Cyclic loading test on geogrid stabilised model trackbeds

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Physical Modelling in Geotechnics

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ABSTRACT: Faced with increasingly demanding maintenance challenges, SNCF Réseau (the French railway infrastructure manager) proposes to use geogrids to improve trackbeds during renovations on its conventional rail lines (speed limit ≤ 220 km/h). This communication presents the design and deployment of a large scale physical model, which reasonably simulates the trackbeds usually found under conventional SNCF rail lines. Cyclic loading is applied, at similar amplitudes to those produced by a train on the field. Measurements (including surface settlement, induced soil pressure, soil-geosynthetic interface settlement…) are used to assess the impact of various geogrids on trackbed performance, mainly characterized by a light falling deflectometer test modulus and the settlement rate during the cyclic loading process.

Keywords: trackbeds, geogrids, cyclic loading, physical modelling, SNCF.

1 INTRODUCTION

The increase of traffic imposes large cyclic loads on railway trackbeds (interlayer or subballast with capping layer), which contribute to the appearance of geometry defects on the tracks. This phenomenon is particularly remarkable on French conventional rail lines (speed limit ≤ 220 km/h) and can impact train safety as well as passenger comfort. Thus, SNCF has undertaken major efforts to find a cost-effective remedy. The use of geosynthetics, particularly geogrids, in the subballast layer represents one such remedy. When placed at the interface of granular soils, geogrids (which have apertures of various sizes and shapes) could improve the mechanical properties of these soils by interlocking the grains in their apertures (Carroll, 1988).

Several field experiments have been installed on the rail network (Yaba et al., 2022), in order to improve knowledge of the mechanical behaviour of geogrid stabilised subballast. Despite their utility in assessing the operational effectiveness of using geogrids, the analysis of these field experiments is hampered by the presence of many uncontrolled parameters as well as the long timescales over which observations must be made. Furthermore, the cost of such experiments limits the number of designs that can be tested. Hence, it is necessary to conduct comparable experiments on a physical model in order to aid in the interpretation of field results, to accelerate the timescale and to provide a basis of comparison between various options which cannot be tested on the field.

This communication presents the design and deployment of such model, which reasonably simulates the trackbeds usually found under conventional SNCF rail lines.

2 MODEL TRACKBED DESIGN

Studies of railway tracks are often simulated with rigid tanks or boxes, of varying sizes, containing different layers with specific properties depending on the objectives and choices of each researcher. Review of various publications has shown that the validity of their results depends on their specific conditions. Hence, the experimental conditions of this study have been adjusted to meet SNCF specific objectives, with consideration to available technical facilities.

The experimental set-up consists of a tank with a volume of approximately 2 m^3. The model includes (Cf. Fig. 1): i) a subgrade; ii) a subballast/capping layer; iii) a geosynthetic layer between the subgrade and subballast. The superstructure (ballast, sleepers and rails) are not physically included due to practical and technical limitations. However, the presence of the superstructure is simulated by maintaining a minimum load equivalent to its weight.

The subgrade is the natural existing soil which supports the track structure. The stiffness of the subgrade, characterised by its Ev2 modulus (static deformation modulus or strain modulus), plays a major role in determining the pertinence of geogrid installation. In general, geogrids are more effective when used on softer subgrades (Brown et al., 2007). The most improvements are observed for soils with Ev2 values below 30 MPa (Aursudkij, 2007). Hence, it was decided that a subgrade with an Ev2 modulus of 10 to 20 MPa would be the most appropriate. This corresponds to the range of values measured in the weakest track sections on some SNCF lines (Yaba et al., 2022).

In this study, the soft subgrade is an analogous material composed of a mixture of Fontainebleau NE34 sand, expanded polystyrene pellets and water (for binding the solids). The role of polystyrene in this mixture is to increase the compressibility of the material and consequently reduce the Ev2 modulus. Several sand-polystyrene (SP) mixtures were tested and one containing 40% polystyrene (by volume) and 10% water (by mass) was retained. This mixture (called SP40) has a Ev2 modulus of approximately 17 MPa, when packed into the tank at a density of 1200 kg/m^3.

The subballast materials are the coarse-grained materials confined between the ballast and subgrade. The main purpose of the subballast layer is to form a transition zone between the ballast and subgrade to avoid migration of soil into the ballast, and to reduce the stresses applied to the subgrade. For maximum efficiency, the subballast material should be such that its nominal grain size (D_{50}) is approximately 70% the geogrid aperture size (Brown et al., 2007). However, SNCF Réseau has standards which require the use of a specific type of aggregate in the construction of subballast layers.

The subballast was sourced from an SNCF approved quarry. Tests were performed to characterize the material according the French specifications (GTR). Considering the material characteristics (summarized in Table 1), the subballast is identified as a B31 soil (silty gravel) according to AFNOR NF P11–300 classification.

Table 1. Subballast characteristics.

Physical characteristics					
D_{10}	D_{30}	D_{50}	D_{60}	Cu / Cc	VBS
0.2 mm	2 mm	8 mm	9 mm	45 / 2.2	0.2
Mechanical characteristics					
Micro-Deval	Los Angeles	max. dry density		opt. water content	
20	24	2300 kg/m^3		4%	

The maximum dry density and optimal water content (in Table 1) were determined using a standard Proctor test. It should be noted that although the subballast was prepared with a 4% water content, it could only be compacted to 2000 kg/m^3 dry density in the tank.

The geosynthetics are placed at the interface between the subgrade and the subballast, because it is the most practical position (with regards to SNCF maintenance techniques). This layer consists of a single non-woven geotextile (reference case) or a geogrid on top of the same non-woven geotextile. On the field, the geotextile provides separation/filtration to avoid subballast and ballast fouling. Considering that weak soils generally contain a high percentage of fine particles, the geotextile is almost always present (hence its use in the reference case).

As previously stated, there is an optimal ratio between geogrid aperture and subballast nominal grain size (geogrid aperture / D_{50} = 1.4). Most commercially available geogrids do not meet this condition relative to standard SNCF subballast. However, prior research has shown that said geogrids provide improvements even if this ratio is not respected (Horton et al., 2017). Considering the aforementioned research, a range of the most common geogrids was selected for this study.

The experiments were performed in a rigid rectangular tank, which is 2.00 m long, 0.95 m wide and 1.00 m high. The sides of the tank are lined with a smooth PVC film, used to reduce skin friction. This is in line with the tanks used by other researchers, and large enough to limit the impact of boundary effects on experimental results. More specifically, the border conditions were verified using numerical simulations performed on FLAC3D (Khan, 2020).

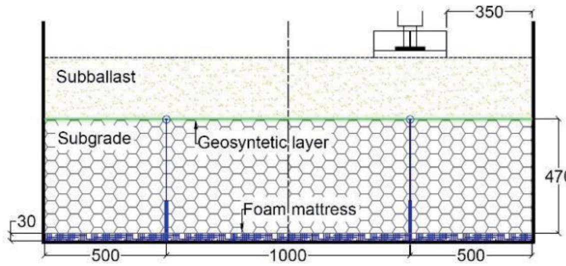

Fig. 1. Cross-section of the experimental setup (distances in mm).

Fig. 1 depicts a cross-section of this setup. A 30 mm thick dense foam mattress is used to line the bottom of the tank and thus limit the effects of the rigid bottom on Ev2 measurements. The subgrade is packed into a 470 mm layer on top of the foam mattress and topped with the geosynthetic layer. Finally, a 250 mm layer of subballast is compacted onto the geosynthetics.

The tank is equipped with an electromechanical actuator (with integrated force and displacement sensors) and a circular plate for loading. The displacement of the loading plate is measured using four Linear Variable Differential Transformers (LVDT), which are positioned as shown in Fig. 2. The setup allows for the actuator and loading plate to be moved such that two consecutive tests can be performed before emptying the tank (first on the right side, then on the left side).

Two LVDTs, placed in the axis of the loading directions and fixed to the bottom of the tank, are used to measure the settlement of the geosynthetic layer (subgrade/subballast interface). These LVDTs are shown traversing the subgrade in Fig 1.

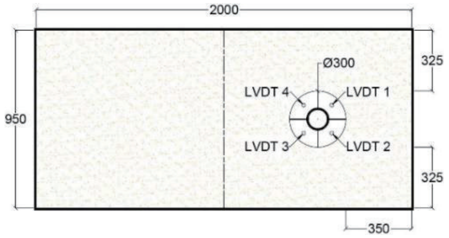

Fig. 2. Overhead view of the experimental setup, with the loading plate positioned on the right side of the tank (distances in mm).

Finally, geogrid rib strain (strain gauges in the horizontal direction of Fig. 2) and subgrade stress are measured during some tests. They provide a qualitative understanding of the interactions between each element of the system and of the mechanisms by which the geogrid is expected to improve trackbed performance.

3 TESTING PROCEDURE

Each test consists of several phases including the installation the model trackbed and measurement of the Ev2 modulus on the subballast surface, the application of cyclic loading on each side of the tank, and the measurement of Ev2 modulus after loading followed by the dismantlement of the trackbed.

The installation phase starts with the weighing of a prepared SP40 mixture (~1026 kg) and of the subballast material (~1075 kg at 4% water content), such that the desired densities can be achieved. The SP40 mixture is placed in the tank and compacted, in two layers, using a static mass. The surface of the subgrade is levelled to the top of the LVDTs and pressure sensors are installed on the levelled surface (if need be). The geotextile is then laid, followed by a geogrid (if need be). Care is taken that neither geosynthetics is in contact with the sides of the tank. The subballast is then placed on top of the geosynthetics and compacted, in a single layer, using a vibratory-plate compactor.

After the trackbed has been assembled, the Ev2 modulus is measured in three different positions, as shown in Fig. 3. Each measurement is the average value of three impact tests performed using a lightweight falling deflectometer (LWD, specifically a Rincent ND Technologies Minidyn^{TM}). After this, the actuator and loading plate placed at position 3 and LVDTs 1 to 4 are installed as explained in section 2.4.

Cyclic loading is applied at similar amplitudes to those produced by trains on the field (a max. surcharge of 70 kPa). A minimum load of 15 kPa is maintained between cycles. This load is equivalent to the stress applied by the ballast, sleepers and rails on the field. Hence the load is applied in cycles with magnitudes ranging from 15 to 85 kPa, at a frequency of approximately 1.5 Hz. Although it does not accurately represent real traffic, this loading frequency was chosen, after testing several other options, because it provides the best compromise between test duration and process control. During loading, data from the sensors (Cf. section 2.4) is recorded with a sampling frequency of 20 Hz (> 2 times the signal frequency) as proposed in the sampling theorem (Shannon, 1949).

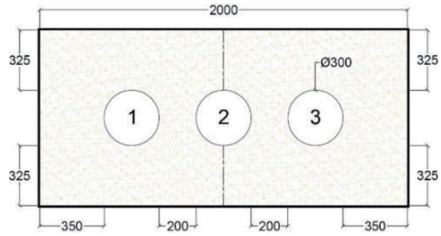

Fig. 3. Positions of Ev2 measurements (distances in mm).

The final parameter is the number of loading cycles, which was fixed at 250,000. This is the equivalent of 25,000 Bombardier B81500 4 car trains (shown in Fig. 4) or approximately 3 to 4 years of typical traffic on most rural rail lines. This also results in approximately three days of loading for each side of the tank (position 3, then position 1) or two weeks for a full test; after factoring in time required for installation, repositioning of the actuator (with the loading plate and its LVDTs), dismantlement and data processing.

Fig. 4. Bombardier Class B 81500 passenger train, 4 car variant.

After 250,000 load cycles have been applied to each side of the tank, the actuator, loading plate and its LVDTs are removed. The Ev2 modulus is once again measured in positions 1, 2 and 3. These provide an indirect measure of subballast densification at each position, which in turn allows one to hypothesize about the amount of load spread for any given test relative to another.

Each full test produces 8 to 9 GB of raw data, which is cleaned, processed and visualized using a set of Python scripts that were developed specifically for this study. The processing consists of converting the raw data (millivolts, ohms, milliamps…) to mechanical values (mm, µm/m, kPa…), separating the loading sequences applied to each side of the tank, isolating each individual loading cycle and extracting various indicators. It takes 24 to 36 hours to process each full test, depending on whether or not geogrid rib strain and subgrade stress are recorded.

4 PRELIMINARY RESULTS

The initial results confirm that loading on one side of the tank does not provoke any settlements on the other side. For example, Fig. 5 shows the settlement curves for two tests when position 1 (left side) of the tank is being loaded. During both tests, the LVDT below the loading plate (Interface_L) settles while the other one does not.

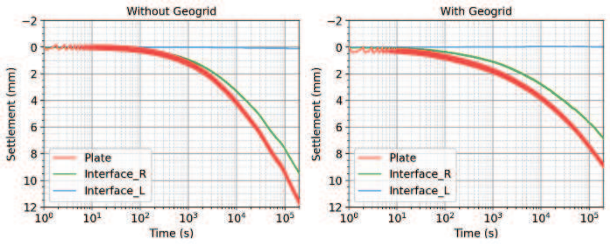

Fig. 5. Settlements of the plate and of the geosynthetic layer without a geogrid (left) and with a geogrid (right).

Furthermore, Fig. 5 shows that the introduction of the geogrid results in a reduction of settlement of both the subballast surface (plate) and the interface. After 250,000 cycles (or 25,000 trains), the settlement is reduced by 28% on the surface and 35% at the interface.

Table 2 summarizes the values of Ev2 measured at each of the three positions (Cf. section 3.1). As expected, the values are between 45 and 50 MPa. The introduction of a geogrid did not increase the Ev2 before loading, however it resulted in more uniform values. This is probably because the LWD does not transfer enough energy to mobilize soil-geogrid interactions, hence it cannot directly be used to quantify improvements provided by a geogrid. After loading, in the presence of a geogrid, the Ev2 modulus of position 2 increases significantly (despite the fact that it was not loaded). This is likely because the presence of the geogrid resulted in an increase in the angle of load spread.

Table 2. Subballast characteristics: Ev2 measured with LWD (MPa).

	Without Geogrid			With Geogrid		
Position	1	2	3	1	2	3
Before Loading	51	46	41	46	47	48
After Loading	65	48	58	67	52	58
Increase	27%	4%	41%	46%	11%	21%

The geogrid rib strains behave as expected. Each loading cycle produces a strain with an amplitude of approximately 100 μm/m, and small residual strains accumulating progressively as shown in Fig. 6. However, the amplitude of each cycle is much lower than those observed on the field for the same geogrid (800 μm/m). This is likely due to the fact that real train loads are dynamic, and thus produce a higher impulse (the integral of the resultant force with respect to time). For context, most geogrids are characterised for strains starting at 5000 μm/m (0.5 %) because it is the smallest value for which a reliable force/strain relationship can be measured. The stabilisation application is usually considered for strains below 2%, so the current results are well within its scope.

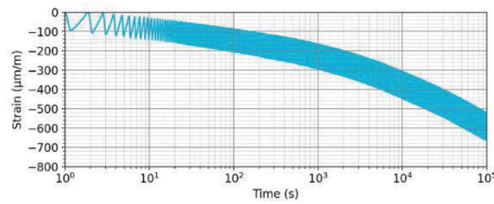

Fig. 6. Cumulated tensile strain in the transvers rib of a geogrid directly below the loading plate (negative strain = extension).

5 CONCLUSIONS

As of the writing of this communication, this study has led to the design and validation of an experimental apparatus for the physical modelling of geogrid stabilised railway trackbeds, and to the development of a corresponding testing protocol. Initial tests have shown that the introduction of a geogrid between a weak subgrade and subballast could lead to a reduction of settlements under cycling loading. These results will need to be further analysed and confirmed by conducting more tests over the coming months.

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