Railway Foundation Design Principles

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Abstract: There are a number of design procedures which have been developed to determine the appropriate thickness of trackbed layers on a railway track in order to reduce train induced stresses to an acceptable level thus ensuring that subgrade failure does not occur prematurely. This paper briefly describes four such procedures and compares the thickness of trackbed layers proposed by each for a number of hypothetical situations. To demonstrate further the suitability of each procedure, two existing sites in the UK are analysed and the trackbed layer thickness given by each procedure is then compared. The research shows that the procedures do not give consistent results. Subsequently it is suggested that it is important to consider other aspects in addition to the prescription of a suitable thickness of trackbed layers in any new build, renewal or remediation scheme.

Key words: Railways, railway foundations, track deterioration, ballast, subgrade.

1. Introduction

Conventional ballasted railway track (Fig. 1) deteriorates progressively over time due to the combined effects of traffic and climate. Appropriate maintenance treatments are periodically applied to reduce the effects of this deterioration but an important and often neglected part of the track structure is the subgrade which, unlike the ballast, does not lend itself to be maintained easily.

Subgrades of fine-grained material without adequate protection from repeated train induced loads and the effects of climate, may fail primarily by attrition from the ballast, progressive shear failure, an excessive rate of settlement through the accumulation of plastic strain and massive shear failure [1]. Attrition is the process of the subgrade surface being worn away by the ballast or sub-ballast, and may be prevented by using an appropriate subballast layer, such as sand. Progressive shear failure occurs where train induced cyclic stress levels are sufficiently high to cause the soil to be sheared and remoulded (Fig. 2) but at stress levels below those causing massive shear.

Excessive settlement may cause pockets to form in the subgrade as a result of ballast punching into the underlying soil (Fig. 3). Water may collect in the pockets further weakening the subgrade possibly causing mud pumping (wet spots).

Provided that a suitable sand blanket has been used, progressive shear failure and an excessive rate of settlement are the most important design criteria. These are associated with cyclic shear stresses. The former concerns the stresses at the granular layer/subgrade interface (where theses stresses are likely to be at their highest), whilst the latter is associated with the stresses throughout the subgrade. Several design approaches may be adopted to prevent these failures including the use of non-ballasted track forms, introducing an asphalt layer, increasing the flexural rigidity (EI) of the rail and using techniques, such as soil stabilization, to permit higher stresses in the subgrade [2]. The most common effective and economical approach however is to prescribe a sufficient thickness of the ballast and subballast (i.e., the trackbed layers, see Fig. 1). This paper describes four such procedures which have been developed for use around the world and investigates their effectiveness using data from two in-service railway sites.

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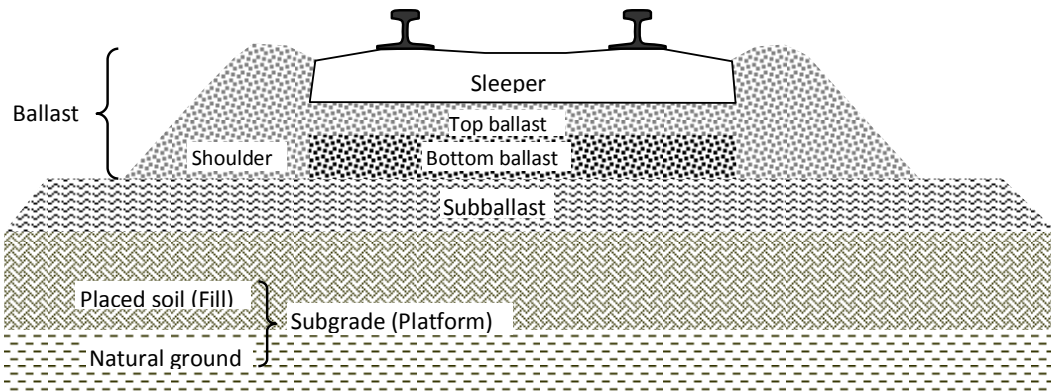
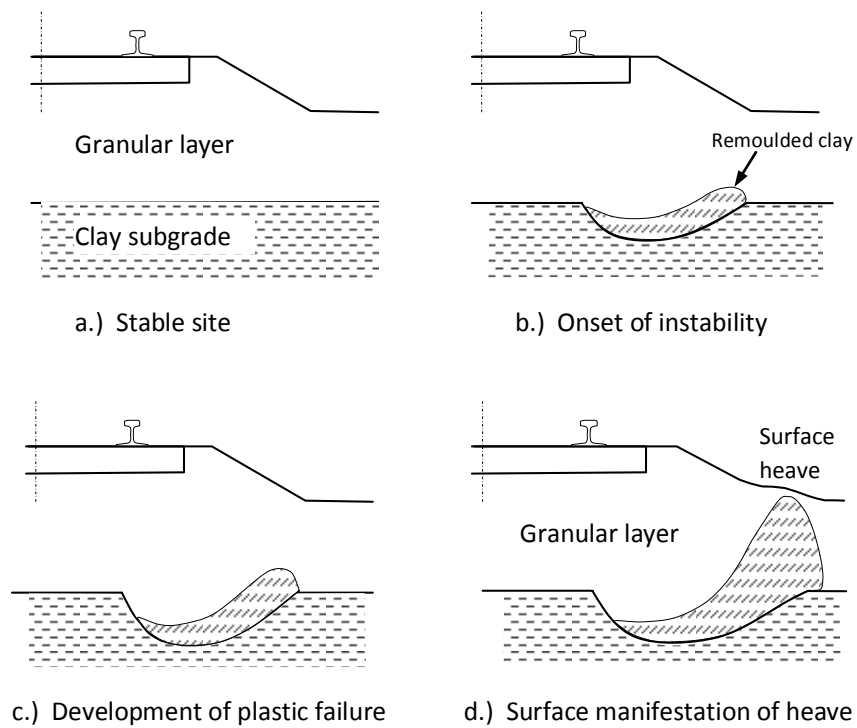**Fig. 1 The railway track structure after Ref. [1].**

Fig. 2 Subgrade progressive shear failure after Ref. [1].
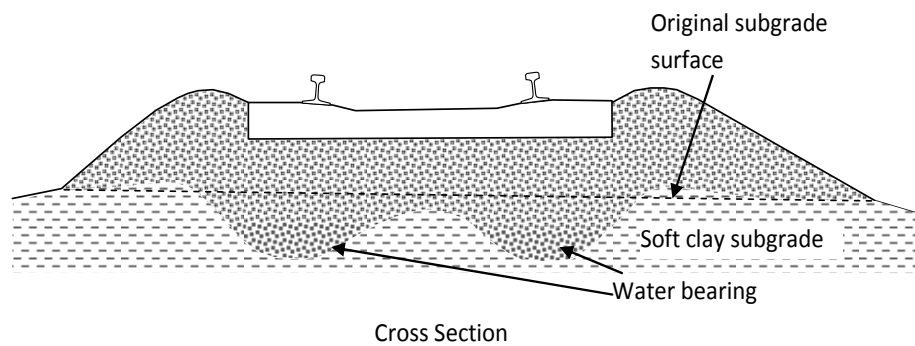

Fig. 3 Excessive subgrade plastic deformation after Ref. [4].

2. Design Procedures Considered

To facilitate the research reported herein, four design procedures, from the USA (a method proposed by Li et al. [5]), Europe (The International Union of Railways standard UIC 719R [6]) and the UK (a method developed by British Rail Research [7] and the current Network Rail code of practice [8]). Table 1 summarizes the factors considered by the four procedures considered.

These methods are described briefly in the following sections.

2.1 Li et al.'s Method

Li et al.'s procedure is an analytical method which aims to prevent progressive shear failure and excessive plastic deformation [2]. It was developed by determining train induced stresses in the subgrade, using an analytical model of the track structure, known as GEOTRACK, and a model to predict the expected cumulative permanent settlement of the subgrade under repetitive loads. The model of expected settlement was based on data from triaxial tests and related the permanent settlement to the

induced stresses and the engineering properties of the subgrade soil.

By setting limits on the allowable settlement and comparing the train induced stresses required to give this settlement with the stresses determined using GEOTRACK, Li et al. [2] were able to determine the theoretical thickness of the trackbed layers for a variety of subgrade soils. Two sets of design charts were subsequently produced. The first gives the minimum thickness of the trackbed layers to prevent progressive shear failure for a variety of subgrade conditions. The thicknesses are functions of the trackbed layer, the subgrade resilient modulus (defined as the repeated deviator stress divided by the recoverable axial strain), soil type and traffic loading. The second set of design charts, which in addition are a function of subgrade depth, give the thickness of the trackbed layers to prevent excessive plastic deformation.

2.2 UIC 719R

UIC 719 R is an empirically founded procedure believed to be based largely on French best practice [9]. It specifies that the substructure may contain some or

Table 1   Factors accounted for in the four design procedures reviewed (after Ref. [3]).

Factors	Li et al.	UIC 719R	BR Method	NR Code 039
Method	Analytical/Charts	Empirical	Analytical/Charts	Charts
Static axle load	GEOTRACK model used to formulate their design charts	Yes	From an elastic model – charts only go up to an axle load of 24 tonnes	No – but 25.4 tonne axle load limit on UK network
Sleeper type, length & spacing	Modelled by GEOTRACK	Yes	No difference in stresses found for sleeper spacings of 630–790 mm	No
Rail section	Modelled by GEOTRACK	No	No	No
Speed	Considered indirectly in the specification of the dynamic axle load	Yes	No but could be incorporated by using a dynamic axle load	Considered indirectly by means of minimum requirements for the dynamic sleeper support stiffness. Also 200 km/h is fastest speed on UK network
Annual tonnage	Yes	Yes	No	No
Cumulative tonnage	From annual tonnage multiplied by the design life	No	No	No
Subgrade condition	Expressed by the resilient modulus and soil shear strength	Soil quality is determined primarily from the number of fines in the soil	Threshold stress for the material in question.	Undrained subgrade modulus or undrained shear strength.
Design criteria	• progressive shear failure • plastic deformation	N/A	• plastic deformation	• subgrade modulus

all of the following layers: ballast, granular sub-ballast, a geotextile, and prepared subgrade [6]. The combined thickness of the trackbed layers is determined from the type of soil forming the subgrade, traffic characteristics, track configuration and quality, and thickness of the prepared subgrade. No information is given on how the individual thicknesses of the ballast and sub-ballast should be determined. The prepared subgrade is the layer below the sub-ballast that has been treated to improve its engineering properties. Its inclusion in the design is optional.

2.3 British Rail Method

British Rail research developed a procedure to protect against subgrade failure by excessive plastic deformation [7]. To this end, a series of design charts were produced to relate the required thickness of the trackbed layers to a measure of the strength of the subgrade known as the threshold stress. The charts were developed by combining traffic induced subgrade stresses, predicted from a linear elastic model of the track system, with soil threshold stresses determined by a series of cyclic triaxial compression tests. The tests indicated the existence of a threshold stress, above which repeated load applications cause increasingly large permanent deformations and below which the plastic strain associated with each load cycle reduce to a stable condition where the permanent deformations are small.

2.4 Network Rail Code

A recent Network Rail code of practice, NR/SB/TRK/9039 "Formation treatments" gives recommendation for the thickness of the trackbed layers on the UK network [8]. At sites where track geometry has not been adequate the required thickness of the trackbed layers can be determined from a chart which relates the thickness of the trackbed layers to undrained subgrade modulus (i.e., Young's modulus) for three different values of the dynamic sleeper support stiffness (30, 60, and 100 kN/mm sleeper end). The values of the dynamic sleeper support stiffness relate to minimum requirements for existing main lines both with and without geogrid reinforcement and new track, respectively.

2.5 Recommended Trackbed Layer Thickness as a Function of Subgrade Condition

To compare the designs produced by the four methods, two hypothetical traffic loading scenarios are considered both of which assume a mixture of 50% freight and 50% passenger traffic [3]. For the freight traffic a Class 66 locomotive travelling at 125 km/h, pulling wagons with axle loads of 250 kN was used, and for the passenger traffic, a high speed locomotive-hauled passenger train with an axle load of 170 kN. For the first scenario, the passenger trains were assumed to travel at 200 km/h, and for the second at 300 km/h. These were considered to be representative of conditions on a main line in the UK and a high speed line, such as the Channel Tunnel Rail Link (CTRL), respectively. Using these input data, the trackbed layer thicknesses were calculated, following the four procedures, as a function of a number of subgrade conditions. These are given in Fig. 4 from which it may be seen that the trackbed layer thicknesses given by the procedures are not in close agreement and that only Li and Selig's method gives different design thicknesses for the two traffic loading scenarios considered. Interestingly, the UIC 719 R method gives the same thickness for any subgrade strength. The reasons for the differences between the procedures may be explained in part with reference to the assumptions made by the procedures, the methods used to determine the traffic loads and the performance models of the material considered. However, further analysis of the approaches adopted by the various procedures is beyond the scope of this paper, but an in depth study of the design methodologies conducted under a variety of conditions has been described by Burrow et al. [3].
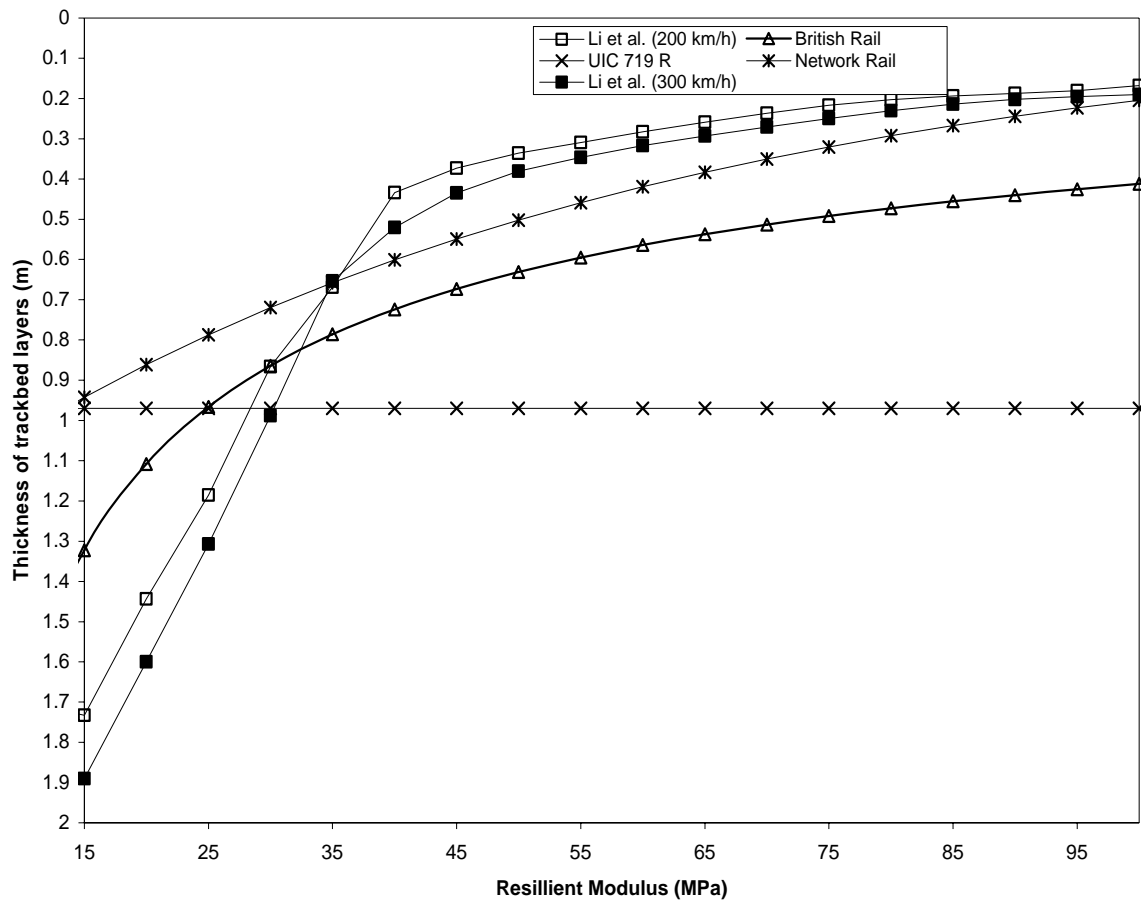
Fig. 4   Variation in design thickness with subgrade condition [3].

3. Case Studies

In practice in the UK, the thickness of the trackbed layers may vary from less than 300 mm to over 1 m and to demonstrate the suitability of the procedures described above case studies are presented of two contrasting sites in the UK. The first is an existing site in Leominster, Herefordshire, which has been in operation for a number of years and has required frequent track maintenance due to track geometry deterioration. It has been chosen to investigate the usefulness of the design procedures for track renewal. The other, a site on the CTRL at Ashford in Kent has been built comparatively recently, has required little maintenance to date, and has been chosen to demonstrate the suitability, or otherwise, of the procedures for the design of new foundations. Data relating to the performance of the track at both sites has been collected and analysed accordingly.

3.1 Leominster

3.1.1 Data Considered

The site at Leominster consists of an approximately 420 m long section adjacent to Leominster station which is subject to a mix of passenger and freight traffic. It was chosen for research as it has been in operation for some time and the up line, which carried heavily laden freight trains transporting steel, required frequent track maintenance and the imposition of speed restrictions due to track geometry deterioration. These trains returned empty on the down line where the track related problems were less apparent. Over the years the thickness of the trackbed layers has grown, due to the addition of ballast during maintenance activities, to between 0.9 m and 1.3 along the site [10]. The trackbed layers are underlain by a layer of firm to very soft clay to depths of between 3.8 and 4.4 m with undrained shear strength, C_u, values at the surface of the layer

ranging between 50 kPa and 140 kPa. A medium dense to dense sand and gravel layer was present below the clay layer. For the purposes of this study, a lower bound C_u value of 50 kPa was used and a simplistic relationship between the resilient modulus, E_s and C_u, of the form $E_s \approx 500 \times C_u$ was adopted [1]. The design line speed for the section concerned was 128 km/h (although there are speed restrictions in place) and the annual tonnage at the site was approximately 6 MGT/yr. Using the above values, and assuming 50% freight/passenger traffic mix, the trackbed layer thicknesses recommended by the four procedures are given in Table 2.

3.1.2 Discussion

It may be seen from Table 2 that the recommended thicknesses given by Li et al. and UIC 719 R are similar. However, the British Rail recommended thickness is approximately 15% greater than these thicknesses and the Network Rail recommendation is significantly lower. However, as all of the recommendations are less than, or at the lower end in the case of the British Rail procedure, the 0.9 m to 1.3 m trackbed layer thickness found at the site. This would suggest that if the thickness of the trackbed layers is the sole consideration in trackbed design then there should be no need for the excessive maintenance which has occurred. However, site investigation data as described by Brough et al. [10] may help explain why the addition of ballast has not remedied the problems which have manifested as poor track geometry. An automatic ballast sampler (ABS) device was used to obtain disturbed continuous core samples of the trackbed layers at a number of locations along the site. These showed that the trackbed layers were saturated with water and contaminated with silt at depths below approximately 0.3 m and there was evidence of subgrade mud pumping. In addition, the ABS data

indicated that there was a very shallow water table in the trackbed which was possibly due to subgrade depressions (ballast pockets). These findings, which were further verified via trial pits and static cone penetration tests (SCPT) indicate the occurrence of excessive subgrade plastic deformation (see Fig. 3). Whilst ballast has been added to offset the loss of track elevation caused by the subgrade settlement it has had the effect of exacerbating the problem as suggested by the ponding of water in subgrade depressions (i.e., ballast pockets). Although increasing the depth of the ballast may reduce the large repetitive train induced stresses, the formation of ballast pockets has trapped water, which in turn has led to increased softening of the clay subgrade. Whilst trackbed layers are free draining, enabling water to reach the subgrade, they do not allow water to evaporate easily and therefore the subgrade at Leominster, which is not free draining, has become saturated and therefore weakened. Furthermore, the trackbed layers at Leominster have become contaminated with clay, thereby degrading their characteristics and thus performance [4].

3.1.3 Further Analysis

Of further interest is the dynamic sleeper support stiffness of the up-line which was measured using the Falling Weight Deflector (FWD) device (Fig. 5).

As may be seen from Figure 5, the dynamic sleeper support stiffness ranged from approximate 28 kN/mm sleeper end to just over 70 kN/mm sleeper end and was for a considerable length of the site less than the 60 kN/mm sleeper end recommended by Network Rail for existing main lines. In addition, the standard deviation of 8.3 kN/mm sleeper end was approximately 20% of the mean value, indicating a high variation in sleeper support stiffness across the site. Such heterogeneous sleeper support conditions are also believed to be an important contributory factor to track quality deterioration as they encourage non uniform dynamic train loading and consequently differential settlement [11]. Furthermore it is felt that the devices such as the

Table 2   Leominster trackbed layer thickness [3].

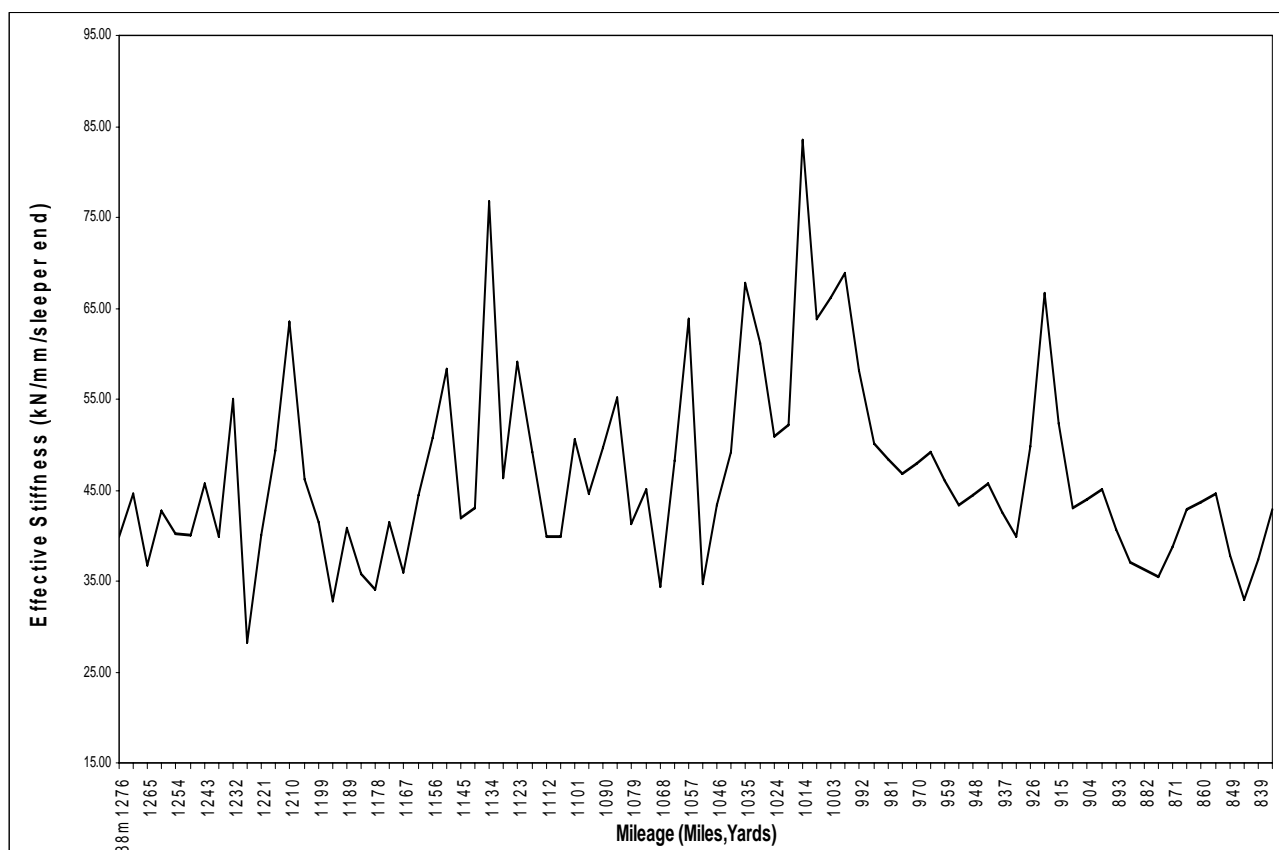| Depth of trackbed layers (m)			
Li et al.	UIC 719 R	British Rail	Network Rail
0.86	0.82	0.97	0.49

Fig. 5   Track stiffness at Leominster [3].

FWD should be more widely used and the data collected from them should be analysed so that an insight may be acquired into the structural properties of the foundations and their special and temporal variation. By examining the materials of the track foundations, it is felt that the problems of excessive plastic deformation, where ballast pockets have formed and the heterogeneity of sleeper support evidently cannot be addressed by the addition of ballast alone. Further remedial measures are necessary, and at Leominster these should include the introduction of adequate drainage incorporating drainage channels in the ballast pockets to allow removal of water from the trackbed. Contaminated ballast should also be replaced and ballast shoulders cleaned to initiate drainage paths. Furthermore, where stiffness variation is apparent, suitable remediation techniques should be adopted to ensure homogeneous support conditions [10].

3.2 CTRL

3.2.1 Data Considered

The CTRL is a 108 km high speed railway line running between London and the Channel Tunnel. 75 km of the line, from Dartford to the Channel Tunnel is mainly on ballasted track with the underlying subgrade consisting of either heavily overconsolidated clays or Folkestone sands. The trackbed layer design (ballast + sub-ballast + prepared subgrade) was based on the UIC procedure together with French best practice for high speed lines layers and varies between approximately 0.85 m and 1 m [9, 12]. For the sections constructed on overconsolidated clays, 0.65 m of the clay below the base of the prepared subgrade was replaced with the stronger and stiffer Folkestone sand sandwiched between geotextiles. The earthworks were built with a design life of 60 years and it was anticipated that track

renewal would take place at 20 year intervals with realignment maintenance occurring every 3 years. Since opening in September 2003 there have been no reported problems in track performance and it has been suggested that the time between tamping and realignment maintenance activities may be increased [13]. Additionally, measurements along sections of the CTRL have shown that the track deflections are small further indicating that the track is performing adequately [14].

Using the traffic loading conditions and the lower bound undrained shear strength of 50 kPa of the clays reported by O'Riordan and Phear [12] and assuming a corresponding resilient modulus value, E_s, of 25 MPa (see above) the thickness of the trackbed layers determined from each procedure are given in Table 3.

3.2.2 Discussion

From this table it may be seen that the trackbed layer thicknesses recommended by the British Rail procedure is similar to UIC 719 R, although the former was not intended for high speed lines. Li et al.'s procedure on the other hand gives a value greater than the UIC 719 R one by approximately 30%, however as mentioned previously the over-consolidated clay subgrade on the CTRL was replaced with sand (to a depth of 0.65 m) which is likely to have somewhat higher resilient modulus than the clay. Therefore, it may be argued that a more representative thickness of the trackbed layers for the CTRL built on the overconsolidated clays is somewhere between 1 m and 1.65 m (i.e., 1+0.65 m), depending on the engineering properties of the Folkestone sands. The thickness given by the Li et al. procedure is within this range of values. Network Rail's procedure gives a smaller value than UIC 719 R by approximately 20% and may suggest that the code may not be suitable for designing high speed lines.

Table 3   CTRL trackbed layer thickness (after Ref. [3]).

Depth of trackbed layers (m)			
Li et al.	UIC 719 R	British Rail	Network Rail
1.31	1.00[1]	0.97	0.79

[1] Including prepared subgrade.

4. Conclusions

The main conclusions that may be drawn from this comparative analysis of railway foundation design methods using the case studies reported are the following:

(1) The current design methods may not always give consistent results for the same set of initial conditions.

(2) There is a need to develop a new generation of design methods that can consider (a) appropriate design criteria based on the defects likely to be induced in the track structure by the dynamic loads of the trains and (b) associated parameters that may be analytically calculated using appropriate computer models.

(3) There is a further need to validate and verify such design procedures using data from existing sites.

(4) In addition, it seems necessary to develop robust design procedures that will concern and integrate, dynamic track modeling, material characterization, simulation (response) models, failure criteria and long-term performance models.

(5) Such procedures should include life cycle analysis concepts that consider scheduled or responsive maintenance.

(6) A major component of such a design process should be drainage as it has a major impact on the performance of the railway foundations.

(7) With regard to railway maintenance, it appears necessary to develop structural evaluation procedures based on sound analytical principles that may facilitate the calculation of verifiable design parameters using field or laboratory testing data. It seems also appropriate to reconsider the use of the ballast and seek to develop enhanced materials.

Acknowledgements

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