Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast

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Abstract: Despite being the most used worldwide, railway ballasted tracks presents high maintenance cost related to ballast settlement and particle degradation. With the aim of reducing life cycle costs, bitumen stabilised ballast (BSB) has been recently proposed as a relatively cheap alternative maintenance solution to be applied to existing tracks. This study aims at assessing the potential advantages of this technology, defining a novel maintenance strategy of traditional ballasted track-beds. A protocol for the application of the BSB technology and its associated maintenance strategy is defined. To estimate minor and major maintenance operations of BSB scenario in comparison to traditional ballasted track-bed, an integrated model, based on laboratory tests, combining the evolution of track irregularities and ballast contamination with traffic, was used. Results together with a sensitivity analysis related to main parameters adopted revealed that the application of BSB is expected to provide a significant increase of intervals between both minor and major maintenance activities.

Author keywords: Bitumen stabilisation; railway ballast; maintenance; asset management; degradation model; tamping; settlement; life cycle approach.

1. Introduction

1.1. Background

The railway plays a fundamental role in most transportation systems. It provides a fast means of transportation via a durable and economical system. Ballasted track, which consists of track superstructure supported on a layer of granular material (ballast), represents the most used type of structure compared to other alternatives such as concrete slab (Michas 2012; UIC 2016). This type of track presents relatively low construction costs, high maintainability at a relatively low cost (for a single operation), and the possibility of using indigenous material while providing relatively high damping capacity, noise absorption and high flexibility, self-adjusting properties (in the case of non-homogeneous subgrade) and high hydraulic conductivity (Michas 2012; Pratico and Giunta 2017; Profillidis 2016; Selig and Waters 1994; Sugrue 2013).

However, the unbound nature of ballast, which allows it to fulfil its main functions, is also related to reduction of geometric quality of the track, and therefore, its safety and ride comfort (Boler 2012; Dahlberg 2004; Jeffs and Tew 1991; Marsal 1967; Raymond 1985; Salim 2004). The passage of trains causes cyclic movements of the particles that result in permanent vertical and lateral deformations. Thus, for this track form vertical settlement of granular layers and ballast particle degradation represent the major problems affecting frequency of maintenance and track durability. In particular, differential settlement, which is generally due to abrupt changes in vertical stiffness, leads to increased dynamic loading, which can further increase permanent deformation, leading to a self-perpetuating mechanism (Read and Li 2006).

Ballast layer settlement, which forms the highest contribution to total track settlement (Selig and Waters 1994), occurs in two major phases (Dahlberg 2004). The first one is faster and occurs when ballast is in a loose state (after tamping or renewal) and is a consequence of initial major consolidation (re-compaction). The second is due to various mechanisms that occur under cyclic loading: densification, distortion and degradation. Densification is characterised by a progressive consolidation; distortion is the mechanism where by individual particles slide and roll; and degradation represents the change in particle size due to attrition and breakage (Sun et al. 2010).

Aside from contributing to permanent deformation, the degradation mechanism can also prevent the ballast layer from fulfilling its main functions. Indeed, mineral contamination from particle breakage and wear due to traffic loading and maintenance represents the highest source (with more than 70%) of ballast layer fouling (Pires and Dumont 2015; Selig and Waters 1994). This phenomenon jeopardises the rapid draining and elastic characteristics of the ballast layer as well as its ability to be effectively maintained by tamping (Calla 2003; Selig and Waters 1994).

1.2. Track degradation and degradation models

Track geometry degradation is affected by several factors: traffic loads and speed, construction materials and methods, and maintenance history, among others (Audley and Andrews 2013). The track geometry is described by several parameters (BS EN 13848-5:2008+A1:2010 2010): vertical alignment (or longitudinal level), horizontal alignment, gauge, cant and twist (Fig. **1**).

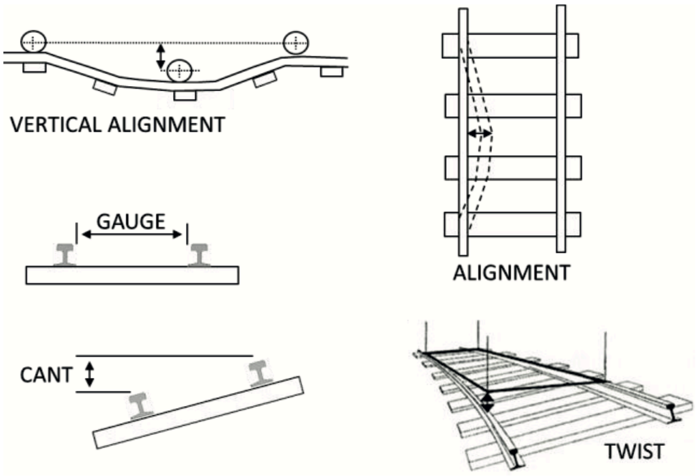

Fig. 1. Track quality parameters (Pires 2016)

Standards prescribe minimum and maximum allowable values for these parameters based on the type of railway line. BS EN 13848 (BS EN 13848-5:2008+A1:2010 2010) states the existence of three indicators of track quality: extreme values for isolated defects, standard deviation (SD) over a typical length (200 m), and mean value. Depending on the type of line and the speed, there are three main limits for these indicators above which different actions need to be undertaken (BS EN 13848-5:2008+A1:2010 2010): the Immediate Action Limit (IAL), which, if exceeded, requires measures to reduce the risk of derailment to an acceptable level; the Intervention Limit (IL), which, if exceeded, requires corrective maintenance in order that the immediate action limit is not reached before the next inspection; and the Alert Limit (AL), which, if exceeded, requires that the track geometry condition is analysed and considered or regularly planned maintenance operations.

In order to plan and/or predict maintenance interventions, rail authorities and practitioners often use the standard deviation as a convenient means of quantifying the geometric quality of a track section

(Chrismer and Selig 1991). In this regard, Table 1 shows the Alert Limits for the longitudinal level SD according to European Standards (BS EN 13848-5:2008+A1:2010 2010).

Table 1. Longitudinal level AL standard deviation according to BS EN 13848 (adapted from BS EN 13848-5:2008+A1:2010 2010)

Speed (in km/h)	**Standard deviation (SD) (in mm) AL**	
	Minimum	**Maximum**
V ≤ 80	2.3	3
80 < V ≤ 120	1.8	2.7
120 < V ≤ 160	1.4	2.4
160 < V ≤ 230	1.2	1.9
230 < V ≤ 300	1	1.5

When quality indexes exceed these limits, maintenance is needed to restore the quality of the track.

Predicting future degradation of infrastructure components is an essential element in maintenance planning. In this regard, the loss of track quality is due to a combination of many factors, the major one being the repetitive passage of trains (Pires 2016). Experience shows that track quality degradation is a function of load amplitude and number of repetitions (Million Gross Tons, MGT) (Hausgaard 2013). By periodic inspection of the track this relationship can be determined for each specific section. However, according to Veit (Veit 2007), variations are observed in the deterioration rate at the same loading level; indeed, the heterogeneity and anisotropy of all granular layers can cause differing local settlements.

Esveld (Esveld 2001) reports deterioration rates in terms of SD of track irregularities (vertical alignment) varying from 0.007 to 0.02 mm/MGT. Similar results (0.005 to 0.025 mm/MGT) were reported by Khouy (Khouy 2011) for a Swedish line with mixed passenger and freight traffic. Slightly lower values, varying between 0.00217 and 0.0119 mm/MGT, were presented by Hawari and Murray (Hawari and Murray 2008) for three heavy haul lines in Australia.

Over the past 30 years, several efforts have been employed to develop analytical models to predict degradation of railway tracks. An extensive literature review (Audley and Andrews 2013; Pires 2016) revealed that field data of track geometry degradation (SD of track irregularities) are best fitted by linear empirical laws as in Equation (1):

$$SD(MGT) = A + C \cdot MGT \quad (1)$$

where $SD(MGT)$ is the standard deviation corresponding to the traffic in MGT; A is the initial value of standard deviation; and C is the coefficient which relates the standard deviation to the cumulative traffic after the initial degradation phase (A).

Nevertheless, most of the models consider track settlement (or track vertical strain) as the main controlling factor in track degradation (Chrismer and Selig 1991; Shenton 1985; Shimatake 1997). This convenient parameter can be simulated through field trials and laboratory tests and can be used for comparing different design and maintenance technologies/strategies, especially at the early stage of the development process.

However, in order to relate settlement to maintenance requirements, there is a need to establish a link between track irregularities, which vary along the track, and track average settlement. Selig and Waters (Selig and Waters 1994) and Berggren (Berggren 2009) reported studies showing that, excluding the initial settlement just after maintenance, the SD of track irregularities grows almost proportionally to track settlement over at least a moderate range of ballast life (Fig. 2).

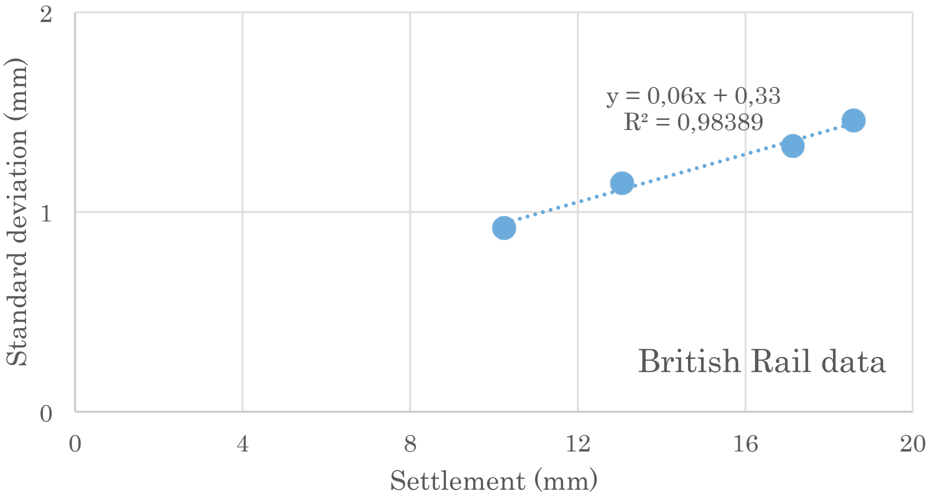

Fig. 2. Relationship between the standard deviation of track irregularities and average track settlement (adapted from Selig & Waters 1994)

1.3. Ballast maintenance

In order to guarantee adequate levels of safety and ride comfort, when the above-mentioned quality indexes exceed prescribed limits, maintenance is needed to restore the quality of the track.

In this regard, from the 1960s until now automatic tamping has been the most used method to correct track geometry defects. The vibrating action of its tines, indeed, allows for re-arranging of particle positions, thus restoring the original position of the track. However, this operation is accompanied by certain detrimental effects: vibrating tines disturb and dilate the densely packed ballast layer, degrading particles and reducing track stability (Calla 2003; Indraratna et al. 2011). In this regard, tamping may not produce a durable track geometry, and the track profile may quickly revert back to its original state, a phenomenon known as ballast memory (Selig and Waters 1994). Another issue related to tamping is the production of a high amount of fines (Aursudkij 2007; Calla 2003; Lim 2004; Sol-Sánchez et al. 2016). A typical 'tamp', due to the vibrating action, can produce up to 4 kg of fines/sleeper/tamp (Fair 2003), increasing progressively the contamination (fouling) of the ballast layer. For these reasons, this operation typically reduces in efficiency after every application (Pires 2016).

As tonnage accumulates, the ballast layer becomes progressively contaminated. Furthermore, ballast layer resistance to permanent deformation, the efficiency of tamping, and the general ability of ballast to fulfil its main functions depend primarily on the content of fine-grained (fouling) material (Nurmikolu 2005). The highest contribution to contamination is given by particle breakage and wear due to traffic loading and maintenance (Pires and Dumont 2015; Selig and Waters 1994). When the contamination level reaches critical limits, the ballast layer needs to be renewed.

Overall, ballasted track-bed requires frequent and costly maintenance. Nonetheless, its use is widespread, and interest is therefore growing in alternative solutions which can reduce the maintenance costs. In addition, the continuing depletion of raw materials with adequate properties presents a need to reduce the degradation of in-service ballast (increasing its durability and reducing the need for renewal), as well as solutions that allow the use of aggregates that are excluded, according to current Standards because of their mechanical properties.

In this context, in recent decades ballasted tracks have been the object of diverse research focused on slowing down the loss in track quality associated with ballast settlement and its progressive degradation. The most common techniques have been aimed at ballast stabilisation using different gluing materials, such as polyurethane, resins or biodegradable polymers (Kennedy et al. 2013; Lakušic et al. 2010; Momoya et al. 2016).

1.4. Bitumen Stabilised Ballast (BSB) as solution to reduce track-bed maintenance costs

Among other stabilisation techniques developed over the past few years, Bitumen Stabilised Ballast (BSB) represents an innovative solution designed to be used for new track-beds as well as to reinforce existing ones. It consists in the use of bitumen emulsion (BE), which is poured or sprayed at ambient temperature onto the ballast. This technology is being developed through small-scale and full-scale laboratory tests simulative of field conditions, optimising the main factors affecting the stabilised ballast behaviour (D'Angelo et al. 2016a; b, 2017a; b; c).

The initial concept behind this technology was to reduce maintenance of existing ballasted tracks with a relatively economic solution to extend ballast service life, which is also relatively easy to apply. In this regard, in order to minimise the traffic disruption, the bitumen stabilisation would be ideally applied during a routine maintenance operation to correct track geometry such as tamping or stoneblowing. The calculated amount of BE would be sprayed over the ballast surface by a system analogous to that used by the stoneblower when the sleeper is raised during the maintenance process, as illustrated in Fig. **3**. For instance, an optimum dosage for clean ballast was found to be 1.44% by weight of the ballast underlying the sleeper/ballast contact area (D'Angelo et al. 2017a), typically equating to about 1.5 litres per sleeper end.

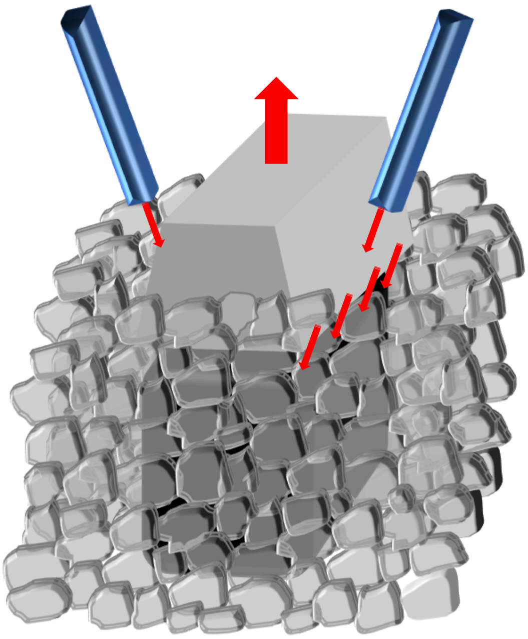

Fig. 3. Schematic illustration of ballast stabilisation process with bitumen emulsion

To carry out this operation, conventional tamping and stoneblowing machines would need to include an additional railcar storing the bitumen emulsion and a system to spray the required dosage under each sleeper end.

In order to stabilise only the ballast subjected to the highest contact pressure (Pires 2016; Shenton 1975) it is considered that one third of the sleeper length per sleeper end should be treated by this operation. This procedure, which was simulated by D'Angelo et al. (D'Angelo et al. 2017b) using full-scale ballast box tests, represents a convenient way to use the same machine to perform both geometry correction and ballast stabilisation with bitumen at the same time.

Despite having shown in previous studies the potential reduction in the need for both minor and major maintenance activities, bitumen stabilised ballast track-bed will require a certain amount of maintenance to restore track geometry and will need renewal at the end of its life. Indeed, based on the initial concept, the stabilised layer would ideally be maintained by stoneblowing in order to not alter the cohesive bridges between particles given by the bitumen application. This operation, simulated in a full-scale ballast box (D'Angelo et al. 2017a), would not modify the BSB structure and so represents an optimum way to restore track geometry while preserving the improvements brought about by BE application. However, stoneblowers are available in only a few countries, tamping being the most common maintenance process used for geometry correction worldwide. In contrast to stoneblowing, tamping may damage the BSB structure due to the vibrating action of tines. In this regard, as with other stabilisation techniques (Kennedy et al. 2013; Lakušic et al. 2010; Laurans et al. 2016), BSB can be considered to have built-in safety to the extent that the loss of cohesion would result in the ballast reverting back to an unbound state. Nevertheless, until further studies on BSB maintainability are conducted, it would be conservative to assume an additional BE application where tamping is used to correct track geometry.

By the same principle, at this stage of the technology development, and especially when using a lifecycle approach to assess the economic feasibility and environmental impact of this innovative technology, it would be conservative to consider the total replacement of old BSB during renewal. In this regard, future studies should focus on the maintainability of BSB through methods which can optimise the reuse of the bitumen coated aggregate, allowing recycling of BSB during renewal operations and increasing savings from a lifecycle point of view.

1.5. Aim of the study and research steps

The aim of this study is to evaluate the potential advantages of the application of BSB and to define a novel maintenance strategy for traditional ballasted track-beds. Indeed, the main objective of this work is to propose a protocol for the application of BSB technology as a new construction and maintenance procedure. An integrated model will be used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound). The integrated model developed in this paper combines the evolution of SD with traffic and the level of contamination of ballast allowing calculation of the timing of maintenance activities. To understand how variations of a set of parameters and assumptions affect the robustness of the model a sensitivity analysis has been carried out. The schedules for tamping and renewal operations over the life cycle of the entire infrastructure are then calculated for different traffic volumes and required SD limit.

2. Development of an integrated track deterioration model

To schedule maintenance activities over a period of analysis, track degradation models, evaluating the evolution of track quality indicators, need to be used. Two indicators were considered for the evaluation of maintenance strategies of both BSB and the reference (unbound) ballast: the standard deviation of track irregularities (vertical alignment) and the ballast contamination level. The minor and major maintenance operations here considered (tamping and renewal) are scheduled after critical levels of track geometry (SD) and ballast layer contamination are reached.

2.1. Standard deviation of track irregularities

The evolution of the standard deviation of track irregularities with traffic for both reference ballast and BSB was calculated using Equation 1.

For this equation, the coefficient A, which is the initial value of standard deviation, was assumed to be equal to 0.33 mm (Pires 2016; Shimatake 1997). This was assumed to be the same for both materials because it represents the initial condition of the track after construction or major renewal.

To evaluate the coefficient C, which controls the rate of degradation with the traffic, the value of settlement rate per loading cycle (SRLC, calculated as curve slope over the last 40,000 cycles) from full-scale laboratory tests on BSB and reference ballast carried out using a ballast box was used (Fig. 4) (D'Angelo et al. 2017b).

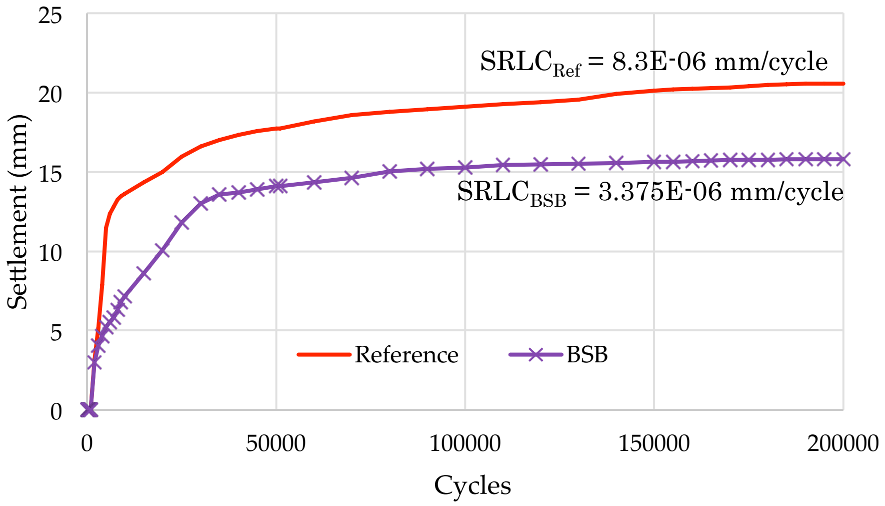

Fig. 4. Evolution of settlement with loading cycles for BSB and reference ballast during over full-scale ballast box dynamic tests (adapted from D'Angelo, Sol-Sánchez, Thom, et al. 2017)

SRLC values were converted to SD using the correlation proposed by Selig and Waters (Selig and Waters 1994) for British Rail, as in Equations (2) and (3):

$$C_{Ref} = SRLC_{Ref} \cdot 40000 \cdot 0.06 = 0.02\, mm/MGT \tag{2}$$

$$C_{BSB} = SRLC_{BSB} \cdot 40000 \cdot 0.06 = 0.008\, mm/MGT \tag{3}$$

In these equations, the SRLC values were firstly converted from mm of settlement/cycle to mm/MGT (40000 factor – 25 t axle) and then to mm of SD/MGT (0.06 - Fig. 2).

The C_{Ref} value, calculated in this way, ties in with those reported by other authors using field measurements (0.005-0.025 mm/MGT) (Esveld 2001; Khouy 2011).

In order to take into account the progressive loss of effectiveness of maintenance (Audley and Andrews 2013), an efficiency of 95% in restoring the geometry after tamping, compared to the previous intervention, was assumed (Caetano and Teixeira 2016; Pires 2016; Shimatake 1997).

2.2. Ballast contamination level

Another important parameter used to determine the appropriate timing of renewals is ballast contamination level (Pires 2016). In this regard, current practice is usually that railway infrastructure managers refer to predetermined values of MGT thresholds or other indicators, using as a criterion the level of ballast contamination. This indicator of degradation of the ballast layer must not exceed specific limits. Nevertheless, these values vary between countries (Bruzek et al. 2016), with no common requirements and a lack of consensus on grain-size diameter and fouling parameters used to define contamination levels. In European countries, for instance, one suggested limit is 30% for particles passing the 22.4 mm sieve (Nurmikolu 2005).

Several studies have evaluated ballast degradation in test arrangements simulating traffic loading. An extensive review of these studies is provided by Nurmikolu (2005). The intention of this analysis is to use laboratory results of ballast particle deterioration obtained in these studies in order to predict the level of contamination in the ballast. For this purpose, in agreement with European standards (BS EN 13450 2013; Nurmikolu 2005), ballast degradation $D(MGT)$ has been defined as the percentage of particles passing the 22.4 mm sieve. Two contributions are considered in the evaluation of ballast degradation: the mineral contamination due to the progressive abrasion and breakage under the cyclic loading and the contamination due to maintenance operations (Audley and Andrews 2013), as in Equations 4 and 5:

$$D_{ref}(MGT) = D_{traffic,ref} \cdot MGT + D_{tamping} \cdot N_{tamping}(MGT) \tag{4}$$

$$D_{BSB}(MGT) = D_{traffic,BSB} \cdot MGT + (D_{tamping} + D_{BSB}) \cdot N_{tamping+BSB}(MGT) \tag{5}$$

where $D_{traffic,ref}$ and $D_{traffic,BSB}$ are the percentages of particles passing the 22.4 mm sieve per MGT for reference ballast and BSB, respectively, obtained from Fig. 5 (the authors' own data);

$D_{tamping} = 0.5\%$ is the percentage of particle passing the 22.4 mm sieve generated per tamping operation (Nurmikolu 2005); $D_{BSB} = 1.52\%$ is the additional percentage of material passing the 22.4 mm sieve due to the addition of BE (calculated from the dosage used for clean ballast); $N_{tamping}$ and $N_{tamping+BSB}$ are the number of maintenance operations for reference ballast and BSB, respectively.

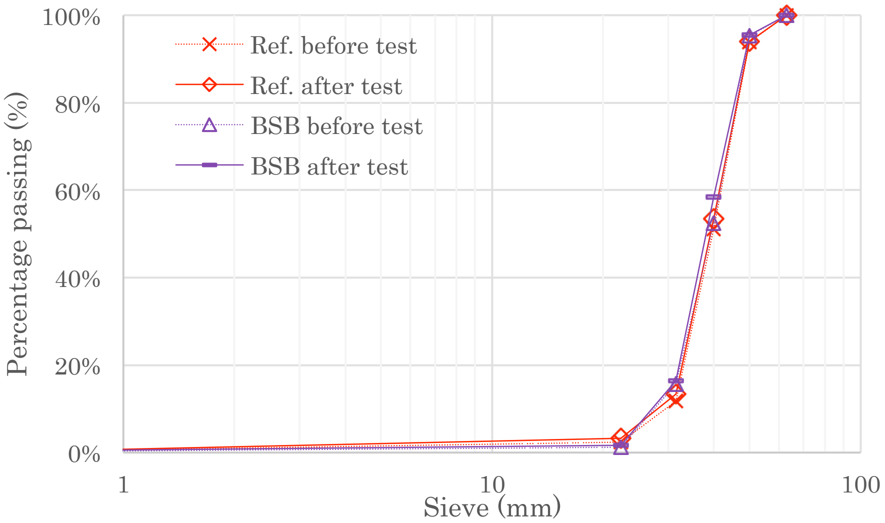

Fig. 5. Particle size distribution for BSB and reference ballast before and after full-scale Precision Unbound Material Analyser (PUMA) dynamic tests (D'Angelo et al., unpublished data, 2017)

3. Results of simulations and sensitivity analysis

Having defined both models, it is possible to predict minor and major maintenance operations as a function of MGT, as shown in Fig. 6 and Fig. 7, where the sudden improvements represent the tamping and renewal actions, respectively.

In this scenario maintenance strategies, are defined as a function of traffic for both tamping (indicated as Reference) and tamping + BSB (indicated as BSB) considering a SD limit of 2 mm (BS EN 13848-5:2008+A1:2010 2010) and a 30% limit for particles passing the 22.4 mm sieve (Nurmikolu 2005).

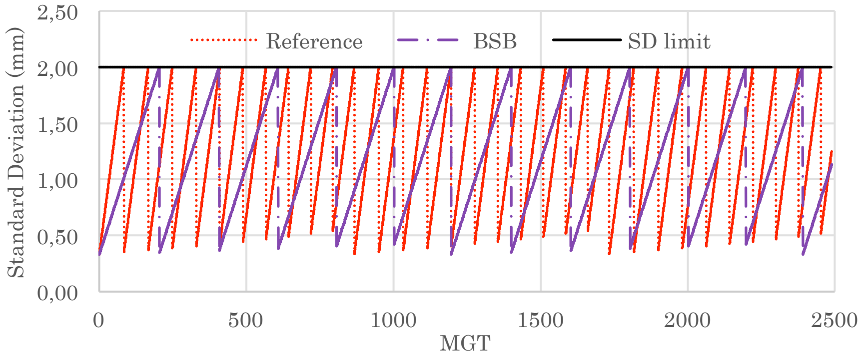

Fig. 6. Evolution of standard deviation of track irregularities with MGT for reference ballast and BSB for an SD limit of 2 mm

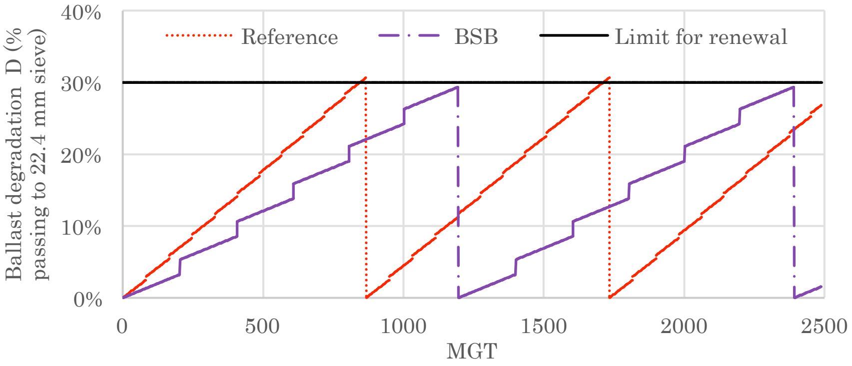

Fig. 7. Evolution ballast contamination due to MGT and tamping operations for reference ballast and BSB for a 30% limit of particles passing the 22.4 mm sieve

It is possible to observe increased intervals between maintenance activities due to the use of BSB which, if proven in reality, would result in important economic and environmental benefits.

In the following section a sensitivity analysis will be presented in order to understand how variations in the set of parameters and assumptions affect the output from the model. Thus, the relative effects of different factors may be evaluated and compared. Two parameters have been considered with different levels: SD limit and annual MGT.

3.1. Influence of traffic and SD limit on maintenance strategies

In order to assess the sensitivity of this technique to the SD limit and traffic, maintenance strategies have been evaluated following the same method, but varying the SD limit from 1.5 mm to 4 mm (with intervals of 0.5 mm) for two values of annual traffic: 20 MGT/year and 40 MGT/year. The traffic growth rate was assumed to be 0.5% per year while a 30% limit is taken for particles passing the 22.4 mm sieve (Berggren 2009; Nurmikolu 2005). In this study, which focuses only on maintenance operations related to the ballast layer, the period of analysis was taken to be 60 years (MAINLINE Deliverable 5.4 2013; Pires 2016). Based on these assumptions, the results of this sensitivity analysis are summarised in Fig. 8 and Table 2.

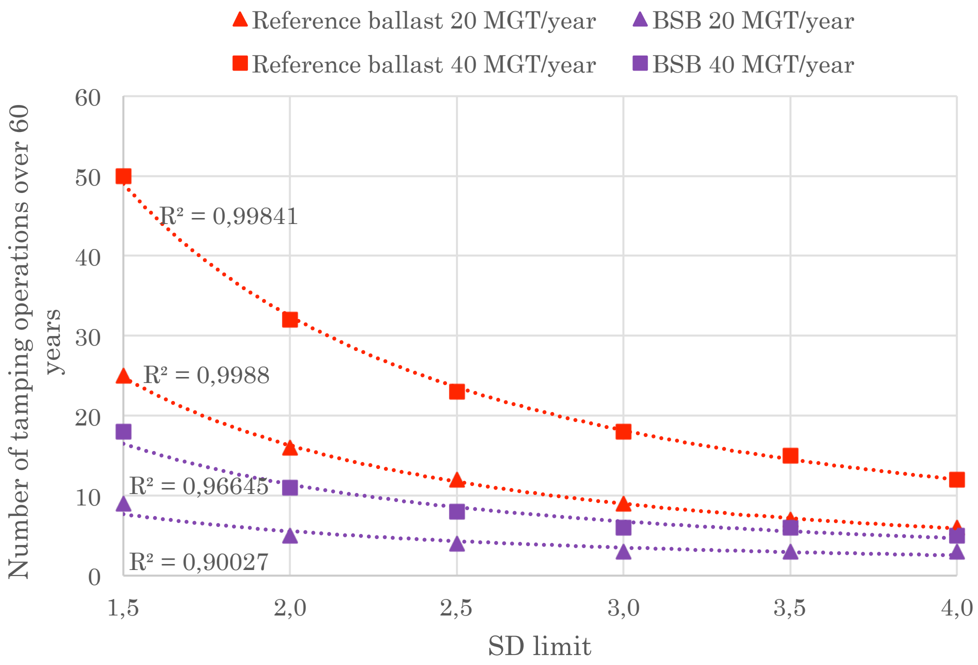

Fig. 8. Evolution of the number of tamping over the period of analysis (60 years) with SD limit for both traffic levels considered (20 and 40 MGT/year) for reference ballast and BSB

Table 2. Predicted ballast service life (year of first ballast renewal)

Traffic	20 MGT/year		40 MGT/Year	
SD limit	Reference ballast	BSB	Reference ballast	BSB
1.5	35.4	48.3	18.4	25.5
2.0	39.4	52.6	20.6	27.9
2.5	38.4	57.0	20.1	30.4
3.0	41.4	56.5	21.7	30.1
3.5	42.3	65.7	22.2	35.3
4.0	41.1	74.4	21.6	40.4

As expected, since BSB gives a lower settlement rate, the number of tamping operations is reduced by almost 60% (±10%) with respect to the reference ballast. In particular, by comparing the central curves, it can be observed that, even doubling the annual traffic, BSB results in a lower number of operations.

The effect of this reduction can then be appreciated also looking at the ballast contamination predictions: while for a single maintenance operation BSB makes a higher contribution to material passing 22.4 mm (due to addition of BE), the reduced number of interventions together with a lower degradation rate increases the intervals between renewals in comparison to the reference ballast. This improvement increases (up to approximately 80%) with higher SD limits (lower quality level of track geometry), as can be noted from Table 2. In this regard, it is interesting to observe that, while for reference ballast the service life is not significantly affected by the quality level, for BSB it increases almost proportionally with the SD limit. A small variation (as in the case of reference ballast), indeed, is expected because the number of tamping operations gives a lower contribution to contamination compared to traffic. However, when the intervals between operations become relatively long (BSB scenarios with increasing SD limits), the lower particle degradation rate given by bitumen stabilisation plays the most important role in increasing ballast service life.

It is worth remarking that, for each scenario, the intervals between tamping operations progressively decrease due to the loss of efficiency of the operation itself and the assumed increase in traffic.

Furthermore, it may be observed that for each scenario the evolution of the number of tamping with the SD limit is well fitted (R^2 values reported in Fig. 8) by a power law, indicating how maintenance costs and impacts are not proportional to the quality level of the infrastructure.

4. Summary and conclusions

This study has been aimed at evaluating the potential advantages of the application of bitumen stabilised ballast (BSB) defining a novel maintenance strategy of traditional ballasted track-beds. A protocol for the application of the BSB technology and its associated maintenance strategy was defined. An integrated model, based on laboratory tests simulative of field conditions, was used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound). The integrated model developed in this paper, by combining the evolution of SD with traffic and the level of contamination of ballast, allowed evaluation of the timing of correct maintenance activities. A sensitivity analysis related to traffic volume and SD limit has been carried out in order to understand how variations affect the robustness of the model.

From the results obtained it can be concluded that: (i) overall the use of BSB can increase intervals between both minor and major maintenance activities; (ii) the reduction in maintenance operations to correct geometry due to the use of BSB is almost independent of the quality level set for the infrastructure and the traffic level while the increase in ballast service life provided by ballast stabilisation is greater with higher SD limits; (iii) according to the proposed model, the evolution of the number of tamping with the SD limit follow a power law, indicating, thus, costs and impacts due minor maintenance are not proportional to the quality level set for the infrastructure.

The lower number of maintenance operations expected when BSB is adopted, represents a substantial step forward in reducing the use of non-renewable resources. Indeed, even allowing for the cost of bitumen emulsion, the improvement in ballast performance, which increases the durability of its function, is likely to result in net benefits in terms of environmental and economic impact. However, in order to evaluate the feasibility and sustainability of BSB, future research will focus on life cycle cost analysis (LCCA) and life cycle assessment (LCA) of such technologies, based on the maintenance strategies developed in this study.

Moreover, the integrated model proposed in this paper, which is deterministic in nature, could usefully be graded by introducing a probabilistic approach, taking into account the variability of the different parameters.

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