Effects of Plastic Properties on the Fluidization Behaviour of Subgrade Soil under Heavy Haul Rail Load

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ABSTRACT

Recent studies indicate low to medium plastic soils can fluidize and spread over the track surface, i.e., mud pumping, although, the question on the influence of plastic parameters such as the plasticity index (PI) and fines content on mud pumping has not been well understood. This study therefore aims to investigate the role of plastic parameters on the subgrade instability through a series of field and laboratory studies. The site investigations show that all soils collected from mud pumping sites have PI smaller than 26 while poor drainage condition is found as a major factor causing subgrade fluidization. The laboratory study shows that the specimen experiences a redistribution of water content at an adverse loading which transforms the top portion of the specimen to a fluid-like state. Kaolin content significantly affects the cyclic response of subgrade soil as increasing this fraction to a reasonable degree can mitigate soil fluidization.

INTRODUCTION

The soft soil deposits along the eastern coast of Australia form the foundation for the extensive rail network in the country. These soft soil deposits are characterized by their low permeability, high water content, and excessive deformation potential (Nguyen and Indraratna 2021). Further, the tracks laid over the soft subgrade undergo substantial maintenance, especially in recent years due to the rapid increase in transport demand, i.e., higher axle load and train speed (ARTC 2020). Likewise, similar maintenance burden and associated costs may be drawn for the railways laid on soft soil deposits which are spread across the world. Often, near-saturated in low-lying coastal ground, a commonly reported problem on these soft subgrades is rapid yielding and mud pumping (Hayashi and Shahu 2000; Duong et al. 2014; Kuo et al. 2017; Nguyen et al. 2019).

Mud pumping involves the upward migration of fluidized subgrade fines into the ballast layer under hydraulic gradients caused by excessive cyclic train loading. However, the actual mechanisms of subgrade fluidization have still not been fully understood. Takatoshi (1997) hypothesised the creation of dynamic suction at the sleeper-ballast interface which draws the subgrade fines upwards. In contrast, recent studies (Duong et al. 2014; Chawla and Shahu 2016; Indraratna et al. 2020a) attribute this to the development of cyclic excess pore water pressure (EPWP) in the saturated subgrade that corroborates with the susceptibility of the infiltrating fines. As the EPWP exceeds a critical level, it breaks the soil fabric and loosens particle contacts, making soil particles migrate under upward flows. Experimental studies (Indraratna et al. 2020b) show that the larger the axle load, the earlier the inception of soil fluidization. The transported fines cause a significant reduction of the inter-particle friction within the ballast layer while hindering the free-draining capacity of the granular assembly (Selig and Waters 1994; Sussmann et al. 2012; Nguyen and Indraratna 2021). Therefore, it is essential to study the generation of excess pore pressure within the shallow subgrade in relation to the inception of the fluidized soil.

Previous studies usually focused on several types of soils while varying loading parameters for simplicity during experimental tests. For example, many past studies (Duong et al. 2014; Chawla and Shahu 2016; Indraratna et al. 2020b) collected soils at one or several locations for their investigations, resulting in a lack of comprehensive understanding of how varying soil properties can affect the inception of subgrade fluidization. Soils with higher plasticity and clay content usually have larger inter-particle cohesion, thus their soil particles are less vulnerable to migration under hydraulic flows, including soil piping, internal erosion and fluidization (Nguyen and Indraratna 2020). It is therefore essential to understand the role of plasticity index and overall fines content in governing soil fluidization, thus enabling the practical guidelines to be established.

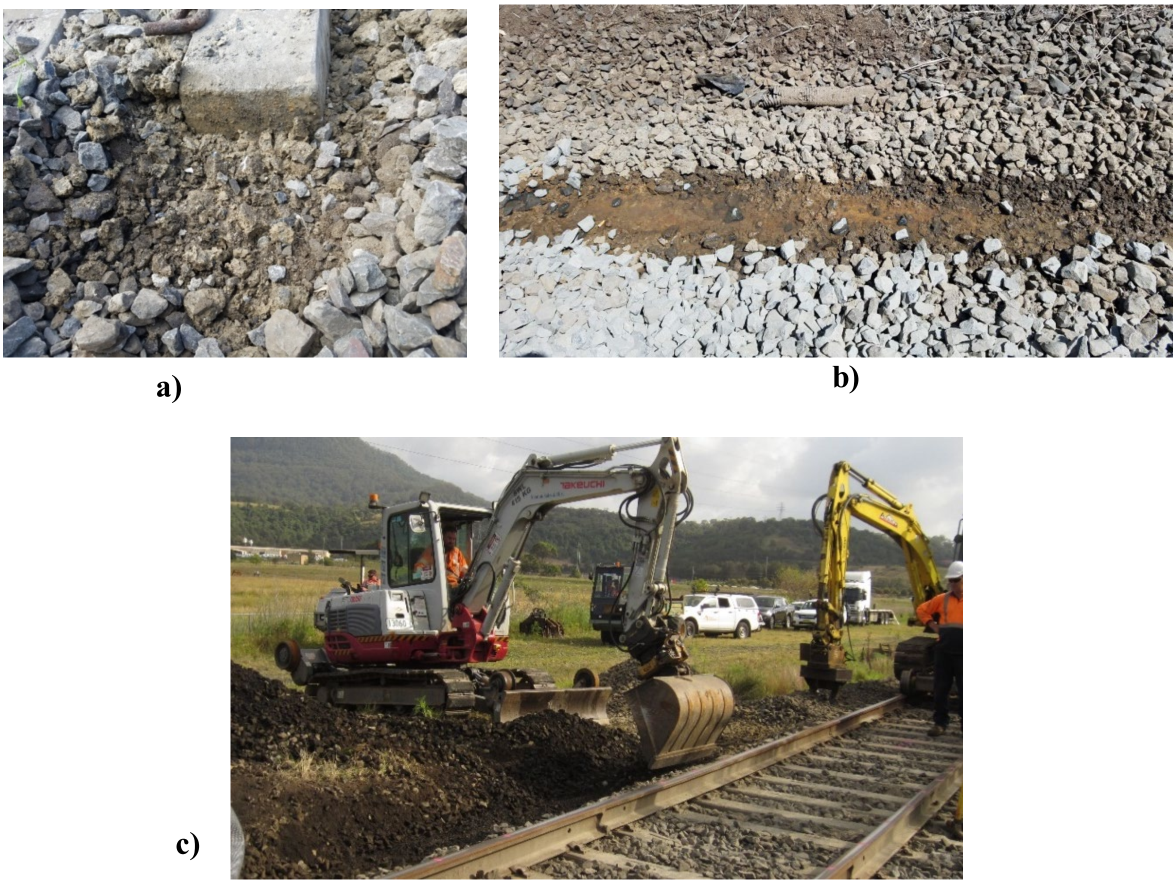
In this paper, a series of site investigations across different mud pumping locations along the South Coast rail line in New South Wales (NSW), Australia are presented. Plastic properties of subgrade soils collected from these mud pumping tracks are reported. Furthermore, a subgrade soil obtained from the field is mixed with different kaolin contents before subjected to cyclic triaxial tests to clarify how varying plasticity index and fines content can affect the response of soils.

SITE AND LABORATORY INVESTIGATIONS

This section presents two different stages of the current study; they are (*i*) site investigation into mud pumping rail tracks, accompanied with sample collection; and (*ii*) laboratory tests including fundamental tests and undrained cyclic triaxial tests

Site investigation and sample collection

An investigation on mud pumping sites (also termed as bog holes) along the South Coast rail line, NSW, Australia was carried out in 2019 and 2020. There were more than 300 bog holes including different types of formation such as subgrade fluidization, ballast degradation and the accumulation of external sources (i.e., dust and transport materials) along this line. In the current investigation, only tracks with significant fouling (i.e., the fouling index FI ≥ 19) were attended. Note that FI was defined as the percentage of fines (< 4.75 mm) plus the percentage of silt and clay (< 0.075 mm) (Selig and Waters 1994). At each location, these steps were implemented (Figure 1): (*i*) visual assessment of the mud pumping tracks, which included measurement of track deformation and the scale of muddy zone; (*ii*) investigation on drainage condition, which included site ditches, water ponding and slope gradient; and (*iii*) excavation and sampling, which included removal of fouled ballast and collection of samples (subgrade, capping material and fouled ballast). During excavation, the development of mud pumping was also examined through the migration paths of subgrade fines, for example, how subgrade fines extended their size from subgrade to the ballast surface could be determined. The collected samples were then subjected to a series of laboratory tests.



a) b) c)

Figure 1. Site investigation: a) ballast fouling induced by subgrade fluidization, b) poor drainage condition; and c) removal of fouled ballast and sampling

The site investigation showed that for most mud pumping sites, poor drainage was major reason causing water ponding and the associated subgrade failure. For example, many locations from Wollongong to Nowra had insufficient drainage capacity (e.g., side ditches were not properly designed) while the water table was relatively high as the rail line run through the low-lying coastal region, i.e., Nowra floodplain (Medawela and Indraratna 2020). This resulted in saturated track foundation and consequent accumulation of excess pore water pressure

(EPWP) and subgrade fluidization under heavy haul rail tracks. Note that the South Coast rail line is a shared network between freight and passenger trains where the axle load can often reach 25 tons. Many heavy freight trains in Australia are 2 to 4 km long, and travel in an average speed from 50 to 80 km/h.

Laboratory tests

Subgrade soil samples were subjected to laboratory tests to determine water content, Atterberge's limits (i.e., LL, PL and PI), and particle size distribution (PSD). The results (Figure 2) show that all subgrade soils subjected to mud pumping had low to medium plasticity index PI. Specifically, the largest PI, i.e., (PI = 22) was found at Coniston A location while many locations had PI less than 10. In comparison with soil data given by past studies, it can be concluded that mud pumping tends to occur with low to medium plasticity soils (e.g., PI ≤ 26 considering the current data). It is also noted that all these soils position near and above the A line as shown in the plasticity chart. This is understandable because as the soil has higher PI, soil particles are stronger to resist migration due to larger cohesive bonding between particles. Recent micro-scale studies (Nguyen and Indraratna 2020) explain that soil tends to break its fabric and the particles begin to migrate under increasing hydraulic pressure, however, for those soils with larger plasticity, soil particles cannot migrate easily.

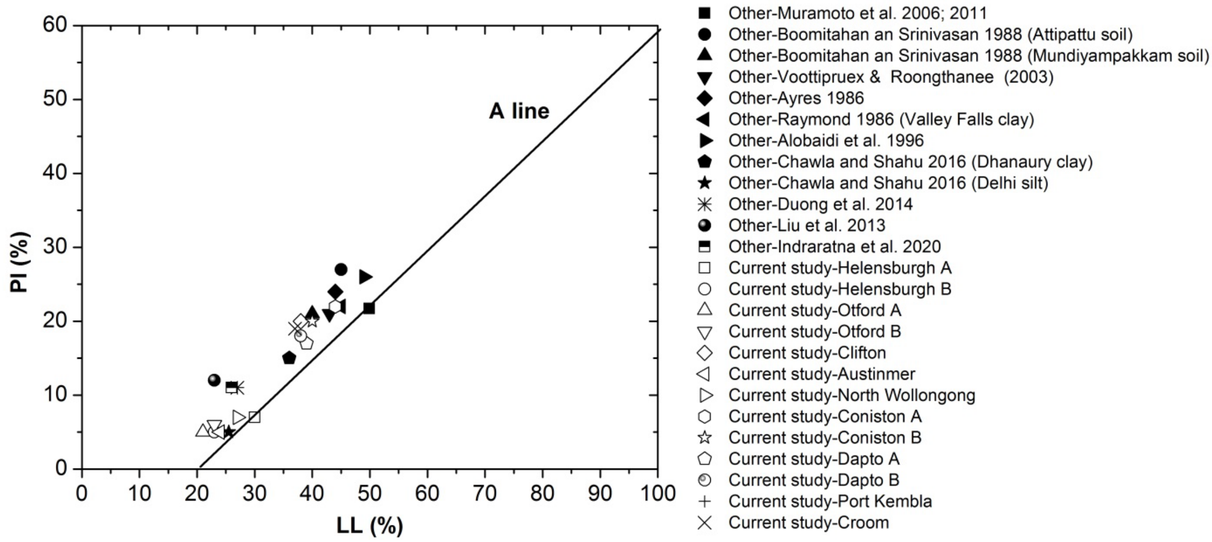


Figure 2: Plasticity chart of subgrade soil prone to mud pumping (current data compared to previous studies)

In order to understand how plastic properties of soil can affect the fluidization, the subgrade soil collected at Port Kembla site was used to mix with different kaolin contents. A series of cyclic triaxial tests were carried out on 3 different sets of soils, i.e., (*i*) the original subgrade soil (OS); (*ii*) the original soil mixed with 10% of kaolin (KS10); and (*iii*) the original soil mixed with 30% of kaolin (KS30). Basic properties of these soils are summarized in Table 1.

Table 1: Properties of soils used for cyclic tests

Specimen label	Description	Liquid limit	Plasticity limit	PI	Clay content	Silt content	Specific gravity
OS	Original soil	26	15	11	10	54	2.65
KS10	Original soil with 10% kaolin	29	16	13	10.5	62.5	2.63
KS30	Original soil with 30% kaolin	32	17	15	12.2	70	2.62
	Pure kaolin	55	28	27	58	42	2.61

Soil specimens of 50mm in diameter and 100mm in height were made by moist tamping method which was commonly used in past studies (Ladd 1978; Indraratna et al. 2020b; Nguyen et al. 2021). The compaction was carried in 10 layers at 15% water content to achieve the desired density. In this study, an initial dry density (γ_d) of 1620 kg/m^3 (i.e., equivalent to 89% relative compaction) was selected. Note that while this value of dry density was relatively smaller than the in-situ value, it was selected to mimic soft and loose subgrade soils, thus enabling the effect of kaolin content to be captured apparently. All specimens had the same initial dry density and were subjected to the same loading condition.

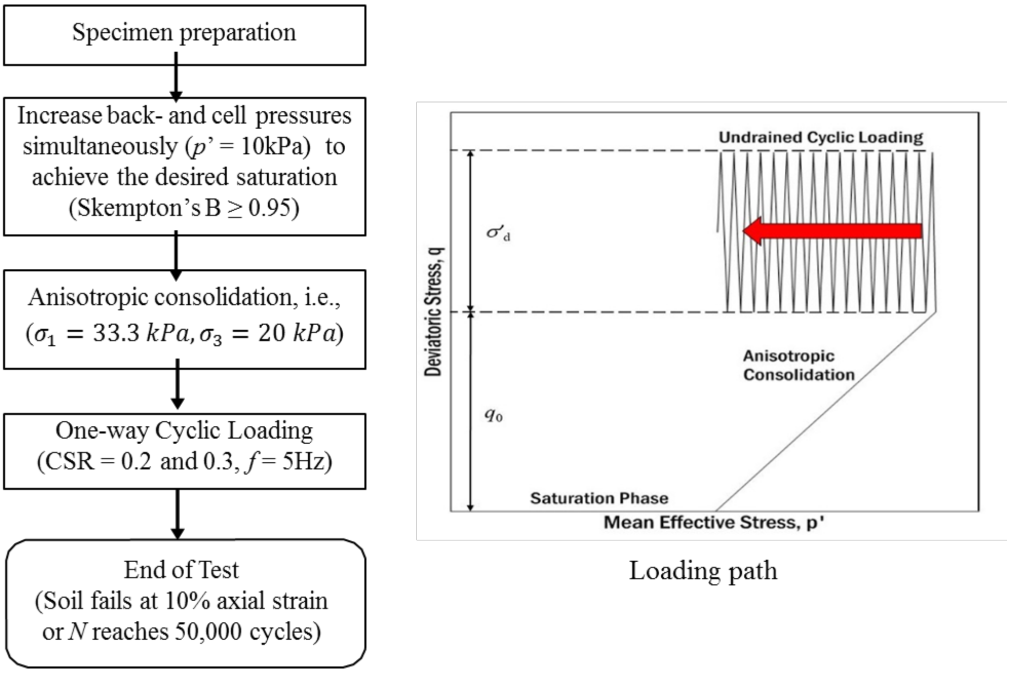


Figure 3 Major steps of cyclic triaxial tests

Figure 3 shows the major steps to carry out cyclic triaxial tests in the present study. The specimen was subjected to a saturation process where the back and cell pressures were increased gradually and simultaneously to maintain an effective stress of 10 kPa. After reaching the desired saturation degree (i.e., B > 0.95), an anisotropic consolidation (the ratio of horizontal and vertical stress was 0.6 during consolidation) to simulate the field condition was applied onto the specimen. A low confining pressure (i.e., σ_c= 20 kPa) which mimicked shallow subgrade soil was considered in this study. One-way cyclic loading was then applied on the specimen until one of two following criteria was achieved, i.e., (*i*) the axial strain = 10% or (*ii*) the number of cycles (N) = 50,000. In this study, a loading frequency of 5Hz which corresponded to an average speed of heavy haul trains from 50 to 80 km/h was used with respect to previous measurements in the field (Priest et al. 2010; Trinh et al. 2012). The cyclic stress ratio (CSR) which is defined as the ratio between the applied deviator stress (Δq) and twice the confining pressure σ_c (i.e., CSR = $\Delta q/2\sigma_c$) was used to evaluate the effects of cyclic deviator stress in this study.

RESULTS AND DISCUSSION

Subgrade fluidization under cyclic loading

The results from cyclic triaxial tests on the original soil (i.e., OS specimens) showed that when the cyclic stress ratio CSR exceeded a certain degree, the axial strain developed rapidly while the top part of the specimen turned into fluid-like state. Figure 4 shows that for CSR = 0.2, there is a certain reduction in the effective stress p' (i.e., increasing EPWP), but the stress path reaches a stable state despite N continuing to increase to 50,000 cycles. In this case, the residual axial strain slightly increases and settles at about 0.5% while the peak deviator stress can maintain its magnitude well. As CSR reaches 0.3, the peak deviator stress begins to drop (i.e., early softening) after a certain number of cycles, followed by a steep increase in axial strain (Figure 4b). This occurred because the soil experienced cyclic degradation that reduced its shear stiffness. When this degradation reached a critical stage with a substantial loss in shear stiffness, the soil could not bear the applied deviator stress further, resulting in a drop in the stress path. The same soil behaviour was also reported in several past studies (Konrad and Wagg 1993; Indraratna et al. 2020b). Indeed, the top part of the specimen became slurry in this case where the fabric of the soil was full broken (Figure 4b).

The water content (w) at the top and bottom parts of the fluidized specimen was measured after the test. The results showed that w at the top part was about 27% which exceeded the liquid limit of the soil whereas w at the bottom part became lower compared to the initial value before cyclic test (22%). This indicates that there was a moisture migration from the bottom to the top under cyclic loading, resulting in an increase in water content at the top and a decrease at the bottom of the specimen. Note that the total amount of water and soil did not change during undrain tests, but they redistributed themselves along the specimen under cyclic loading. Indeed, recent studies (Indraratna et al. 2020b) measured the PSD after cyclic tests and found that fines can migrate to the specimen surface during this redistribution process. When the water content approached and exceeded the liquid limit, the soil broke its fabric and its particles loosed their contacts, thus slurry formation under rising EPWP (Nguyen and Indraratna 2020).

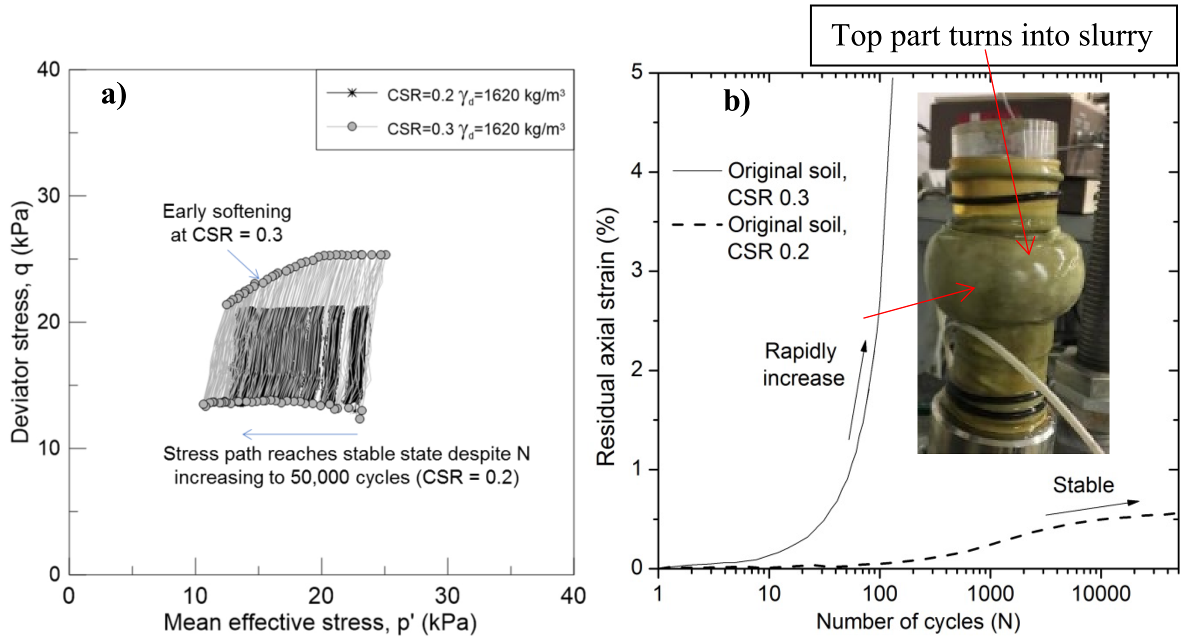
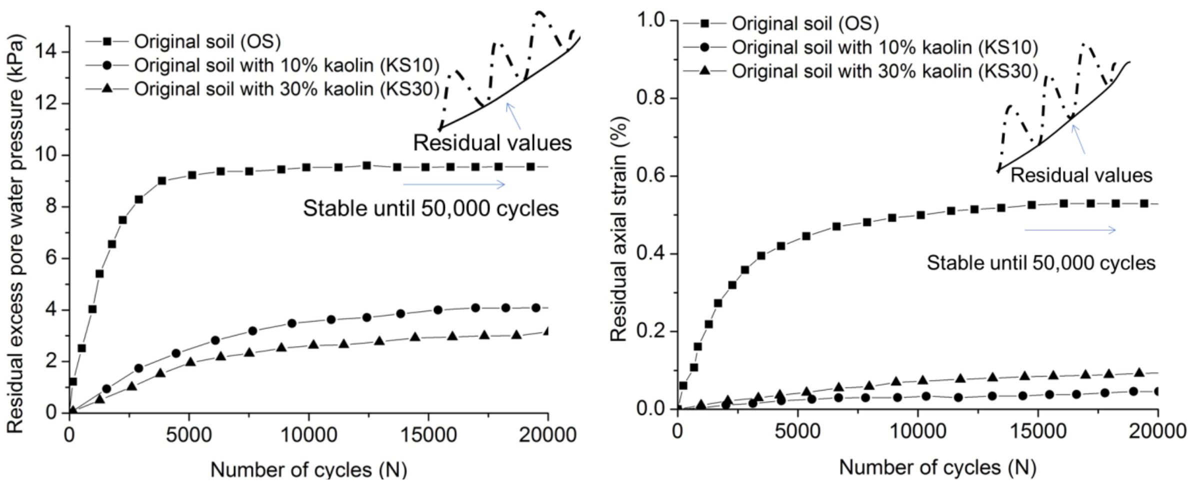


Figure 4: Response of the original subgrade soil to cyclic loading: a) stress path and b) development of residual axial strain with fluidized specimen under cyclic loading

Influence of plasticity index and fines (kaolin) content

Increasing kaolin content in the soil specimen resulted in increasing plasticity index PI and clay content, as shown in Table 1. As a result, the response of the soil to cyclic loading changed significantly. For example, Figure 5 shows that for stable specimen which did not fail under cyclic loading (i.e., CSR = 0.2, *f* = 5Hz), the accumulated EPWP decreases substantially when kaolin is added to the original soil and the plasticity index and clay content increase accordingly. Specifically, the peak residual EPWP decreases from around 9.5 to only 4 and 3 kPa when 10 and 30% contents of kaolin are included, respectively. The corresponding residual axial strain also decreases apparently, i.e., from around 0.5% to less than 0.1% (Figure 5b). Note that in this analysis, the residual values which were the remaining EPWP and axial strain after each loading cycle were considered (see demonstration of determining residual values in Figure 5).

The effects of kaolin content on the cyclic response of subgrade soil can also be seen more apparently in a larger cyclic stress CSR = 0.3 (Figure 6). The results showed that inclusion of kaolin helped mitigate soil fluidization. Specifically, for the same loading condition, while the original soil experienced fluidization, the soil specimens with 10 and 30% kaolin contents did not fluidize. Indeed, Figure 6 shows that for 10% kaolin specimen, the axial strain begins to increase significantly after around 200 cycles but it then stabilizes at 8% axial strain. This means that by adding 10% kaolin, the soil specimen can resist a larger number of loading cycles and better mitigate fluidization. For a larger percentage of kaolin (i.e., 30%), although the soil specimen did not fluidize, it failed earlier than 10% kaolin specimens (i.e., the axial strain begins to increase steeply at smaller number of cycles as Figure 6 shows). This was because the shear strength of the soil decreased significantly when the fraction of fine particles (i.e., clay and silt) increased much in the soil (see Table 1), making the soil fail under conventional shear mechanism rather than fluidization. This means having an optimum ratio of fines content is important to balance the fluidization resistance and shear strength of soils. Nevertheless, determining specific value for this optimum level is complex requiring considerably more effort, thus it is not covered in this current paper. Furthermore, it is interesting that inclusion of kaolin did not increase PI of the soil significantly (see Table 1), but it helped mitigate soil fluidization apparently. This indicated that apart from plastic properties, the overall fines content (<75 μm) contributed certainly to modifying PSD of the soil, consequently improving fluidization resistance.



a) **b)**

Figure 5: Influence of kaolin content on cyclic response of stable specimen (CSR = 0.2): a) excess pore water pressure, and b) axial strain

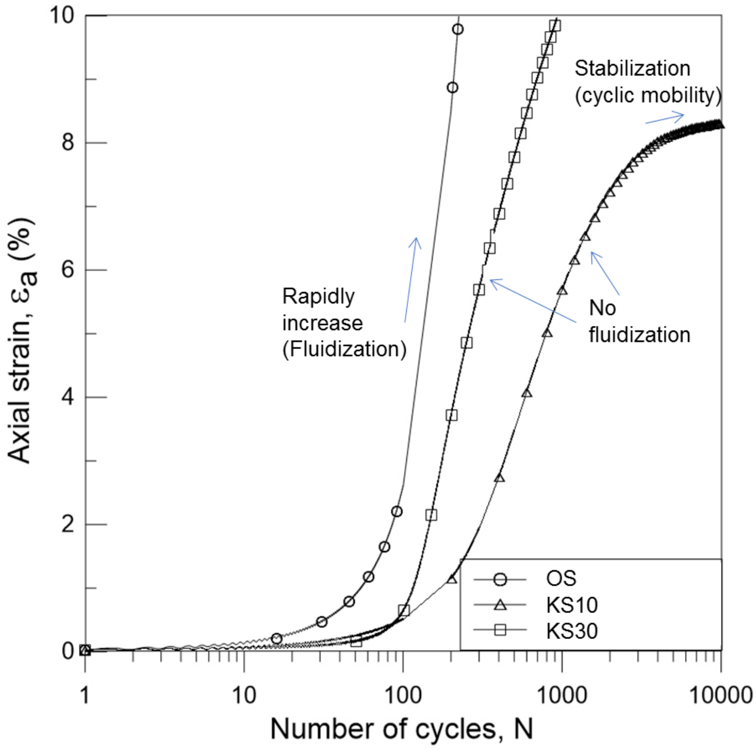


Figure 6 Different responses of soil specimens to large CSR 0.3 cyclic loading considering different kaolin contents

CONCLUSIONS

The current study presents site and laboratory investigations into the effects of plasticity properties and fines (kaolin) content on the fluidization failure of subgrade soils under rail track condition. Salient findings can be highlighted as follows:

- Low to medium plasticity soils (PI < 26) are highly vulnerable to fluidization and the consequent mud pumping subjected to heavy haul rail loads. In this process, the moisture tended to migrate upwards under increasing excess pore water pressure induced by cyclic loading, resulting in an increase in moisture content at the topmost part of the soil specimen. When the moisture content approached and exceeded the liquid limit, the soil turned into a slurry state. Accompanied with this process was the degradation in the fabric and shear stiffness of the soil.
- The fractions of clay (≤ 2 μm) and the entire fine particles (≤ 75 μm) play an important role in fluidization resistance of soils. The study showed that increasing kaolin content helped mitigate soil fluidization significantly, for example, inclusion of 10% kaolin content enhanced the critical number of cycles from around 60 to 200 given the same loading condition. Furthermore, the soil did not experience fluidization and tended to stabilize itself under cyclic loading.
- When the kaolin content was too large, i.e., 30%, it weakened the shear strength of the soil as fine particles tended to contribute more significantly to the soil fabric, albeit there was no fluidization in this case.

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