Use of Geosynthetics in Mitigating the Effects of Mud Pumping: A Railway Perspective

Mandeep Singh, Buddhima Indraratna and Cholachat Rujikiatkamjorn

Abstract In Australia, where the major network of railways traverses along the coastal regions, millions of dollars are spent on track maintenance annually to mitigate track differential settlement. One of the recurring problems faced with ballasted tracks on estuarine soils is mud pumping. Mud pumping is a complex phenomenon involving the migration of fine soft subgrade particles into the coarser ballast/sub-ballast layer. The problem has been widely reported and is of interest among the railway engineers over the last couple of decades. The migration of fines causes excessive settlements and track degradation leading to track instability, thereby incurring excessive maintenance costs. The primary objective of this paper was to assess the existing remediation measures for mud pumping reported. The current mitigation techniques range from the in situ mixing of additives to the use of geosynthetics to separate the layers in a track structure. On the other hand, the use of geosynthetics has proven to act as a separator between the track layers; their effectiveness is highly dependent on the type of subgrade soil. The comprehensive study reveals the probable causes of mud pumping and a better understanding of the phenomenon.

Keywords Track maintenance · Mud pumping · Geosynthetics · Triggers

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1 Introduction

Railways have become one of the predominant modes of transportation in several countries, carrying goods and commuters from one place to another. With the increasing demand for faster and heavy-haul trains, the responsibility lies with the rail industries to provide lucrative and efficient services. Further, the economic aspect of the track construction and operations is also to be taken into account. For example, the track maintenance costs are estimated around 14–15 million dollars in the state of New South Wales alone (Hussaini et al. 2012). The identification of the localised track-bed problems and providing a cost-effective and efficient remediation measure is a twofold problem for the rail engineers.

One such localised track-bed problem is the formation of wet spots or bog holes (Fig. 1), which can occur when soft saturated subgrade soils are subjected to repetitive rail loading and result in the development of mud pumping. With the subsequent passage of trains over the wet spots, the fines squeeze into the coarser upper layers and foul the ballast. This phenomenon is known as mud pumping. It causes severe track deterioration and forms pockets of ballast under the sleeper. As the trains pass over these locations, the sleepers interact with the ballast and form cracks on the sleeper base. Upon successive passes of the train, the rough angular surface of the ballast rubs and leads to the more rounded ballast. The ballast loses the interlocking thereby compromising on track stability. In Australia, where the majority of the eastern rail corridor was built on soft subgrade soils, such as silty clays, the problem of mud pumping is widespread. Many case studies present in the literature report of the mechanism behind mud pumping (Alobaidi and Hoare 1999;

Fig. 1 Mud pumping prone site in New South Wales, Australia

Aw 2007; Hayashi and Shahu 2000) but predominantly they propose measures for mitigating the effects of mud pumping (Alobaidi and Hoare 1998; Aw 2007; Ayres 1986; Duong et al. 2014; Hudson et al. 2016). This paper summarises the reported occurrences of mud pumping in the literature and reviews the existing remediation measures for mud pumping. The main objective of this article was to discuss the triggers that cause the pumping of fines. Also, it makes an effort to understand the phenomenon of mud pumping in the context of railway engineering.

2 Critical Review of the Existing Literature

From the past studies, soils prone to mud pumping lies around the zone of fine, inorganic silts and clays (Table 1). The plasticity of the soils is shown in Fig. 2. It is noteworthy that most of the problematic subgrade soils comprise of inorganic clays with low to medium plasticity.

Table 1 Reported studies on mud pumping

References	PI	LL (%)	USCS	Remarks
Chawla and Shahu (2016)	5	25.5	ML	—Delhi silt —Model tests —Geosynthetic layer
Duong et al. (2014)	11	27	CL	—70% sand + 30% Kaolin clay Soil —Pumping occurred on saturated subgrade —Formation of ‘interlayer’
Trinh et al. (2012)	24	57.8	MH	—Sénissiat, France —Highly plastic with >50% fines —Influence of water content
Voottipruex and Roongthanee (2003)	21	43	CL	—Railway embankment in Thailand —Remediation by fly ash and type I Portland cement —Strengthening of soil to reduce pore pressure build-up
Hayashi and Shahu (2000)	–	–	SW	—Shirasu soil, Japan —Propose fluidisation as governing mechanism —Provision of weep holes to mitigate mud pumping
Alobaidi and Hoare (1999)	26	49	CL	—Keuper Marl soil —Unit cell tests with spherical sub-base particles —High permeable geotextile may cause erosion of the subgrade
Ayres (1986)	24	44	CL	—Overconsolidated marine deposited calcareous clay —Classifies mud pumping by two types of erosion failures

2.1 Liquefaction Susceptibility

Liquefaction of soils is a well-established theory in the field of soil dynamics. Soils tend to liquefy when the effective stresses in the reach near zero due to an increase in pore pressure. Duong et al. (2014), while conducting large-scale triaxial tests on subgrade soil observed the excess pore pressures in the subgrade soil rose to values higher than the minimum applied cyclic loading, thereby, reducing the effective stresses to zero after a certain number of cycles. Liquefaction criterion proposed by Bray and Sancio (2006) is imposed on the existing pool of soil data (Fig. 3). The approach considers the water content of the soils in addition to the Atterberg limits (Plasticity Index and Liquid Limit) to quantify liquefaction susceptibility. It can be seen from Fig. 3 that the liquefaction criterion is not applicable to soils that are prone to mud pumping.

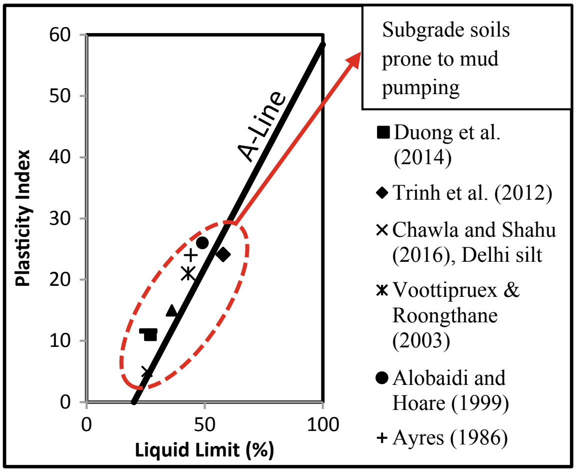

Fig. 2 Plasticity chart of the soils reported at the mud pumping sites

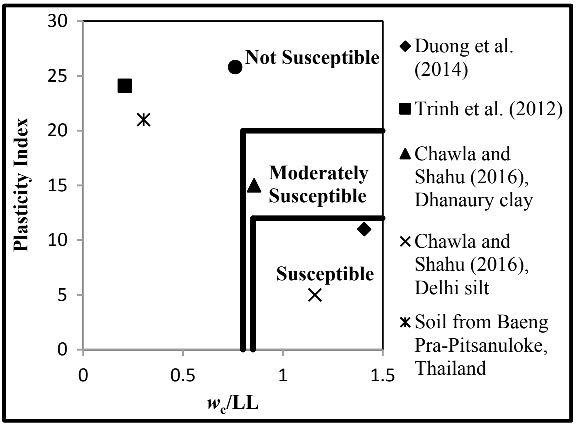

Fig. 3 Liquefaction susceptibility of soils prone to mud pump

2.2 Mitigation Measures for Mud Pumping

There are various remediation methods widely used in industry, and they can be categorised into the following:

i. Track realignment and ballast addition

Realignment of the rail track provides a cheap yet ineffective solution to mud pumping. The train driver visually reports the undulations on the railroad, and then, the extensive manual surveys notify the affected sites. Heavy machinery is used to either raise the rails or remove them and fill the track with fresh ballast. It is, however, a short-term solution as the problem of pumping is not resolved but alleviated. An additional granular capping layer between the subgrade and the ballast can act as a filter by preventing the migration of subgrade into the ballast (Ayres 1986).

ii. Subgrade improvement

The inclusion of geosynthetic layers in the track substructure is known to increase the strength of the track (Chawla and Shahu 2016). The geosynthetics layers may be placed at the interface of the ballast and the capping layer. It provides a uniform distribution of the load coming from the rail and increases the longevity of the track. However, the rails and the sleepers are to be removed entirely to lay the geosynthetics in the existing track, thereby increasing the maintenance time. Another popular method of stabilisation involves the mixing of cementitious elements to the soil. The use of fly ash and Portland cement mix to strengthen the soil provides an alternative to the ground improvement by geosynthetics. The use of cementitious materials reduces the pore pressure build-up in the rail subgrade (Voottipruex and Roongthanee 2003). But these cementitious lumps may induce stress concentration zones in the subgrade layer and assist in the intermixing of subgrade soil.

iii. Track monitoring

Track monitoring methods include manual (e.g. displacement/settlement pegs) and the automated measurements (e.g. geophones and digital image correlation). These monitoring methods are useful to observe the long-term behaviour of the track. The use of dynamic piezometers can indicate the changes in pore water pressures in the subgrade with subsequent passage of trains (Aw 2007). It indicates the probable causes of failure rather than prevent them.

2.3 Experimental Investigations

The pumping of subgrade soils, in the context of pavement engineering, has been investigated in the late 1950s (Yoder 1957). However, in the context of railway engineering, the problem of mud pumping garnered gradual interest since the 1980s (Ayres 1986). It is suggested that with an increase of frequent passenger services at higher speeds, the use of geotextiles, shows an early promise of static filtering, and does not quite live up to the expectation under dynamic rack conditions. The inspected trenches conducted at old and new tracks suggest that the track movement was severe even when the subgrade had higher strength (Ayres 1986). The precedent of a track prone to pumping is that slurry may exist at or above the base of the sleeper level (similar to Fig. 1). The upward pumping of subgrade fines is termed as the erosion pumping failure (EPF) while the deposits in the upper ballast layer due to wind-blown deposits, attrition of ballast, coal is termed as dirty ballast pumping failure (DBPF). Ayres (1986) conducted experimental tests by sandwiching the geotextile layer between 25 mm of undisturbed soil and 25 mm of gravel, saturated to the top surface. The set-up is transferred to a pulsator apparatus, which can operate at a frequency of 3 Hz. The gradient of the plot of the vertical displacement versus the square root of the number of cycles is used to determine the efficiency of the geotextiles. The ratio of the weight of the eroded subgrade to the number of cycles was used as a practical measure of the applicability of the geotextile. Geotextiles successfully act as a separator by inhibiting the rate of rising of the slurry. However, it is crucial to identify the type of the failure of the track before selecting the geosynthetics for mitigation measure.

Alobaidi and Hoare (1998) conducted a series of pumping tests to quantify the use of geocomposites to mitigate mud pumping. The researchers define soil contamination value as the ratio of the subgrade soil mass passing through the geotextile to the area of the geotextile. To simulate the coarser particles, a sub-base plate made of hemispherical steel balls applies the load onto the subgrade soil in a triaxial pumping apparatus (Alobaidi and Hoare 1994). The amount of fines passing through the geotextile was measured at the end of each test. It is noteworthy that the rate of fines migration decreases with the number of loading cycles predominantly due to the reduction in the contact stress of the sub-base particle with the subgrade, and the percentage of precipitated fines increases with the number of cycles. The predictions from the finite element show a high hydraulic gradient near the interface (Alobaidi and Hoare 1996). The selection criteria are as follows: (i) high vertical compression modulus, (ii) low cyclic flexural movement, (iii) uniform distribution of concentrated load and (iv) act as a separator and restrict the flow of water (Alobaidi and Hoare 1998). Alobaidi and Hoare (1999) proposed that the subgrade soil weakening occurs due to the saturation of unloaded zone at the surface and shear failure due to high contact cyclic stresses occurring under the contact areas. Having a highly permeable geotextile could be the reason for the rapid water outflow during loading-unloading cycles. There is a 'mixing' of the subgrade soil into the subbase particles due to the plastic flow of the soil. To study the physical migration of fines from the subgrade layer into the ballast, Duong et al. (2014), designed a 550-mm Perspex triaxial cell and observed the formation of an 'interlayer'. The cell consisted of an artificial mix of soil (70% crushed sand and 30% kaolin clay by dry weight) compacted in layers, and a 160-mm ballast was placed atop the subgrade. The pumping of fines did not occur when the subgrade was unsaturated. In contrast, the cyclic loading led to the penetration of the ballast forcing the fine particles upward, also the pore pressure dissipation caused the fines to migrate into the ballast. The cyclic pore pressure generation could well be the governing mechanism for the pumping of soils.

Hayashi and Shahu (2000) believe that fluidisation is the apparent cause of mud pumping as it involves scouring and gradual loss of particles. 'Fluidization is the operation by which fine solids are transformed into a fluid-like state through the contact with a gas or liquid' (Kunii and Levenspiel 2013). It is proposed that upon the passage of the train, there is a rise in the pore water pressure of the base soil that increases the seepage velocity and leads to fluidisation of the soil particles. The effusion of water and the soil leads to mud pumping. To simulate the phenomenon of pumping in a laboratory environment, the researchers designed model set-up to represent the soil beneath the invert and walls of the tunnel. The main aim was to achieve the optimum location of the weep holes in the geometry design under various hydraulic gradients and loading frequencies. It is seen that the loading frequency had little to no effect on the amount of fines pumped, which depend mainly on the hydraulic gradient. The researchers also point out that there is a likelihood of clogging of the geotextile under long-term loading.

Geotextiles serve numerous functions, viz. reinforcement, filtration, drainage and separation. Geotextiles have the prospective to remediate the pumping problem on rail tracks when used at the interface of the sub-ballast and subgrade (Chawla and Shahu 2016). A series of 15 model tests were conducted on a full-panel model track with a similitude ratio of one-third. The efficiency of geotextiles and geogrids was investigated by placing them at the interface between sub-ballast and subgrade. The results from the monotonic and cyclic tests indicate that the reinforcement causes a stable behaviour by inducing a uniform distribution of the stresses. Further, typical silty soils are more prone to pumping because of low plasticity making it easier to dislodge with increasing pore water pressure. This is also consistent with Fig. 2 where most of the soils prone to pumping have low plasticity. Chawla and Shahu (2016) recommend the use of geogrid as a remediation measure for clay type of subgrade soils as they reduce the tie displacements, strains in the ballast and sub-ballast and subgrade displacement in comparison to the geotextile. However, the provision of both geogrid and geotextile provides the combined advantage of either reinforcement.

2.4 Field Studies

A conventional method of soil stabilisation, mixing fly ash and Portland cement, was reported for remediating a mud pumping site in Thailand (Voottipruex and Roongthanee 2003). While the optimum soil–cementitious mix proportion was found by comparing the unconfined compressive strengths, there was a significant reduction in the stresses in the subgrade soil. It is concluded that this method resulted in lesser excess pore pressure water, thereby reducing mud pumping.

However, long-term benefits of the proposed solution are yet to be seen because the cementitious lumps may form an ‘interlayer’ (Duong et al. 2014) and could cause more intermixing of soils instead of providing a permanent solution.

Aw (2007) introduced a low-cost wireless monitoring platform for monitoring the data for settlements, accelerations, seasonal temperature variations and long-term variation in pore pressures. Hudson et al. (2016) reported field remediation of a track site showing recurring signs of severe mud pumping. The wet bed area was reinforced with a microporous filter sandwiching the geotextiles to separate the slurried sub-ballast from the ballast. The track was monitored using digital image correlation (DIC) technique and geophones. The site showed significant reductions in the sleeper deflections after five months of site monitoring, indicating the efficiency of the geotextile.

3 Discussion

It is evident that the problem of mud pumping is prevalent in the context of railway engineering. The findings of the earlier study lead to classifying the possible triggers that initiate mud pumping. A trigger may act individually or in conjunction with the others and lead to the migration of subgrade fines. The possible triggering mechanisms are (in no particular order):

- High cyclic excess pore pressures upon the passage of trains.
- Dynamic fluidisation of the low plastic soil particles under high hydraulic gradient.
- Intermixing of the subgrade and the ballast layer to form an ‘interlayer’.
- Improper drainage in the track substructure causes the presence of free water on the surface.

The use of fault chart approach by Usman et al. (2015) which takes into account the typical subgrade failure mechanisms can provide a plan for track maintenance but it cannot predict the occurrence of mud pumping a priori. In addition, the use of geosynthetics, as inclusions to the track substructure, can inhibit the migration of the fines and increase the longevity of the track. The underlying problem of facilitating drainage under cyclic loading may be solved by the application of prefabricated vertical drains (PVDs). PVDs are extensively used in cohesive soil deposits to assist in consolidation by providing a shorter radial drainage path. Experimental studies undertaken at the University of Wollongong (Indraratna et al. 2009) indicate that PVDs not only assist in consolidation the soft soil but assist in controlling the excess pore pressure build-up under cyclic loading (Fig. 4). This suggests that the PVDs have a stabilising effect when the soft soil is subjected to repeated loading. In addition to that, PVDs continue to dissipate the pore pressures during the rest periods, so that during the next loading cycle, the cyclic pore pressures do not rise to a substantial value. The field predictions carried out at

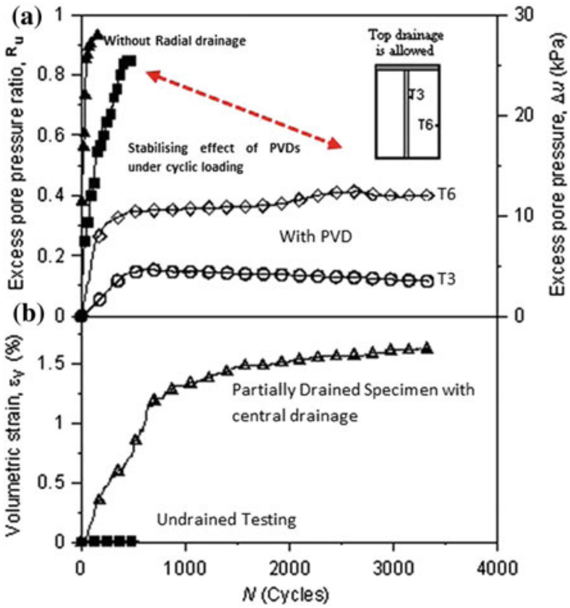

Fig. 4 **a** Cyclic excess pore pressures developed with and without PVD; **b** volumetric compressive strains generated under cyclic loads with PVD (Indraratna et al. 2009) (with permission from ASCE)

Sandgate show promising results of the use of short vertical drains under the railway track (Indraratna et al. 2010). The use of PVDs can also prevent the failure of soft subgrade under high-speed rail conditions. (Ni et al. 2013). Thereby, the role of PVDs can be accounted for even during the post-construction phase.

4 Conclusion

The paper highlights mud pumping under track environment. The sightings of mud pumping sites indicate that the soils prone to mud pumping are primarily low plasticity silty clays. The triggers causing mud pumping are described as a result of combined factors to initiate the complex phenomenon of fines migration. The inclusion of geosynthetics into the track design prevents the squeezing of fines, and to an extent mitigates the excess pore pressure generation by providing a reinforcing effect. The use of a geosynthetic is site specific and depends on the in situ soil properties. However, further geotechnical studies are recommended to investigate the governing mechanism of mud pumping. The use of prefabricated vertical drains may provide a viable alternative to prevent mud pumping by dissipating the cyclic excess pore pressures.

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