Proposition for in Situ Evaluation of Geotechnical and Structural Aspects of a Heavy Haul Track

Robson Costa, José João Pires, Edson Moura, Rosângela Motta, Guilherme Castro, Liedi Bernucci, and Luciano Oliveira

Abstract Over time railroad tracks have their structural quality varying in function of traffic accumulation and maintenance. These changes can provoke different track responses in terms of unexpected stresses and deformations that, in turn, can bring on some loss of geometric quality and cause impact to the trafficability. Track condition monitoring can indicate the variation of geotechnical and structural characteristics in terms of traffic accumulation, maintenance, drainage, etc. The knowledge about these variations can provide information about the major factors that affect track behaviour and so support the maintenance planning of a railroad management operator. The aim of this paper is to propose a procedure for in situ evaluation by monitoring geotechnical and structural responses of typical sections of a heavy haul track (314 kN/axle) in the north region of Brazil. The implemented instrumentation was conceived using strain gauges for deformation measurements, vertical pressure cells for stresses monitoring and linear variable displacement transducer (LVDT) coupled to displacement measurement device (DMD) and tactile sensors. In addition, suction sensors were installed for measuring negative pore-pressure in the subgrade. From

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R. Costa (🖂) · J. J. Pires · E. Moura · R. Motta · G. Castro · L. Bernucci
Polytechnic School of University of São Paulo, Prof. Alm. Prado Ave. 83, São Paulo, Brazil
e-mail: robsoncosta@usp.br

J. J. Pires
e-mail: eng.josejoao@gmail.com

E. Moura
e-mail: edmoura@usp.br

R. Motta
e-mail: rosangela.motta@usp.br

G. Castro
e-mail: guilhermecastro@usp.br

L. Bernucci
e-mail: liedi@usp.br

L. Oliveira
Vale S.A, Dante Micheline Ave. 5500, Espírito Santo, Brazil
e-mail: oliveira.luciano@vale.com

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the deformations in the web rail and considering an analytical model, it was possible to determine the wheel dynamic loads. It was observed the load factor values varying according to train speed and track quality, as well as the influence of the dynamic load in the stresses over the profile. Concerning the subgrade, the suction pressure presented slight variation (condition near saturation) during the period of analysis, so it could influence the track structural responses to the loads.

Keywords Railroads · In situ instrumentation · Heavy haul track · Geotechnical and structural responses

1 Introduction

The structural condition of the permanent way is related to the stresses and deformations acting on the track components (rails, sleepers, ballast, etc.). Normally, the methodology in structural analysis is based on the comparison of acting stresses with respective allowable materials, which should be superior to the allowable ones [1]. In heavy haul railroads, the pressure among competitors for larger world market shares requires company strategies to achieve better results [2]. In order to target these results, companies can speed up vehicles, carry larger volumes of cargo or even both combined. However, these factors contribute significantly to the increase of stresses acting on all components of the track over time, considering traffic accumulation and maintenance actions, especially on heavy haul tracks [3].

Along the traffic accumulation, geotechnical elements of the track, including the subgrade that crosses different soil horizons, influenced by weathering actions, thus being susceptible to resistance changes [4].

The function of the track components is to reduce the stresses transmitted by the dynamic passage of vehicles from the wheel-rail contact to the foundation. Magnitude of values generated at the interfaces is presented by Esveld [5] and Lichtberger [6]. Also, according to Selig and Waters [7], the loading imposed with the passage of trains added to the temperature changes generate stressing efforts on the track structure. These efforts can be classified according to the direction of operation (longitudinal, transverse and vertical).

Regarding the railroad track quality, it is known that through the track deflection measurements, it is possible to calculate the track modulus (u) and so obtain the elasticity and stiffness conditions of the substructure [8]. However, this condition may be influenced by the presence of voids between the base of the sleeper and the top of the ballast [9]. Related to geotechnical materials, studies conducted by Tutumluer [10] at the facility accelerated service testing (FAST) for high axle load in Pueblo (Colorado) indicated, in terms of vertical displacements in the evaluated section, that there is a greater contribution of the ballast layer compared to the subgrade (10% of the total displacement). On the other hand, evaluations performed by Selig and Waters [7] showed that the subgrade is one of the most important components of the substructure, providing resilient support to the loading of the vehicles' wheels, besides contributing substantially to the elastic deflection of the rails.

The importance of the subgrade is due, among others, to the fact that in the different seasons of the year, the actions of weathering altering its bearing capacity. In this regard, Fredlund and Rahardjo [11] describe that variations in climatic conditions significantly influence the proximity of the soil surface. In arid and semi-arid climates, which have higher evaporation rates than precipitation, in addition to low water levels, cracks in the soil may occur. This phenomenon is caused when the pore suction stresses in all directions exceeds the confinement stresses to which the soil is subjected. In relation to the soil of the railroad subgrade, it is located in the unsaturated zone (above the water table), as well as most engineering structures designed with compacted soils, being very sensitive to local climatic conditions.

The objective of this study was to propose a procedure for in situ evaluation of structural and geotechnical aspects by adopting sensors between the track components measured over the dynamic passage of vehicles on a heavy haul track. This study contributes to the assessment of the increase in load per axle of the wagons through a better understanding of the efforts generated in the components of the permanent track dynamically and the subgrade conditions facing climate actions throughout the year.

2 In Situ Tests Using Devices and Sensors

Obtaining in situ parameters of a railroad track in operation is extremely relevant in the analysis of mechanical behaviour between the different superstructure and substructure components. According to Manda [15], the instrumentation in the railroad track using known loads allows the quantification of deformations, stresses and displacements. In addition, in order to better understanding the railroad behaviour, such studies are of great importance for improvements in the design of the individual elements (rail, sleepers, ballast, subballast), aiming to increase vehicle traffic safety and transported load capacity.

Concerning the materials that compose the subballast and subgrade, the water dynamics change the state of densification and stresses between the particles, causing changes in bearing capacity. The bearing capacity can be verified, for example, through light weight deflectometer, LWD [12, 13] and dynamic cone penetrometer, DCP [9, 14].

Data provided by such equipment concerning geotechnical materials is essential in the structural evaluation of the railroad track since the forces acting in the vertical direction are the ones that most impact the railroad structure, especially under dynamic loading [7]. They cause high stress levels and, if they are above the resistance of the track components, there is an acceleration of the deterioration of these track elements, which can even lead to rupture (concrete rails and sleepers), degradation (ballast) and permanent deformation (subballast and subgrade).

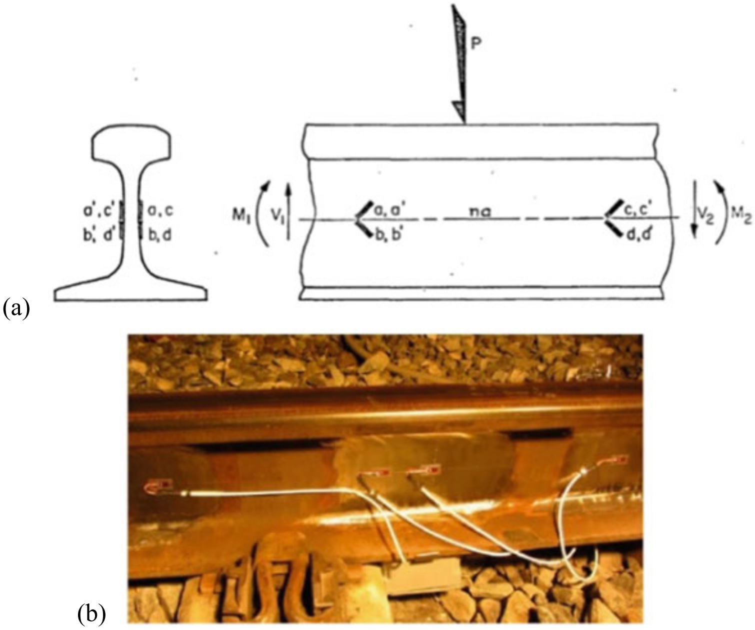

Fig. 1 **(a)** Sketch of the SG arranged on the rail web faces [16] and (**b)** fixed to the rail web [17]

Regarding the vertical load transmission with the dynamic passage of the vehicles, deformations measured from strain gauges (SG) fixed to the rail web [16–18] can be obtained, so the assembled circuit forms a Wheatstone bridge.

Figure 1 (a) and (b) shows, respectively, a sketch of the SG arranged on the faces of the rail web and oriented 45° with respect to their neutral axis [16] and (b) fixed in the rail web of the railroad [17], where the vertical load (P) is calculated by an analytical model [16], considering the (i) strain measurements in the SG, (ii) the difference between the shear forces (V_1 and V_2), and (iii) rail parameters: modulus of elasticity (E), moment of inertia (I), Poisson's ratio (ν), rail thickness at neutral axis (t) and static moment of cross-sectional area (Q).

Regarding the efforts transmitted from rail to sleeper, it has been measured [18, 19] through the matrix-based tactile surface sensors (MBTSS) system. It consists of a triad composed of a thin-film pressure sensor and a sensor-attached data acquisition handle and connected via a USB cable to a computer that contains a dedicated software (I-Scan, Tekscan).

Concerning the tensions transmitted by the sleeper to the geotechnical materials, pressure cells have been employed to evaluate vertical and transverse stresses at different depths. Indraratna et al. [20] conducted in situ tests on a 60 m track section containing a ballast thickness of 300 mm and a subballast of 150 mm, divided into four railroad sections of 15 m (composed of recycled ballast; recycled ballast and geocomposite; new ballast and geocomposite and new ballast) in the city of Bulli

(Australia). The results showed vertical and horizontal tensions in the sleeper/ballast interfaces, respectively, close to 300 and 50 kPa (passing trains with 25 tons per axle). Considering the same directions at a depth of 300 mm, they were, respectively, close to 90 and 25 kPa.

In terms of assessing the contribution of the components underlying the rail, one parameter used on several railroads around the world as an indicator of elastic response [8] and rail quality is the track modulus (u). It requires the measurement of field displacements for an analysis of a particular railroad. In these, studies conducted in situ [4, 7, 20–30] employed different devices (Multidepth deflectometers—MDD; remoting video monitoring—RVM; laser dynamic deflectometer—LDD; and device for measurements of displacements—DMD) and sensors (linear variable displacement transducers—LVDTs; geophones and laser). It is noteworthy that some studies included the evaluation of displacements within the layers at different depths.

In the case of the subgrade, due to the fact that it serves as an elastic support to the acting stresses of the overlying components, it is of fundamental importance to the railroad track [31], so the soil must present geotechnical properties compatible with weathering actions (deformability, resistance and permeability).

Lu and Likos [32] explain that the variation of soil moisture and suction as a function of climate is a unique feature of unsaturated soils. According to Fredlund and Rahardjo [11] and Marinho [33], several methods have been proposed in order to determine the constitutive relationship between suction and soil moisture. Such methods can be classified as direct and indirect, which vary depending on the type of suction measured the measurement interval and the equilibrium time with the soil. In this case, the granular matrix sensor can be used for in situ evaluations (GMS 200SS) [34], which operates similarly to the porous gypsum block, based on the principle of electrical conductivity [11, 35]. This model was used by Castro [36] to evaluate the influence of geotechnical and climatic conditions on the hydro-mechanical behaviour of a railroad subgrade. After developing a numerical model of unsaturated infiltration and field monitoring, the author found that during the dry season, the suction values increase and, consequently, the subgrade soil present better behaviour.

Cui [37] monitored the variation of suction and water content throughout the seasons through suction sensors (tensiometers) installed on the interlayer (geotechnical layer formed by the mixture between ballast and subgrade soil) of a high-speed rail track. The devices were installed at a depth of 20, 30 and 50 cm, protected both under the track and at its ends. The results showed that the ballast, besides facilitating the presence of water in the subgrade, also hinders its evaporation, maintaining low suction values compared to the outside of the railroad.

3 Methodology

The methodology employed in this study aimed to propose an in situ procedure in order to measure structural and geotechnical aspects of the railroad track components. It was based on the use of sensors in two railroad track sections (rigid and elastic foundation) of the Carajás Railway (EFC), which is 892 km long and located in the north of Brazil. Tests sections are, located at km 538 + 250 m (Açailândia—Maranhão State) and km 656 + 516 m (São Pedro da Água Branca—Maranhão State). Some characteristics of the EFC railroad are: 1600 mm gauge; TR-68 (RE 136) rail; Pandrol fastenings; concrete sleepers, 610 mm spacing between sleepers; crushed rock ballast of 300 mm thickness and subballast (executed in the 200 mm thickness design phase). Iron ore is the main product in the operations of the EFC railroad, and usually, each train has 330 wagons carrying 314 kN per axle (heavy haul).

In the track sections of this study, the following activities were performed: (i) in situ tests using light weight deflectometer (LWD) and dynamic cone penetrometer (DCP); (ii) strain measurements with strain gauges (SG) attached to the rail web; (iii) installation of matrix-based tactile surface sensors (MBTSS) between rail/pad and sleeper; (iv) installation of cells for measuring vertical stresses between sleeper-ballast (VSB) and ballast-subballast (VBSB); and transversal stresses underlying the sleeper-ballast (TSB) and sleeper edge (TSE); (v) installation of sensors to measure the suction stress; and (vi) measurements of displacements with DMD. It is noteworthy that in the study sections, geotechnical materials were sampled for laboratory characterization in addition to fresh (new) ballast stored in nearby areas.

The in situ characterization of the geotechnical layers of the track was performed using LWD and DCP, respectively, according to ASTM E2583 [38] and ASTM D6951/6951 M [39]. For this, it was performed near the rail/sleeper using the equipment's shown in Fig. 2 (a) LWD and (b) DCP. Regarding the laboratory characterization of the geotechnical materials, AREMA recommendations [40] were considered. Resilient modulus test was performed with the soil from the subgrade in accordance with AASHTO [47] and IPR [48].

(a) (b)

Fig. 2 Characterization aspects at km 538 + 250 m with (**a**) LWD and (**b**) DCP

(a) (b) (c)

Fig. 3 Aspects of (**a**) preparation of the web rail; (**b**) gluing SG; (**c**) SG fixed between sleepers

3.1 Strain Gauges Installation

Rosette strain gauges (XY41—350 Ω, supplied by HBM) were employed and fixed to the rail web following the authors' recommendations [16–18] in order to measure the deformations and, from them, to calculate the dynamic load (*P*). So, initially it was necessary to sand the rail web, so that the surface was smooth and regular. Then, a template was used for marking the neutral line and fixing the SG. After cleaning the surface with solvent, the SG was fixed with appropriate glue to the rail web [Fig. 3 (a), (b) and (c)]. Regarding the acquisition of signal data, the HBM quantum system was adopted, which allows the use of frequencies above 2000 Hz.

3.2 MBTSS Installation

The stresses at the rail/pad-sleeper interface were measured using the MBTSS (model 5101), which is based on the ink resistivity change as the load is applied, sensitizing the sensels and generating what is called frame. The representation in 2D or 3D of all matrix sensels at a given moment is in Fig. 4. It is noteworthy that the sensor must be calibrated in the laboratory previously for an in situ use.

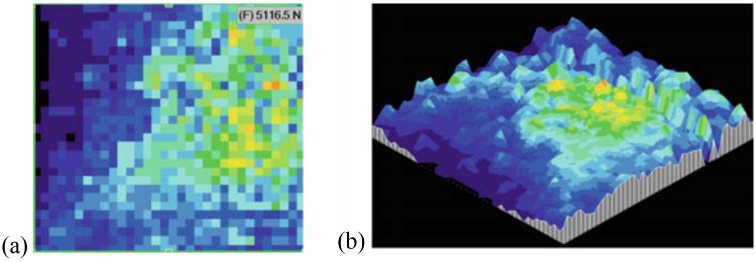

Fig. 4 (**a**) 2D and (**b**) 3D representation of the same frame of a MBTSS

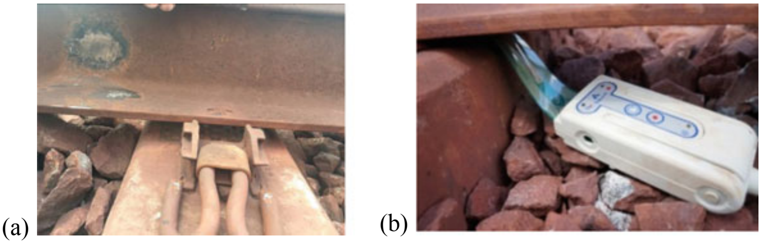

Fig. 5 **(a)** Aspects of the raised rail and **(b)** MBTSS positioned between the rail and top of the sleeper

When installing the sensor on the railroad track sections, it was necessary to remove the fixation of the sleeper and lift the rail a few millimetres with a hydraulic jack, in order to obtain adequate depth and thus the exact position of the MBTSS on the rail/pad-sleeper interface (Fig. 5). Then it was attached to the handle via an USB cable to a computer, thus logging the data through Tekscan's I-Scan software.

3.3 Pressure Cells Installation

The pressure cells used to measure the stresses at the different interfaces (VSB, VBSB, TSB and TSE) were model 3515 (capacities of 100, 250, 600 and 1000 kPa), supplied by Geokon. As previously mentioned, here also it is noteworthy that for in situ use, calibration must be previously performed in the laboratory. Figure 6 shows aspects of pressure cells installed in situ.

3.4 Displacements Measurement

With respect to vertical displacements within the layers, settlement pegs were positioned at the ballast-subballast and sleeper-ballast interfaces, shown, respectively, in Fig. 7 (a) and (b). Regarding to the displacements measured in the web rail, it was recorded through the displacement measuring device (DMD) developed by Costa [30]. It is a metal "arm" which contains at its extremity, linear variable displacement transducers (LVDTs) type sensors that are positioned in the rail base and at a little base connected to the settlement pegs located at different interfaces. The LVDTs, in turn, are connected to an acquisition system (HBM—PMX), which allows adopting frequencies above 2000 Hz of data, recording the displacements with the dynamic passage of vehicles. Figure 8 shows aspects related to DMDs positioned at points A (settlement pegs) and B (reference).

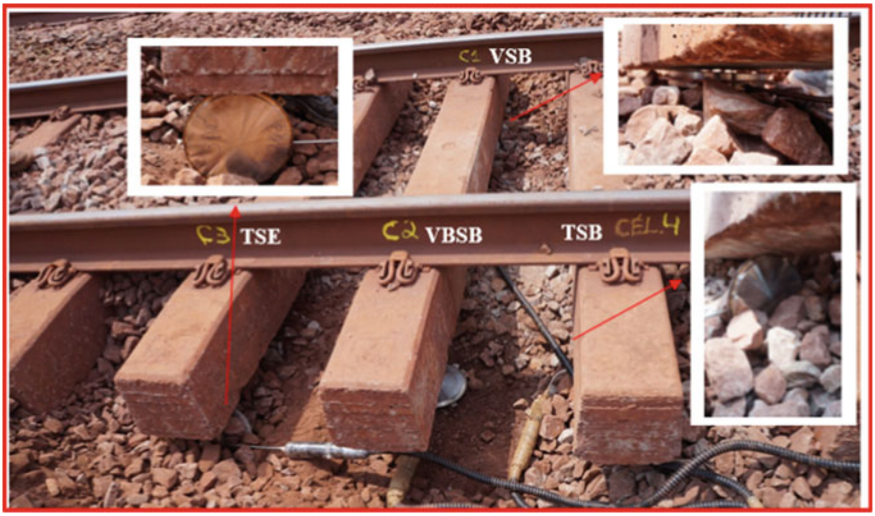

Fig. 6 Pressure cell aspects placed at different interfaces (VSB, VBSB, TSB and TSE)

(a) (b)

Fig. 7 Settlement pegs positioned at interfaces (**a**) ballast-subballast and (**b**) sleeper-ballast

3.5 Suction Sensor Installation

The measurement of the soil matrix potential (suction stresses) of the railroad track subgrade was performed through installation of 5 Watermark granular matrix sensors (GMS-type) at different depths, under a subballast of approximately 200 mm on average. GMS sensors are connected to a data logger for continuous monitoring of data over time with 2 h interval between each measurement. Figure 9 shows the location of each sensor in depth across the subgrade.

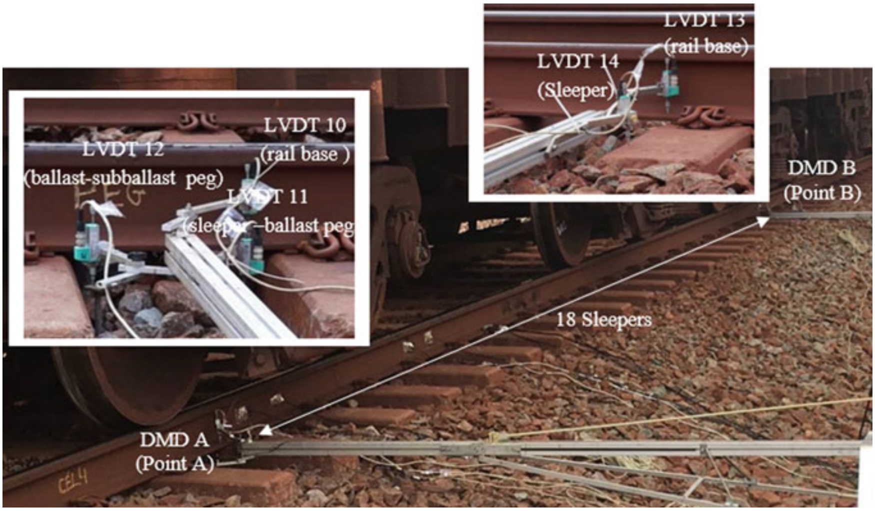

Fig. 8 General aspects of the DMDs positioned in the railroad and LVDTs details

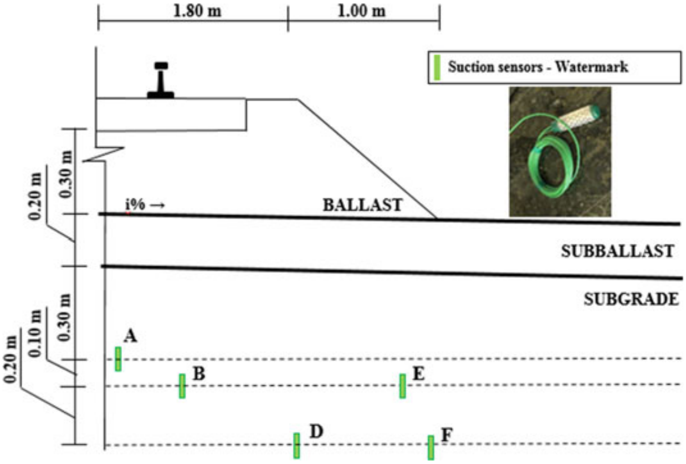

Fig. 9 Location of sensors on subgrade

4 Results and Discussion

4.1 *In Situ Characterization*

The resistance value measured at km 538 + 250 m on the surface of the layer through the LWD was 104 MPa, indicative of high stiffness material. It is noteworthy that this parameter could not be obtained in km 656 + 516 m, due to the presence of

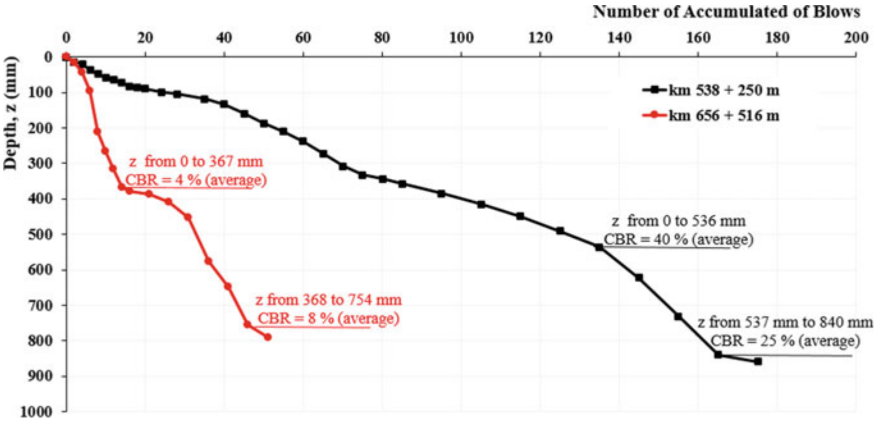

Fig. 10 In situ CBR results through DCP tests in the evaluated segments of EFC

surface water in the layer. The DCP and CBR values were calculated according to the ASTM standard equation results for the two segments evaluated in this study and the results are shown in Fig. 10. In general, it is observed that both segments present significant differences in terms of resistance of the materials underlying the ballast that increase with depth. The results showed good and low bearing capacity, respectively, at 538 + 250 m (CBR value above project minimum, 20%) and km 656 + 516 m (CBR value below project value).

Additionally, grain size distributions [41] of the ballast material are shown in Fig. 11 and compared to the limits of the AREMA N°. 24 grading [40]. Both track ballasts have been found to have slightly departed from the specification limits, while the fresh (new) ballast is slightly below the lower limit and is prone to uniformity.

Regarding the results of characterization of the material underlying the ballast, it was performed only for km 656 + 516 m, due to the low bearing capacity denoted "in situ". From the particle size distribution [42] and consistency limits [43], the soil classification according to TRB [44] was determined, indicating that it is A-2-6 material (excellent to good subgrade quality). Through the universal soil classification system (SUCS) [45], the classification was SC, denoting that it is a clay sand with gravels. In addition, by means of the expeditious method MCT [46], the classification was LG', showing that in the constituent materials, there are clays and sandy clays. The MCT classification was developed in Brazil addressing tropical soils.

Also, in order to evaluate the mechanical behaviour of the subballast material at different stress levels, resilient modulus test [47, 48] was performed. For this, it was necessary to obtain through the Proctor test [49] in the modified energy, the optimum moisture content ($W = 8.7\%$) and the dry bulk density ($\gamma s = 2.140$ g/cm^3). Figure 12 shows the results of resilient modulus as a function of the deviatoric stresses. As expected, it is observed that the increase of the deviatoric stresses influences the behaviour of the material, in order to decrease its resistance.

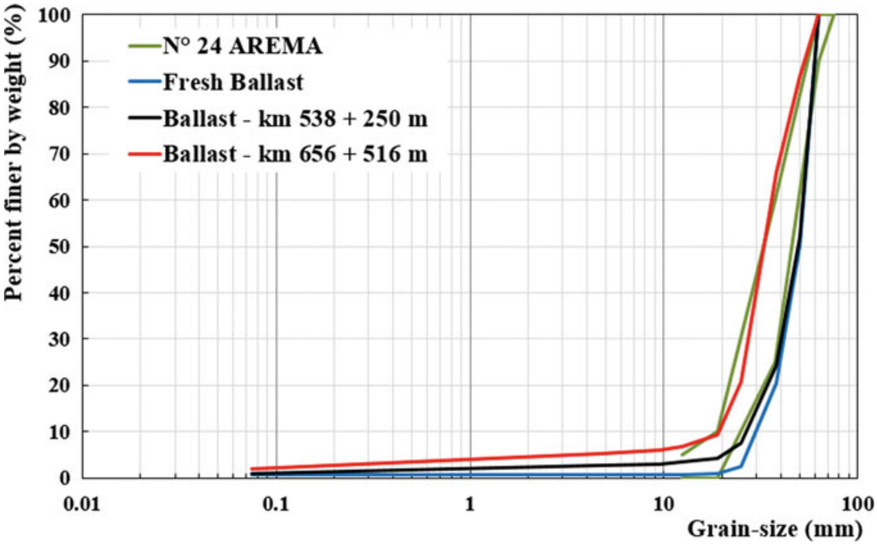

Fig. 11 Grain size distribution results for the sampled ballast

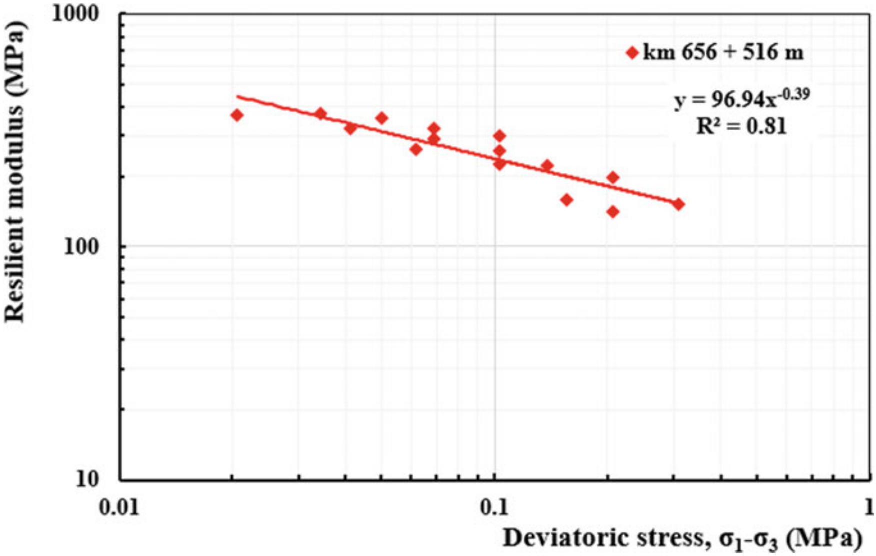

Fig. 12 Resilient modulus results of subballast material

4.2 Measurements Performed by Sensors

Through the SG fixed in the rail web, the deformations in both segments were measured, and through the calculation model mentioned in the item 2 [16], it was possible to determine the dynamic vertical wheel load (P). Signal results obtained in the 538 + 250 m segment with the passing of an empty vehicle (M005—average static wheel load wagons and speed, respectively, 24.5 kN and 65 km/h) and loaded (M818—average static wheel load wagons and speed, respectively, 155.0 kN and 42 km/h) are shown, respectively, in Fig. 13 (a) and (b). From the signals obtained in both trains, it is verified in the case of empty wagon that there is a definition between the peaks generated by the vertical wheel load of the locomotives and wagons, showing that the analytical model used [16] is valid for dynamic load determination (*P*). Comparing both cases, it was observed that there is a high concentration of points above static whell load, showing increases between 20 and 60% in signal levels in relation to the static load, and few that approach or even exceed 100% of that.

Still in the same railroad track section, considering the loaded wagon (M818), the tensions with the MBTSS on the rail/flexible pad-sleeper interface were recorded (Fig. 14). It is observed that there is a small variation between the maximum values of

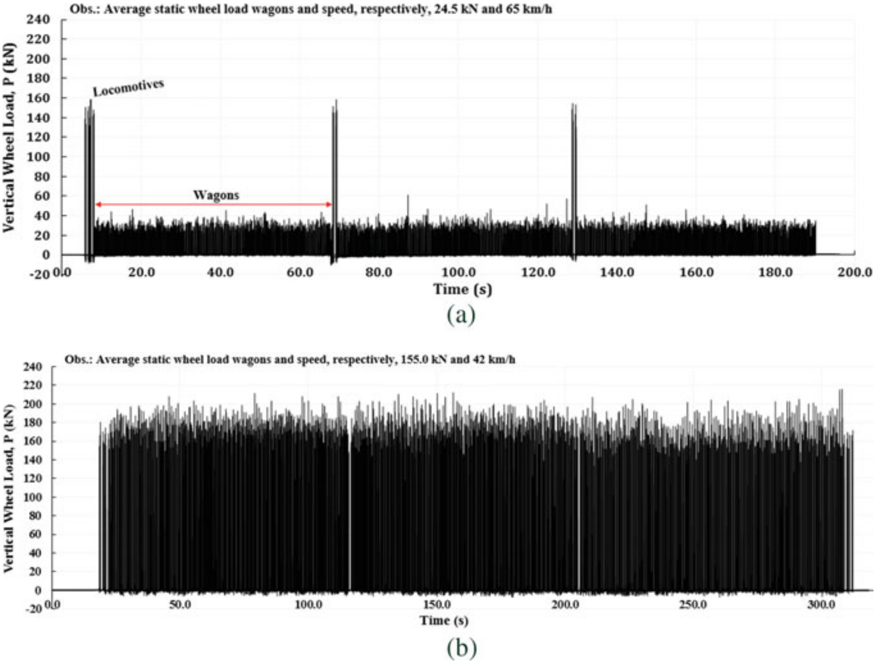

Fig. 13 Full load signal (*P*) obtained with SG with (**a**) an empty wagon and (**b**) a loaded vehicle

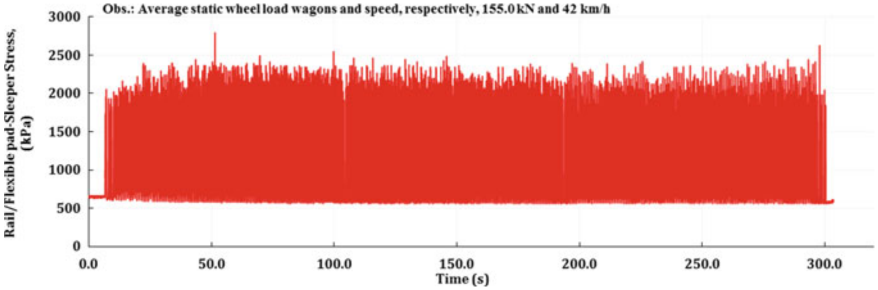

Fig. 14 Signals registered for a loaded vehicle with MBTSS

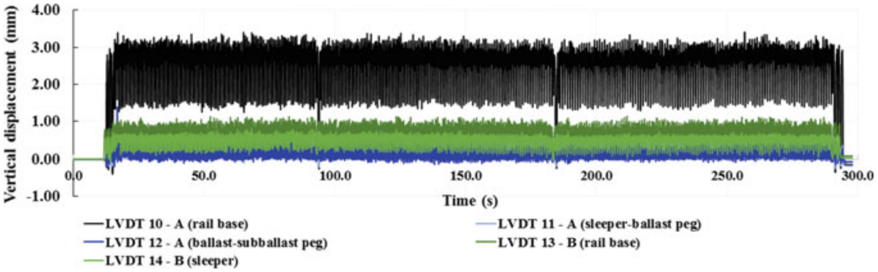

Fig. 15 Signals recorded with LVDTs in the DMDs

tensions measured at the top of the sleeper by the MBTSS with flexible pad (mostly between 2000 and 2500 kPa).

With respect to vertical displacements, considering loaded vehicle (M854 with average static wheel load wagons and speed, respectively, 157.0 kN and 44 km/h) at two points (as Fig. 8), the results were obtained through DMDs (Fig. 15). As previously observed, a slight variation in the maximum amplitude of the basins generated between the axles and trucks was verified. However, an important aspect in these measurements is the difference between the displacements generated in the sensor area (LVDT 10) and the reference (LVDT 13), where the maximum values were, respectively, 3.07 and 0.95 mm in average. This observation was due to the fact that the track structure under the LVDT 10 was disturbed for installation of pressure cells and settlement pegs, differently from the LVDT 13 place, which was not disturbed and so the track structure is presumed to be more consolidated.

In the railroad track section located at km 656 + 516 m, data were also obtained with the same types of sensors presented above. However, due to the low bearing capacity denoted “in situ”, it will only be shown in Fig. 16 the results for pressure cells at different interfaces (VSB, VBSB, TSB and TSE) during the passage of the vehicle M706 (average static wheel load of 153.0 kN and 45 km/h). It is observed through the signals of vertical and transversal stresses that there is variation of what is transmitted by each wheel, generating maximum values at the interfaces VSB, VBSB, TSB and TSE, respectively, of 342, 93, 60 and 47 kPa.

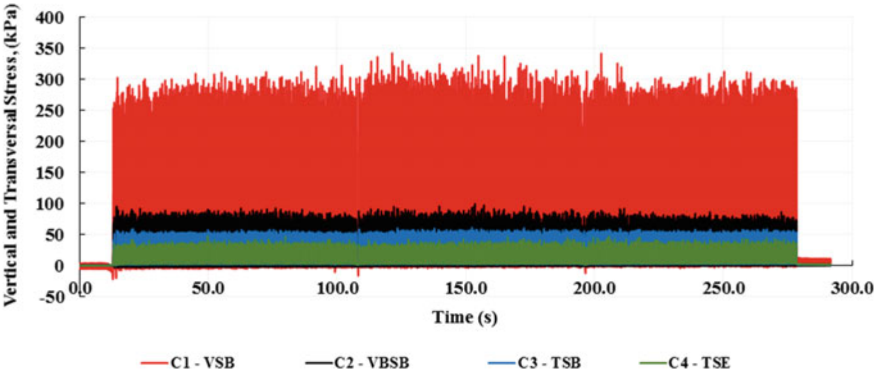

Fig. 16 Signal results from the pressure cells installed

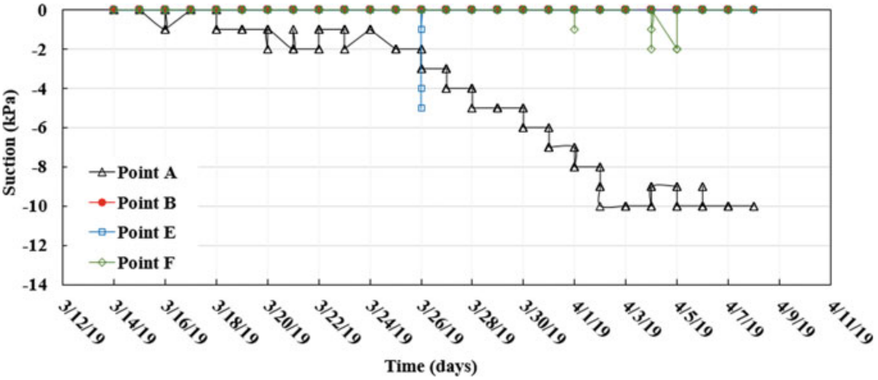

Fig. 17 Signal results of the suction sensors

In the same railroad track section (km 656 + 516 m), suction sensors were installed at different points and depths (A, B, E and F), and the results are shown in Fig. 17. Throughout a month, the suction stresses varied slightly (0–10 kPa), indicating that the materials are under high humidity, close to the saturation condition. However, for a better evaluation of the subgrade quality in terms of water content/suction pressure, it is needed to have more data, especially in different seasons where the variation on precipitation/evaporation could provide significant differences on that parameters and consequently to the mechanical behaviour of the platform.

5 Conclusions

The analytical model adopted for rail deformation using SG based on the literature for dynamic load calculation (*P*) can be evaluated by the passage of loaded and empty wagons. The results of these compared to the static wheel load showed that there were significant increases in the load factor, showing that the analytical model is valid for load determination with the passing of vehicles.

MBTSS sensors showed a very little variation over time considering flexible pad while pressure cells revealed vertical stresses in the interface ballast-subballast of about 25% of that one in sleeper-ballast interface. On the other hand, horizontal stresses in the interface sleeper edge-ballast were found of about 60% of that one in sleeper-ballast interface.

Concerning to railroad displacements, there is a clear influence of material condition in terms of densification. Displacements in the undisturbed region were about 30% lower than the one on the disturbed track structure location.

Results from suction stresses varied slightly over a month period, indicating that the material is under a hydraulic condition very near to saturation. This corroborated with the in situ tests results (LWD and DCP) that showed a subgrade with low bearing capacity.

The signals recorded in all sensors (SG, MBTSS, LVDT, pressure cells and suction sensors), considering different foundations, were compatible with those presented in other studies.

The proposed in situ procedure using sensors is valid for the measurement of structural and geotechnical aspects in a heavy haul railroad track, considering the dynamic passage of loaded and empty vehicles.

In order to contribute for a better understanding of the railroad acting forces and, consequently of the general mechanical behaviour of the track, laboratory evaluations through triaxial tests on geotechnical materials, controls during construction and maintenance phase should be implemented.

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References

1. Doyle NF (1980) Railway track design: a review of current practice. Occasional Paper No. 35, Bureau of Transport Economics, Commonwealth of Australia, Canberra
2. Profillidis VA (2006) Railway management and engineering. Third edn. Ashgate Publishing Limited
3. Pires J (2016) Integrated maintenance model for heavy haul tracks. École Polytechnique Fédérale de Lausanne, Switzerland, 189 p
4. Read D, Chrismer S, Ebersohn W, Selig E (1994) Track modulus measurements at the Pueblo soft subgrade site. Transportation research record 1470. Washington, D. C., p. 55–64. 1994
5. Esveld C (2001) Modern railway track, v. 2. Delft University of Technology, ZaltBommel, Netherlands, 632 pp
6. Lichtberger B (2005) Track compendium: formation maintenance. Econ Eurailpress Permanent Way 3-7771-0320-9, 374p
7. Selig ET, Waters JM (1994) Track geotechnology and substructures management. Thomas Telford Services Ltd., London, p 446p

8. Selig ET, Li D (1994) Track modulus: its meaning and factors influencing it. Transportation Research BoaRD 1470. Washington, D. C., pp 47–54
9. Li D, Hyslip J, Sussmann T, Chrismer S (2016) Railway geotechnics. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, p 584
10. Tutumluer E, Qian Y, Hashash YMA, Ghaboussi J, Davis D (2011) Field validated discrete element model for railroad ballast. In: Proceedings of AREMA annual conference. Minneapolis, Minnesota
11. Fredlund DG, Rahardjo H (1993) Soil mechanics for unsaturated soils. Wiley
12. Nazzal HD, Abu-Farkash MY, Khalid A, Mohamad L (2007) Evaluating the light falling weight deflectometer device for in situ measurement of elastic modulus of pavement layers. Trans Res Board 2016:13–22
13. Costa RC, Motta RS, Bernucci LLB, Moura E, Oliveira Filho JAP (2017) Bearing capacity evaluation of a subgrade in a heavy haul railway in Brazil. In: Proceedings of the 10th international conference on the bearing capacity of roads, Railways and Airfields (BCRRA 2017), June 28–30. Taylor & Francis Group, Athens, Greece, London. https://doi.org/10.1201/9781315100333-280
14. Fortunato E, Pinelo A, Fernandes MM (2009) In situ characterization of an old railway platform with DCP. In: Proceedings of the 17th international conference on soil mechanics and geotechnical engineering
15. Manda KR (2014) Understanding the vertical load path under static and dynamic in concrete crosstie and fastening systems. University of Illinois at Urbana-Champaign, Urbana, Illinois, 62 pp
16. Ahlbeck DR, Johnson MR, Harrison HD, Prause RH (1976) Pilot study for the characterization and reduction of wheel/rail loads—field measurement and data reduction plan. U. S. Department of Transportation Federal Railroad Administration, Washington, D. C., 49 pp
17. Mishra D, Tutumluer E, Boler H, Hyslip JP, Sussman T, (2014) Instrumentation and performance monitoring of railroad track transitionsusing multidepth deflectometers and strain gauges. In: 93rd annual meeting of the transportation research board. Washington, D.C
18. Wei S (2017) Determination of load path through concrete crosstie and fastening system: a laboratory and field investigation. University of Illinois at Urbana-Champaign, Urbana, Illinois, 304 pp
19. Rose J, Stith J (2005) Pressure measurement in railraod trackbeds at the rail/tie interface using Tekscan sensors. University of Kentucky, Lexington, KY
20. Indraratna B, Salim W, Rujikiatkamjorn C (2011) Advanced rail geotechnology-ballasted. Taylor & Francis Group, London, UK
21. American Railway Engineering Association—AREA (1918) First progress report of the special committee on stresses in railroad track. Bull American Railway Eng Associat 19:875–1058
22. Kerr AD (1983) A method for determining the track modulus using a locomotive or car on multi-axle trucks. Bull American Railway Eng Associat 692 84:269–286
23. Gräbe PJ, Clayton CR, Shaw FJ (2005) Deformation measurement on a heavy haul track formation. In: Proceedings of the 8th international heavy haul conference. IHHA, Rio de Janeiro, pp 287–295
24. Silva FCM, Paiva CEL, Aguiar PR (2007) Evaluation of track/ballast behavior under increased axle load: measuring deflections on track. In: Proceedings of the international heavy haul conference. Specialist Technical Session. Kiruna. IHHA, Sweden, pp 31–38
25. Anderson JS, Rose JG (2008) In-situ test measurement techniques within railway track structures. In: IEEE/ASME/ASCE 2008 joint rail conference. Delaware, USA pp 187–207
26. Priest AJ, Powrie EW (2009) Determination of dynamic track modulus from measurement of track velocity during train passage. ASCE J Geotech Geoenviron Eng San Diego 135(11):1547–1778
27. Zakeri AJ, Abbasi R (2012) Field investigation on variation of rail modulus in ballasted railway tracks. Latin American J Solids Struct 9:643–656
28. Vorster DJ, Gräbe PJ (2013) The effect of axle load on track and foundation resilient deformation under heavy haul conditions. In: Proceedings of the 10th international heavy haul and innovation developments. IHHA, New Delhi, India

29. Nimbalkar S, Indraratna B (2016) Improved performance of ballasted rail track using geosynthetics and rubber shockmat. J Geotech Geoenviron Eng 142(8):04016031
30. Costa R, Motta RS, Moura , Oliveira Filho JAP, Bernucci LLB (2017) Measuring device for in situ determination of the track modulus in a heavy haul track. In: Proceedings of the 11th international heavy haul conference: advancing heavy haul technologies and operations in a changing world. Cape Town, South Africa
31. Hay WW (1982) Railroad engineering. Wiley
32. Lu N, Likos W (2004) Unsaturated soil mechanics, vol 19
33. Marinho FAM (1997) Medição de Sucção em Solos. In: Simpósio Brasileiro de Solos Não Saturados, 3, Rio de Janeiro, 373–397. [in Portuguese]
34. Irrometer Company website. http://www.irrometer.com/, acesso em 10/04/2018
35. Shock C, Barnum J, Seddigh M (1998) Calibration of watermark soil moisture sensors for irrigation management. In: Proceedings of the 1998 irrigation association conference on international irrigation show, pp 139–146
36. Castro GB (2019) Avaliação da Influência das Condições Geoténicas e Climáticas no Comportamento Hidromecânico de um Subleito Ferroviário. Master Dissertation. Escola Politécnica da Universidade de São Paulo. São Paulo. [in Portuguese]
37. Cui YJ (2016) Unsaturated railway track-bed materials. E3S Web of Conferences, v. 9, p 1001
38. ASTM. Standard test method for measuring deflections with a light weight Deflectometer (LWD), E2583—07 (Reapproved 2015)
39. ASTM. Standard test method for use of the dynamic cone penetrometer in shallow pavement applications, ASTM. D6951/D6951M—18
40. AREMA. American railway engineering and maintenance-of-way association. Manual Railway Eng (1–4):1-2-12
41. ASTM. Standard test methods for sieve analysis of fine and coarse aggregates, ASTM C136–06
42. ASTM. Standard test methods for particle-size distribution (gradation) of soils using sieve analysis ASTM 6913–04
43. ASTM. Standard methods for liquid limit, plastic limit, and plasticity index of soils, ASTM D4318–10
44. ASTM. Standard practice for classification of soils and soil-aggregate mixtures for highway construction purposes. ASTM D3282–15
45. ASTM. Standard practice for classification of sils for engineering purposes (unified soil classification system) ASTM D2487–11
46. Nogami J, Villibor D (1981) Um Novo Sistema de Classificação de Solos para Rodovias. In: Simpósio Brasileiro de Solos Tropicais em Engenharia, COPPE UFRJ, pp. 30–41. Rio de Janeiro BRA. [in Portuguese]
47. American Association of State Highway and Transportation Officials (AASHTO) (1999) T 307-99–Determining the Resilient Modulus of Soils and Aggregate Materials, USA. 37p
48. IPR. DNIT 134/2010—ME. 2010. Pavimentação—Solos—Determinação do Módulo de Resiliência—Método de Ensaio. Instituto de Pesquisas Rodoviárias—IPR, 1–11. [in Portuguese]
49. ASTM. Standard test methods for laboratory compaction characteristics of soil using standard effort. ASMT D698–12 (2012)