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Effect of drainage components on the stiffness of ballast under cyclic loading

Effet d'un élément de drainage sur la rigidité des ballasts sous chargement cyclique

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ABSTRACT: The need for resilient railway tracks to avoid closure of lines and maintenance is vital. Conventional solutions for railway drainage systems such as sand blankets and geosynthetics require maintenance and, depending on condition and severity of rainfall, may not be able to dissipate excess water quickly enough. Alternative options for railway drainage are being studied at the University of Nottingham in terms of hydraulic response and mechanical behaviour. The candidate drainage options should satisfy hydraulic as well as mechanical (i.e. strength and stiffness) requirements. This paper focuses on the latter and presents data from a series of cyclic loading tests carried out to investigate the effect of drainage units on the stiffness of a ballast layer. Two drainage units have been tested: a geocellular module known as "Permavoid" and a perforated pipe surrounded by expanded polystyrene (EPS) known as "Polybed". Cyclic loading amplitudes up to 45 kN were applied at a frequency of 2 Hz using a Composite Element Test (CET) apparatus, which replicates a portion of a full-scale track/ballast system. Results are provided to illustrate the effect of the drainage units and ballast thickness above the units on the overall track stiffness.

RÉSUMÉ: Le besoin de voies ferrées résilientes pour éviter la fermeture des lignes et la maintenance est vital. Les solutions classiques pour les systèmes de drainage des chemins de fer, telles que les nappes de sable et les géosynthétiques, nécessitaient un entretien et, en fonction de l'état et de l'importance des précipitations, pourraient ne pas être en mesure de dissiper rapidement l'excès d'eau. L'Université de Nottingham étudie actuellement d'autres possibilités de drainage des voies ferrées en ce qui concerne la réponse hydraulique et le comportement mécanique. Les options de drainage candidates doivent satisfaire aux exigences tant hydrauliques que mécaniques (résistance et rigidité). Cet article se concentre sur ce dernier point et présente les données d'une série d'essais de chargement cyclique réalisés pour étudier l'effet des unités de drainage sur la rigidité du ballast. Deux unités de drainage ont été testées: un module géocellulaire appelé «Permavoid» et un tuyau perforé entouré de polystyrène expansé (EPS) connu sous le nom de «Polybed». Des amplitudes de chargement cycliques allant jusqu'à 45 kN ont été appliquées à une fréquence de 2 Hz à l'aide d'un appareil de test d'éléments composites (CET), qui reproduit une partie d'un système de voie / ballast à grande échelle. Les résultats sont fournis pour illustrer l'effet des unités de drainage et de l'épaisseur du ballast au-dessus des unités sur la rigidité globale de la voie.

Keywords:railway drainage system; ballast stiffness; cyclic test;

1 INTRODUCTION

The drainage system plays an important role in the long term performance and overall safety of rail tracks. Forecasted increased occurrence of extreme weather and flash flood events could result in the accumulation of additional water in tracks, causing wet beds and the reduction in bearing capacity and stiffness of subgrade materials (Hudson *et al.*, 2016; Selig and Waters, 1994). The implementation of resilient railway drainage systems is vital in order to address these issues. The University of Nottingham Centre for Geomechanics is investigating the potential use of new drainage components within a railtrack as part of an EPSRC (The Engineering and Physical Sciences Research Council)/RSSB (The Rail Safety and Standards Board)/DfT (The Department for Transport) funded research project. It is well known that the long-term performance of track is directly influenced by track stiffness (Stewart & Selig, 1982; Wang *et al.*, 2016). Alterations to the track substructure, including ballast thickness, inclusion of drainage units within track foundation, subgrade condition, or type of sleeper/fastening could change track stiffness (Heelis *et al.*, 1999; Le Pen *et al.*, 2014; Li and Selig, 1998; Murray *et al.*, 2014; Safari Baghsorkhi *et al.*, 2015). Candidate drainage solutions must therefore benefit the hydraulic performance of the track, but also ensure that the mechanical response (i.e. ballast stiffness) is satisfactory. This paper focuses on the latter requirement related to track stiffness when new drainage unites are included in the under-track area.

In the paper, two candidate drainage units are considered and results from cyclic loading tests using a physical model of a ballasted track at a frequency of 2 Hz are presented to illustrate the effect of including the units. The physical model represents a unit cell under the rail which can accommodate ballast and a portion of a sleeper. The model considered the worst-case scenario where drainage units are located directly underneath the sleeper where the highest stresses are transmitted to the ballast. The two candidate drainage units were "off the shelf" drainage systems available on the market: a geocellular module known as "Permavoid" (supplied by Wrekin Products) and a perforated pipe surrounded by expanded polystyrene (EPS) known as "Polybed" (supplied by The Forest Group) as shown in Figure 1(c). In addition, ballast thickness was varied to evaluate its effect on the overall stiffness. Due to limitations of the experimental setup, the results presented mainly provide a relative assessment of the stiffness performance of the tested scenarios. Further testing is required to obtain a better absolute assessment of track stiffness when including the drainage units.

2 EXPERIMENTAL SET UP

Cyclic loading tests were carried out using a composite element test (CET) apparatus (Figure 1), which was previously developed at the Nottingham Centre for Geomechanics (Kwan, 2006). For the tests presented here, the CET was configured to measure 1500 mm in length, 600 mm in height, and 675 mm in width, replicating a unit cell between the centres of two sleepers. The container is made of plywood with additional supports on the external sides, as shown in Figure 1(a). The inner sides of the container were covered with steel sheet to reduce frictional effects. A wooden sleeper measuring 700 × 285 × 170 mm was used to transmit load from a hydraulic jack to the ballast. A hydraulic jack capable of applying cyclic loading up to 100kN at a maximum frequency of 3 Hz was attached to the reaction frame of the CET.

Four linear variable differential transformers (LVDTs) were placed at the corners of the sleeper for displacement measurement, as demonstrated in Figure 1(c). The average value from the four LDVTs was used for stiffness calculations.

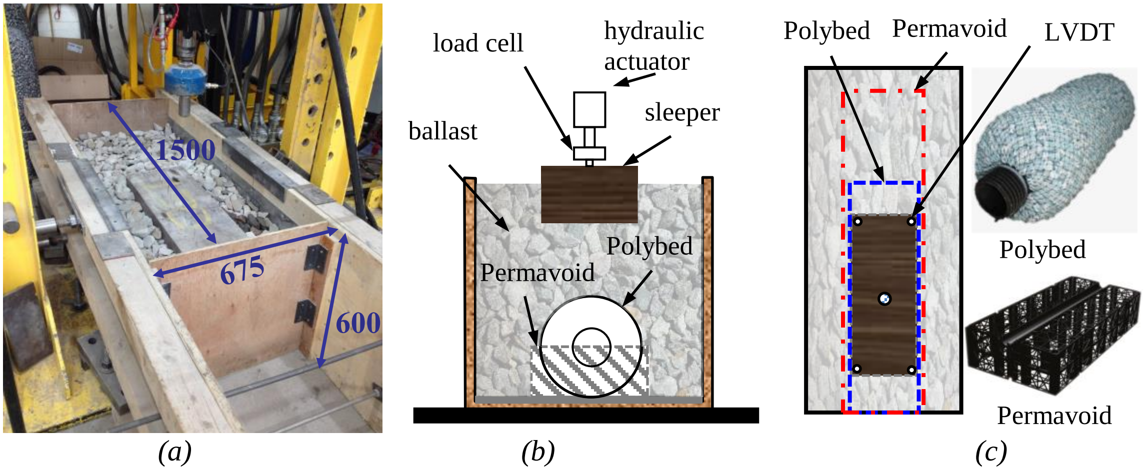

Figure 1. (a) CET equipment; all units in mm, (b) section view of the experiment (two drainage units shown, however only one drainage unit was included in a single test), and (c) plan view and images of the drainage units.

The location of the drainage units within the model is shown in Figure 1(b) and (c) (note that Figure 1(b) shows both drainage units, however only one unit was placed in the model in any given test). The exterior diameter of the Polybed is 300 mm with a unit length of 1 m, whereas Permavoid is 350 × 150 × 700 mm. One unit of Polybed was used in the tests, whereas two units of Permavoid were placed in the container, as illustrated in Figure 1(c).

Data collected from the CET experiments can be used to calculate track stiffness considering the effect of upper layers and components (i.e. ballast, drainage unit, and sleeper). As with any physical model, there are limitations to the applicability of the CET test results, due in large part to issues relating to boundary conditions. The relationship between absolute values obtained from the CET tests and reality is therefore uncertain, hence the outcome of the tests presented here are considered preliminary in nature. However, in relative terms (i.e. what proportional change in stiffness occurs as a result of a change in track configuration), the CET results presented here provide valuable insights into the relative performance of the different systems under consideration.

2.1 Model preparation

In this investigation, six models were prepared to test the drainage units and the effect of ballast thickness above the units (see Table 1). Note that the overall ballast thickness was kept constant at 600 mm for all tests to eliminate its effect on results – this resulted in different levels of embedment of the sleeper into the ballast. For the Polybed tests, the thickness of the ballast layer from the top of the drainage unit to the bottom of the sleeper was 150 mm and 250 mm (tests 2a and 2b), whereas this distance was 300 mm and 400 mm for the Permavoid tests (tests 3a and 3b). The drainage unit was placed at the bottom of the container and then ballast was compacted in 100 mm thick layers using an electric vibratory compactor until reaching the desired level for the sleeper. The sleeper was then installed and more ballast was placed around the sleeper. Once the model was prepared, four LVDTs were attached to the corners of the sleeper. Finally, a solid steel plate was placed at the centre of the sleeper to transmit the load from the actuator. A summary of the test programme and stiffness results (at steady-state part of test) is presented in Table 1.

Table 1. Summary of test programme and stiffness results

Test	**Type of drainage unit**	**Distance from base of container to underside of sleeper (mm)**	**Steady state stiffness (kN/mm)**
1a	-	450	33.7
1b	-	550	32.3
2a	Polybed	450	31.2
2b	Polybed	550	30.0
3a	Permavoid	450	27.5
3b	Permavoid	550	30.0

2.2 Loading condition

A load-controlled system was used to apply the cyclic loading to the sleeper, with maximum and minimum amplitudes of 45 and 3 kN, respectively. The cyclic loading was applied by a servo-hydraulic actuator at a frequency of 2 Hz for up to 40,000 cycles (some tests were terminated at a lower number of load cycles once no further changes in displacement over a load cycle was observed). As described earlier, the plan area of the sleeper is 700 × 290 mm, thus the stress under the sleeper varied between 15 and 230 kPa. These stresses are equivalent to stresses applied by a 25 ton axle load.

3 RESULTS AND DISCUSSION

An example of results from test 2b with Polybed and 550 mm of ballast (from base of container to underside of sleeper) is presented in Figure 2. The load-settlement result in Figure 2(a) shows that, initially, the rate of increase in settlement within a load cycle is relatively high due to the movement and densification of ballast particles and also the deformation of the Polybed. After a certain number of cycles, the change in settlement during a load cycle becomes negligible (i.e. the stage that the stiffness of the system approaches a constant value).

The overall stiffness of the system considering all elements (i.e. drainage unit, ballast, and sleeper) was calculated using $k = \Delta \mathrm{F}/\Delta S$, where k is stiffness (kN/mm), $\Delta \mathrm{F}$ is change in applied load during one load cycle, and ΔS is change in settlement within a load cycle.

In Figure 2(b), the track stiffness against number of cycles for test 2b is shown. The initial lower stiffness of the system (around 22 kN/mm) is due to the fact that ballast particles could rearrange to reach to a denser condition. The rate of settlement decreases with load cycles and eventually stiffness reaches a constant value of approximately 30 kN/mm at 35,000 load cycles for test 2b.

In order to obtain a better understanding of the effect of the drainage unit on track stiffness, the results of all these tests are compared and presented in Figures 3 and 4. Figure 3 shows the variation of model settlement against number of load cycles for all six tests. For all tests, settlement increased rapidly during the first few hundred cycles, mainly due to particle rearrangement. In the subsequent load cycles, the rate of settlement diminished and, after nearly 25,000 cycles, it reached a constant value.

Figure 3 shows that the settlement of a ballast only layer is the lowest; the ballast particles are clearly stiffer compared to the Polybed and Permavoid units. The initial settlement for the ballast and Polybed (i.e. test 2a) is significant compared to the other tests. The differences in the initial trends of the data is mainly a result of inconsistencies in the initial level of compaction of the ballast. Though not ideal, this inconsistency will have little impact on the steady-state values of stiffness, which are most important in the context of this study. It should be noted that test 3b was performed after completion of test 3a without preparing an entirely new sample (i.e. by adding more ballast on top the model); therefore, the settlement of the model is relatively low.

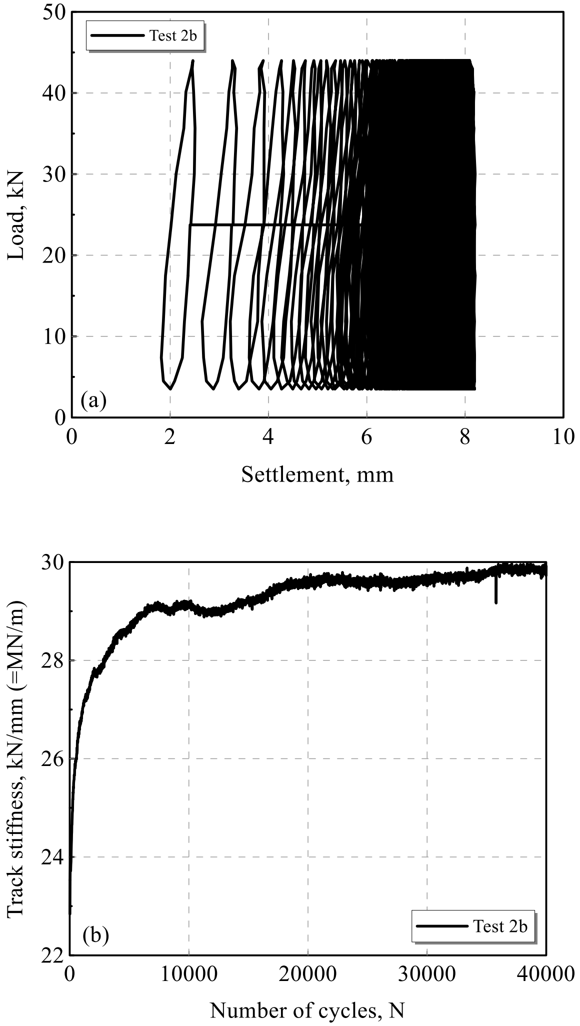

Figure 2. Test 2b results: (a) load-settlement, and (b) stiffness against number of load cycles

Figure 4 shows the evolution of track stiffness against number of load cycles for all tests. A significant change in stiffness is observed during the first 2000 cycles. This is mainly governed by the initial density of the ballast and particle rearrangements. After that, the rate of increase in stiffness reduces. After about 25,000 load cycles, the stiffness of the system approaches a relatively constant steady-state value. Generally, the stiffness for models with less ballast is higher for each set of tests and existence of a drainage unit results in a reduction of stiffness.

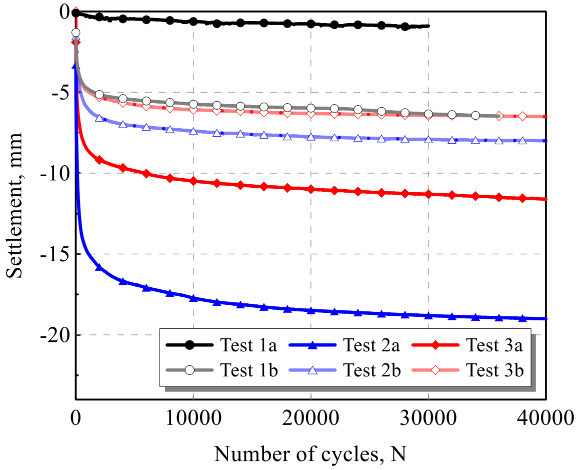

Figure 3. Settlement of sleeper against number of load cycles

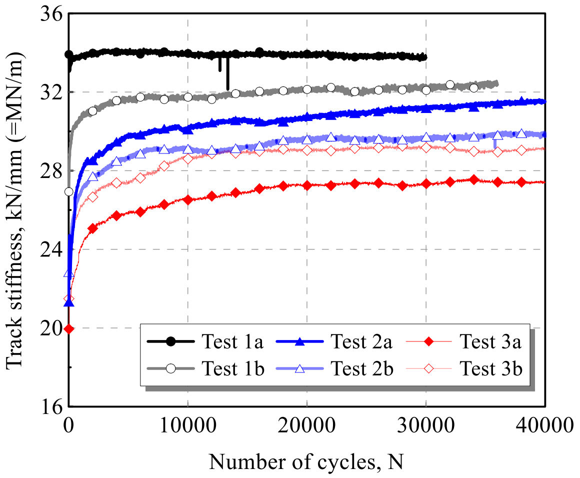

Figure 4. Comparison of track stiffness with number of cycles

A summary of steady-state track stiffness is presented in Figure 5. The effect of including a drainage unit on stiffness is more significant for the model with 450 mm of ballast thickness under the sleeper. For this model, the reduction in stiffness is 7.5% and 18% for Polybed and

Permavoid, respectively. The better stiffness performance of the Polybed compared to the Permavoid is likely an outcome of the circular shape of the drainage unit and the arching effect, allowing more effective transfer of load within the ballast around the sides of the drainage unit. Modifications to the design and/or shape of the Permavoid may enable a better stiffness performance whilst maintaining the same hydraulic characteristics (an area of future study). In addition, it should be noted that the loading on these drainage units was relatively severe, given the magnitude of loads applied and the location of the units directly beneath the sleepers. Future work is needed to obtain better estimates of the absolute values of track stiffness when including these drainage units.

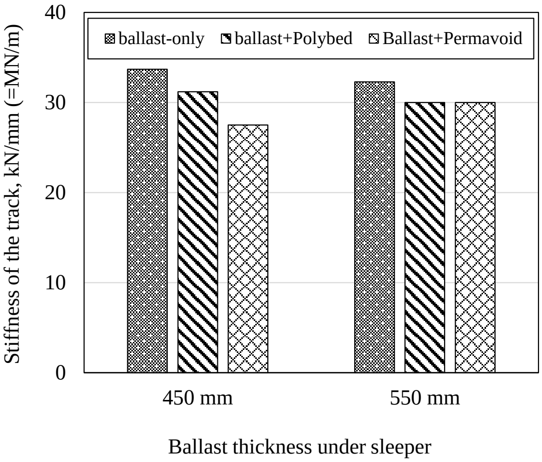

Figure 5. Comparison of steady-state track stiffness

4 CONCLUSIONS

As part of a research project investigating the potential use of new drainage systems within rail tracks, the University of Nottingham conducted a series of cyclic loading tests within a physical model of a track “unit cell” using two candidate drainage units (Polybed and Permavoid) buried within varying depths of ballast. The paper showed how settlement varied with number of loading cycles for the different drainage units and compared results against reference cases with no drainage units. A steady-state load-settlement response was generally obtained after about 25,000 loading cycles, from which the steady-state track stiffness could be calculated. Results indicated that the effect of the drainage units on steady-state track stiffness was more significant when the ballast thickness between the sleeper and the drainage unit was reduced. For a ballast thickness of 450 mm, trackbed stiffness reduced by 7.5% and 18% for the Polybed and Permavoid units, respectively, compared to the reference case with no drainage unit.

The results presented in this paper are considered preliminary in nature due to limitations in the experimental setup for assessing absolute values of track stiffness. The results do, however, give some insight into the relative stiffness performance of the considered drainage units. Modifications to the design of the drainage units could provide significant improvements to their stiffness response, whilst maintaining good hydraulic characteristics. This, and improved assessment of the real track stiffness when including drainage units, are areas where future research is needed.

5 ACKNOWLEDGEMENTS

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