

Migration of fine granular materials into overlying layers using a modified large-scale triaxial system

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Abstract. The primary goal of this study is to evaluate the migration of fine granular materials into overlying layers under cyclic loading using a modified large-scale triaxial system as a physical model test. Samples prepared for the modified large-scale triaxial system comprised a 60 mm thick gravel layer overlying a 120 mm thick subgrade layer, which could be either tailings or railway sand. A quantitative analysis of the migration of fine granular materials was based on the mass percentage and grain size of migrated materials collected in the gravel. In addition, the cyclic characteristics, i.e., accumulated axial strain and excess pore water pressure, were evaluated. As a result, the total migration rate of the railway sand sample was found to be small. However, the total migration rate of the sample containing tailings in the subgrade layer was much higher than that of the railway sand sample. In addition, the migration analysis revealed that finer tailings particles tended to be migrated into the upper gravel layer easier than coarser tailings particles under cyclic loading. This could be involved in significant increases in excess pore water pressure at the last cycles of the physical model test.

Keywords: cyclic characteristics; migration of fine granular materials; modified large-scale triaxial system

1. Introduction

The migration of fine particles under cyclic loading is known as the upward ejection of fines from a fully saturated subgrade soil into the overlying layer. Fig. 1 illustrates the mechanism of the migration of fines into the overlying layer of a railway substructure. As the subgrade is saturated during wet seasons, cyclic loading caused by traffic may lead to the migration of fine particles from the subgrade into the overlying layer (Alobaidi and Hoare 1994). The migration of fines might cause poor performance and reduce service life of the railway or pavement substructure and may eventually lead to its failure (Do *et al.* 2023, Kermani *et al.* 2018, Kermani *et al.* 2019) and in many cases, improvement of grounds subjected to cyclic loads caused by moving vehicles on roads, rail tracks is needed (Mittal and Meyase 2012). With regard to the migration of fine particles due to cyclic loading, there have been a number of studies addressing this problem in both fields of railway substructure (Aw 2007, Ayres 1986, Duong *et al.* 2014, Ding *et al.* 2022, Indraratna *et al.* 2011, Raymond 1999, Sussmann *et al.* 2001) and pavement substructure

(Alobaidi and Hoare 1994, Alobaidi and Hoare 1998, Alobaidi and Hoare 1996, Alobaidi and Hoare 1999, Henry *et al.* 2013, Kermani *et al.* 2018, Kermani *et al.* 2019).

Alobaidi and Hoare (1994) performed a laboratory test to investigate fundamental factors affecting the number of migrated particles at the subgrade-subbase interface of highway pavements. They found that cyclic loading frequency, soil over-consolidation ratio, magnitude of applied cyclic stress, number of cycles, specimen thickness, confining pressure, and size of subbase particles were fundamental factors affecting the amount of migrated particles. Henry *et al.* (2013) performed a series of cyclic triaxial tests to study the upward movement of silt from a silty soil subgrade. A silt layer with various compaction levels and water content was provided, and the migration of fine particles was evaluated. Their results indicated that the upward movement was pronounced when the relative compaction was less than 82 %. In the study by Kermani *et al.* (2019), a physical model test was used to study the migration of fine particles due to cyclic loading. The simulated pavement sections were constructed on a partially saturated aggregate subbase overlying non-plastic saturated silt as subgrade. After the tests, they found a significant amount of fine particles ejected upward into the subbase. A quantitative analysis on the migration of fine particles based on the mass percentage (migration rate) was proposed in their study. Based on the results, they indicated that more fines were deposited in the lower section (closer to the subgrade) than in the upper section of the subbase. Duong *et al.* (2014) addressed two common phenomena, mud pumping and interlayer creation, which are involved in the migration of subgrade soil into the ballast of an ancient railway substructure. ‘Mud pumping’ is a degradation

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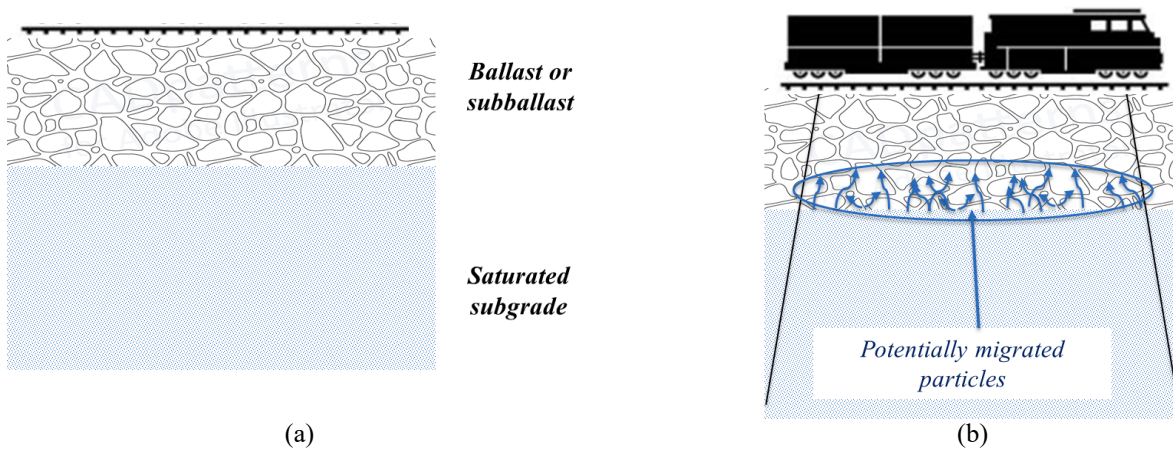


Fig. 1 Mechanism of migration of fine particles into the overlying layer of a railway substructure: (a) without cyclic loading, and (b) with cyclic loading (not to scale) (Do 2021)

phenomenon that poses a significant risk to railway substructures. This phenomenon is characterized by the rapid upward migration of fine particles from the sub-soil, which are pumped up to the surface of the ballast. On the other hand, 'interlayer' can form near the interface between the subgrade and ballast, created by particles that have migrated upwards. This upward migration of these particles occurs as a result of ballast penetrating into the subgrade soil (Duong *et al.* 2014). Duong *et al.* (2013, 2014), Trinh *et al.* (2012), Cui *et al.* (2013) all reported that, along with mud pumping, interlayer creation also plays an important role in the overall behavior of railway tracks. Although the discussion on the interlayer phenomenon is relatively recent, the mud pumping phenomenon has received much attention over the years. While several mechanisms have been proposed to explain mud pumping, they remain mostly controversial. Takatoshi (1997) stated that the mud pumping is due to the suction generated by the upward and downward moving of sleepers. When a train comes and passes, the generated suction pressure facilitates fine particles in the subgrade to be pumped upward into the ballast layer. Subsequent studies by Alobaidi and Hoare (1996), Alobaidi and Hoare (1999), Duong *et al.* (2014) proposed the existence of an apparent relationship between the development of excess pore water pressure and the mud pumping phenomenon. Alobaidi and Hoare (1996) emphasized that it is mainly due to the water pressure developed at the interface between the subgrade and subbase layers. They developed a new laboratory test to measure cyclic excess pore water pressures at the contact area between subbase with subgrade layers. Their results indicated that excess pore water pressure changes had significant effects on the mechanism of the pumping process. In addition, some others factors affecting the migration of particles due to cyclic loading have also been addressed in the literature, e.g., density of subgrade (Duong *et al.* 2014, Henry *et al.* 2013), and moisture content of subgrade (Aw 2007, Duong *et al.* 2014).

In summary, previous studies on the migration of fine-grained materials have been conducted in both the fields of railway substructure (Aw 2007, Ayres 1986, Duong *et al.*

2014, Ding *et al.* 2022, Indraratna *et al.* 2011, Raymond 1999, Sussmann *et al.* 2001) and pavement substructure (Alobaidi and Hoare 1994, Alobaidi and Hoare 1998, Alobaidi and Hoare 1996, Alobaidi and Hoare 1999, Henry *et al.* 2013, Kermani *et al.* 2018, Kermani *et al.* 2019). However, most of these studies have mainly focused on the migration of fine-grained subsoils containing a high proportion of fine particles, such as silty loam or clay, commonly referred to as 'cohesive' soils. In practice, however, other fine-grained materials, such as non-cohesive and non-plastic soils (e.g., silty sand, silt, tailings), would also be involved in this phenomenon. Particularly, there has been no study to date investigating this aspect specifically on tailings materials. Therefore, this study focuses on investigating the migration of fine granular materials into overlying layers using a modified large-scale triaxial system as a physical model test. A quantitative analysis was conducted to evaluate the migration of fine granular materials and their cyclic characteristics, including cyclic strain and excess pore water pressure.

2. Experimental program

2.1 Materials used and sample preparation

In this study, samples, which composed of a 60 mm thick gravel layer overlying a 120 mm thick subgrade layer (tailings or railway sand), were prepared for the modified large-scale triaxial system. These physical model tests were conducted for both a conventional railway track with ballast overlying on the subgrade and a porous pier with waste rock overlying on tailings. For this study, two types of subgrade materials were chosen: the first being sandy soil, taken from a railway embankment (Inlandsbanan) in Sweden, and the second being tailings obtained from a tailings dam in Kiruna, Sweden. It should be noted that upward pumping of migrated particles have been reported by both (Sundvall 2005) and (Knutsson and Laue 2016). The gravel was submerged for one day, thereafter washed using the wet sieving device to eliminate fine particles, which could affect

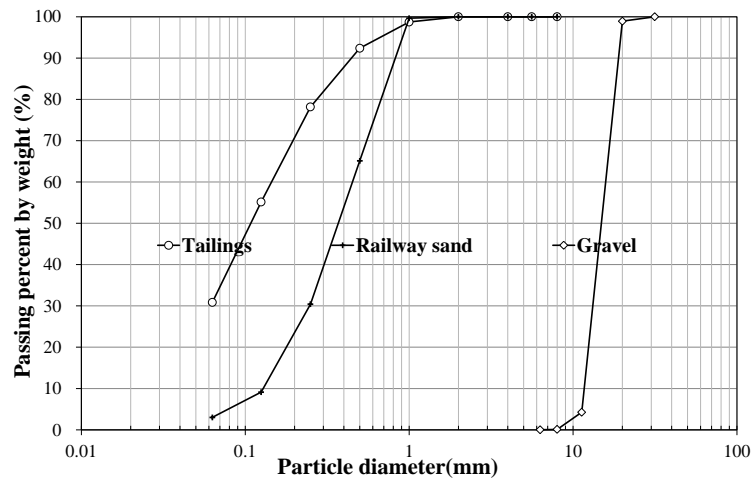


Fig. 2 Particle size distribution curves of all materials used in the modified large-scale triaxial system

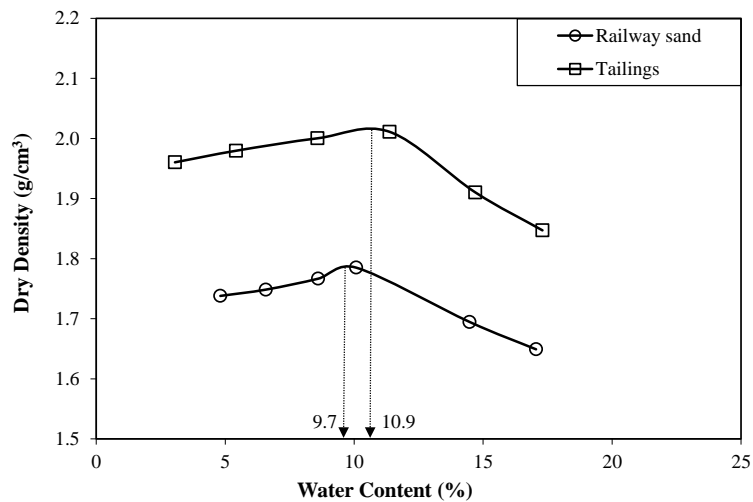


Fig. 3 Standard proctor compaction curves of railway sand and tailings

the migration analysis. Fig. 2 shows the particle size distribution curves of all materials used in the modified large-scale triaxial system. Fig. 3 presents the standard proctor compaction curves of railway sand and tailings that were obtained. The optimum water contents of railway sand and tailings are 9.7% and 10.9%, respectively. These values were used for the sample preparation in this study. All samples were compacted using the tamping method. Water was added to the samples to reach the optimum water content for the tailings and railway sand samples. The quantities of each layer were determined first. Then, the predetermined quantities of soil samples were spread carefully and sequentially into the four layers within the mold. Each layer was then densified by tamping with a steel rod marked into four designated portions. The subgrade part of the specimen was compacted to a depth of 30 mm each inside the large-scale standard triaxial mold to reach a relative compaction of 84% (Fig. 4(a)). It should be noted that the relative compaction of 84%, used in this study, corresponds to medium relative density for both samples.

Initially, a preliminary testing program with element cyclic triaxial tests was performed under both medium and dense conditions. Then, the worst-case scenario was selected for the modified large-scale triaxial system to study the migration of fine granular materials. A gravel layer was spread carefully on the subgrade layer. The surface of the gravel layer was arranged as flat as possible for good contact between the piston and the gravel surface (Fig. 4(b)). The top of the sample was then covered with filter paper, and a porous stone was placed on top of the filter paper

2.2 Modified large-scale triaxial system and testing procedure

Fig. 5 shows a schematic diagram of the modified large-scale triaxial system. The system consists of a hydraulic pump, a hydraulically controlled piston, a pore pressure sensor, an external displacement sensor, a data acquisition system, and a physical model cell. After assembling the cell

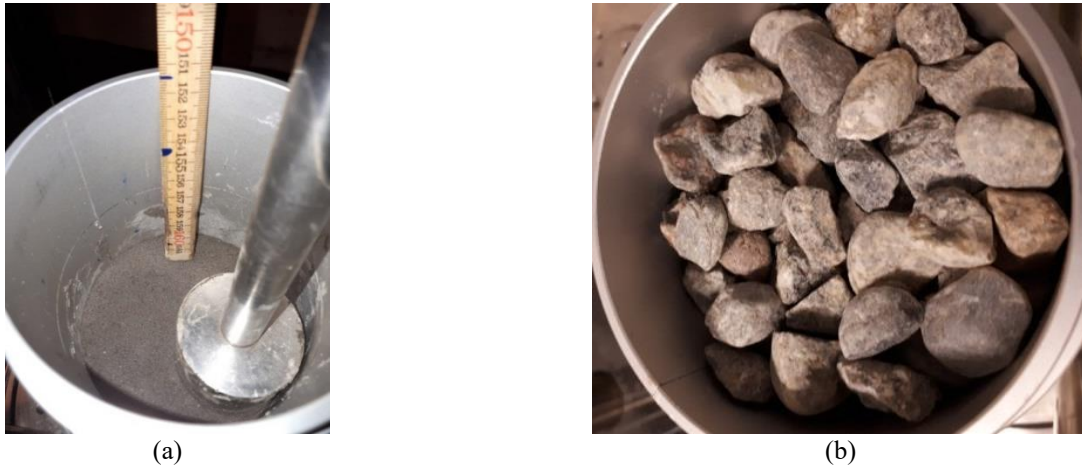


Fig. 4 Sample preparation for the physical model tests: (a) compaction of the subgrade layer (tailings) and (b) overlying layer (gravel)

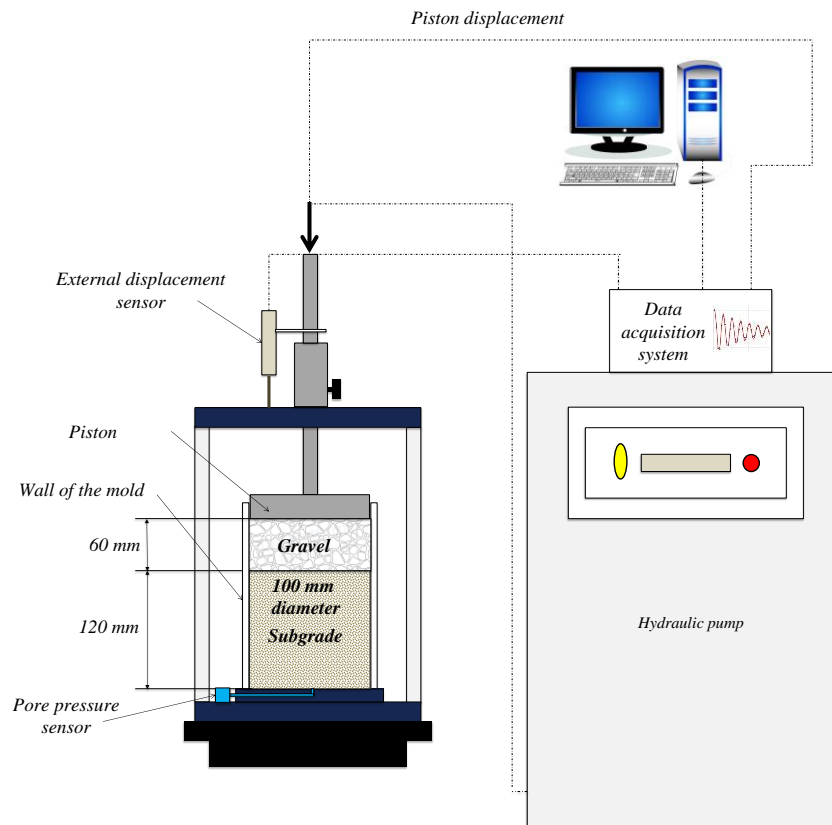


Fig. 5 Schematic diagram of the modified large-scale triaxial system

with a mounted sample and placing it in the loading frame, the subgrade layer was saturated from the bottom using the constant head method. The field conditions are taken into consideration to establish the water-level boundary of the tests. For instance, in the railway sand sample, the water level was maintained at approximately 3 mm above the interface of gravel and soil layers to ensure the subgrade soil's saturated state. Similarly, for the tailings sample, the water level was maintained close to the surface of the gravel (Do 2021). Afterward, the hydraulic piston was manually lowered using Geosys software down to approximately 2

mm above the internal loading piston. In order to keep the vertical alignment between the two rods, an exterior coupler was then used to connect the hydraulic piston to the internal loading rod. This was followed by the loading phase with all measurements of applied cyclic stress (q_{cyc}), axial strain, and excess pore water pressure. The data was logged by the data acquisition system at regular time intervals within each cycle.

In this study, several stress levels are applied until the samples failure, i.e., a multi-step loading procedure. In addition, the procedure could help to decrease the number

Table 1 Experimental program

Test	Initial dry density of subgrade, ρ_d (kg/m ³)	Relative compaction of subgrade, RC (%)	Frequency (Hz)	Multi-step cyclic stress applied, q_{cyc} (kPa)
Ta_MoLCYC	1700	84	4	25
			4	60
			4	-
RaSa_MoLCYC	1523	84	4	25
			4	75
			4	120
			4	180
			4	310

of tests and avoid the variability of samples (Duong *et al.* 2013, Gidel *et al.* 2001, Trinh *et al.* 2012). The samples were loaded to 5000 cycles (tailings) or 30000 cycles (railway sand) for each q_{cyc} stress level at the frequency $f=4$ Hz (four cycles per second). It should be noted that the frequency in field is dependent on the vehicle speed (Duong *et al.* 2013, Milne *et al.* 2017, Trinh *et al.* 2012), and the thickness of the overlying layers (Powrie *et al.* 2007). For example, the frequency of dynamic soil stress responses beneath a railway track is mainly determined by the speed and axle spacing of a moving train. A 4 Hz frequency represents the dominant frequency of conventional railway tracks in Sweden used for ore transportation with a wagon length of 9,4 m. The selected frequency was in line with that reported in the literature (Indraratna *et al.* 2020, Knutsson and Laue 2016, Wang *et al.* 2020). All model tests were terminated after reaching either 10% accumulated axial strain or 25000 cycles for the tailings sample and 150000 cycles for the railway sand sample. After the tests, sieve analysis was used to quantitatively evaluate the migration of fine granular materials. This evaluation is based on the mass percentage of the migrated particles collected at the overlying layers of samples. Migrated particles were collected at the top half and bottom half of the gravel layer for both samples. Finally, the mass percentages of migrated particles from the tailings or sand layers into the gravel layer were calculated separately

2.3 Testing program

Table 1 presents the experimental program in detail consisting of sample sets, so-called Ta_MoLCYC (tailings sample) and RaSa_MoLCYC (railway sand sample). Each test in Table 1 is given a name which is a set of characters. The labels ‘‘Ta’’ and ‘‘RaSa’’ indicate tailings and railway sand, respectively. MoLCYC refers to the type of test performed (modified large cyclic triaxial test). In this table, the multi-step cyclic stresses for the physical model tests are also summarized. The symbol ‘‘-’’ indicates that ‘failure sample’.

3. Results and analyses

3.1 Cyclic strain and excess pore water pressure responses

Fig. 6 shows the accumulated axial strain of the Ta_MoLCYC sample with respect to the number of cycles (N). The Ta_MoLCYC sample reached failure (10% of strain was reached) after two cyclic stress levels, $q_{cyc1} = 25$ kPa, and $q_{cyc2} = 60$ kPa. At the cyclic stress level of 25 kPa, the accumulated axial strain increased dramatically to 4.4% after a few cycles and then increased at a lower rate reaching 7.3% after 2340 cycles. Then, the accumulated axial strain tended to be stabilized despite an increase in the number of cycles up to 5000 cycles. However, at the cyclic stress level of 60 kPa, the accumulated axial strain increased rapidly up to 10% (sample failure) after a limited number of cycles. Fig. 7 presents the excess pore water pressure of the Ta_MoLCYC sample with respect to the number of cycles (N). At the cyclic stress level of 25 kPa, the excess pore water pressure increased dramatically to 14.1 kPa after some first cycles, followed by a gradual decrease. This response could be explained by the sudden increase in the axial strain after some cycles, followed by a lower incremental rate of the axial strain. Similar observations on the cyclic strain and excess pore water pressure responses can also be found in previous studies on the migration of fine particles using a physical model test (Duong *et al.* 2014, Wang *et al.* 2020). Interestingly, the excess pore water pressure became more stable (close to 0) as the accumulated axial strain tended to be stabilized. However, at the cyclic stress level of 60 kPa, the excess pore water pressure increased rapidly again and reached approximately 27 kPa (maximum) after some cycles. Again, this tendency is primarily due to the dramatic increase in the accumulated axial strain up to 10% right before the test terminated. Indeed, it took only approximately 25 seconds (102 cycles) for the accumulated axial strain to reach 10% after the second cyclic stress level ($q_{cyc2}=60$ kPa) was applied. This considerable increase in both strain and excess pore water pressure, may have had an effect on the significant amount of migrated fine particles observed after the test. Indeed, for any saturated soils under cyclic loading, if the pore water pressure does not have enough time to dissipate, excess pore pressure can occur. When the excess pore water pressure is high enough, fine particles lose their contact and can be brought up to the gravel layer by suction effect during the unloading phase. Conversely, the migration of subgrade soil to the upper layers would lead to clogging of pores in the contaminated coarse aggregate layers and a reduction in the drainage capacity of the upper layers. This condition would lead to the buildup of excess pore water pressure when a saturated subgrade is subjected to cyclic loading. This finding is consistent with earlier investigations on fine particle migration using physical model tests (Alobaidi and Hoare 1996; Duong *et al.* 2014). Fig. 8 provides evidence that tailings particles can migrate to both the top (Fig. 8(a)) and bottom (Fig. 8(b)) halves of the gravel layer. The pictures were taken immediately after the test terminated.

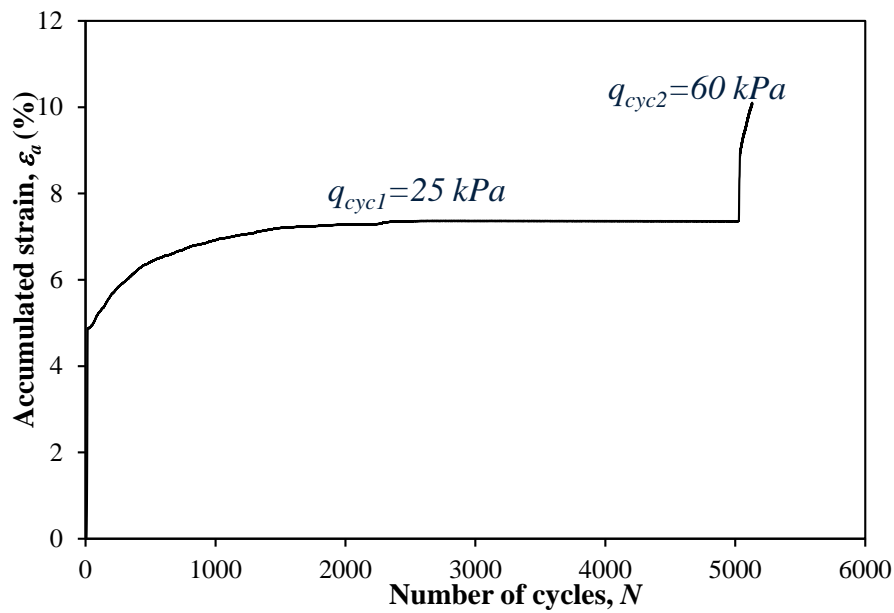


Fig. 6 Accumulated axial strain of Ta_MoLCYC sample with respect to number of cycles

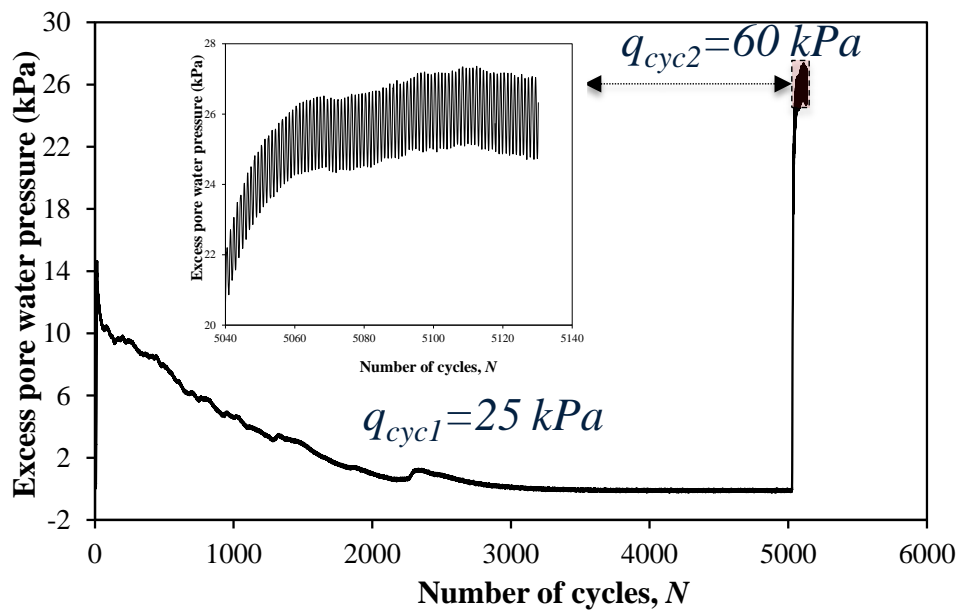


Fig. 7 Development of excess pore water pressure of Ta_MoLCYC sample with respect to number of cycles

Fig. 9 illustrates the accumulated axial strain of RaSa_MoLCYC sample with respect to the number of cycles. In this test, five cyclic stress levels, i.e., $q_{cyc1} = 25$ kPa, $q_{cyc2} = 75$ kPa, $q_{cyc3} = 120$ kPa, $q_{cyc4} = 180$ kPa, and $q_{cyc5} = 310$ kPa were applied to the sample until 150000 cycles, i.e., which means that the 10 % of strain was not reached. For each cyclic stress level, the accumulated axial strains increased quickly after the first cycles followed by an increase with a lower rate. However, the accumulated axial strain tended to be stabilized at the end of each cyclic stress level (30000 cycles for each stress level). The accumulated axial strain at the end of each cyclic stress level 1 to 5, were found to be 0.7%, 2.0%, 3.9%, 5.1%, and

7.5%, respectively. Fig. 10 shows the excess pore water pressure of RaSa_MoLCYC sample with respect to the number of cycles. For most of the cyclic stress levels, the excess pore water pressure increased slightly after the first cycles, then decreased gradually before tending to be stabilized. This finding is in line with earlier investigation on fine particle migration using physical model tests (Tang *et al.* 2018). Take $q_{cyc1} = 25$ kPa as an example (see the enlarged plot inside Fig. 10); after reaching 3.15 kPa, the excess pore water pressure gradually decreased to an almost constant value close to zero after 125 cycles. However, the magnitudes of the cyclic excess pore water pressures (both maximum and minimum values) at the end of the cyclic



Fig. 8 Migration of tailings particles into the gravel layer (Ta_MoLCYC sample): (a) tailings particles at the top half of the gravel layer, and (b) tailings particles at the bottom half of the gravel layer

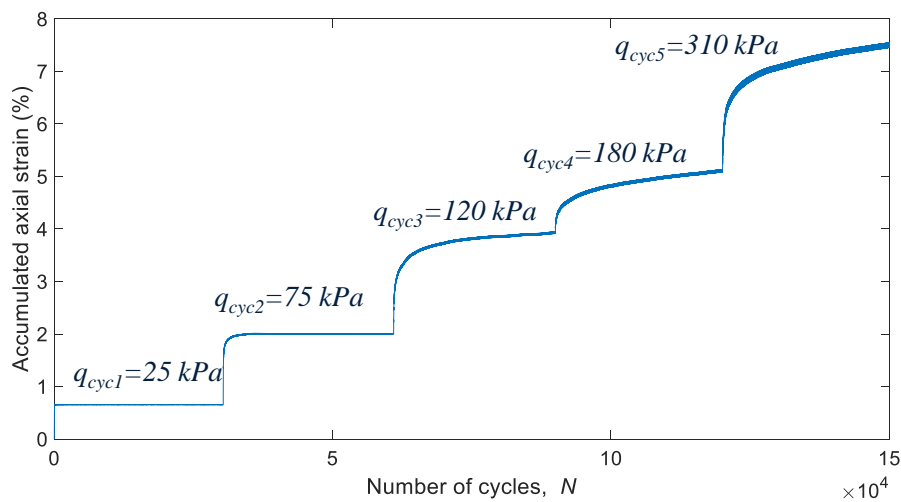


Fig. 9 Accumulated axial strain of RaSa_MoLCYC sample with respect to number of cycles

stress levels were dependent on the magnitudes of the applied cyclic stresses. As a result, the excess pore water pressures at the end of each cyclic stress level 1 to 5 were found to be 0.28 kPa, 0.43 kPa, 0.62 kPa, 0.72 kPa, and 1.01 kPa, respectively. The occurrence of the negative excess pore water pressures in the experimental results of RaSa_MoCYC is primarily due to the cyclic loading applied on the surface of a sample with free drainage (Alobaidi and Hoare 1999). In general, excess pore water pressure generation refers to the change in pore water pressure that occurs within a saturated soil as a load is applied. During cyclic loading on the surface of a sample with free drainage, if a high permeability soil is loaded, then the pore water will have sufficient time to drain and the pressure to dissipate. Such a situation results in a very small generation of excess pore pressure. When the soil is unloaded (second half of cyclic loading), this condition can generate a suction effect, which causes the pore water pressure to decrease. If the pore water pressure drops below the initial pore water pressure, negative excess pore water pressure is produced. It should be noted that the pore water pressure sensor is installed at the bottom of the apparatus, i.e., 0.18 m from the surface of the gravel layer. Negative

excess pore water pressures have been also reported in previous studies on the migration of fine particles using a physical model test (Duong *et al.* 2014, Kermani *et al.* 2019). Fig. 11 displays the condition of the RaSa_MoCYC sample after the test terminated. It can be observed that no sand particles migrated up to the top surface of the gravel layer, indicating that there was no mud pumping (Fig. 11(a)). However, migration of sand particles were observed at the bottom half of the gravel layer near the interface between sand and gravel. Duong *et al.* (2014) pointed out that if small excess pore water pressures are observed during cyclic loading, the upward migration of fine particles is only due to the penetration of ballast into the subgrade soil. The inter-penetration between ballast and sub-grade fine particles under the train traveling over the years is known as an “interlayer” (Duong *et al.* 2013, Trinh *et al.* 2012).

3.2 Quantitative analysis of the migration of fine particles

Quantitative analysis of the migration of fine granular materials is based on the mass percentage (migration rate)

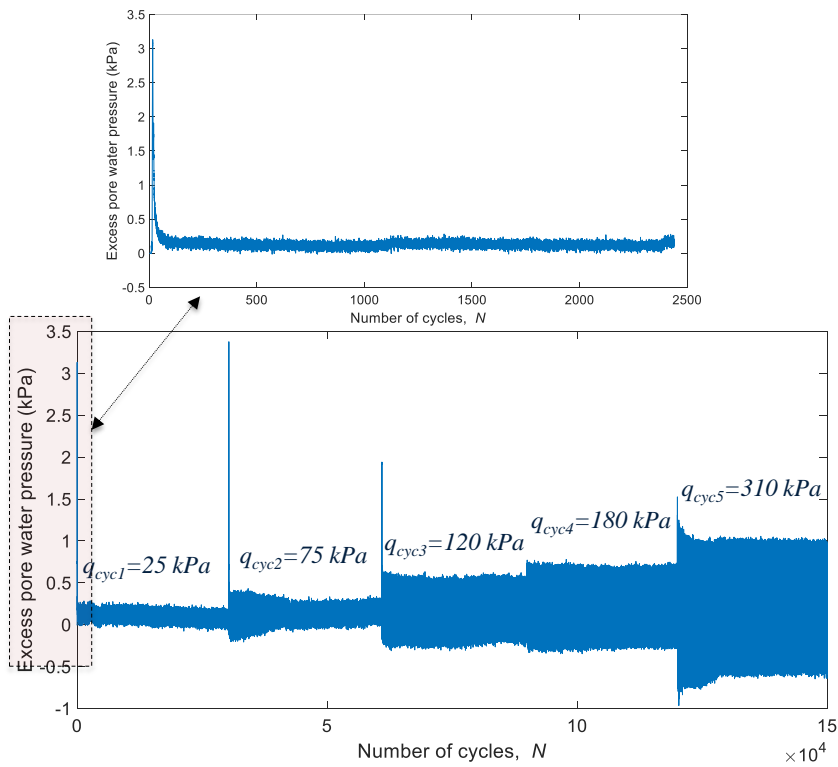


Fig. 10 Excess pore water pressure of RaSa_MoLCYC sample with respect to number of cycles



Fig. 11 Migration of sand particles into the gravel layer (RaSa_MoLCYC sample): (a) no sand particles at the top half of the gravel layer, and (b) sand particles at the bottom half of the gravel layer

and grain size of the migrated particles collected at the overlying layers of samples. Sieve analysis was used for this purpose. Based on this analysis, the grain size distribution curves of the migrated tailings and sand materials are shown in Figs. 12 and 13. Table 2 shows the migration of tailings and railway sand particles collected at the top half and bottom half of the gravel layer for the sample Ta_MoLCYC and RaSa_MoLCYC, respectively. The percentage values in Table 2 are the net mass percentages of migrated particles from the tailings or sand layers into the gravel layer. The migration rate M can be calculated in the form of

$$M = \frac{m_{migrated}}{m_{initial}} \times 100 \quad (1)$$

where: M is the migration rate (%)

$m_{migrated}$ is the dried mass of migrated materials (g)

$m_{initial}$ is the dried mass of the tailings or railway sand before conducting physical model tests (g)

For the tailings sample (Ta_MoLCYC), the total migration rate was found to be 13.7%, which was calculated by the summation of the migration rates at the top half (2.0%) and the bottom half (11.7%) of the gravel layer. It should be noted that the migration of tailings particles was observed at the top surface of the gravel layer after the test terminated (Fig. 8(a)). In addition, more migration occurred at the bottom half (11.7%) than at the top half (2.0%) of the gravel layer. This might be due to a clogging process developed in the gravel layer with time. The clogging process might start from the interface between the tailings

Table 2 Mass percentage of the migrated particles collected at the overlying layers of samples

Particle size range (mm)	Ta_MoLCYC		RaSa_MoLCYC	
	Tailings at the top half of gravel (%)	Tailings at the bottom half of gravel (%)	Sand at the top half of gravel (%)	Sand at the bottom half of gravel (%)
> 2.0	0	0	0	0
1.0 - 2.0	0.0	0.1	0	0
0.5 - 1.0	0.1	0.6	0	1.3
0.25 - 0.5	0.2	1.6	0	1.5
0.125 - 0.25	0.4	2.4	0	0.6
0.063 - 0.125	0.4	2.8	0	0.3
< 0.063	0.9	4.2	0	0.2
All size	2.0	11.7	0	3.9

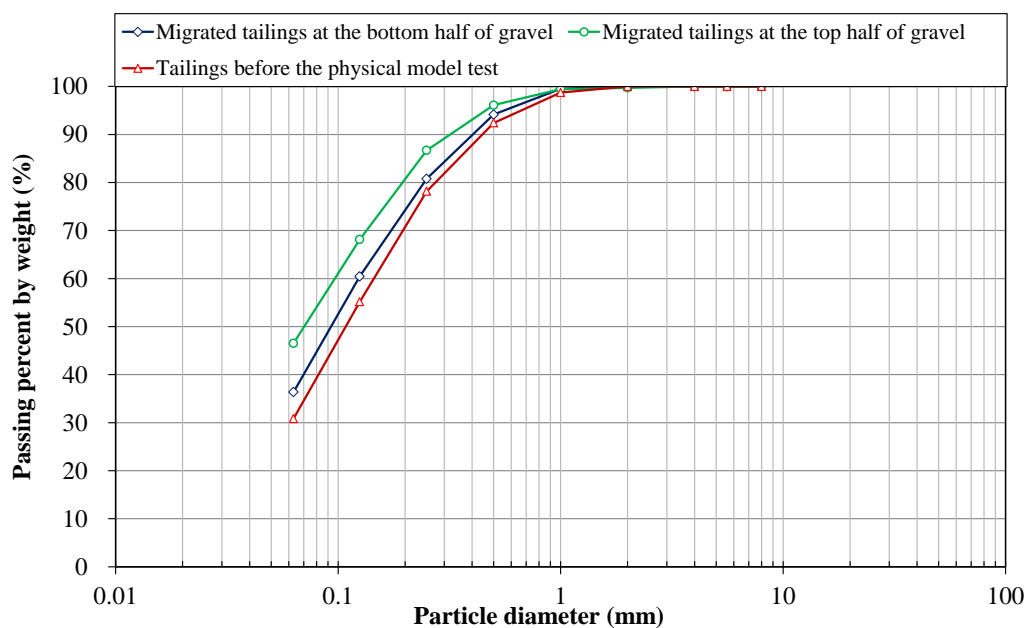


Fig. 12 Grain size distribution curves of the migrated tailings after the test

layer and the gravel layer due to cyclic loading. With time, this may lead to a decrease in the permeability of the gravel layer and hence cause a gradual decrease in the amount of migrated particles into the gravel layer, especially into the upper part (top half). That more migration occurred at the bottom half than at the top half of the upper layer has also been reported in the literature (Alobaidi and Hoare 1999, Kermani *et al.* 2018, Kermani *et al.* 2019). To closely investigate the migration of fine particles, the migration rates with respect to the particle size ranges are also summarized in Table 2. It was found that particles with a size less than 0.25 mm were dominant among the migrated particles collected at the gravel layer (both the top half and bottom half). In addition, it is interesting to discover that finer tailings particles tended to be migrated into the upper gravel layer easier than coarser ones under cyclic loading. This finding is clarified by Fig. 12, showing the grain size distribution curves of the migrated tailings at the bottom half and top half of the gravel layer after the test terminated.

The grain size distribution curve of the tailings before the physical test is also included in Fig. 12 for comparison. The grain sizes of the migrated tailings into the gravel layer were much finer than those of the tailings before the physical test. Moreover, the grain sizes of the migrated tailings at the top half were finer than those at the bottom half of the gravel layer. This can be due to the application of cyclic loading, which causes an upward migration of finer tailings, transported by displaced water, possibly in the form of a slurry or suspension. This migration of tailings particles into the upper layers can result in pore clogging, reducing the drainage capacity of the gravel layer. The clogging process may initiate from the interface between the tailings layer and the gravel layer, forming a layer resembling a filter protection, which only allows finer tailings particles to migrate into the top half of the gravel layer.

Taking the passing percentage of fines (less than 0.063 mm) as an example; there were 46.5% and 36.4% of fines

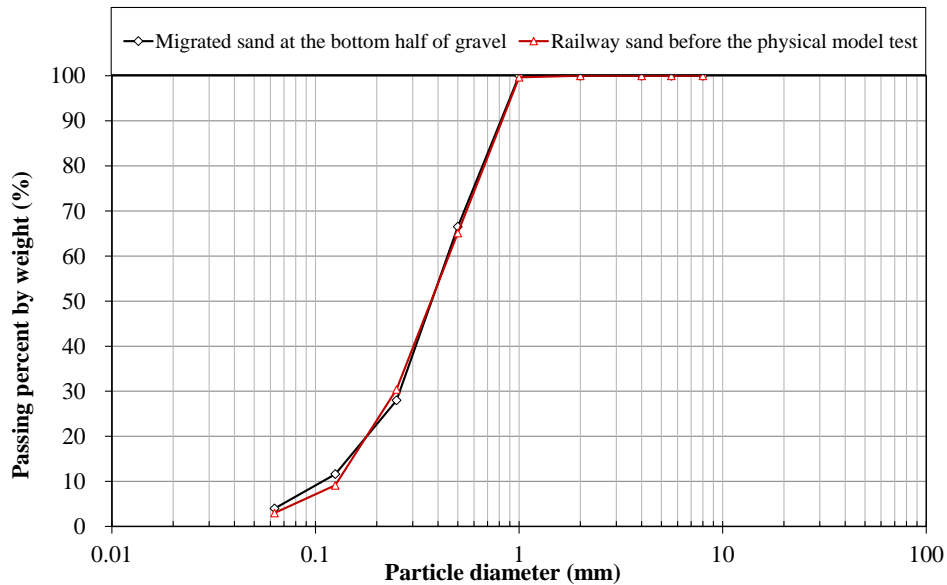


Fig. 13 Grain size distribution curves of the migrated sand particles after the test

in the grain sizes of the migrated tailings at the top half and bottom half of the gravel layer compared to 30.9% in the tailings before the physical test.

For the railway sand sample (RaSa_MoLCYC), the total migration rate was found to be 3.9%, which was calculated by the summation of the migration rates at the top half (0.0%) and at the bottom half (3.9%). As mentioned earlier, there were no sand particles pumped up to the top surface of the gravel (Fig. 11(a)). However, migration of sand particles was observed at the bottom half of the gravel, near the interface between the sand and the gravel, i.e., an interlayer as explained at the end of section 3.1. Moreover, the migrated amount of fines (less than 0.063 mm) was insignificant, i.e., only 0.2% compared to 3.9% migration rate of sand as shown in Table 2. The grain size distribution curve of the migrated sand was not far away from that of the railway sand before the physical test. This could be evidence for that the upward migration of particles is only due to the penetration of gravel. Take the passing percent of fines (less than 0.063 mm) as an example; there was approximately 4.0% of fines in the migrated sand compared to 3.0% in the railway sand before the physical test (Fig. 13).

In this study, the migration rates of the tailings sample and the railway sand sample were 13.7% and 3.9%, respectively. The differences in fines content and grain size distribution for the two selected materials could explain the different amount of migrated particles. In the future, further testing will be needed to investigate the effects of fines content on the migration of subgrade materials under cyclic loading.

4. Conclusions

A laboratory study on the migration of fine granular materials, i.e., railway sand and tailings, into overlying

layers was conducted using a modified large-scale triaxial system. Based on the results of this study, the following conclusions can be drawn:

- A small amount of railway sand particles migrated into the bottom half of the gravel layer near the sand-gravel interface. However, a significant amount of tailings particles migrated into the gravel layer (i.e., both the bottom half and the top half of the gravel layer). The migrated tailings particles were observed at the top surface of the gravel layer after the test terminated, i.e., mud pumping occurred. It might be explained by the significant increases in excess pore water pressure at the last cycles of the physical model test. Similar observations on cyclic excess pore water pressure response can also be found in the literature dealing with the migration of fine particles. In addition, the differences in fines content and grain size distribution for the two selected materials could affect the amount of migrated particles.
- The observations from the modified large-scale triaxial tests agreed well with the results obtained from the migration analysis. The total migration rate of the railway sand sample was found to be much smaller than that of the tailings sample. It might be associated with higher excess pore water pressures generated in the tailings sample than in the railway sand sample at the last cycles of the physical model tests.
- In the mud pumping case (tailings sample), it was found from the migration analysis that the migration rate at the bottom half of the gravel layer (11.7%) was higher than at the top half (2.0%). Among the migrated particles, the finer tailings particles (less than 0.25 mm) were dominant in both the top and bottom halves of the gravel layer. In addition, compared to the tailings before the physical test, the grain sizes of the tailings that migrated into the gravel layer were substantially smaller. More importantly, it was discovered that the

migrated tailings' grain sizes at the top of the gravel layer were finer than those at the bottom. In other words, under cyclic loading, finer tailings particles migrated into the upper gravel layer more easily than coarser ones.

This study conducted an in-depth analysis of the migration of fine granular materials into overlying layers under cyclic loading. The study also presented an idea of how excess pore water pressures can influence the migration rate. It is believed that this study will make a valuable contribution to the existing literature on excess pore water pressure and its impact on the migration of fine particles under cyclic loading. However, in this study, both layer gravel and subgrade were compacted in a rigid cell and subjected to cyclic loading. Many previous studies have used a rigid cell containing gravel and subgrade layers as a physical model to investigate the migration of fine particles in the laboratory (Alobaidi and Hoare 1996, Boomintahan and Srinivasan 1988, Ghataora *et al.* 2006, Duong *et al.* 2014, Ghataora *et al.* 2006). The boundary condition of the rigid seems to be doubtful to simulate the actual confining pressure of the subgrade layer in the field. To overcome these limitations of a rigid cell and scale effects, full-scale physical model tests should be considered in future studies.

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