Design and construction of a reduced scale model for a railroad ballast test reinforced with geogrid

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ABSTRACT
Railroads hold an important role for the economy, especially in terms of the flow of products from the most central regions of a country to the Ports. In recent years, there has been an increase in the practiced speed and transported loads, resulting on a faster degradation of the roads and the need for more frequent maintenance. Thereof, the search for technologies that provides the improvement of the road condition and extend their service life has become necessary. The use of geosynthetics at the railway infrastructure is getting more known, due to the diversity of functions that they are able to perform, improving road drainage, acting as a mechanical reinforcement and also containing fine grains. The ballast compaction process and the use of the railroad throughout time, induce zones of materials with a different degree of compaction, which causes deformations of different amplitude. The insertion of a geogrid inside the ballast or sub-ballast layer provides for a stress redistribution, minimizing the possible differential settlements that may appear in the road. This paper aims to present in particular, the design and construction of a reduced railroad model to simulate a geogrid-reinforced ballast.

1. INTRODUCTION

According to the National Transport Confederation, freight transport by railways represents currently around 21% of the total freight transport in Brazil. The goal for 2025, according to the Investments Partnership Program (*Programa de Parcerias de Investimentos* – PPI, 2008), is that this percentage achieve 33%. Given this perspective, it can be concluded that there is a great need for development in the rail sector, regarding the construction of new railways and the implementation of innovative and viable solutions for the existent railroads, maximizing their service life, when under loading that surpass those currently practiced.

Geosynthetics have shown to be a good solution when used as reinforcement of the road infrastructure layers, as a separation element between granular layers and subgrade, preventing the dispersion of fine material and when applied to guarantee an adequate drainage system for the pavement. The use of geogrid as a reinforce of the ballast layer, aims to minimize the vertical deformations and the differential settlements that occur due to the application of cyclic loads, which prolong the service life of the road, resulting in a less frequent maintenance of the ballast layer.

To ensure the efficient use of geogrid as a ballast reinforcement material, several researches have been conducted to obtain optimal geogrid and the ballast material parameters, for example, the ideal height of the geogrid implementation and the best mesh opening for a certain aggregate. The use of reduced models to study the phenomenon of reinforced ballast with geogrid, when performed with an adequate simplification and a extensive knowledge of the boundary conditions and limitations involved, have been successfully implied, providing great results. The present work aims to present the modeling and dimensioning for construction of a test equipment, designed as a reduced model of geogrid reinforced railway infrastructure.

2. DESIGN OF THE REDUCED SCALE MODEL

Prior to implementing certain geotechnical solutions, experimental tests are necessary to confirm the effectiveness and feasibility of this solution. Given the of conducing field tests in certain cases, such as in the railway case where the road operation must be stopped so the test solution can be implemented or built, the reduced scale models are a possibility to develop studies of the geotechnical solution, faster and at a lower cost. It is important to emphasize that the test held directly in real traffic conditions are imperative, due to the ideality presented in your results.

According to Wood (2004), the physical modeling is essential for understanding geotechnical mechanisms, and a model is a simplification of reality. Thus, in order to develop a proper reduced model, it is important to recognize the limitations that this simplification brings to the experimental tests.

Having a good knowledge of the model limitations, the result can be reliable since the errors can be calculated. The reduced model present in this work was built with a 1:2 scale and, through a dimensional analysis, the dimensions and properties of the constituent elements applicable to this scale were found. For this work, the denomination Prototype was adopted for the railroad under real conditions and Model for the reduced scale model.

2.1 – Geometry

Based on the DNIT ISF-207 specification (2015), Brina specification (1979) and the guide AREMA (2009), the following dimensions and specification were considered for the prototype:

- Metric gauge: 1,0 m;
- Rail sleepers: 2,00 m x 0,22 m x 0,16 m (length, height and width);
- Rail TR-68;
- Ballast thickness: 0,30 m;
- Ballast slope of 1:1,5 (height-base);
- Shoulder width: 0,20 m;
- Platform of the subgrade and sub-ballast: 0,50 m from the ballast slope.

Considering the road symmetry, it was decided to simulate only half of the section of the reduced model, and applying the 1:2 scale, it was possible to obtain a reduced geometry as shown in Figure 1 and Figure 2.

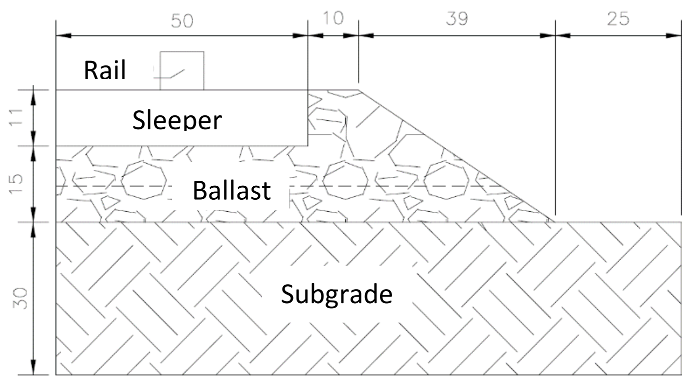

Figure 1. Reduced model dimensions (elaborated by the author)

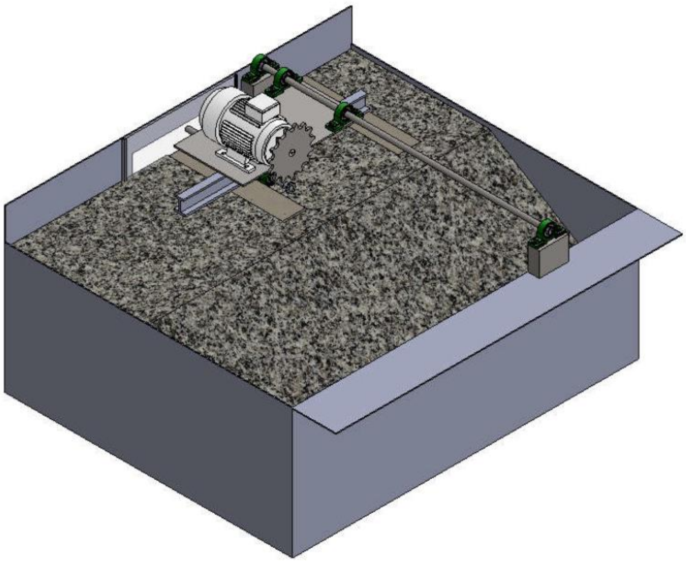

Figure 2. Reduced model design (elaborated by the author)

2.2 Rail and Rail Sleepers Dimensioning

In order to dimension the rail in a reduced scale, the model aimed to maintain a similar stiffness of this element as in the prototype, applying a scale used in the stiffness. Since the rail in both situations is made of carbon steel, the scale can be applied only at the moment of inertia. Taking as reference the rail used in the prototype (TR-68) and its moment of inertia of the order of 3950 cm^4 according to Brina (1979), a reduced rail was dimensioned in 1:2 scale, with a moment of inertia of the order of 247 cm^4.

For the rail sleeper, a similar method was applied. The sleeper considered for the prototype is made of wood, presenting a moment of inertia of the order of 14197 cm^4. Thus, for the reduced model, it was built a rail sleeper with the dimensions of 0,5 m x 0,11 m x 0,08 m (length, height and width) that provides a moment of inertia of 887 cm^4.

2.3 Geogrid Dimensioning

To determinate the geogrid, three variables were taken into account: the stiffness of the geogrid, the mesh opening and the type of the opening.

- Stiffness

To dimension the stiffness used in the reduced model, a dimensional analysis of the variables involved in the greogrid reinforcement of the ballast layer phenomenon was held, based on Chawla and Shahu (2016) research. Figure 3 presents the phenomenon considered in the dimensional analysis.

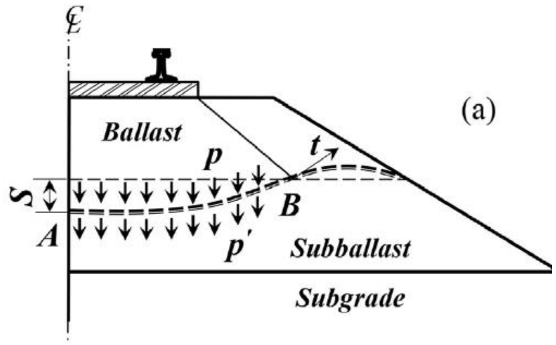

Figure 3. Geogrid reinforcement of the ballast layer phenomenon (Chawla and Shahu, 2016)

As Chawla and Shahu (2016):

P is the vertical stress at ballast-subballast interface (kPa);
P' is the vertical stress é a tensão transferred underground below the geogrid (kPa);
Pg =P- P' (kPa);
B is the angle formed between the traction component with the vertical (°);
T is the tensile strength (kN/m)
S is the settlement of ballast-subballast interface at the center (m).

The dimensional analysis, performed through by dynamic similarity, set an equal p_g value to the prototype and the model, and by the sum of the vertical forces, a applicable scale was found for geogrid stiffness of the 1:4 model, as it follows:

For the prototype:

$$Pg\ x\ 2L = Tp\ x \cos Bp \quad [1]$$

For the model:

$$Pg\ x\ L = Tm\ x \cos Bm \quad [2]$$

Dividing Equation 1 for Equation 2:

$$\frac{\mathrm{Tp}}{\mathrm{Tm}} = \frac{2\mathrm{cosBm}}{\mathrm{cosBp}} \quad [3]$$

Considering the S value infinitely smaller than the L value, then:

$$\cos B\mathrm{m} = \frac{\mathrm{S}}{\sqrt{S^2 + L^2}} = \frac{S}{L} \quad [4]$$

$$\cos B\mathrm{p} = \frac{\mathrm{S}}{\sqrt{S^2 + (2L^2)}} = \frac{S}{2L} \quad [5]$$

Replacing Equantions 4 and 5 at Equation 3:

$$\frac{\mathrm{Tp}}{\mathrm{Tm}} = 4 \quad [6]$$

Being k the geosynthetic stiffiness (kN/m):

$$T = k\ x\ Eg \quad [7]$$

$$\frac{kp\ x\ Eg}{km\ x\ Eg} = 4 \quad [8]$$

$$kp = 4\ x\ km \quad [9]$$

- Mesh opening

According to Palmeira (2018), the reinforce mechanism of the geogrid with soil or aggregate can be divided in two aspects. The first aspect refers to the friction at the geogrid/aggregate interface and the second one refers to the passive resistance of the cross members and the interlocking between the geogrid and the aggregate. This results in the importance of specifying a mesh opening that obtains a optimal interlock with the reinforced material.

In this context, based on Brown et al. (2007), there is a great relationship between the geogrid mesh opening and the D_{90} of the aggregate of the order of 1,4 $D_{90.}$ For the prototype, considering a D_{90} of the order of 55mm based on the specification of NBR 5564:2011, the ideal mesh opening of the geogrid for ballast reinforcement would be of the order of 75mm. Applying the geometric scale used for the model, the ideal mesh opening for the model is of the order of 37 mm.

- Types of openings

Biaxial geogrids with triangular openings have been used as reinforcement for pavements with great success. The triaxial geogrids were introduced to the market in recent years and, according to Peng and Zornberg (2016), they offer advantages such as having three principal directions of stiffness, high resistance due to the hexagonal shape of the opening and they offer thicker mesh elements, increasing the parcel of aggregate confinement.

According to Chen et al. (2013), in biaxial geogrids, the passive resistance is mobilized only in transversal ridges, while in the triaxial geogrid, there is an additional portion of passive resistance in the transversal ridges.

For the reduced model, the Triaxial Geogrid (TRIAX TX8: Polypropylene geogrid, rigid and extruded, with an triangular opening with 33mm and radial stiffness to 0,5% of strain at 225 kN/m) was chosen, which contains the opening mesh size and stiffness coherent to the dimensioned scales.

2.4 Load dimensioning and frequency

The dynamic load on the prototype can be defined through the method present by Arema (1996), as it follows:

$$\mathrm{Pdi} = 1 + \left(\frac{0{,}0052\ \mathrm{x\ V}}{D}\right)\mathrm{Psi} \quad [10]$$

Let:

- P_{di} (kN) is the dynamic load;
- V is the train speed (km / h). For the prototype, it was considered an average speed of load transport practiced of 20 km/h;
- Psi (kN) is the static wheel load. For the prototype, a axle load of 25t was considered;
- D is the wheel diameter (m). Wheel diameter of 0,84 m it was considered for the prototype.

The dynamic load is calculated for the prototype, only for half of the section, and it is of the order of 140 kN.

To consider the load in the reduced model, it was considered studies by Indraratna et al. (2001), which show that the static load applied to the wheel cannot be the same as that considered for the rail section located immediately below the wheel, as a stress distribution occurs along the rail and the adjacent sleepers, and recommends the consideration that 50% of the wheel load is transmitted directly below the wheel. Thus, the load considered for rail application has been reduced to 70 kN.

By dynamic similarity, the scale applied to the force must be the cube of the geometric scale (2^3), which results in a load applied to the model of 8,75 kN.

The frequency verified for the prototype, considering the passage of two adjacent tricks with 5.4m wheelbase at a speed of 20km/h, is of the order of 1Hz. For the reduced model, considering the scale, it was concluded that the applied frequency should be of the order of 8Hz.

2.5 Number of cycles applied

The number of load cycles applied in the reduced model was chosen based on studies of Raymond et al. (1975), Ionescu et al. (1998) and Jeffs and Marich (1987), who concluded that ballast stabilization, when settlement becomes practically constant, occurs around 100,000 (10^5) loading cycles. Other authors also tested reduced models with cyclic loading and all found a critical number of cycles around 10^5, according to Shin et al. (2002). Thus it was chosen to apply a number of cycles equal to 100,000 (10^5) load cycles.

3. MATERIALS USED FOR SUB-BALLAST AND SUBGRADE

3.1 Ballast

For the ballast material in the reduced model equipment, a reduced grading curve was required. For this, the parallel grading technique was used, where the reduced particle size curve is parallel to the original curve and the aggregates must have the same properties in both prototype curve and model curve. Thus, the Brazilian standard NBR 5564: 2011 was used to define the grading curve used for the prototype, and applying the 1: 2 geometric scale, it was possible to obtained the reduced curve as shown in Figure 4 below.

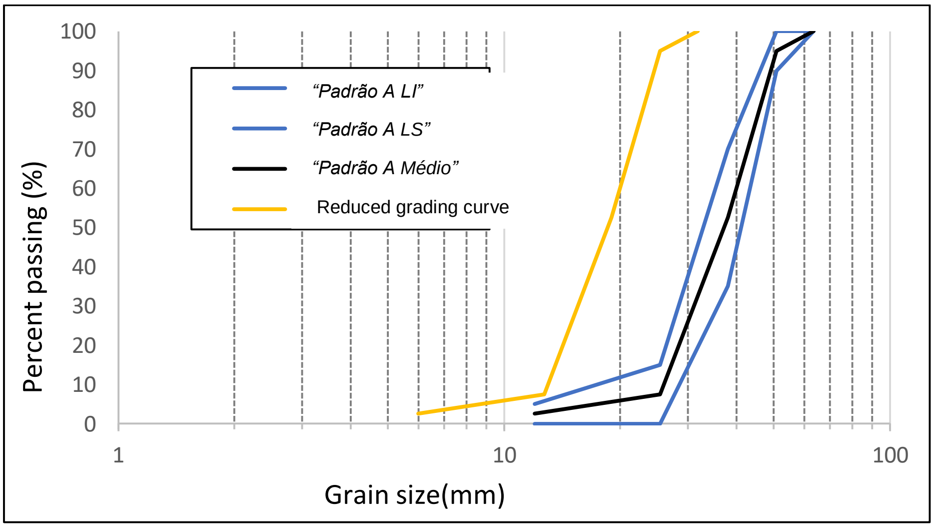

Figure 4. Grading curve (elaborated by the author)

The grading curves "Padrão A LI" and "Padrão A LS" represent the curves recommended by the standard. The decal curve is the reduced mean curve. To determine the reduced curve, grain size tests will be performed to ensure the range of variation of the reduced curve within the expected pattern.

3.2 Subgrade

The soil used in the model was taken from a UFMG test area, located at the Hydraulic Research Center (CPH), excavated to a depth of 1.0m. In order to define soil properties, a sufficient amount of soil was collected for characterization and strength tests for the reduced model. In the tactile-visual analysis, the soil was classified as a red silty clay. The soil was used in real scale, showing a limitation of the model, as it presents properties such as strength and stiffness of the subgrade superior to those expected for the model.

4. INSTRUMENTATION

To measure the stresses along the depth of the ballast layer, full stress cells were used, with location shown in Figure 5 below. The cells located in the ballast/sleeper interface have the objective of possibly verifying the contact stress of the ballast sleeper in the ballast particles and compare it with the expected distributed stress for this interface. The total stress cells located in the subgrade/ballast interface were installed to verify the stress that reaches the subgrade, with and without the insertion of the geogrid, and confirm if there is a change in behavior. The other cells were installed for a possible understanding of the behavior of the stresses along the stress bulb in the ballast layer.

To measure the displacements, LVDT type displacement transducers were used to verify the total displacement (subgrade + ballast). Settlement plates were also used at the subgrade/ballast interface. The first variable minus the second provides displacement only in the ballast layer. This verification becomes necessary due to the limitation of the soil use in the real scale mentioned.

To check the load applied to the rail, a strain gauge system was used. Figure 5 below shows the instruments positioning.

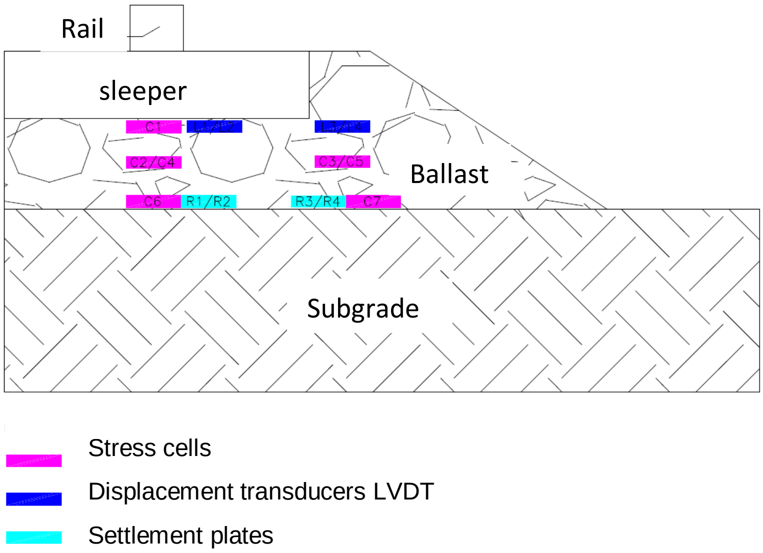

Figure 5. Instruments positioning (elaborated by the author)

5. CONCLUSIONS

The reduced model was built to simulate a seismic load test at railways reinforced or not with geogrid. The objective was to evaluate if the accumulated permanent deformation is reduced with the insertion of the geogrid in the ballast layer. Also, it was evaluated what would be the optimum height of the geogrid placement for the conditions of this test and what is the ballast breakage verified at the end of the simulation.

It is important to mention that every model has limitations, and in this case, some of them can be cited, such as the symmetry of the model, that can lead to a different stress distribution in the symmetry section when compared to the real conditions. In addition, the anchorage of the geogrid on the symmetry axis may also represent a different condition than in the field. Another limitation of the model is the fact that the soil has geotechnical properties consistent with the real scale properties, while other properties of the model, such as equipment dimensions, geogrid stiffness and mesh opening were reduced. For this last limitation, it is likely that the soil will present a stiffer behavior than under actual field conditions, which may induce lower deformation values when compared to the field conditions values.

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