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Railway Subgrade Performance During Flooding and the Post-Flooding (Recovery) Period

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Abstract

Railway track is constructed on compacted soil which is, characteristically, unsaturated. The performance of the subgrade, both in the short- and long-term, is dependent on environmental factors, in particular, an increase in subgrade moisture content due to high rainfall can result in subgrade distress or shear failure under cyclic loading (i.e. train passage). Furthermore, due to varying climatic conditions, subgrade soil may fluctuate between a saturated and unsaturated condition. It is necessary, therefore, to understand such soil behaviour to ensure a safe and economical design and in the planning of maintenance work. Previous research has focused on the effect of water on the superstructure, but not the substructure. This paper outlines a full-scale testing programme to study track performance after flooding and, subsequently, during a 2, 4 and 6 week recovery (drying) period. The study investigated the influence of soil suction on subgrade behaviour with measurements made using the filter paper technique, whilst subgrade modulus was measured using the plate load test. The results show that subgrade behaviour is influenced by changes in water content associated with soil suction; particularly, when wetted from a dry state. It is also found that tamping is less effective in the presence of wet/low-stiffness subgrade soil.

Keywords: Ballast, Subgrade, full-scale testing, railway track settlement, soil suction, flooding, railway geotechnics
1 INTRODUCTION

Flooding causes significant problems in railway infrastructure and a challenge for the engineers to keep railway track functional. Post-flood track performance presents many engineering challenges and is complicated due to changes in soil behaviour under cyclic loading. It is well documented that excess water in railway infrastructure induces significant degradation in load carrying capacity. Typically, trains start running immediately after water has drained from the track and Selig and Cantrell (2001) indicated that the track is still considered to be operational if the water is at the base of the surface level. However, if the water-level rises to the base of the sleeper then operations are likely to be halted.

Compacted subgrade soil is usually in an unsaturated condition and it is important that it remains in this state if it is to provide optimum service (Mancuso et al., 2002, Yang et al., 2008 and Siekmeier, 2011). It is necessary, therefore, to understand unsaturated soil behaviour to ensure a safe, low-maintenance and economical design. Changes in the environmental conditions, compacted subgrade undergo different wetting and drying cycles and thus different suction histories. Therefore, soil behaviour changes due to the hysteresis effect associated with changes in soil suction (Dawson and Correia, 1996, Frost et al., 2004 and Ng and Xu, 2012). Generally, unsaturated soil can either be natural-unsaturated or compacted whereas in conventional geotechnics, soil is often considered as being either completely dry or fully saturated (Dawson and Correia, 1996 and Uchaipichat, 2010a). The behaviour of unsaturated soil is determined by the presence of air and water in the pore space, which influences the stress state via air and water pressure (Mancuso et al., 2002). Unsaturated soil analysis has been avoided due to its complicated nature (Fredlund et al., 1996 and Atkinson, 2007). Compacted soils are initially in an unsaturated state however, over time, they may fluctuate between a saturated and unsaturated
condition. In order to characterise the hydraulic and mechanical response of soil, consideration must be given to soil suction conditions viz. the saturated and unsaturated states (Vinale et al., 1999). Moisture content is an important factor which governs subgrade behaviour and a change in soil moisture content will influence a number of soil properties such as degree of saturation, void ratio, suction, permeability, dry density and shear strength. However, moisture content alone cannot explain the behaviour of unsaturated/saturated subgrade soil.

2 MATERIALS AND EXPERIMENTAL TECHNIQUES

2.1 Materials

To analyse railway track behaviour during flooding and recovery, full-scale experiments were used. The experimental track set-up consisted of a bed of 700 mm kaolin clay subgrade layer, a 100mm kaolin clay formation layer and a 300 mm ballast layer which included three half hardwood sleepers overlain by an I-section steel beam rail. The ballast layer was placed according to Network Rail line specification (RT/CE/S/006, 2000). The grading of ballast is presented in Figure 1. The track and compacted soil was inherited from a previous experiment (more than a year ago). The purpose of keeping the subgrade soil was to investigate the track performance on an operational track. If the subgrade was replaced, then it would have been considered as a new track which cannot simulate the operational track. Also, a newly constructed track experienced significant track settlement from the subgrade, as the newly constructed track never have experienced traffic load. To investigate the soil properties, subgrade samples were collected at predetermined depths and locations under the three sleepers; the properties investigated were moisture content, void ratio and soil suction (both matric and total suction). Table 1 presents the kaolin clay properties. Some formation layer of subgrade was replaced due to levelling the subgrade and checking the soil properties.
2.2 The GRAFT Facility

To understand track behaviour after a flooding event, the Geopavement and Railway Accelerated Fatigue Testing (GRAFT-I) facility at Heriot Watt University was used for this investigation which allowed testing at full-scale. A longitudinal cross section of the GRAFT-I facility is presented in Figure 2. The track was constructed with three half sleepers and an I-section steel beam which has similar stiffness properties to a BS 113A rail section (Kennedy, 2010). One actuator was used to simultaneously excite the 3 sleeper track model, using a force, P, of 90 kN. The applied load, P (kN), was calculated from, (Li et al., 2007 and Kennedy, 2010),

\[ P = W \times S_{lf} \times L_{sf} \times D_{lf} \]  

(1)

where, W is the wheel load (=250 kN); S_{lf} is the sleeper load factor (=0.85); L_{sf} is the load area stress factor (=0.35), and D_{lf} is the dynamic load factor (=1.2). The axle load was 25 tonnes, this being the maximum load permitted on UK track. Figure 3 shows the track testing arrangement under the cyclic loading actuator.

A plate load test (PLT) was conducted to evaluate the subgrade stiffness, which was undertaken in accordance with BS EN 1997-2:2007. A series of stacked circular plates was placed in the middle of the tank and the corresponding vertical deflection of the bottom plate was measured. The diameter of the steel circular plate on the subgrade surface was 440 mm, it was overlaid by a 400mm diameter load cell and three, 300 mm diameter steel plates (Figure 4). Two linear variable displacement transducers (LVDT’s) were placed on the bottom plate to measure deflection. The stressed zone of influence of the PLT is considered to be approximately two times
the diameter of the plate (Ping et al., 2002); therefore the zone of influence of the test covered the full depth of subgrade in the GRAFT.

At the start of the test, five monotonic load cycles were applied at a rate of 1 kN/s which was followed by 50 cycles applied at a rate of 0.1 Hz to obtain the load-deflection curve. The data were recorded at a frequency of 30 Hz and the applied load for the test was 15 kN. This value was calculated to avoid any substantial plastic settlement of the subgrade surface as well as maintaining a stress level of approximately 100 kPa below the plate.

The subgrade modulus, \( E_{PLT} \), was calculated from equation (2) (Alshibli et al., 2005 and Kennedy, 2010) and was used to evaluate both the initial tangent modulus and reloading tangent modulus from the reloading curve. In both cases, the second cycle was used to avoid any problems associated with initial set-up effects.

\[
E_{PLT} = \frac{2P (1-\nu^2)}{\pi r \delta}
\]  

(2)

Where, \( E_{PLT} \) is the elastic modulus (MPa), \( P \) is applied load (kN), \( r \) is plate radius (mm), \( \nu \) is Poisson’s ratio and \( \delta \) is deflection of plate (mm). Poisson’s ratio was assumed to be 0.30 and 0.49 for unsaturated and saturated clay subgrade respectively (Bowles, 1997).

2.3 Soil Suction Measurements – The Filter Paper Method

This method is a simple and sufficiently accurate method to measure suction (Chandler et al., 1992, Ridley and Burland, 1993, Houston et al., 1994, Leong et al., 2002, Bulut et al., 2001,
Marinho and Oliveira, 2005 and Rahardjo and Leong, 2006). The method involves placing a piece of filter paper between two larger size protective filter papers alongside a soil sample and with one other filter paper on top of the sample. If the filter paper is contact in the middle of the two soil specimens, then it gives the matric suction through menisci of water formations. In order to measure the total suction, a piece of filter paper was placed on top of the sample without direct contact. The soil specimen is placed in an airtight container at a constant temperature (25°C±1°C) to achieve moisture equilibrium condition between the filter paper and soil specimen. Generally, the filter paper comes into equilibrium with the soil either through vapour (total suction) or fluid flow (matric suction); at the state of equilibrium state the soil and the filter paper suction value is the same. The filter paper (Whatman’s No. 42) water content was calculated using the calibration curve presented by Haghighi et al. (2012):

\[
\ln \psi = \frac{(a + bW_f + cT + dW_fT)}{(1 + fW_f + gT + hW_fT)}
\]  

(3)

Where, \( \psi \) is soil suction (in kPa), \( W_f \) is the filter paper water content (%), \( T \) is temperature in Kelvin (K), and \( a = 10.86 \), \( b = -6.376 \times 10^{-2} \), \( c = -4.056 \times 10^{-2} \), \( d = 2.186 \times 10^{-4} \), \( f = 1.908 \times 10^{-2} \), \( g = -3.648 \times 10^{-3} \), \( h = -7.650 \times 10^{-5} \) are constant parameters.

2.4 Testing Regime
To understand the influence of flooding on track performance, the experimental programme was divided into three phases as presented in Table 2:

- Phase-I: initial pre-flooding phase (unsaturated state),
• Phase-II: after flooding (track placed under load immediately after drained water)
• Phase-III: Recovery period (after 2, 4, and 6 weeks). Figure 5 presents a time plan for the experiments.

3 RESULTS AND DISCUSSION

3.1 Track settlement behaviour during Phase –I (unsaturated conditions)
Initially the subgrade soil was in an unsaturated state. The moisture content and void ratio at the surface layer (100 mm) were approximately 10% and 0.91 respectively, and the degree of saturation was 30%. The matric and total suction were evaluated as 1300 kPa and 2000 kPa respectively. At other depths and locations in the GRAFT, soil suction (matric and total) was found to be less than at the surface layer. At depths between 100-500 mm, the average moisture content was 15% and the average degree of saturation was approximately 50%. The matric and total suction were, approximately, 700 kPa and 1500 kPa respectively and the subgrade tangent and reloading modulus were, respectively, 109 MPa and 122 MPa. Figure 6 shows the variation of moisture content, the degree of saturation, matric and total suction at the different depths under the middle sleeper.

The purpose of the first test was to investigate the track performance in the dry condition, including the influence of tamping maintenance. In this research, the ballast layer was tamped under the sleepers using the Kango hammer to bring back up to level. The track settlement behaviour before and after tamping is presented in Figures 7 and it is evident that this follows the same trend as that of previous research (Aursudkij, 2007, Ionescu, 2004, Kennedy, 2010 and Ghataora et al., 2004). At the start of the test (Figure 7), the initial rapid track settlement (first stage settlement) was approximately 5 mm due to initial ballast densification, which was
followed by a second stage linear settlement with number of cycles (Dahlberg, 2001). After
densification of ballast, the track settlement increased linearly, to approximately 7 mm (black
colour) at the end of $2\times 10^5$ cycles.

The subgrade is shown to be very stiff resulting from a high soil suction (1300 kPa). Increasing
soil suction with increasing stiffness of unsaturated compacted soil occurs as the matric suction
generates an additional effective confining pressure within the soil structure (Mendoza and
Colmenares, 2006). The capillary menisci between the particles create additional inter particle
forces which cause the increase of modulus of contacts (Gupta et al, 2007). This implies that the
modulus of unsaturated soil particulate media depends on matric suction and that the matric
suction increases due to an increase of surface tension forces between the particles. Water
remaining within the voids of unsaturated soils causes a very high negative pressure which
creates tensile forces which increase the effective stress thereby bringing the soil particles
together (Lu and Likos, 2004). At higher suction, it has been observed that the sensitivity of
stiffness to deviatoric stress increases (Dawson and Correia, 1996) and that a higher-quality track
performance results.

The ballast was subsequently tamped under the sleepers after $2\times 10^5$ cycles to restore the track to
the level prior to tamping. After tamping, a further $3\times 10^5$ cycles were applied at 90 kN at a
frequency of 3 Hz. At this stage, the track settlement was 18 % (Figure 7-blue curve) higher than
the pre-tamping stage. Aursudkij (2007) and Selig and Waters (1994) also noted that the tamping
induced a faster rate of initial track settlement. After completion, the track settlement was
approximately 9 mm (blue curve). However, the settlement rate of the track was low (0.10
mm/1000 cycles) due to the stiff support from the subgrade.
3.2 Track settlement behaviour during Phase-II (saturated conditions)

In order to investigate post-flooding behaviour, the track was flooded to the upper ballast level, and held in a saturated state for a week. Flooding was performed using a low pressure hose to prevent subgrade erosion.

The following sections discuss the track behaviour immediately after water drainage and the subsequent drying period. In this phase, the primary challenge was the collection of samples without disturbing the track. After removing the rail, the ballast was carefully removed from under the middle sleeper and a 100 mm (diameter) × of 200 mm (length) pipe was placed into the ballast to prevent side-wall collapse. A 100 mm (long) × 20 mm (diameter) pipe was then inserted into the subgrade to collect the soil samples.

The moisture content of subgrade surface layer was approximately 43 % and the degree of saturation was 100 % as shown in Figure 8 (a) and (b). The soil suction (matric and total) was found to be zero up to a depth of 200 mm (i.e. soil fully saturated). The soil sample was collected over the 500 mm length under the middle sleeper. The moisture content at this location ranged between 26-33 % and the degree of 88-100 %. The matric suction was measured between 10-450 kPa (Figure 8c) and the total suction 150-550 kPa (Figure 8d).

3.2.1 Track performance after flooding

After the flooding, water was allowed to drain from the tank after which the track was placed under the loading actuator. In reality, trains run on track immediately after water drainage or even run with water inside the track. Figure 9 presents the settlement behaviour before and after flooding of the track at the middle sleeper location after $10^5$ cycles. The track settlement
increased by a factor of 9 (Figure 9). The settlement behaviour can be divided into two stages: the first stage of track settlement was approximately 22 mm after $10^4$ cycles; the second stage settlement was approximately 60 mm after $10^5$ cycles. The surface moisture content was in excess of 40% and the void ratio reduced to 0.80 (from 0.91). The track surface layer (100 mm) became fully saturated with the result that there was no soil suction at that level and track settlement was significantly high. Brown (1996) reported that dry soil, which is placed well above the water table, the suction would be high, thus the effective stress will be increased; whereas under wet conditions, the suction will be reduced which will reduce the effective stress.

The two main functions of the subgrade soil are, (i) to bear the traffic load without damage, and, (ii) to drain the water to the sides of the track. If the bearing capacity is low, then the drainage could fail due to the development of water pockets. Consequently, the soil becomes weak due to the presence of water and the necessary stability may not be maintained which can lead to subgrade failure (Wenty, 2005).

Li and Chrismer (2009) reported that flooding track performance was reduced and the subgrade deformed rapidly due to an increase in subgrade stress. Sudden settlements after flooding have also been observed Ionescu (2004) with a 40% increase over that of the total settlement in the dry condition. Rapid track settlement due to soft track bed occurred as a result of ballast penetration into the soft subgrade soil. Excessive settlement could then create pockets in the subgrade which can collect water, causing further weakening of the subgrade as a result of ballast punching into the underlying soil (Burrow et al., 2007). Water entering from the ballast layer also forms water pockets thereby inducing subgrade soil failure (Li and Selig 1998). Progressive shear failure then develops at the surface layer due to repeated loading.
3.2.2 Track behaviour after tamping (after flooding)

Maintenance was undertaken after $10^5$ cycles. This entailed removal of the I-section beam in order to tamp the ballast. After tamping, a further 50,000 cycles were applied at 2 Hz with resultant rapid settlement (2 mm/1000 cycles). Figure 10a shows the track performance in the wet condition after tamping maintenance. However, it is evident that tamping did not improve the track performance as each time both the primary and secondary settlements were higher resulting from the soft track bed which was unable to give support to the track.

The track settlement, shown in Figure 10b, was approximately 30mm after the second tamp when only $3 \times 10^4$ cycles of loading had been applied. The first and second phase settlement occurred rapidly, this can be explained by penetration of the ballast into the soft soil. The test was stopped to bring the track back up to level and thereafter another $3 \times 10^4$ cycles were applied, resulting in a settlement of approximately 40 mm (Figure 10c). A fourth tamp was undertaken where settlement was greater than 30 mm after $2 \times 10^4$ cycles were applied (Figure 10d).

An important aspect of this work shows that in poor subgrade soil, tamping does not improve the subgrade to any great extent and can even damage the ballast properties. At the end of the test, small particles were observed during the ballast removal. Wenty (2005) reported that, after frequent tamping and very quick return of ballast fouling after track undercutting and ballast cleaning indicated subgrade failure. Another disadvantage of tamping is that it loosens the ballast and fractures the particles (Selig and Waters, 1994 and Esveld, 2001). The ballast is highly dependent on the performance of the subgrade and it has been shown that ballast tamping does not correct poor subgrade; indeed, tamping could damage the ballast and may not be economical (Selig and Li, 1994 and Selig and Cantrell, 2001). Selig and Water (1994) reported that the
ballast causes both average and differential settlement between surfacing operations (known as short-term settlement), whereas long-term settlement is related to the subgrade soil. Thus, after flooding, tamping was unable to restore the track to pre-flooding performance due to the presence of the poor subgrade.

The subgrade was allowed to dry to investigate how long it would require to regain strength without further maintenance.

3.3 Track performance during the recovery (drying) period during Phase-III

Two days after the ends of the 4th tamp, soil samples were collected - no load applied to the track at this stage. The samples were obtained over the 500 mm depth under the middle sleeper to obtain moisture-content, soil suction and void ratio. The surface layer moisture-content had decreased to approximately 36 % (Figure 11a-yellow) and the void ratio was 0.80. The surface layer (100 mm) was fully saturated (Figure 11b-yellow) therefore no soil suction was measured (Figure 11c, d). However, at other locations, the moisture content increased and soil suction decreased due to downward percolation of water (equilibrium soil water content).

Water movement through the soil is complicated, particularly, under cyclic loading. In transportation systems, cyclic loading causes differential settlement which causes safety problems and also increases maintenance costs. A small change in water content or degree of saturation will have a significant impact on the stress-strain behaviour of soil under cyclic loading (Miller et al., 2000).
The subgrade properties were measured again one week after the end of the 4th tamp. The moisture content of surface layer remained high at approximately 35.17 % (Figure 11a-purple) and the degree of saturation was 100 % (Figure 11b-purple). The soil suction profile decreased in the subgrade as the entire subgrade reached a state of equilibrium. This is shown (along with data after 2 days) in Figures 11 (c-purple) and (d-purple). The surface layer remained saturated; at this point, no load was applied on the track and it was allowed to dry for a further two weeks.

**3.3.1 Track settlement after two weeks**

The moisture content in the surface layer was approximately 34.63 % (Figure 11a-green) and the degree of saturation was 100 % (Figure 11b-green). At other depths, the moisture content and the degree of saturation did not change significantly. The matric suction (Figure 11c-green) at 500 mm decreased by approximately 40 %. However, in the surface region the matric suction had increased in comparison with the values obtained at one week. At the depth of 100 mm the suction was 1.74 kPa, indicating the presence of air within the soil.

The track performance after two weeks (black colour) is presented in Figure 12. An important outcome of this work is that after two weeks of drying, the track did not show any improvement. The track settlement was approximately 20 % higher than when the test was run immediately after flooding (grey colour in Figure 12). Thus, the track could be regarded as unsafe to be returned to operation even after two weeks drying/draining. Subsequently, after $2 \times 10^4$ cycles applied at 2 Hz, the settlement was approximately 38 mm. Some water was observed to weep out from two bottoms drainage holes during loading and, to avoid further damage to the track, the test was not undertaken. This outcome can be explained by the water movement into the subgrade.
and the presence of water at the bottom section in the subgrade hence the subgrade soil behaviour is dominated by the bulk water.

### 3.3.2 Track settlement after four weeks

The track was allowed to dry for a further two weeks and then investigated for improvement. The surface moisture content of the subgrade soil was approximately 28 % (Figure 11a-light blue) and the degree of saturation was approximately 91 % (Figure 11b-light blue). The moisture content of the bottom section (500 mm) of the subgrade (approximately 30 %) decreased by 18 % in comparison with the data at two weeks. In the surface layer of subgrade, matric and total suction was approximately 100 kPa and 250 kPa respectively. In the lower section (500mm) of the subgrade matric suction decreased by approximately 38 % (Figure 11c-light blue) and the total suction also decreased by approximately 40 % (Figure 11d-light blue). The moisture content decreased and the soil suction increased at the upper section and the moisture increased and the soil suction decreased at the bottom section.

The first stage settlement was approximately 15 mm (at 1600 cycles) and at the end of test the settlement was approximately 35 mm after only $2 \times 10^4$ cycles. This is shown in Figure 12 (blue colour). The settlement decreased by almost 30 % and 9 % in comparison with the test immediately after flooding and the previous stage (after two weeks) respectively.

### 3.3.3 Track settlement after six weeks recovery

The track was placed under loading after six weeks and it was observed that the track performance did not improve significantly. The entire subgrade moisture content and the degree of saturation varied between 25-30 % (Figure 11a-blue) and 82-99 % (Figure 11b-blue)
respectively. The matric suction varied between 100-250 kPa (Figure 11c-blue) and the total
suction 400-460 kPa (Figure 11d-blue). The soil suction (matric and total) of subgrade in the
lower section (500 mm) decreased and moisture content increased in comparison with those
obtained at four weeks. The soil suction reached an equilibrium state as shown in Figure 11 (c)-
blue and (d)-blue.

The settlement was found to be 30 mm after \(2 \times 10^4\) cycles (pink colour in Figure 12). Compared
with the test immediately after flooding, after two and four weeks, the settlement decreased by
approximately 18 %, 26 % and 8 %, respectively, during the drying periods. The track
performance could still be regarded as poor, as the subgrade soil was unable to give sufficient
support; furthermore, because the subgrade was covered in ballast, it was drying relatively
slowly.

During Phase-III, the track performance had improved at the end of six weeks but during the first
two weeks, the worst track performance occurred due to water movement. A further problem
observed was due to tilting of the track on the drainage side where some water was found after
removing the ballast as shown in Figure 13; additionally, the track bed was softer compared to
that on the non-drainage side.

3.4 Subgrade Performance after flooding
It was observed that significant softening occurred due to flooding; both the subgrade modulus
and reloading modulus decreased with soil suction (surface layer matric suction =150 kPa) to 30
MPa (from 109 MPa) and 35 MPa (from 122 MPa), respectively. At the end of the test, on
removal of ballast from the GRAFT, visual inspection found extensive ballast penetration into the
formation layer as presented in Figure 14. The combination of water and cyclic loading served to produce a slurry which resulted in mud pumping. Mud pumping is formed in two ways: (i) erosion pumping failure where ballast particles penetrate into the subgrade thereby forcing soil particles upwards, and (ii) dirty ballast pumping failure which occurs due to wind-blown deposits, brake dust and dirt dropping from the train (Ayres, 1986) (Note: the second cause is not related to this current work). Slurry can substantially reduce the ballast modulus of elasticity (Sharpe and Caddick, 2006) and is one of the main reasons of poor track performance after a flooding event.

Figure 15 shows the subgrade soil after removing all the ballast at the end of the test. Removing the ballast from the formation layer was difficult because the ballast was held by the soil very firmly. It was noticed that some of the ballast was coated in mud (Figure 16) and therefore required replacement. Crushed ballast particles were also noticed during ballast removal, attributed to frequent tamping during the wet phase. The surface was uneven after the ballast was removed and considerable softness of the subgrade was found near the drainage side.

4 Concluding Remarks

The test results showed that soil suction plays an important role in track performance (in terms of track settlement) before and after flooding, and during the recovery period. Therefore, even after the water has dissipated, it is important to assess subgrade soil properties such as moisture content, suction and the degree of saturation. In the event of flooding, the upper section (i.e. 100 mm) of the subgrade is most affected and sensitive to changes of water content and soil suction. However, if the water remains in the track for a long period the entire subgrade can be affected. From the full-scale testing programme the following can be drawn:
1. For the periods of scheduled maintenance work, significant attention is given to improving ballast performance. However, the current work involving large-scale investigations showed that subgrade properties should also be checked, especially after extreme events such as rainfall which is sufficiently heavy to cause flooding. The results showed that if tamping of the track does not work satisfactorily, then it may be due to the influence of the subgrade. Under these conditions, tamping cannot return the track up to the required level due to permanent settlement and may just result in further damage to the ballast particles.

2. During the initial recovery period over the first two weeks, the track showed little improvement. The subgrade soil properties indicated that the subgrade soil had reached an equilibrium condition and track settlement increased significantly. Four and six weeks later the track settlement decreased, but not significantly.

3. Track performance varied with changes in soil suction - higher suction values indicated a stiffer track, whereas lower suction indicates poor performance. The settlement of the track was much higher under wet conditions due to the loss of soil suction. The results also confirmed that the subgrade properties did not change significantly, because it was shielded by the ballast, and the subgrade soil dried out quickly after the removal of the ballast.

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Figure 8 Variations of (a) moisture content, (b) degree of saturation, (c) matric suction and (d) total suction after flooding at different depth under the middle sleeper
Figure 9 Middle sleeper settlement behaviour after flooded track
Figure 10 Middle sleeper settlements after (a) 1\textsuperscript{st} tamping, (b) 2\textsuperscript{nd} tamping (c) 3\textsuperscript{rd} tamping and (d) 4\textsuperscript{th} tamping
Figure 11 Variations of (a) moisture content, (b) degree of saturation, (c) matric suction and (d) total suction at different durations at different depth under the middle sleeper.
Figure 12: Middle sleeper settlements after two weeks, four weeks and six weeks.
Figure 13 Track tilted during loading towards drainage side
Figure 14 Ballast penetrations after flooding at surface layer
Figure 15 Track bed after removing the ballast
Figure 16 Foul ballast after flooding
Table 1. Kaolin clay (subgrade) properties

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>2.64</td>
</tr>
<tr>
<td>Maximum dry density (Mg/m$^3$)</td>
<td>1.54</td>
</tr>
<tr>
<td>Optimum moisture content (%)</td>
<td>23.8</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>55.0</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>32.0</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Table 2. Summary of track behaviour before flooding, after flooding and during the recovery period (Note: applied load was 90kN)

<table>
<thead>
<tr>
<th>Experimental phase</th>
<th>Applied cycles ($\times 10^3$)</th>
<th>Surface layer Matric suction (kPa)</th>
<th>Surface layer moisture content (%)</th>
<th>Maximum Settlement (mm)</th>
<th>Loading frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-I: Before flooding</td>
<td>100</td>
<td>1300.00</td>
<td>10.0</td>
<td>7.62</td>
<td>3</td>
</tr>
<tr>
<td>Phase-II: After flooding</td>
<td>100</td>
<td>---</td>
<td>43.3</td>
<td>65.04</td>
<td>2 and 1</td>
</tr>
<tr>
<td>Phase-III: Recovery period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After 2 weeks</td>
<td>20</td>
<td>1.75</td>
<td>35.0</td>
<td>38.04</td>
<td>2</td>
</tr>
<tr>
<td>After 4 weeks</td>
<td>20</td>
<td>110.73</td>
<td>27.7</td>
<td>35.75</td>
<td>2</td>
</tr>
<tr>
<td>After 6 weeks</td>
<td>20</td>
<td>128.72</td>
<td>27.6</td>
<td>30.00</td>
<td>2</td>
</tr>
</tbody>
</table>