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Centrifuge modelling of train passage over clay subgrades

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ABSTRACT: The modelling of large geotechnical structures on the centrifuge is now well established, but there remain technical challenges with each new application. This work arose from a larger project investigating alternative improved embankment designs. The project required full scale modelling of new embankment designs using the GRAFT II simulator at Heriot Watt University together with consideration of the large scale settlement problem over a wider area. To model foundation soil beneath the embankment required the design of a rail simulator at centrifuge scale, together with appropriate measurement techniques and appropriate modelling of useful foundation soil types. This paper therefore describes the design decisions taken to produce a centrifuge mounted rail simulator including details of modelling a translating cycling load. To measure total stress at the base of the embankment during a train passage was a key challenge faced, overcome by use of thin Singletact stress transducers. These transducers are low deflection capacitance-based force sensors that will be further discussed in the paper. In addition to the translating load and the instrumentation, the third aspect presented will be the formation and characterisation of a soft clay subgrade, required due to the nature of soils that are most of concern to UK rail industry. To accelerate consolidation without compromising the ability to achieve a clay-type mechanical response, a hybrid clay-sand-silt mixture known as KSS 541 is installed in the model container as slurry and consolidated in-flight. Experience with this material is discussed.

Keywords: Railways; Embankments; Centrifuge Modelling; Clays; Stress Measurements.

1 INTRODUCTION

This research was carried out as part of the UK EPSRC funded LOCORPS project (Lowering the Cost Of Railways using Preformed Systems), which aims to investigate and assess more efficient alternative embankment solutions for high speed rail that can be more rapidly constructed compared to conventional designs. The project consists of multiple approaches, including testing of full scale embankment sections using the GRAFT II rail test facility at Heriot-Watt University in Edinburgh, focusing on the behaviour of the embankment itself under train loading, as well as centrifuge modelling of the proposed embankment designs at the University of Dundee investigating the embankment performance on different subsoils and the interaction between them. Modelling the subsoil is difficult to achieve using full-scale testing due to the space and volume required, and is an area where centrifuge modelling is advantageous. The research investigated GRS-RW (Geosynthetic Reinforced Soil Retaining Wall) embankments (2.5 m high at prototype, see Figure 1) of the type widely used in Japan, conventional ballasted embankments (1.2 m high) and a new preformed geogrid embankment system proposed by the project (1.2 m high). Details of the scaling and miniaturisation of these embankments will be discussed in forthcoming papers, but this involved precisely scaling model geogrid, facing walls, fill materials, model railway ballast and model track stiffnesses to ensure the miniature 1/50th scale embankments correctly replicate the behaviour of the full-size problems.

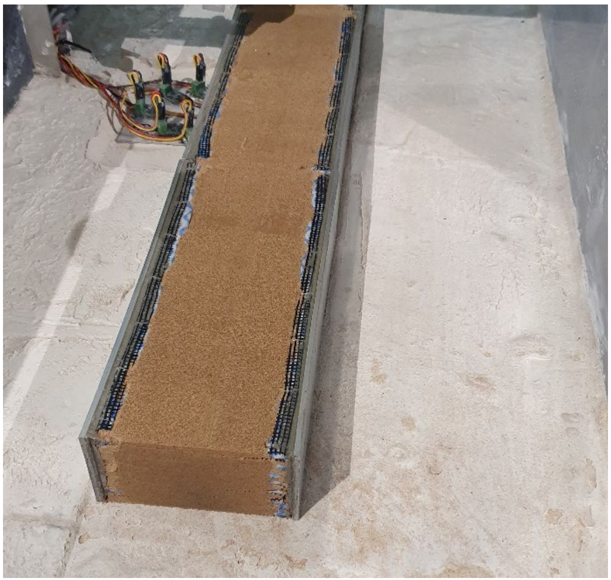

Figure 1. *A section of 1/50th scale (50mm high) geosynthetic reinforced soil retaining wall (GRS-RW) embankment under construction in the centrifuge rail simulator, on a soft clay subsoil.*

The centrifuge modelling aimed to investigate the embankment and subsoil settlements on both sand and soft clay, as well as how the subsoil movements affect the overlying embankments, and measuring how the train loads transfer through the track and embankment creating the resulting stress changes on the top of the subsoil. This is an area that the UK Rail Safety and Standards Board (RSSB) states is an area of poor understanding, on which there is little to no ongoing research (RSSB 2011). The focus of this paper will be the development of methods for simulating model train loading in-flight in the centrifuge, instrumenting the model embankments (including total stress measurements at the subsoil interface) and the preparation of the subsoil models used in the testing.

2 TRAIN MODELS

Before setting out the centrifuge modelling, it is important to define the train characteristics being studied. The research in this paper is based on a TGV-R train (Connolly et al. 2014), which consists of power cars weighing 68 tonnes supported by two bogies each with two axles, resulting in an axle load of 17 tonnes (34 tonnes per bogey). The passenger cars are significantly lighter, but instead share bogies at the carriage connections, resulting in a similar axle load of 16 tonnes (31 tonnes per bogey). Bogies are spaced at 14 m centre to centre on the power cars and 18.7 m on the passenger cars. The train model used in the centrifuge was based on the TGV-R power car, but due to the similarity in the axle loads between the power and passenger cars, the axle passes modelled in the centrifuge could be considered to be representative of either. This required a 1/50th scale train model (Figure 2) weighing 550 g, with model bogies (Igus WJ200QM-01 bearings) spaced at 280 mm centre to centre.

Figure 2. *1/50th scale model train used to simulate a 68 tonne TGV-R power car (550 grams, 280 mm bogey spacing).*

In centrifuge modelling of high-speed rail, it is necessary to ensure that the conditions in the model are in keeping with the full size problem. Two of these considerations which arise in respect of high-speed rail are the dynamic effects from train vibrations, and also the scaling of the train velocity to match the real-world drainage conditions.

First dealing with the dynamic effects, the vibrations generated by a train whilst in motion could potentially increase the rail settlements beyond those caused only by the stress change in the embankment and subsoil due to the weight of the train. This would occur if the shear strains induced by the vibrations were greater than the elastic shear strain threshold of the subsoil, meaning that plastic deformation from the vibrations could accumulate. Connolly et al. (2014) conducted field monitoring of a high-speed rail line to measure these vibration-induced shear strains in the surrounding soil. It was found that the shear strains varied depending on the distance from the track, but that the maximum strain recorded for the case where an embankment is present was $\gamma = 5.9 \times 10^{-6}$. For clay soils, the elastic shear strain threshold is of the order of $\gamma = 1 \times 10^{-4}$ (for Kaolin, the main component of KSS 541), nearly two orders of magnitude higher than the maximum measured shear strain from vibrations. This suggests that deformations generated by the vibrations could be considered to be elastic (and recoverable) and would be unlikely to significantly affect the model embankment settlements measured during the cyclic train loadings investigated in this research, and that modelling of these dynamic effects is unnecessary. Hence the train was modelled as a smooth passing load.

Secondly, the train velocity in the field determines the drainage conditions that occur. An indication of these drainage conditions can be obtained from the train's normalised velocity (Eq. 1) where v is the train velocity, d is the representative dimension (assumed to be the track width of 2.5 m in this case) and c_v is the coefficient of consolidation (c_v =17.2 m^2/year for KSS 541). For a full-scale train moving at 300 km/h (Connolly et al. 2014) this would correspond to $V = 3.81 \times 10^8$. A value of V greater than 10 to 30 indicates fully undrained conditions (Randolph and Gourvenec 2011) with no pore pressure dissipation during the passage of the train, hence, the normalised velocity of the model train must be greater than 30 to correctly simulate the undrained nature of the problem. The maximum actuation velocity possible with the system used was 108 m/h and considering the centrifuge scaling of the problem this means that the normalised velocity of the model train was V = 2750, significantly greater than that required to correctly simulate undrained conditions.

$$V = \frac{vd}{c_v} \tag{1}$$

3 MODELLING APPROACH

Consideration was given to the loading approach adopted. Two options were possible; to model the embankment in the centrifuge as a 2D problem with a plane strain approach, or to simulate the train using a 3D approach with a moving load. Preliminary 1 g testing was undertaken to investigate the performance of a 400 mm length of 50 mm high GRS-RW embankment placed in a model container of dimensions 400 mm square and filled with 500 mm of loose HST95 sand. Uniform cyclic loading was applied to the embankment via a 50 mm wide, 400 mm long force applicator representing the width of track. The force was applied using an Instron 5985, equivalent to a uniform stress of 1 kPa across the track area. The stress was estimated based on the 34 kN bogey load being evenly distributed over the area underneath the bogey (2.5 x 3 m) giving a stress of 47 kPa, which was scaled down by N = 50 to account for the 1 g stress conditions in the subsoil. The embankment was subject to more than 800 cycles of loading, resulting in a final settlement of 0.22 mm (11 mm at full scale) (Figure 3).

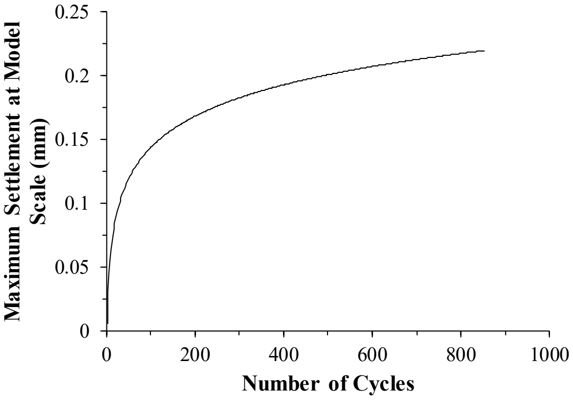

***Figure 3.** Maximum settlement in each cycle for a 1 g test of 1/50th scale GRS-RW embankment on loose HST95 sand.*

However, the preliminary testing raised a number of issues. Firstly, the stresses (and hence also stiffnesses) in the subsoil were N times too low due to the 1 g nature of the tests, and would not be consistent with the stresses in the full scale problem. Secondly, high speed rail lines increasingly adopt high stiffness concrete slab tracks on top of the embankments, and these slab tracks act to distribute the load from the train not just laterally across the embankment, but also longitudinally along the embankment ahead and behind each bogey. The comparatively high GRS-RW embankments would also have a similar effect. A 2D plane strain approach such as the type used in the preliminary tests would fail to capture this behaviour and mean that the stresses which reach the subsoil beneath the embankment (which are of interest in this research) would be unrealistic. To overcome these two issues, it was decided to adopt a novel approach and model the train loading and embankments using a 3D approach with a 1/50th scale model train moving along a 1 m length of model track whilst in flight at 50 g in the University of Dundee's 3 m radius beam centrifuge. To the knowledge of the authors, this is the first time that moving train loads on embankments have been tested in a centrifuge, with all previous studies using 2D plane strain methods (Zhang et al. 2018; Vorster et al. 2017; Viswanadham et al. 2012).

***Figure 4.** Model train and track on a model conventional ballasted embankment in the centrifuge actuation system.*

This introduced further scaling requirements, such as the need to correctly scale the longitudinal bending stiffness of the track to ensure the distribution of the train load in the direction of the track is correctly modelled. Hence, the bending stiffness, EI, was scaled down by N^4, including accounting for the differing material moduli of the steel and concrete used at full scale against the aluminium used at model scale. To achieve this, two 1.08 m long model track lengths were created, each incorporating integral low friction Igus WSQ-06-30 double bearing rails for the model train to move along (Figure 4). One length of track was scaled to match the bending stiffness of UIC60 rails typically used in combination with conventional G44 sleepers on ballasted embankments (with model sleepers also attached to match the interface with the ballast), whilst a stiffer model track was created with a bending stiffness designed to match the scaled stiffness of the concrete slab track (made up of hydraulically bonded layer (HBL), slab track and rails) used in the full scale testing (Figure 5). The longitudinal bending stiffness of the GRS-RW track facing walls was also scaled for the same reason.

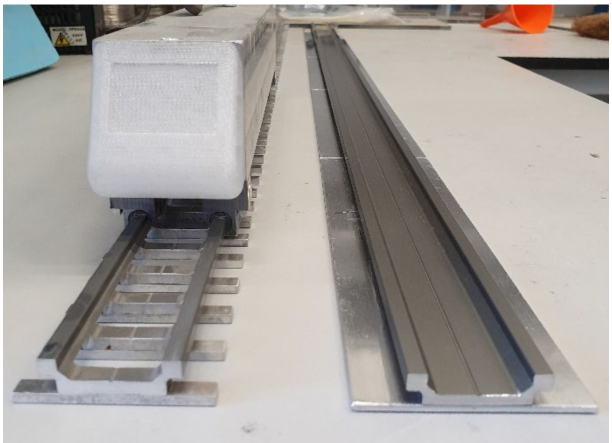

Figure 5. *Comparison between the conventional UIC60 rail and sleeper model (l) and the rail and slab track model (r).*

4 METHODOLOGY

4.1. Actuation system

To accommodate the track lengths required, the testing was carried out in a centrifuge strongbox with internal dimension 1500 mm long, 400 mm wide and 650 mm deep (Figure 6). A viewing chamber with a Perspex face was placed at one end of the box to allow a cross-section of the track and embankment to be viewed in-flight, which reduced the length of track and embankment to 1080 mm. The 1/50th scale train model weighing 550 g ran on the track, connecting via two 3D joints to a moving platform on an actuator attached to the top of the box such that the train was free to move vertically. Using this system, it was possible for the model train to have a travel distance of up to 600 mm which was sufficient for the train to pass and clear an instrumented section in the middle of the track length by 150 mm and ensure the stress from the train at this point was fully relieved before the actuator reversed direction and the train passed in the opposite direction. Each cycle of the actuator resulted in the train passing this point twice, delivering four bogey passes at a speed of 30 mm/s. The cyclic testing continued for 6 hours, allowing up to 2000 bogey passes to be simulated in each centrifuge test.

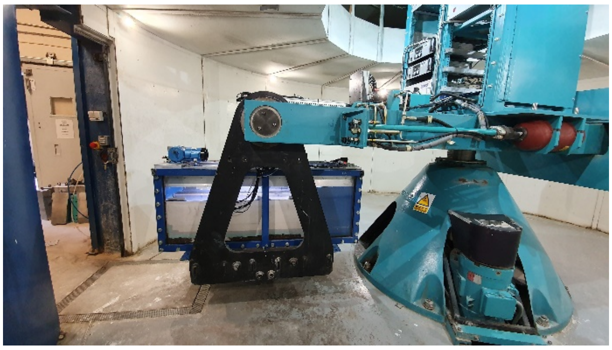

Figure 6. *Rail simulator and 1.5 m long strong box installed on the University of Dundee's 3 m radius beam centrifuge.*

The actuation system itself consisted of a moving platform above the model running on Igus drylin WSQ-16 linear rails at each side of the box driven via a belt system by a Parvalux SD12-LWS high torque 220V DC motor (Figure 7). Displacement of the platform was measured by a Multicomp SP1-50 draw wire transducer. The system is described in detail in Robinson et al. (2019), but for this testing it was upgraded to allow programmable movement such that the cyclic testing could be automated via Labview. This was achieved by interfacing the motor's reversing DC controller with an inexpensive set point isolator, allowing the

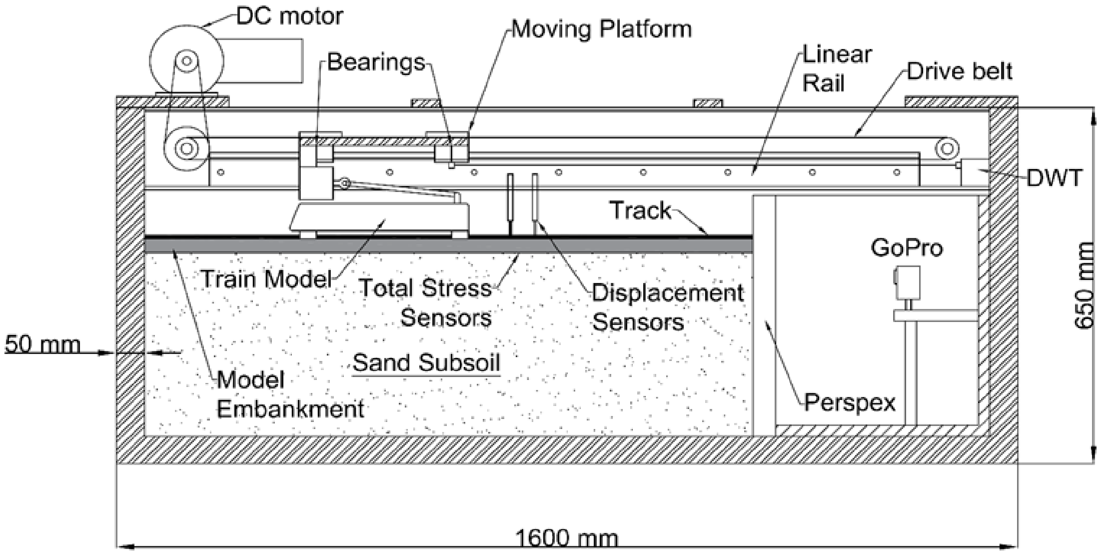

Figure 7. *Schematic cross section of centrifuge rail simulator showing actuator, strong box, model and instrumentation.*

motor's direction and speed to be easily controlled by a 0 to 5 V signal and an existing relay unit within the centrifuge's National Instruments CompactRIO 9047 chassis. Control signals for the motor were generated by an NI 9264 voltage output unit within the chassis, which already provides individual software programmable supply voltages for the 32 instrumentation channels on the centrifuge which pass through a custom built low-noise power conditioning unit. This allows the low current voltage signals from the NI 9264 to be used to independently power instruments with a higher current demand with a highly regulated voltage supply. By using the same CompactRIO system for both the instrument logging and the motor control signals, it was possible to implement a feedback control loop with the draw wire transducer in Labview to carry out the cyclic testing using software control.

4.2. Instrumentation

A range of instrumentation was used to during the testing. Three miniature Honeywell displacement sensors were used to monitor the track, embankment and subsoil settlements at the middle of the track length, capable of measuring settlements less than 1 micron. A GoPro Hero 4 in the viewing chamber was also used for PIV analysis of a cross section of the subsoil underneath the embankment at one end of the track through a Perspex window which was fitted with markers, allowing the displacement field under the embankments to be investigated. However, the most challenging measurement was the total stress at the interface between the embankment and the subsoil. This is a key measurement in the tests as it could indicate how effective the various embankment designs were in distributing the load of the train and how the stress is transferred down through the embankment to the subsoil. Total stress measurements can be problematic to achieve, as total stress sensors can in themselves change the stress distribution in their vicinity as well as being difficult to miniaturise for use in such small models.

The total stress measurements were achieved using Singletact S8-10N capacitive force sensors, 8 mm in diameter and 350 microns thick with a sensing range of up to 200 kPa and a sensing resolution of 0.4 kPa. These operate using a stiff elastomer between two foil layers covered with a thin protective polyamide outer layer, with small changes in the thickness of the elastomer due to the applied stress causing measurable changes in the capacitance. The sensors have Singletact SE units which convert capacitance into a straightforward analogue voltage output. These differ from other thin film pressure sensors which using printed conductive ink, which require an amount of compression ('switch-on distance') before pressure changes begin to be detected, which is unacceptable if correct in-situ stresses are to be measured. Capacitive sensors do not suffer from these issues.

If a comparatively thick sensor is stiffer (or less stiff) than the surrounding soil, then stress arching around the sensor can occur. The Singletact sensors avoid these issues due to their thin profile which minimises the volume of the inclusion used and also due to the fact that they have a stiffness which is similar to the stiffness of the surrounding materials used in the embankments and subsoil. The sensors have a Young's modulus of 7 MPa (based on manufacturer's data), which is comparable in magnitude to the stiffness of the model embankment ballast (E_o' = 4 to 8 MPa) and the KSS 541 subsoil (E_o' = 2 to 3 MPa) as well as HST95 sand (E_o' = 5 to 12 MPa, used in tests not described in this paper).

An array of five of these sensors (See Figure 8) were placed in the middle of the length of track ranging from the centre of the embankment to the edge, to allow a 3D model of the stress field around a bogey to be measured at the subsoil as the bogey approaches and passes the instrumentation point. The sensor electronics were coated with epoxy resin whilst the exposed edges of the sensing area were sealed with a fine layer of flexible adhesive.

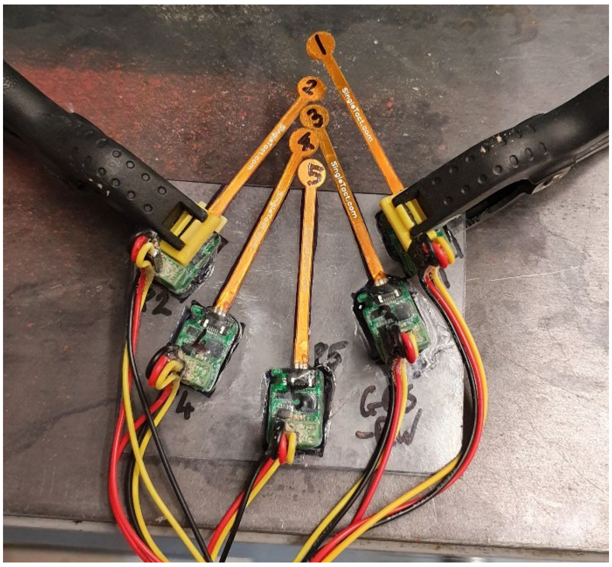

Figure 8. *Array of Singletact S8-10N pressure sensors used for total stress measurement.*

Figure 9 shows typical results (from the 5th and 6th train passes) from a total stress sensor located in the centre of the embankment at the ballast-subsoil interface. The change in stress generated by the passage of the individual bogies is clearly visible as four peaks in the stress measurements. The maximum change in vertical stress due to the bogey load ranged from 13 to 22 kPa, with an average of 18 kPa. These maximum stresses were relatively constant, and showed no indication of changing with increasing cycle numbers.

Expected real-world vertical stress changes from a passenger train on the subsoil immediately beneath ballasted embankment range from 20 to 30 kPa depending on the ballast thickness (RSSB 2011). These figures are based on ballast thicknesses (including sub-ballast) ranging from 350 to 1000 mm. The ballast thickness used in this case was slightly thicker than this range at 1250 mm at prototype scale (to match other embankment weights and stresses studied in the project), which would distribute the train load over a greater area of the subsoil. Hence, the stress change for the embankment studied would be expected to be just below the lower end of the recommended range (i.e. just below 20 kPa), meaning that the average measured value of 18 kPa would be in keeping with this.

The measurements also clearly indicate that the subsoil experiences the stress change from the model train bogies approximately 220 mm (11 m at prototype) ahead of the arrival of the bogey itself. This suggests that the effect of the embankment distributing the load of the train along the length of the track is an important effect, validating the decision to adopt a 3D approach, modelling the train as a moving load.

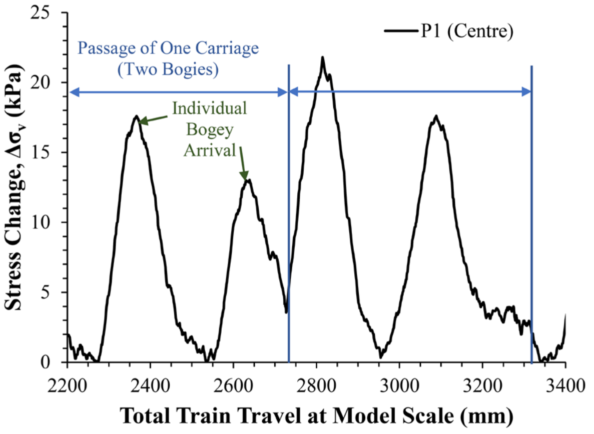

Figure 9. *Typical output from a Singletact pressure sensor underneath the track (conventional ballast, 25 mm thick) for one cycle of train loading on KSS541*

4.3. Subsoil preparation

The soft clay subsoil required to be consolidated in-flight from slurry. This was necessary to achieve a realistic shear strength variation with depth, as opposed to the uniform profile that would occur if a press was used to prepare the clay at 1 g. One of the primary reasons for using KSS 541 (a mixture of 50% Kaolin, 40% HST95 silica sand and 10% A50 silica silt) for the clay material was that it still provides a cohesive soil, but with less reduction in height during consolidation, as well as shorter consolidation times than pure Kaolin. The properties of KSS 541 are given in Table 1. If Kaolin had been used, it would not have been possible to have a sufficiently thick layer of clay to avoid boundary effects. The KSS 541 slurry was mixed at a moisture content of 50% and placed (400 mm deep) into the strong box on top of a 30 mm thick gravel drainage layer covered with a filter membrane and filter paper. The moisture content of the slurry was critical as it was necessary to mix it at the lowest possible moisture content which avoided air entrapment occurring, in order to minimise the height loss during consolidation. Higher moisture contents would also have risked segregation of the sand fraction in the KSS 541 during spin up. The clay was consolidated at 50 g for 3 days, with monitoring of the mass of water lost indicating this was sufficient to achieve near full consolidation. The drainage outlet location was set at 10 mm below the expected final surface level, such that the water table was held at this location, resulting in a final clay thickness of 300 mm.

Table 1. *Properties of KSS 541.*

Parameter	Unit	Value
Gradient of CSL, M	-	0.73
Critical friction angle, ϕ'_{crit}	°	19
Clay fraction	%	41
Plastic limit	%	18
Liquid limit	%	38
Plasticity index	%	20
Coefficient of consolidation, c_v	m^2/year	17.2

The GRS-RW embankment sections were constructed at 1g in the lab and placed onto the model. However, prior to this it was necessary to use an aluminium bar of the same area and mass as the embankment to pre-consolidate the embankment area to prevent excessive deformation during consolidation of the embankment in-situ. The aluminium preload was consolidated at 50 g for 24 hours before the actual embankment sections were installed and consolidated for a further 24 hours. Oedometer testing of KSS 541 indicated that 90% consolidation would require 12 hours, hence the 24 hour periods were selected to ensure consolidation settlements would be negligible compared to the expected embankment settlements. During testing, the exposed surfaces of the KSS 541 were covered to prevent moisture loss. The shear strength and moisture content profiles with depth for KSS 541 are shown in Figure 10, which had a final saturated unit weight of 19.1 kN/m^3. Shear strengths were measured using a Controls Testing pocket shear vane.

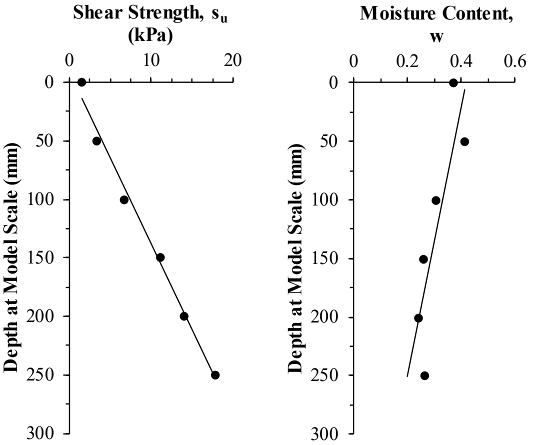

__Figure 10.__ Shear strength and moisture content with depth variation (free field) for KSS 541 clay prepared in flight at 50g.

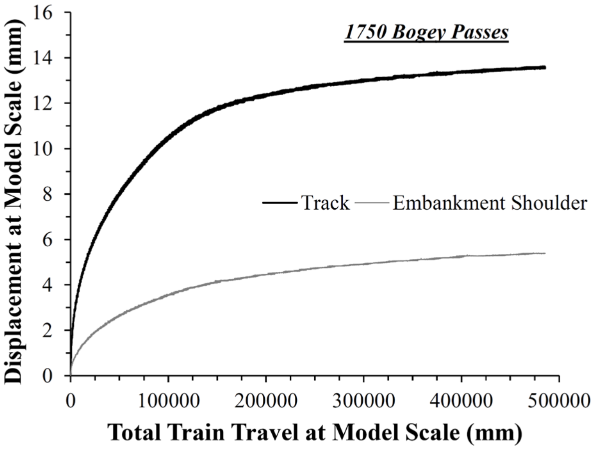

__Figure 11.__ Model track and embankment shoulder settlements with increasing cycles of train loading for a conventional ballasted embankment (25 mm high) on KSS 541, measured at the middle of the length of track (at 50 g in the centrifuge).

Figure 11 shows the measured settlements of both the track and the embankment shoulder with the application of 1750 bogey passes for a model conventional ballasted embankment on KSS 541. The embankment shoulder settlement increases with the number of bogey passes reaching a final value of 5.39 mm (269 mm at prototype), whilst the track itself reaches a significantly larger settlement of 13.52 mm (676 mm at prototype). These settlements are clearly large compared to the settlement limits on rail lines, highlighting a need for better understanding of the mechanisms behind rail embankment behaviour on soft clay soils.

The reasons for the track displacement being greater than the displacement of the embankment shoulder are clear in Figure 12, which shows the surface displacements of the subsoil for a cross-section of the model visible at the Perspex viewing chamber. The subsoil displacements are primarily focussed around the centreline of the track, reducing significantly with distance from this point and are far lower at the distance from the centreline (40 mm from centreline) at which the embankment shoulder displacements are measured. This highlights the need to study the behaviour of rail embankments considering the embankment and subsoil in combination together, rather considering the embankment alone; a task which is well suited to the use of centrifuge modelling.

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5 CONCLUSIONS

A range of challenges faced during the modelling of a rail simulator for centrifuge application have been discussed. Vibrations from a moving train were considered but identified as secondary to the effects of the change in stress caused by the train load, as existing research suggests that shear strains induced by the vibrations are significantly below the elastic shear strain threshold for clays.

A 3D approach with a moving train load was chosen to ensure the true behaviour of the embankment and track combination was captured, instead of a 2D plane strain method. This required careful scaling of the track bending stiffness and a sufficiently long model container to permit a complete cycle of load for each train pass.

Total stress measurement was achieved through the use of Singletact force sensors. These produced results comparable with the stresses expected in this application. Total stresses measured during testing indicated that the model container was sufficiently

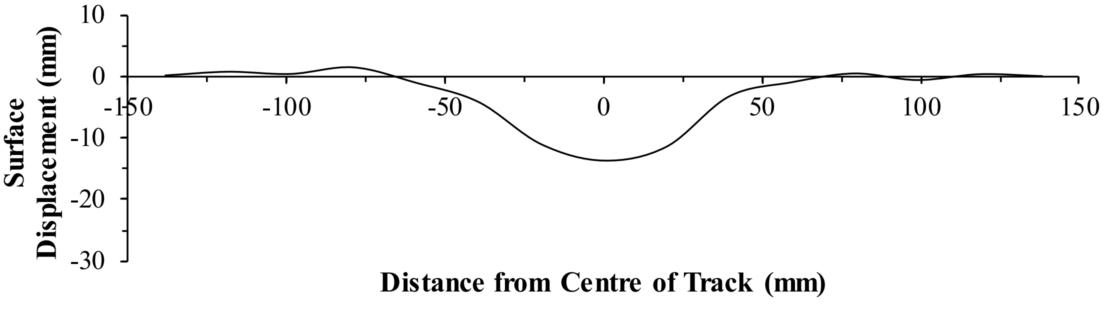

__Figure 12.__ Variation of the subsoil surface displacement (relative to original surface levels) across the width of the model (in cross-section) after 438 bogey passes at the Perspex viewing window.

long to model the full approach and pass of a train over the instrumentation point, and that in these tests the subsoil experienced stress from the train bogey at a distance of 11 m (at prototype scale).

Preparation of a suitable soft clay subsoil was accelerated by use of a KSS 541 clay-sand-silt mixture. This soil shares cohesive mechanical behaviour with clay but has a higher coefficient of consolidation, accelerating the consolidation phase. Even so, the models required 72 hours of initial consolidation, followed by 24 hours consolidation between the construction of the embankment and the application of the rail loads. A soil with undrained shear strengths varying with depth from 2 kPa near surface to 15 kPa at 300 mm deep was achieved as a result.

6 ACKNOWLEDGEMENTS

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