A Review and Evaluation of Ballast Settlement Models using Results from the Southampton Railway Testing Facility (SRTF)

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Abstract
Many of the world’s railways run on ballasted track, which has for nearly 200 years provided a stable support for train operation. However, with trafficking the geometry of the track deteriorates, mainly as a result of the development of differential settlement of the track-bed (ballast and sub-base). When the geometry defects become too severe, maintenance is needed to realign the track to enable the continued safe running of trains. Maintenance is a major cost associated with ballasted railway track, which usually takes the form of tamping. However, tamping damages the ballast, resulting in a diminishing return period between maintenance interventions until eventually the track-bed requires full renewal. A major component of the differential settlement can be attributed to the ballast layer. However, differential settlement of lengths of track cannot easily be modelled or predicted either computationally or experimentally. Thus the total plastic (permanent) settlement is often used as a proxy for the potential for the development of differential settlement along a length of track in the field. Many empirical models have been developed to predict ballast settlement, usually as a function of the number of train axle passes and/or the cumulative load. However, these models may produce very different results, perhaps indicating that the input variables have not been adequately formulated. This paper describes some current empirical ballast settlement models, and evaluates them using experimental data generated using the Southampton Railway Testing Facility (SRTF). This apparatus represents a section of track consisting of a single sleeper bay 650 mm wide, confined by rigid sides that enforce plane strain conditions. The paper summarises the strengths and weaknesses of the existing models, and suggests variables that could be taken into account to improve them.

Keywords: Railway ballast, ballast permanent settlement, settlement model, axle load, testing facility

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1 Introduction

Most of the world’s railways run on ballasted track - a situation which, owing to the historical stock of such track, is unlikely to change in the foreseeable future. Ballasted track consists of rails, supported by sleepers on a ballast bed. In the UK, the continuing increasing rail use has seen a doubling in passenger numbers over the past 20 years (Department for Transport, 2013, Office of Transport Safety Investigation, 2005, Powrie, 2014). This has led to railways becoming more intensively used than ever before, with increasingly costly maintenance requirements. Maintenance is needed when the differential geometry of a length of track reaches certain threshold values, as quantified by the standard deviation of the vertical level over a length of track. The propensity of a length of track to settle differentially is related to the plastic (permanent) settlement of the individual sleepers, and it may reasonably be expected that where individual sleepers experience larger absolute settlements the associated differential settlement along a length of nearby sleepers is also likely to be larger. However, there are only limited data to confirm this.

A better understanding of the potential for a given arrangement of ballasted track to settle differentially could lead to the design of more cost-effective ballasted track systems, requiring less maintenance. However as a precursor to this, the relationship between plastic settlement and loading needs to be better understood, and this must then be related to differential settlement. This paper investigates the ability of existing empirical ballast settlement models to estimate the settlement in laboratory tests carried out using the Southampton railway testing facility (SRTF).

2 Background

Dahlberg (2001 & 2004) observed that the severity of track settlement depends on the quality and the behaviour of the ballast, sub-ballast and subgrade and that there are two basic phases of settlement; a rapid phase following placement of new ballast or after maintenance tamping and a second phase of ongoing slower settlement at a rate that generally decreases with increasing traffic. The initial phase of ballast settlement can be attributed to ballast compaction. After the ballast achieves a higher density, the second phase of ballast permanent settlement begins to dominate. This second phase of settlement may be characterized by particle damage/fracture and further particle rearrangement. It is controlled by several factors that may include deviatoric stresses, vibrations, degradation and subgrade stiffness (Budiono et al., 2004, Dahlberg, 2001, Dahlberg, 2006, Holtzendorff, 2001, Tzanakakis, 2013).

There are differing parameters that can be used to formulate a ballast settlement model to relate trafficking with settlement. In such models, the formulation often implies that ballast settlement is proportional to the logarithm of the number of axles. That this is approximately true can be observed from the measurements on which such models are based. However, further factors that influence behavior include the variability in the load from differing train types at differing speeds. Settlement may also be dominated by the maximum individual repeated load. This paper compares 14 published models with new test data as described in the next sections.

3 Test Data used for Comparison to Settlement Models

The SRTF apparatus is a laboratory representation of a single sleeper bay of track (Figure 1 and 2). The apparatus comprises two vertical sides 5.0 m long and 0.65 m high, constructed from heavy steel sections and panels. These are located on a strong floor and held at a fixed distance of 0.65 m apart, corresponding to a typical sleeper spacing. The SRTF maintains conditions as near as practicable to plane strain. Wooden panels were fixed to the inside walls of the SRTF apparatus and a double layer of plastic sheeting placed in each sidewall to minimize side interface friction. 12 mm of rubber matting was placed at the bottom of the apparatus. The rubber matting models a uniform slightly compressible subgrade. Further details of the apparatus are available in: Le Pen & Powrie (2011) and Abadi et al (2015).

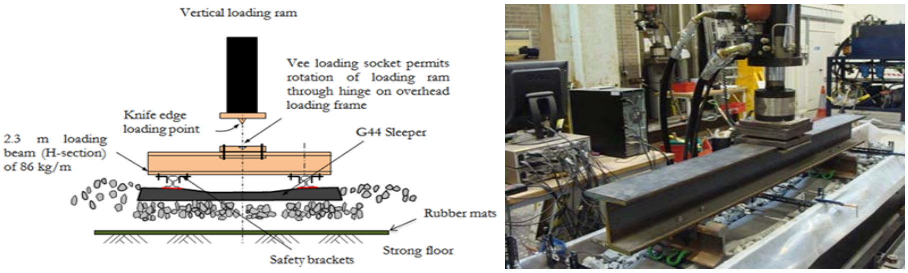

Figure 1: Figure 1 (a) Schematic view (b) photograph of the SRTF laboratory tests

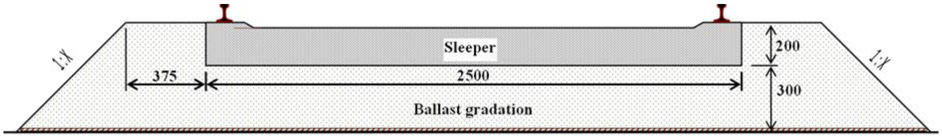

Figure 2: Test cross-section through a typical test set-up

To measure ballast permanent settlement, vertical LVDTs were placed on either side of the sleeper at the four corners and in the middle (Figure 3). To determine the average, each LVDT reading was weighted in proportion to the nearest area of sleeper as shown by the respective shaded regions in Figure 3. Data were recorded at a frequency of 100Hz.

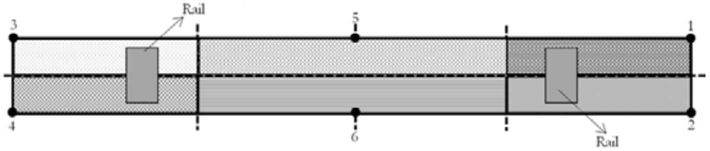

Figure 3: LVDT locations on the sleeper to analyse permanent settlement by area weighted method

The percentage of the axle load transferred to a sleeper depends on the properties of the rail, the sleeper spacing, and the sleeper support stiffness. An estimate of the load on an individual sleeper can be made using the Beam on Elastic Foundation (BOEF) model (Timoshenko, 1927). Based on this, the results of previous published work and recommendations by railway authorities (e.g. Standards Australia (2003), Network Rail (2005)) a 50% load transfer to a sleeper immediately below an axle is considered reasonable. Due to the space constraints of this paper, only two tests are reported where repeat tests had also been carried out. In test 1 a vertical load of 10 tonnes (98.1kN) was applied, representing a train having a 20 tonne axle load. This is somewhat higher than most UK passenger trains (10 to 15 tonnes) but less than the maximum freight axle load of 25 tonnes. For test 2, a vertical load of 16 tonnes (157.0kN) was applied to represent a heavier freight train with a 32 tonne axle load, typical of the higher freight axle loads common in some parts of the world.

Two different types of mono-block concrete sleeper were used. in these tests: a type G44 sleeper (British Standards Institution, 2009) in test 1 and a mono-block sleeper produced by PCM Strescon Overseas Ventures Ltd and used in parts of the Middle East in test 2. These sleepers had similar stiffnesses and footprint dimensions of 0.285 m × 2.5 m and 0.295 m × 2.6 m respectively.

Two types of ballast/aggregates were used. The ballast in test 1 was granite sourced from Cliffe Hill quarry, Leicestershire, U.K. The ballast in test 2 second was gabbro, a type of intrusive igneous rock similar to granite sourced from Saif Bin Darwish quarry in the Emirate of Fujairah. Granite is felsic rock (high in silica) while gabbro is a mafic rock (high in magnesium and iron mineral). Gabbro is denser and darker in colour than granite. Both particles size distributions (PSD) were within the current standard ballast specification for the UK and Europe (Grade A, British Standards Institution, 2013). The material properties of the two ballasts are presented Table 1.

Type of test	Maximum test value	
	Granite	Gabbro
Passing sieve size 0.5 mm	0.19%	0.07%
Flakiness index	15%	16%
Los Angeles abrasion	16	12%
Micro deval abrasion	6.5%	1%
Specific gravity	2.78	2.96
Water absorption	0.31%	0.10%
Uniaxial compression strength (MPa)	>250	250
Moh's hardness scale	6-7	5-7

Table 1: Granite and Gabbro ballast (after Marinos and Hoek, 2001, SBD Crushers, 2010)

The ballast was placed and compacted using 22 passes of a 5 kN vibrating compactor plate in one layer. Prior to placement the ballast was weighed, and after placement measurements of the volume of the ballast were made to determine the initial porosity (41.75% and 43.24% respectively).

In each test a sinusoidal loading function was applied at 3Hz for 3 million cycles. The ballast permanent settlement results are shown in Figure 4. In the test with the heavier load the overall settlement (20 mm) is twice that of the lighter load test (10 mm). A possible cut off between the two phases of settlement suggested by Dahlberg is the second inflection point of the curves marked in Figure 4. However, this places two reverses in the trend in log gradient in phase 1, wherein another inflection point is also visible. A feature of the data in Figure 4 is that the settlement lines are in in perfect proportion and the inflection points occur at the same number of cycles for the two tests.

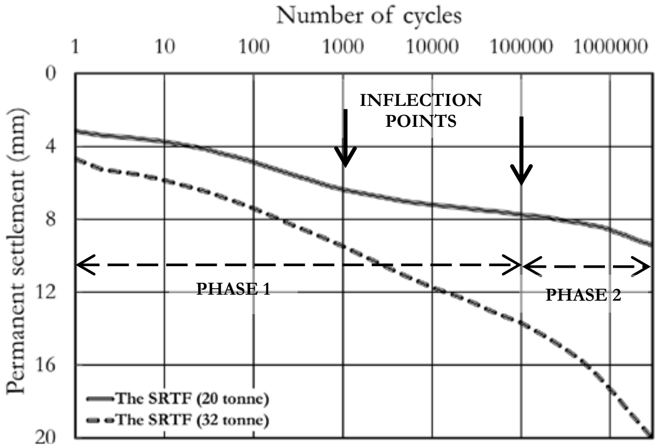

Figure 4: Ballast permanent settlement test 1 (20 tonne axle load) and test 2 (32 tonne axle load)

The variables changed between the two SRTF tests were the ballast type, load magnitude, number of cycles, initial porosity (a measure of compaction or relative density) and sleeper properties whereas the ballast depth, shoulder dimensions, lateral confinement and sleeper spacing were kept constant. It may be expected that at least some ballast settlement models would explicitly consider all these factors. However, this is not the case as is demonstrated below.

4 Models Evaluated

A selection of previously published ballast settlement models are shown in Table 2. Common symbols are as follows: N is the number of cycles, ε_1 is the strain at first cycle, ε_N is the strain at N cycles. Symbols specific to particular models are shown in Table 2.

Model label	Model	Reference	Variables	Empirical constants
ORE	$\varepsilon_N = 0.082\left(100n - 38.2\right)\left(\sigma_1 - \sigma_3\right)^2 \times (1 + 0.2 \log N)$	ORE (1970)	n= porosity, σ_1 & σ_3= principle stresses	
Shenton 1	$\varepsilon_N = \varepsilon_1\left(1 + 0.2\ \log_{10} N\right)$	Shenton (1978)		
Shenton 2	$S = K_s \frac{A_e}{20}\left(\begin{matrix}(0.69 + 0.028L)\ N^{0.2} + \\ \left(2.7 \times 10^{-6}\right)N\end{matrix}\right)$	Shenton (1984)	A_e= average axle load, L= tamping lift	K_s
Hettler	$S_N = r\ (F)^{1.6}\ (1 + C\ \ln\ (N))$	Hettler (1984)	F= force	C, r
Alva-Hurtado	$\varepsilon_N = (0.85 + 0.38\ \log\ N)\ \varepsilon_1 + (\varepsilon_1)^2 \times (0.05 - 0.09 \log N)$	Alva-Hurtado & Selig (1981)		
Stewart 1	$\varepsilon_N = \varepsilon_1\left(1 + C\ \log_{10} N\right)$	Stewart & Selig (1984)		C
Stewart 2	$d_N = d_1(1 + C_b \log N)$			C_b
Selig 1	$\varepsilon_N = \varepsilon_1(1 + C\ \log N)$	Selig & Waters (1994)		C
Selig 2	$S_N = 4.318\ N^{0.17}$			
Selig 3	$\varepsilon_N = 0.0035\ N^{0.21}$			
Thom 1	$S = \left[\log_{10}\ (N) - 2.4\right]^2$	Thom & Oakley (2006)		
Thom 2	$S = \left[\log_{10}\ (N) - 2.4\right]^2 \left(\frac{\sigma}{160}\right)\left(\frac{47}{k_s}\right)$		σ= vertical pressure, k_s=subgrade stiffness	
Cedex	$S_N = 0.07\ N^{0.1625}$	Cuellar et al (2011)		
Indraratna	$S_N = S_1(a\ \log N + 1)$	Indraratna et al (2013)		a

Table 2: Ballast settlement models

To apply the ballast settlement models to the SRTF data, relevant input variables are replaced by the parameters for the two SRTF tests while empirical constants are kept at the values recommended from the source publications (Table 3).

5 Comparison of Settlement Models with the SRTF Data

Graphs of permanent settlement against the logarithm of the number of cycles is plotted in Figure 5 for tests 1 and 2, using a selection of six (test 1) and seven (test 2) of the fourteen models presented in Table 3. Models not included in the comparison either showed large discrepancies with the test results or gave results very similar to one of the models that is plotted. Specifically,

- Shenton 2 (Shenton 1984) over-predicted the settlement, reaching some 24 and 38 mm for the respective tests. This may be because Shenton averaged worldwide data.
- Stewart 2 (Stewart and Selig 1984) gave similar results to the model proposed by Alva-Hurtado (Alva-Hurtado and Selig 1981).
- Selig 1 (Selig and. Waters 1994) gave the same settlement as Shenton 1 (Shenton 1978).

- Selig 2 (Selig and Waters 1994) gave 37 mm of settlement at 3 million cycles in test 1 and 55 mm in test 2, much more than that measured in the laboratory tests. This may be because the box test on which this model was based were generated using loads with very high stresses.
- For the 20 tonne axle load, Selig 3 (Selig and Waters 1994) over-predicted the test settlement considerably, (24 mm). This may be because the model is correlated from test track measurements where the settlement of subgrade may have been included and the vehicles on the track may have been heavier. However, this same settlement model is in reasonable agreement with the test 2 data (32 tonne axle load, presented in Figure 5b). This is largely because the load is not an input variable to this model.
- Thom 1 and 2 (Thom and Oakley 2006) gave unrealistic results - after a certain number of loading cycles there was a reduction in the ballast permanent settlement. This may be explained by the curve fitted model being validated against a limited number of test cycles.
- Cedex (Cuellar et al 2011) generated the least settlement (less than 1 mm) but the model was devised to estimate permanent settlements of bituminous sub-ballast.

Model label	Input Variables used for:		Varied load (Y/N)
	Test 1 (20 tonne axle load)	Test 2 (32 tonne axle load)	
ORE	σ_1 = 0.138MPa, σ_3=0	σ_1 = 0.205MPa σ_3 = 0	Y
Shenton 1	C = 0.2, ε_1 = 1.16%	C = 0.2, ε_1 = 1.56%	N
Shenton 2	K_s = 1.1, A_e = 20, L = 0	K_s = 1.1, A_e = 32, L = 0	Y
Hettler	r = 0.00095, F = 98, C = 0.43	r = 0.00095, F = 157, C = 0.43	Y
Alva-Hurtado	ε_1 = 1.16%	ε_1 = 1.56%	N
Stewart 1	ε_1 = 1.16%, C= 0.29	ε_1 = 1.56%, C= 0.29	N
Stewart 2	d_1 = 3.49, C = 0.35	d_1 = 4.68, C = 0.35	N
Selig 1	None (solely a function of cycles N)		N
Selig 2	None (solely a function of cycles N)		N
Selig 3	None (solely a function of cycles N)		N
Thom 1	None (solely a function of cycles N)		N
Thom 2	σ = 137.7kPa, k_s = 42MN/m	σ = 204.6kPa, k_s = 42MN/m	Y
Cedex	None (solely a function of cycles N)		N
Indraratna	a = 0.345, S_1 = 2.31	a = 0.345, S_1 = 2.31	N

Table 3: Values used

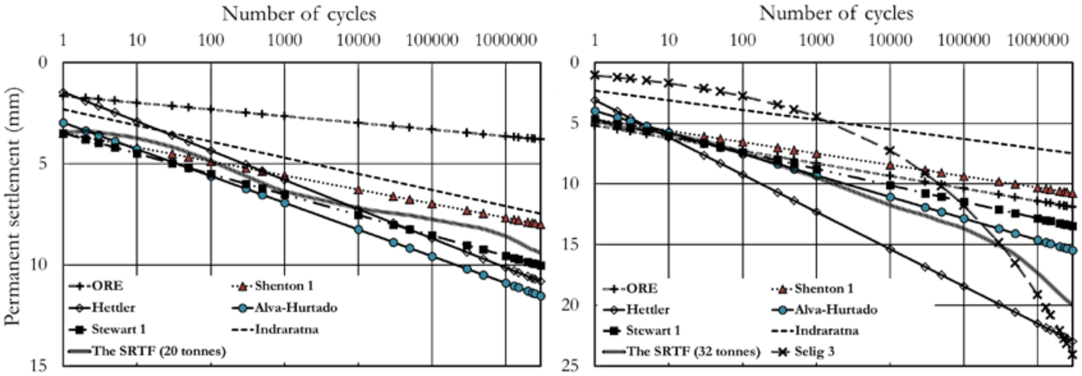

Figure 5: Comparison of ballast permanent settlement models with SRTF (a) test 1 (b) test 2

Figure 5 (a & b) show that there is some variation between the models; plotting on the log axis shows that many of these are effectively log linear formulations or power laws unable to reproduce the changes in the gradient apparent in the SRTF data between the different phases of settlement (Figure 4). The variation between calculated settlements may be because the models were based on experimental and/or field data for ballast with different degrees of compaction and/or higher applied loads. It can also be seen that both the settlement models and test data generate the major proportion of the final settlement within the first 10,000 loading cycles.

Figure 5 also shows that the settlement at 3 million cycles for the equivalent 20 tonne axle load test is most closely approximated by Stewart 1, while the heavier equivalent 32 tonne axle load test is most closely approximated by Alva Hurtado, Hettler and Selig 3. However, at different numbers of cycles other models are closer.

6 Concluding Comments

Comparison of the various ballast settlement models shows that they all follow a similar pattern in describing the behaviour of ballast settlement under cyclic loading. However, none of the models allow for sleeper properties, sleeper spacing, ballast type, ballast depth or shoulder dimensions. Also, while changes in load magnitude are implied by some of the models, this tends to be lumped in with the vertical strain after the first loading cycle, which is a result of a combination of initial ballast compaction as well as the applied vertical load.

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