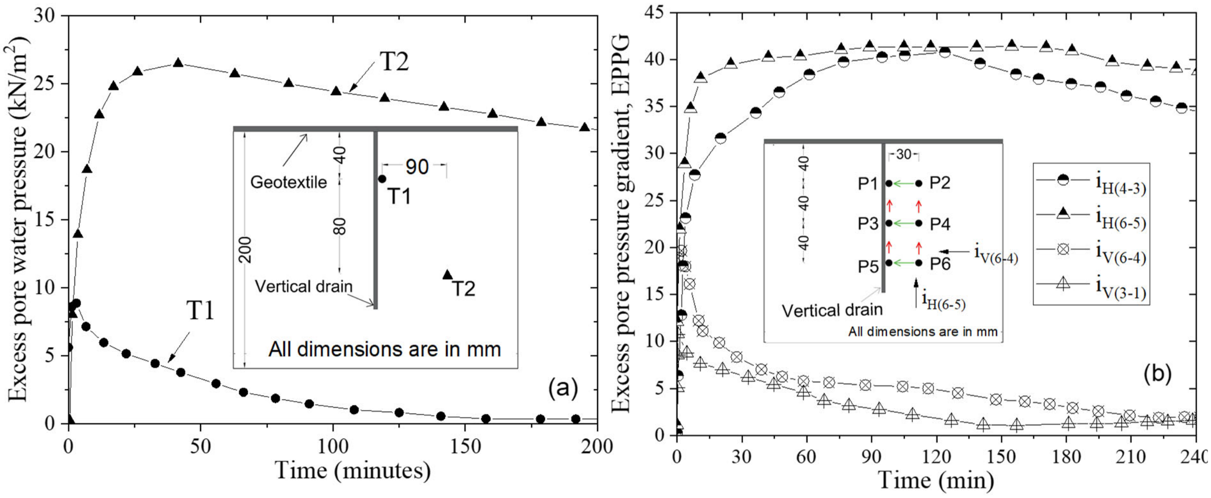

Figure 7: Effectiveness of a combined PVD-Geocomposite system (a) Excess pore water pressure and (b) Vertical and Horizontal EPPGs (modified after Arivalagan et al. (2022))

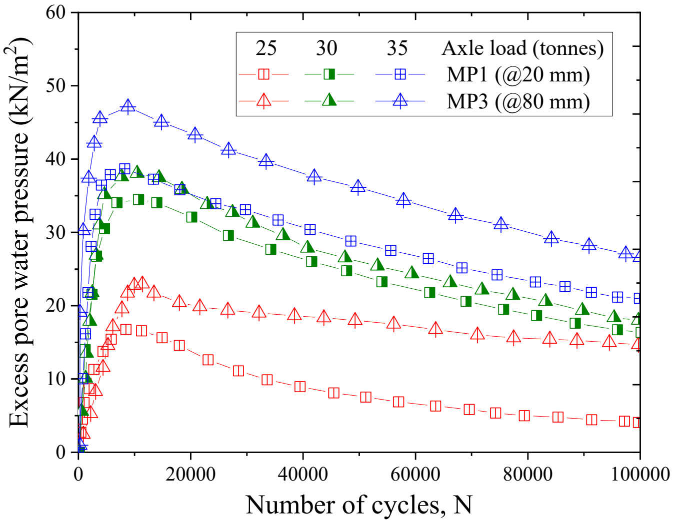

Figure 8: Excess pore water pressure under different cyclic stresses (modified after Arivalagan et al. (2022))

Figure *8* shows the generation of EPWP with a combined PVD-Geocomposite system under different loading conditions. For instance, EPWP at MP3 (@80 mm) approached above 45 kPa prior to reaching 10,000 cycles, under 35 tonnes of axle load. Moreover, an increasing trend in axial strain (up to 2.5%) was also observed under increased cyclic stresses. Under lower axle loads (25 – 30 tonnes), the EPWPs reduced below 20 kPa at MP1 and MP3 (20 and 80 mm). Although a rapid development in the EPWP occurred as the amplitude of cyclic stress increased in the undrained tests, the rate of dissipation of EPWPs was high, and continued to reduce below 30 at 100,000 cycles in the top and middle layers (MP1 and MP3) due to the inclusion of PVD and geocomposite. From a practical perspective, the prefabricated vertical drains combined with a drainage filter (geocomposite at the interface) further reduced the development of EPWP in a radial direction, which suggests that a combined P+G system could increase track stability by preventing soil softening.

4. CONCLUSIONS:

This study reports that the application of geosynthetics could accelerate the rate of dissipation of excess pore water pressure at the subgrade/ballast interface and prevent slurry formation (early soil softening). The dynamic filtration results revealed the key role of excess pore pressure gradient (EPPG) in inducing fines to migrate from the middle region towards the subgrade surface. However, the inclusion of PVDs significantly reduced the generation of critical EPPGs by activating the radial drainage path, and thus mitigated the fluidisation potential or migration of fine particles under heavy haul train loading. The following salient findings are summarised as follows:

- The undrained cyclic response of soil revealed that a high cyclic excess pore water pressure developed near the interface, and no significant reduction was observed until the test ended. The study showed that particles of less than 75 µm accumulated near the interface, and subsequently the subgrade surface turned to a liquid-like state with the liquidity index close to unity. This proves that the significant EPPGs that developed under undrained tests could potentially dislocate the fines in the middle layers and induce soil softening under repeated cyclic loading.
- Geosynthetic inclusions such as geotextiles are effective at dissipating the cyclic excess pore water pressure at the interface and reducing the overall deformation. This study demonstrated that prefabricated vertical drain (PVD) when combined with geocomposite, could provide additional track stability and help control subgrade fluidisation. For instance, horizontal EPPGs that developed in the subgrade were up to 40 after 30 minutes of cyclic loading, whereas the vertical EPPGs remained less than 8. This certainly confirmed that the rapid increase in horizontal EPPGs could facilitate radial drainage and reduce the critical build-up of EPWPs in the subgrade, thus alleviating the occurrence of subgrade fluidisation even under higher axle loading.

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