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Subgrade Soil Fluidization under Cyclic Loading of Heavy-haul Trains and Preventive Measures

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ABSTRACT: Soft soil deposits along Australia's low-lying coastal regions pose significant challenges for the safety and stability of rail infrastructure. The undrained instability of these often saturated formations exacerbated by excess pore water pressure (EPWP) in tandem with upward hydraulic gradients under dynamic wheel loading is the primary cause of soil fluidization (mud pumping). This paper identifies critical ground (subgrade) conditions prone to fluidization and proposes novel solutions to ensure an efficient and safe operation of rail tracks. Using an iconic custom-built Dynamic Consolidation Apparatus (DCA) capable of assesiing the fluidization potential, laboratory testing under cyclic loading was conducted to investigate: (i) the occurrence of subgrade instability under various drainage conditions and intermittent cyclic loading with rest periods, (ii) the role of drainage geotextiles in stabilising the subgrade-ballast interface, and (iii) the effectiveness of a combined system of a prefabricated vertical drain (PVD) and a geocomposite (i.e. an impervious membrane sandwiched between two drainage geotextiles). Experimental results indicated that prior to fluidization, the water content in the upper soil layer approached its liquid limit due to internal moisture redistribution, effected by very fine particles from the bottom half of the test specimen migrating towards the top surface. This unique failure mechanism, characterized by fluidised soil (slurry) being pumped to the surface under high EPWP gradients, differs from traditional cyclic undrained yielding. The inclusion of the geocomposite at the ballast-subgrade interface could effectively impede particle migration by reducing the EPWP gradients. The findings also revealed that longer rest periods between loading cycles could reduce the likelihood of mud pumping. Additionally, PVDs on their own significantly reduce EPWP build-up in thicker soil layers. A case study at the town of Sandgate, NSW, demonstrated the effectiveness of relatively short PVDs (approx. 6m) in enhancing the stability of a track built on deep estuarine clay deposits (> 15m).

KEYWORDS: Fluidization, Geocomposite, Railways, Soft Subgrade, Vertical Drains

1 INTRODUCTION

Railway construction across Australia has progressed significantly in recent years, with major initiatives such as the Inland Rail project (i.e. linking freight corridors between Brisbane and Melbourne) designed to enhance transport efficiency and stimulate economic development. Despite these advancements, geotechnical challenges associated with subgrades remain a critical concern, particularly in regions with soft, compressible, and saturated soils. These problematic ground conditions demand continued research to inform the design of resilient and durable railway infrastructure. Saturation of subgrade introduces complex pore pressure behaviour under dynamic wheel loads causing potential instability. In particular, the dynamics of pore water pressure play a central role in the onset and progression of subgrade failure mechanisms.

Research over the past decade has identified three types of instability mechanisms due to pore pressure build-up under cyclic loading: (i) excessive plastic deformation; (ii) progressive shear failure, and (iii) subgrade fluidization (Indraratna et al., 2024c). Figure 1 schematically presents the behavioural patterns of these three instability mechanisms under undrained cyclic loading. In saturated subgrade, excess pore water pressure (EPWP) accumulates with repeated loading cycles. As the accumulation continues, the corresponding stress path progressively approaches the failure envelope, ultimately resulting in sudden and unacceptable subgrade deformation.

Understanding the development and propagation of dynamic stresses beneath rail tracks is vital for addressing these subgrade-related issues. However, actual field measurements of subgrade stresses are relatively rare. The dynamic stresses generated from rail loads move from sleepers to subgrade and exhibit large variations in magnitude and direction during train passage, along with high stress concentrations. While ballast primarily helps to control the transfer of complex dynamic stress to the subgrade with both the magnitude and frequency of load attenuating with depth, the subgrade stresses usually take the form of being cyclic. Using a 1:1 scale model track, Indraratna et al. (2021) showed that when a rail embankment was subjected to a 25-tonne axle load (typical of freight trains operating in NSW), the maximum vertical stress generated at the sleeper-ballast interface could be approximately 225 kPa for a conventional sleeper spacing of 1.4 m on a standard gauge track, but this then decreased to 48 kPa at a depth of 0.8 m beneath the subgrade surface. In-situ measurements of vertical stress at a maintenance site in Western Sydney (i.e., Chullora Rail Precinct) indicated that the axle load of a 22-tonne locomotive could result in a stress amplitude of about 40 kPa at a depth of 0.5m in soft clayey subgrade (Indraratna et al., 2024a). Furthermore, vertical stress data generated by coal trains in the coastal town of Bulli (south of Sydney) recorded a maximum cyclic stress of 70 kPa at the subgrade surface (Trani and Indraratna, 2010). These results verify that for typical freight trains operating in NSW at relatively low speeds (40-60 km/h), a subgrade stress in the range of 40-70 kPa is expected within a relatively shallow subgrade depth of 1m.

The response of soft subgrade soil to railway loading can be systematically investigated through laboratory testing by applying appropriate cyclic stress paths. While plastic deformation and shear failure under cyclic loading are well-documented in existing literature, the phenomenon of subgrade fluidization (commonly referred to as mud pumping) remains relatively underexplored. The underlying instability mechanisms, the tell-tale nature of susceptible subgrade, and effective mitigation strategies are not yet fully understood. Furthermore, railway loading is inherently intermittent, with significant rest periods between train passages. The instability mechanisms associated with intermittent cyclic loading, and how they differ from those under continuous loading, are poorly characterised. In this context, the objectives of this study are to: (i) present experimental investigations into subgrade deformation and EPWP behaviour under intermittent cyclic loading; (ii) explain the mechanisms of fluidization through pore pressure analysis and identify vulnerable soil types; (iii) propose innovative subgrade stabilisation techniques using prefabricated vertical drains (PVDs) and geocomposite; and (iv) showcase case studies where these novel solutions have been successfully implemented.

2 PHENOMENON OF SUBGRADE FLUIDIZATION

Subgrade fluidization is a geo-hydraulic process characterized by the upward movement of fine particles toward the subgrade surface when exposed to certain hydraulic conditions. As illustrated in Figure 1, previous experimental findings indicate that the initiation of subgrade fluidization can occur after fewer cycles or at lower stress levels than those defined by the cyclic failure envelope. The specimens experience failure relatively early, demonstrated by a drop in the stress path intensity, while resulting in significant strains once the stress path intersects the early softening line.

2.1 *Effect of cyclic stress ratio*

Under cyclic triaxial conditions, cyclic stress ratio (CSR) can be used instead of the actual cyclic stress to normalize the effect of cyclic stress with confining pressure. The CSR is usually defined as $0.5\sigma_d/\sigma'_c$; where σ_d is the applied cyclic deviator stress and σ'_c is the effective confining pressure. Indraratna et al. (2020a) conducted a comprehensive study to investigate the effect of CSR on soil fluidization; the CSR varied between 0.2 and 1.0 (loading frequency = 0.1 Hz). The results indicated that there is an exponential trend in the growth of axial strain within the subgrade soil when subjected to a critical cyclic stress ratio (CSRc). When the applied cyclic stress exceeds the CSRc, the specimen exhibits a marked reduction in stiffness similar to the behavior presented in Figure 1, which depicted subgrade fluidization.

Notably, samples that underwent fluidization exhibited fluid-like behaviour at the specimen's upper surface, as illustrated in Figure 1a. Subsequent water content testing confirmed that the moisture level in the upper soil layer increases to nearly the liquid limit of the soil, accounting for this observed behaviour. Additionally, particle size distribution (PSD) analyses conducted at different sample heights revealed an accumulation of fine particles in the upper layers and a corresponding reduction of the fines fraction in the middle layers, as shown in Figure 1b. This redistribution is attributed to internal moisture and particle migration induced by cyclic loading and associated subgrade fluidization.

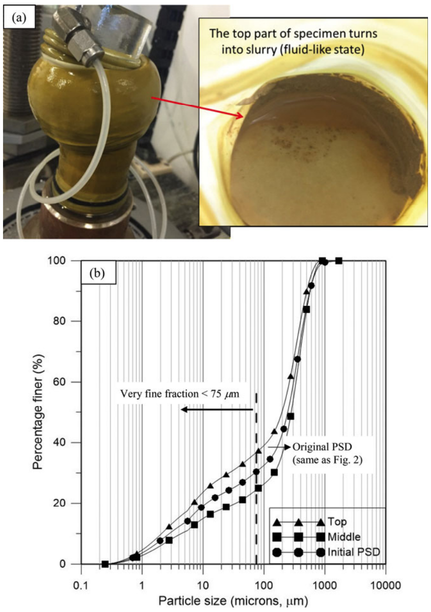

Figure 1. (a) Photograph of the fluidised specimen; (b) Particle size distribution (Indraratna et al., 2020).

2.2 *Geo-hydraulic process of upward migration of fines*

An increase in EPWP during cyclic loading results in a higher internal hydraulic gradient, producing a hydraulic force that transports finer and softer particles towards the top of the specimen. A numerical approach was presented by Indraratna et al. (2021b) to capture the microscopic properties of both fluid and particles when the soil experiences an increasing hydraulic gradient. Particle behavior was simulated using the discrete element method (DEM), while fluid dynamics were modeled using the lattice Boltzmann method (LBM). The interaction between LBM and DEM ensures continuous updates to both particle and fluid variables. The results presented in Figure 2 show that, when the hydraulic gradient increases to a certain level, the contact forces begin to decrease, and particles become unstable. Moreover, when fluidization occurs, the contact force drops dramatically, making the effective stress almost zero. When the soil approaches this unstable state, it loses most of its shear resistance to the fluid flow. When hydraulic gradient becomes larger than the critical level, the particles begin to migrate upwards, and the contact force falls sharply (Fig. 4).

2.3 *Subgrade characteristics vulnerable for subgrade fluidization*

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 the plasticity of subgrade soils where soil fluidization had previously been reported. Their results, presented in Figure 3, indicate 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 fluidization; the liquid limit (LL) of these soft soils generally varies from 20-50, and the plasticity index (PI) remains less than 30.

2.4 *The application of geocomposite at preventing subgrade fluidization*

Although geotextiles can be used as a separator or filter in railway embankments to provide confinement and improved drainage characteristics, the effectiveness of reducing the fluidization potential of subgrade has not been extensively addressed in previous studies. A series of laboratory tests carried out at UTS revealed that the use of a geocomposite (i.e. a filter membrane sandwiched between two drainage geotextiles) can be used to mitigate or reduce the occurrence of subgrade fluidization, as reported by Arivalagan et al. (2021; 2022). Their findings indicated that placing a geocomposite layer at the ballast-subgrade interface could effectively lower the hydraulic gradient at relatively shallow subgrades by preventing the build-up of EPWP with time.

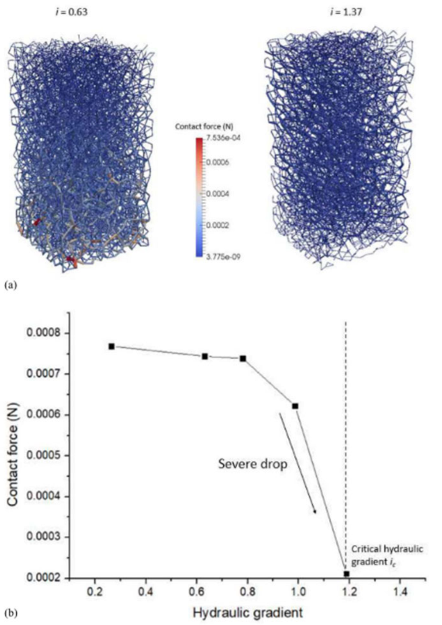

Figure 2. Degradation of contact force due to increasing hydraulic gradient: (a) the matrix of contact force; and (b) evolution of the largest contact force (Indraratna et al., 2021b).

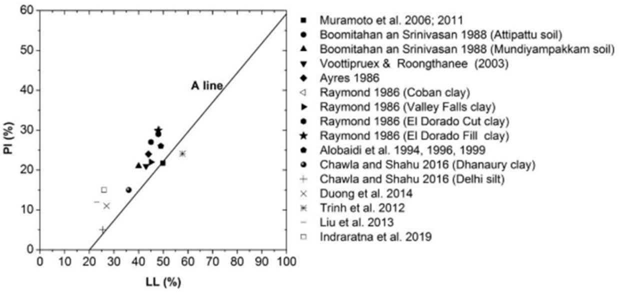

Figure 3. Plasticity chart of subgrade soil where mud pumping is reported (Nguyen et al., 2019).

Different types of non-woven geotextiles and geocomposites were tested under varying hydro-dynamic conditions to assess their potential to reduce mud pumping. Unlike undrained and free drainage tests, the application of geocomposites with an effective filter membrane can dissipate the EPWP from the beginning of the cyclic test and thereby control fine particles from migrating from the middle or lower regions towards the top. Furthermore, the moisture content of the surficial layers was also significantly reduced due to the inclusion of geocomposites under similar track conditions. However, the EPWP that developed when using conventional non-woven geotextiles were significantly higher (critical layers), and the rate of dissipation was not significant as the number of cycles increased. Furthermore, they could not prevent the migration of fine particles, and they became clogged with fine particles trapped inside the pore openings under higher axle loads. Although the aperture size of the geocomposite filter was less than 10µm, it still provided sufficient drainage to alleviate the EPWP that developed near the interface and control particle separation (Arivalagan et al. 2022).

The inclusion of an effective filter membrane at the subgrade/ballast interface reduced the abrupt change in water content and the migration of finer fractions (less than 75 µm). On the other hand, the use of geotextiles without adequate drainage characteristics could not prevent the potential of the fines segregating and migrating even under lower cyclic stress levels, and hence, subgrade fluidization could also occur at lower frequencies in tracks experiencing critical hydraulic conditions (Arivalagan et al. 2021).

3 INTERMITTENT CYCLIC LOADING AND EFFECT OF DRAINAGE CONDITIONS

3.1 *Experimental Setup*

Railway subgrades are unlikely to experience uninterrupted continuous cyclic stress due to train movements. Furthermore, shallow subgrades are likely to behave in partially drained conditions, with free draining (granular) subballast layers typically used when saturated subgrades are present. Results of a laboratory test conducted by Indraratna et al. (2025) using a custom-built Dynamic Consolidation Apparatus (DCA) are presented in this section. This large-scale equipment can measure the EPWP at different locations under cyclic loading, addressing the limitations of commercially available small-scale testing equipment. A schematic diagram of the cell with the locations of pore pressure sensors (MP1 & MP2) is presented in Figure 4. The response of the soil under different drainage conditions and different yield stresses was also investigated. Radial drainage was permitted via prefabricated vertical drain (PVD) in Tests (A), (B, and (C), while Test (D) had no drainage.

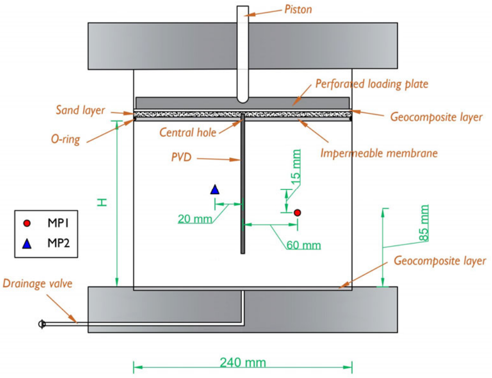

Figure 4. Schematic diagram of the DCA cell (Indraratna et al., 2025).

The relevant drainage characteristics are summarised as follows:

- Test (A) – scaled-down PVD width = 16.5 mm, equivalent to 1.2 m PVD spacing in the field. Only radial drainage is allowed.
- Test (B) –scaled-down PVD width = 36.3 mm, equivalent to 0.6 m PVD spacing.

- Test (C) - combined drainage with PVD (width = 16.5 mm), while introducing a permeable geotextile layer on the top surface to facilitate upward drainage.
- Test (D) - no drainage - this corresponds to a subgrade with no drainage.

The sample was initially reconsolidated to a pressure of 25 kPa. Then to represent train loading, an axial sinusoidal load with minimum and maximum vertical stresses of 25 kPa and 65 kPa, respectively was applied at a frequency of 1 Hz. High-plasticity clay from Ballina, NSW was used (LL=82; PL=29). During the rest period, a static load of 25 kPa was maintained, equivalent to the overburden stress at a relatively shallow depth of subgrade. These loading conditions represent a 25-tonne axle heavy-haul train travelling at about 45 km/h. Cyclic loading was sustained over 9 hours and generated 33,000 loading cycles followed by an overnight rest period. The intermittent loading cycles were applied for 14 stages.

3.2 *Effect of drainage on EPWP behaviour*

Figure 5 illustrates the EPWP recorded at monitoring points MP1 and MP2 over 14 stages of intermittent loading. The sequence (CL1, RP1, CL2, RP2, …, CL14, RP14) represents alternating phases of cyclic loading (CL) and rest periods (RP). Across all plots, a progressive decline in peak EPWP was observed in the later loading stages. This reduction is attributed to a decrease in the void ratio, which corresponds to an increase in resilient modulus resulting from cyclic consolidation. The EPWP values presented reflect the combined effects of pressure build-up during loading and dissipation during rest periods, both of which were influenced by the prevailing drainage conditions.

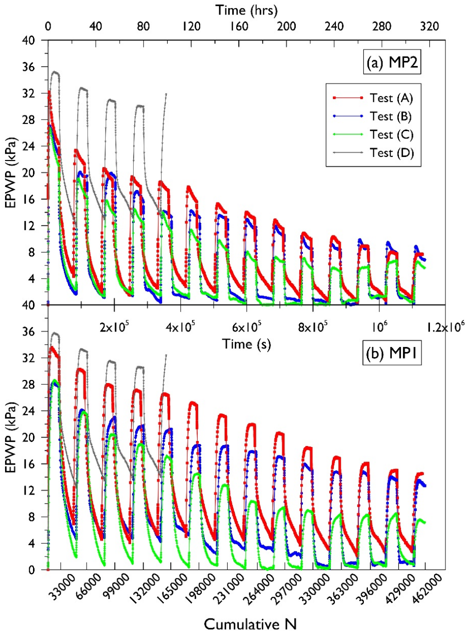

Figure 5. Measured EPWP for Tests (A)–(D) at (a) MP2 and (b) MP1 (Indraratna et al., 2025).

Results of Test (A) and Test (B) were compared to evaluate the effect of reduced PVD spacing. Whereas, Test (C), which included both surface and radial drainage, showed significantly faster EPWP dissipation than the other tests, with MP2 dropping below 10 kPa after CL6 and MP1 after CL8. In contrast, Tests (A) and (B) maintained EPWP above 10 kPa at MP1 through CL14. Results indicate that increasing PVD width and combining drainage methods accelerate the reduction in EPWP and its stabilisation, as evident from Test (C).

Test (D), conducted without drainage, only lasted for 5 intermittent loading cycles (Cumulative N = 148368) before instability caused the top plate to tilt. EPWP increased quickly to 35 kPa in the first 13,000 cycles and then stabilized. Peak EPWP values dropped from 35 kPa in CL1 to 31 kPa in CL4, but increased again in CL5, making the surface soil behave more like slurry and less resistant to shear. This was supported by visible water bleeding at the specimen's surface.

3.3 *Settlement behaviour under intermittence*

Figure 6 displays vertical strain over time for Tests (A)-(D). Despite varying drainage conditions, vertical strain after CL14 in Tests (A)-(C) was about 8%. At the end of CL1, vertical strains were 1.5%, 2.0%, and 2.4% for Tests (A), (B), and (C), respectively. Combined surface and radial drainage accelerated settlement compared to radial drainage alone. Although Test (C) had slightly higher strain rates, ultimate settlements were similar, suggesting that lower EPWP generation may offset faster dissipation. Test (D) exhibited a sudden 1.0% strain increase after CL1 and continued gradual strain until instability at CL5.

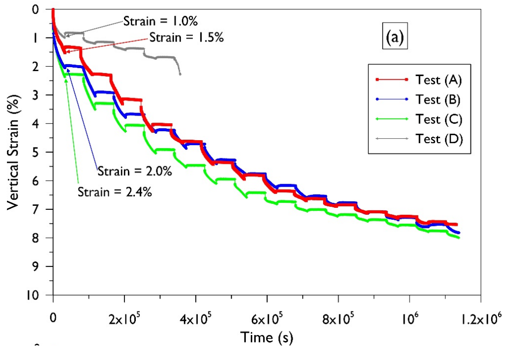

Figure 6. Vertical strains for Tests (A)–(D) (Indraratna et al., 2025).

Interestingly, across all tests, axial strains during rest periods were negligible despite rapid EPWP reduction, with only minor rebounds observed (see Figure 6). For example, after CL1 in Test (A), axial strain reached 1.5%, and EPWP readings at MP1 and MP2 were 31.1 kPa and 23.3 kPa, respectively. However, during the rest period, EPWP decreased to a level below 8 kPa, leading to a significant reduction without inducing any settlements.

Figure 7 conceptually illustrates the effective stress paths influenced by variations in EPWP during cyclic loading, alongside changes in void ratio and yield stress. Path AB represents the initial cyclic loading phase. Laboratory data indicate that EPWP typically follows a right-skewed bell-shaped curve, with dissipation facilitated by prefabricated vertical drains (PVDs). This dissipation promotes consolidation, evidenced by a reduction in void ratio and an increase in yield stress. These changes are assumed to follow the traditional Normally Consolidated Line (NCL), depicted as path AB'. Path BC corresponds to the rest period following cyclic loading. Upon removal of cyclic stress, EPWP redistributes toward equilibrium, causing a rightward shift in the stress path. Experimental results show that minimal consolidation occurs during this phase, and the void ratio remains largely unchanged. At the end of each rest period, some residual EPWP persists. However, due to the increased yield stress from prior loading, the peak EPWP observed during subsequent loading cycles is reduced. This is a trend that continues with repeated loading-unloading sequences. If the duration of cyclic loading is short, EPWP may not reach its peak. Similarly, shorter rest periods result in higher residual EPWP, while longer rest intervals allow for greater redistribution and dissipation, causing the stress path to more closely approach the NCL.

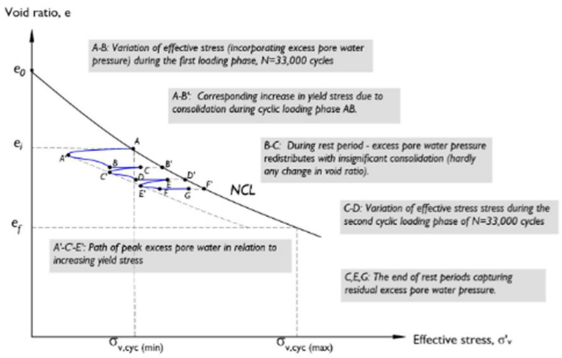

Figure 7. Path of effective stress–void ratio changes (incorporating EPWP) during intermittent cyclic loading (Indraratna et al., 2025).

4 CASE STUDIES

4.1 *Sandgate Rail Grade Separation project*

To increase rail capacity along the Sandgate route near Kooragang Island, Australia—an area servicing major coal mines—additional railway lines were constructed adjacent to existing tracks. The presence of soft clay layers posed significant geotechnical challenges, prompting the use of prefabricated vertical drains (PVDs) to mitigate EPWP build-up and accelerate subgrade consolidation. In railway applications, the load distribution from heavy haul trains typically affects the shallow subgrade within a depth of 6–7 meters beneath the ballast layer. Consequently, relatively short PVDs can be effectively deployed to facilitate EPWP dissipation and limit lateral deformation under cyclic loading conditions.

Subsurface profile consists of a soft estuarine clay ranging from 4 to 30 m deep overlying shale bedrock. The groundwater table was at the ground surface. Short PVDs were installed to a depth of 6-7 m. Due to time constraints that prevented surcharge preloading, the PVDs were used to achieve consolidation within a shallow depth corresponding to the zone influenced by the train load.

A numerical analysis was initially conducted to estimate track deformations resulting from dynamic impact (Indraratna et al., 2010). An equivalent static method, incorporating a dynamic impact factor, was used to simulate field dynamic loading conditions. A vertical load of 80 kPa and an impact factor of 1.3 were applied to represent a train speed of 40 km/hr with a 25-tonne axle load. The Soft Soil and Mohr-Coulomb models were utilized in the finite element software PLAXIS.

Based on the analysis, PVDs at 1.5 m intervals (square pattern) were considered suitable and were installed during construction. Figure 8 presents both the predicted and measured settlement at the rail track centre line, as well as the lateral displacement observed after 6 months. The predicted settlement corresponded with the field data, with the maximum displacement occurring within the shallow clay layer.

4.2 *Chullora Rail Precinct*

A fully instrumented track was constructed at Chullora (NSW, Australia) to investigate real-life scale applications of laboratory-proven recycled rubber elements solutions to reduce the stress propagation underneath railway tracks (Indraratna et al., 2024a). This track was constructed in collaboration with industry stakeholders such as Transport for NSW (state cooperation), Bridgestone Corporation, and Ecoflex. Three different innovative applications were tested:

- Rubber intermixed ballast system (RIBS): optimally blended mix of ballast aggregates (latite basalt) and rubber granules (Arachchige et al., 2022).
- Energy-absorbing rubber geogrids (EARS): Recycled rubber panels derived from discarded rubber conveyor belts as a potential energy-absorbing layer (Siddiqui et al., 2023).
- Infilled tire cell foundation (ITCF): recycled tires infilled with granular waste are assembled beneath the ballast layer replacing traditional capping material (Indraratna et al., 2024b).

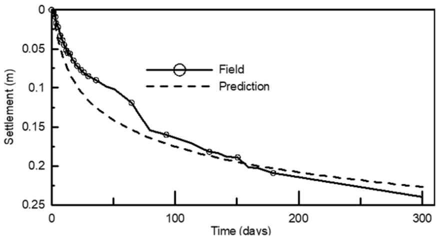

Figure 8. (a) Predicted and measured at the centre line of rail tracks; (Indraratna et al., 2010).

Stress measurements were compared to those from a standard instrumented track. Figure 9 illustrates changes in vertical stress at various sub-structure interfaces. Of the three systems tested, EARS reduced vertical stress at the subgrade-capping interface by about 25% compared to standard tracks.

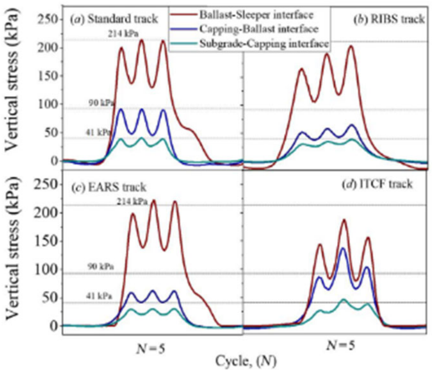

Figure 9. Vertical stress distribution: (a) Standard track; (b) RIBS track; (c) EARS track; (d) ITCF track (Indraratna et al., 2024a)

5 CONCLUSIONS

This paper presented a series of subgrade testing scenarios conducted at the UTS Transport Research Centre to investigate soft subgrade instability, with a particular focus on fluidization mechanisms and drainage conditions. The key findings are as follows:

- Subgrade fluidization is influenced by soil plasticity, the fine particle content, and the hydraulic gradients induced by rising EPWP. A review of documented mud pumping sites revealed that soils with low to medium plasticity are generally more prone to fluidization. Experimental results showed that during fluidization, moisture redistribution had caused the water content in the upper soil layer to approach its liquid limit.
- Simulations using the LBM-DEM numerical model demonstrated that the contact matrix of soil particles (i.e. representing effective stress) undergoes significant degradation during fluidization, indicating a loss of structural integrity.

- Test data from scenarios (A) to (C) revealed that EPWP, vertical strain, and void ratio decreased progressively during intermittent cyclic loading with drainage (CL1–CL14). This behaviour typically reflects soil consolidation, resulting in increased stiffness and resistance to further deformation. These findings suggest that incorporating longer or more frequent rest periods between train loads can enhance track stability.
- Larger PVDs and surface drainage systems were found to accelerate EPWP dissipation during cyclic loading. Tests (A) and (B) at MP2 showed a more rapid post-peak EPWP decline compared to Test (D), epitomising the effectiveness of vertical drains. Results from Test (C) further indicated that combining surface and radial drainage or using wider PVDs offers improved control over EPWP accumulation.
- Observed settlements during rest periods indicated that cyclic consolidation did not occur despite significant EPWP dissipation. This suggests that when cyclic loading ceases, EPWP is redistributed without altering the soil fabric, resulting in negligible deformation.
- The Sandgate case study demonstrated the practical effectiveness of relatively short PVDs in enhancing rail track stability. These drains facilitated EPWP dissipation, reduced lateral displacement, and mitigated mud pumping, validating their use in soft clay subgrades.

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