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STIFFNESS COEFFICIENT IN THE TRANSITION ZONE BETWEEN BALLASTED AND BALLASTLESS TRACK AND ITS INFLUENCE ON FORMATION STRESSING

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ABSTRACT

In this paper, a parametric investigation of the static and dynamic elasticity (stiffness coefficient) of the railway track and of the elastic pads of the fastenings is presented for the cases of Ballastless Track (Slab Track and Embedded Track), Transition Zone and Ballasted Track. Moreover, the influence of the variation of the static and dynamic elasticity on the acting forces on the track superstructure and substructure is investigated, a factor that is of decisive importance for the design of the Track layers and conclusions are drawn for the magnitude of the acting forces and of the mean pressure on formation in comparison to the permissible compressive stress. A methodology is also suggested for the calculation of the actions and stresses that strain the formation of the track structure.

BACKGROUND

In classic Railway terminology, Permanent Way (superstructure) consists of the track panel (rails, sleepers/ties, fastenings), ballast, and if necessary bottom ballast; whatever lies beneath is called Formation (Schramm, 1961). The track panel is seating in a ballast-bed, in the case of the so-called Ballasted Track (Fig. 1, see also Fig. 8). The foundation of the track, with the exception of special cases such as bridges, is the earth body (track bed) formed by filling (embankment) or by excavation (cutting). The top of the track bed is called Formation. (Schramm, 1961). In Fig. 7 a more analytical depiction of this terminology is presented.

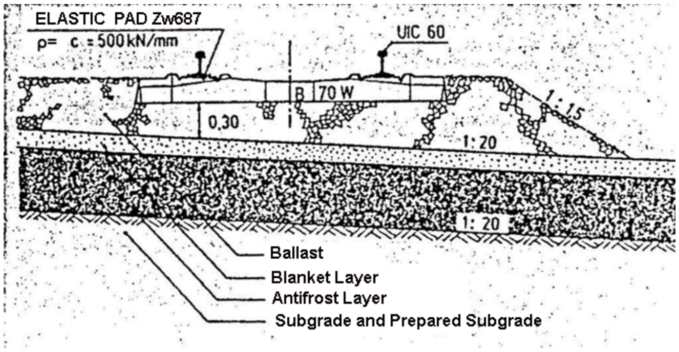
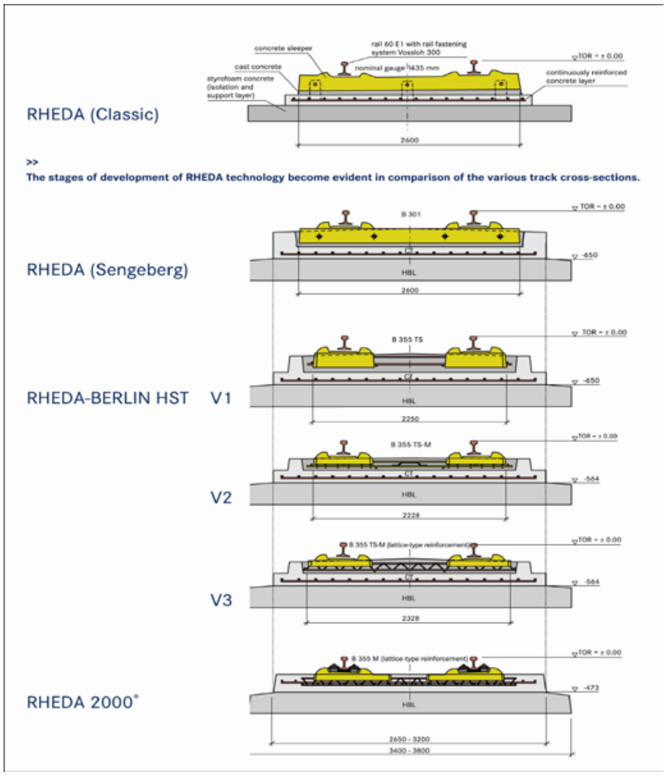


Fig.1. Ballasted Track with rails UIC60 and monoblock sleepers of prestressed concrete B70 type with W1 fastening with elastic pad Zw687 (Leykauf et al., 1990).



. Fig. 2. Evolution of Slab Track Rheda type in Germany (Tsoukantas et al., 2006).

The use of ballastless track is necessary in the case of High-Speed Lines (V>200 km/h or 124.30 m/h) in the form of Slab Track as well as in the cases of terminal port stations, railway vehicles depots etc., with very low speeds, in the form of Embedded Track. In both cases the role of ballast-bed is undertaken by a concrete plate

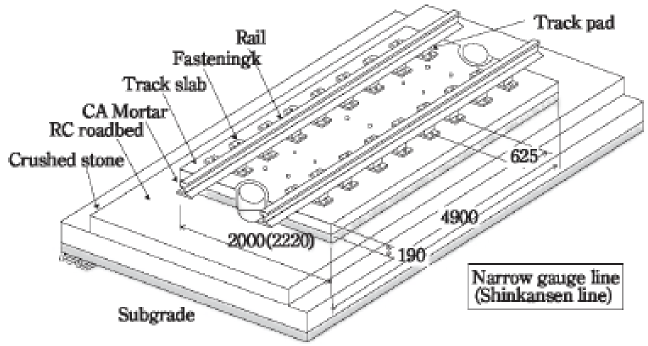


Fig. 3. Slab Tracks with concrete slab on earthworks in Japan (UIC, 2002, Ando et al., 2001)

In this paper a new methodology is presented for the estimation of the actions on the track panel and on the formation of the track, as was derived during a research program for the Greek Railways in collaboration with Universities and research centres of Railway networks in Europe. Moreover, a methodology for the calculation of the average stress on the formation is presented. The subsidence y is also calculated. The results of the investigation should be used for the dimensioning of the track. This paper also presents an investigation of the influence of the change of track stiffness coefficient on the acting forces and consequently on the dimensioning of the formation of the track (Ballastless Track, Transition Zone, Ballasted Track). The methodology is applied for the first time in the cases of: (a) the use of Rheda 2000 type Slab Track in the High-speed network (V>200 km/h) of the Greek Railways (Giannakos, 2008), as well as, (b) the construction of a new railway terminal station at the new –also- commercial port of New Ikonion at Piraeus (Giannakos, 2009a).

BALLASTLESS TRACK, SLAB AND EMBEDDED TRACK

The term "Slab Track" (Feste Fahrbahn in German, Voie sur Dalles, in French) defines the multilayered structure of a Railway Track -in the case of High-Speed Lines- which secures the seating of the track panel not through a ballast-bed (as in the classic ballasted track), but through a rigid reinforced concrete plate (slab), which seats on a series of successive bearing layers with a gradually decreasing modulus of elasticity. The evolution of the Rheda type Slab Track in Germany is depicted in Fig. 2.

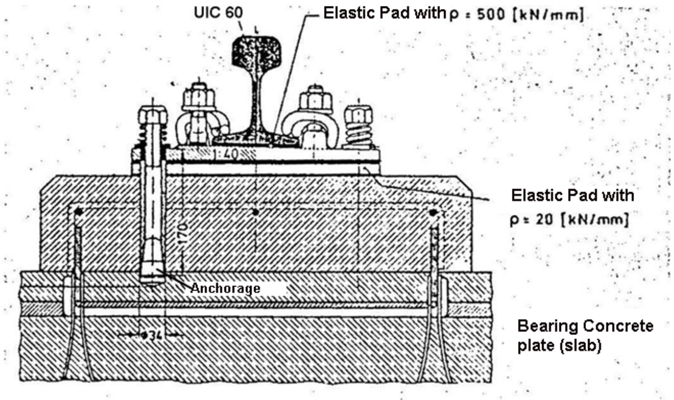


Fig. 4. Embedded Track in a crane track (Leykauf et al., 1990)

After many years of international experience e.g. Japan, Germany, France, etc., in High-Speed lines significant damage of ballast was observed, which was literally crashed, fouled and completely compacted due to excessive dynamic loading, breaking forces etc, resulting in the loss of its resilience, the deterioration of the rain water drainage, the incapability of maintaining the geometry of the track etc. Under these circumstances, maintaining of the track geometry, in the regulations limits, demands repeated and costly interventions. Moreover the individual structural elements of superstructure (rails, sleepers, fastenings etc.) undergo non-permissible wear and it is obligatory to be replaced in a much shorter time than their normal life-cycles. Furthermore very costly interventions cannot be avoided even in the substructure (Tsoukantas, 1999). To solve these problems the Slab Track applications were adopted. In Fig. 3 the Slab Track in Japan is depicted and in Fig. 2 the evolution –in time- of the Rheda type Slab Track system in Germany.

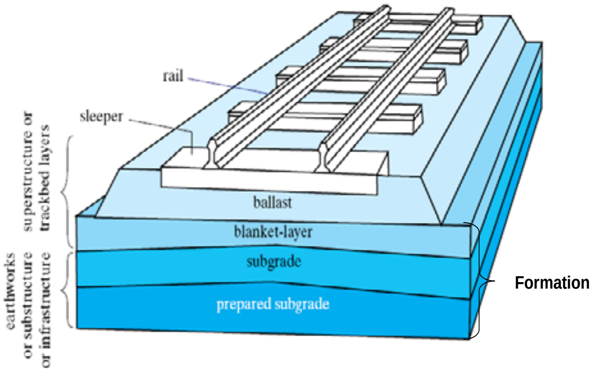


Fig. 5. Terminology of the layers that constitute the Ballasted Track according to International Union of Railways (UIC) Code 719 (Giannakos, 2004)

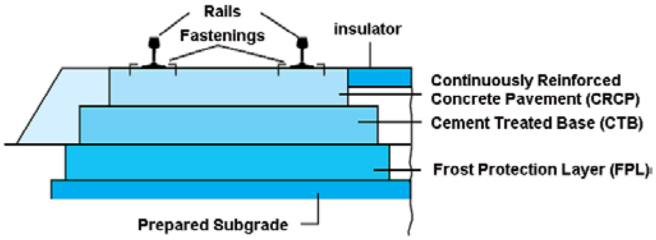


Fig. 6. Terminology of the layers that constitute the Slab Track (Giannakos, 2004)

In the regions of railway terminal stations in ports for securing the combined transport, as well as in depots of railway vehicles and locomotives and rolling stock maintenance facilities, there is a need to replace ballast-bed by concrete floor for functional reasons (washing of vehicles and flowing out of the waste water and oils, maintenance pits between the two rails of track, circulation of road vehicles on the top of tracks, transshipment of cargo etc.) by constructing also a type of ballastless track. In this case an embedded track (a case of embedded track for cranes see Fig. 4) is constructed which should also secure small or zero maintenance needs for the permanent way. Its difference from the slab track is the low speed of circulation.

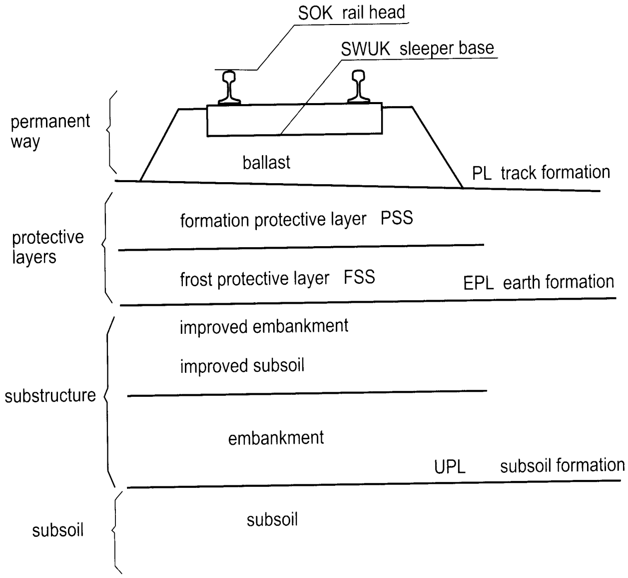


Fig. 7. Terminology of the layers that constitute the Track according to Lichtberger (2005)

The adoption of the Slab Track technology as well as the embedded track construction in a railway network creates the necessity to introduce Transition Zones as interfaces between the Ballastless Track and the Ballasted Track sections. In the Transition Zones, the total stiffness (elasticity) coefficient of the multilayered structure "Track" must change gradually in order to secure a smooth stiffness transition, resulting in an entailed smooth changing of the acting forces on the track.

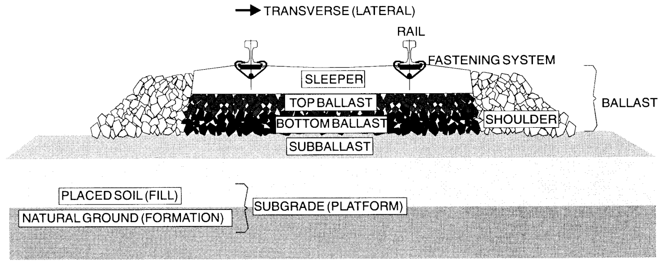


Fig. 8. Longitudinal Section of track with terminology (Selig et al., 1994)

The acting forces are a decisive factor for the dimensioning of the permanent way both for ballasted and ballastless track, as well as of its constitutive elements and layers. For the terminology of the layers of the railway track, according to the International Union of Railways (UIC) Figs 5 and 6 are cited below.

METHODS OF ESTIMATION OF THE ACTIONS, MEAN PRESSURE, SUBSIDENCE

Estimation of Actions

In general, the probabilistic approach, adopted for the calculation of the Design Load, consists of the estimation of the increase of the mean value of the vertical wheel load in order to cover the statistically desirable safety level. In this framework three basic calculation methods are distinguished characterizing three different ways of approaching the matter:

- The method proposed in the French Bibliography (Alias, 1984, Prud'homme et al., 1976, RGCF, 1973),
- The method proposed in the German Bibliography (Fastenrath, 1981, Eisenmann, 2004),
- The method proposed by the author in Greece (Giannakos, 2002, 2004, 2009c).

(a) The equation cited in the French bibliography (Prud'homme, 1976) is:

$$R_{total} = \left(Q_{wheel} + Q_{\alpha} + 2\cdot\sqrt{\left[\sigma^2(\Delta Q_{NSM})\right] + \left[\sigma^2(\Delta Q_{SM})\right]}\right)\cdot \bar{A}_{stat} \cdot 1{,}35 \qquad (1)$$

where: Q_{wheel} = the static load of the wheel (half axle load)
Q_{α} = load due to cant (superelevation) deficiency
$\sigma(\Delta Q_{NSM})$ = standard deviation of the Non-Suspended (unsprung) Masses of vehicle
$\sigma(\Delta Q_{SM})$ = standard deviation of the Suspended (Sprung) Masses of vehicle
$\bar{A}_{stat}$ = reaction coefficient of the sleeper which is equal to:

$$\bar{A}_{stat} = \frac{1}{2\sqrt{2}}\cdot\sqrt[4]{\frac{\rho_{total}\cdot\ell^3}{E\cdot J}} \qquad (2)$$

ρ_{total} = coefficient of total static stiffness (elasticity) of track
ℓ = distance among the sleepers

E, J = Modulus of Elasticity and Moment of Inertia of the rail

(b) The equation cited in the German bibliography (Fastenrath, 1981, Eisenmann, 2004) is:

$$R = S = \frac{Q_{total} \cdot \ell}{2 \cdot L} \Rightarrow R = \frac{Q_{total}}{2} \cdot \sqrt[4]{\frac{\rho_{total} \cdot \ell^4}{4 \cdot E \cdot J \cdot \ell}} = \\ = Q_{total} \cdot \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\rho_{total} \cdot \ell^3}{E \cdot J}} = \overline{A}_{stat} \cdot Q_{total} \qquad (3)$$

where: $Q_{total} = Q_{wheel} \cdot (1 + t \cdot \overline{s})$ (4)

ρ_{total} the total static stiffness coefficient of the track

Q_{wh} is the static load of the wheel,

$\overline{s} = 0.1 \cdot \varphi$ to $0.3 \cdot \varphi$ depending on the condition of the track, that is

$\overline{s} = 0.1\ \varphi$ for excellent track condition

$\overline{s} = 0.2\ \varphi$ for good track condition

$\overline{s} = 0.3\ \varphi$ for poor track condition

and φ is determined by the following formulas as a function of the speed:

For V < 60 km/h: φ = 1.

For 60 < V < 200 km/h:

$$\varphi = 1 + \frac{\mathrm{V} - 60}{140}$$

where V the maximum speed on a section of track and t coefficient dependent on the probabilistic certainty P (t=1 for P=68.3%, t=2 for P=95.5% and t=3 for P=99.7%).

(c) The equation proposed by the author as a result of the research in the Greek railway network (Giannakos 2004, 2009c):

$$R_{service} = \overline{A}_{dynam} \cdot \left(Q_{wheel} + Q_{\alpha}\right) + (3 \cdot \sqrt{\left[\sigma^2(\Delta Q_{NSM})\right]^2 + \left[\sigma^2(\Delta Q_{SM})\right]^2}) \qquad (5)$$

where:

$$\overline{A}_{dynam} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3 \cdot h_{TR}}{E \cdot J}}$$

$$and \qquad h_{TR} = \rho_{dynam} = 2\sqrt{2} \cdot \sqrt[4]{E \cdot J \cdot \left(\frac{\rho_{total}}{\ell}\right)^3} \qquad (6)$$

and h_{TR} the total dynamic stiffness of the track,

ρ_{total} the total static stiffness coefficient of the track.

It must be noted here that in all three methods the total static stiffness coefficient of the track ρ_{total} is of decisive importance for the calculation of the action/reaction on each sleeper. In general according to international bibliography:

$$\frac{1}{\rho_{total}} = \sum_{i=1}^{\nu} \frac{1}{\rho_i} \qquad (7)$$

where i are the layers that constitute the multilayered structure."Track" or "Permanent Way", and

ρ_{total} the total static stiffness coefficient of track, which must be calculated for each case.

In Greece since the 1970's were laid on track twin-block concrete sleepers Vagneux U2, U3 with RN fastenings, quite the same as the ones used in the French Railways (SNCF). Of the above three types, 60% (and more) exhibited cracks only in the Greek network, at a position under the rail from the lower bearing area of the sleeper propagating upwards (Giannakos, 2009d). The same type of sleepers are laid on the French network with operational speed 200 km/hr and daily tonnage 50,000 t/day, whereas in Greece until the beginning of 2000, the maximum operational speed was 120÷140 km/hr (it is now≥160 km/hr) and the daily tonnage did not exceed 10,000 t/day. It is noted that the same sleeper type in the French Railways network did not exhibit any problems at all (Giannakos 2004, 2009d). The load that derives when applying the two methods (of German and of French bibliography) under the most adverse conditions, gives values that justify –in very extreme conditions of loading- either no cracking at all or sporadic appearance of cracks (in the order of 1-2%) but do not justify at all their systematic appearance at 60% at least of the sleepers. On the contrary the method in Giannakos (2004) justifies completely the appearance of extended cracking (60% and over). In this paper the method Giannakos (2004) is applied, for the parametric investigation, so it is cited briefly below.

Mean pressure on formation and subsidence

For the cases of the blanket layers, subgrade, and prepared subgrade (Fig. 5) that constitute the formation, dimensioning is performed with Design Loads/Actions derived by Eqn (5) with 2 times (or 1 time for the upper surface of the prepared subgrade) the standard deviation of the dynamic component of the load instead of 3 as in Eqn (5), corresponding to a possibility of 95.5 % instead of 99.7 % for the earthworks (Giannakos 2004, 2010, Giannakos et al., 2009d). Thus the following equation is derived from Eqn (5):

$$R = \overline{A}_{dynam} \cdot \left(Q_{wheel} + Q_{\alpha}\right) + (2 \cdot \sqrt{\left[\sigma^2(\Delta Q_{NSM})\right]^2 + \left[\sigma^2(\Delta Q_{SM})\right]^2}) \qquad (8)$$

and the average pressure on the upper surface of formation can be calculated by the following equation:

$$\overline{p} = \overline{A}_{subsidence} \cdot \left(Q_{wheel} + Q_{\alpha}\right) + \frac{\sqrt{\left[\sigma\left(\Delta Q_{NSM}\right)\right]^2 + \left[\sigma\left(\Delta Q_{SM}\right)\right]^2}}{h_{TR}} \cdot C \qquad (9)$$

where: F_{sleep} = the sleeper's seating surface (for monoblock sleepers the central non-loaded area should be subtracted)

$$C = \frac{\rho_{total}}{\left(\frac{F_{sleep}}{2}\right)} \tag{10}$$

the rest of the parameters as above.

The subsidence y_{total} of the track multilayered structure should be calculated by the following equation (Giannakos, 2009c):

$$y_{total} = \bar{A}_{subsidence} \cdot \left(Q_{wheel} + Q\ \right) + \frac{2\left(\sqrt{\left[\sigma\left(\Delta Q_{NSM}\right)\right]^2 + \left[\sigma\left(\Delta Q_{SM}\right)\right]^2}\right)}{h_{TR}} \tag{11}$$

where: $$\bar{A}_{subsidence} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3}{E \cdot J \cdot h_{TR}^3}} \tag{12}$$

It must be noted that bibliography cites that the measurements on track indicate that we should take into consideration the dispersion which enters the theoretical calculation through coefficients depending on the probability of the appearance of various individual parameters (Eisenmann 1980, 1988). In German bibliography as well, a smaller coefficient of probability of appearance (95.5% with t=2 or even 68.3% with t=1) is used for the formation of the track (Eisenmann, 1988).

THEORETIC TRACK TOTAL STIFFNESS

The stiffness (elasticity) coefficient ρ_i of each layer is a "spring coefficient" (as in Hooke's law) that contributes to the total track stiffness coefficient $\rho_{total.}$ The calculation of stiffness ρ_i and ρ_{total} is used to determine the action/reaction on a sleeper. It is cited that, after experimental on-the-track investigation, the theoretical subsidence is the same with that deriving from the calculation of the track's vertical stiffness (Eisenmann et al., 1984). Professor J. Eisenmann (1980, 1988) also ascertains that theoretical calculations –as above-performed for the dimensioning of the superstructure correspond to the average value of the measurements. The calculation of ρ_{total} is performed for springs in a parallel arrangement:

(i) for Slab Track (with concrete sleepers embedded in its structure like classic Rheda type) according to the equation

$$\frac{1}{\rho_{total}} = \frac{1}{\rho_{rail}} + \frac{1}{\rho_{pad1}} + \frac{1}{\underbrace{\rho_{pad\,2}}_{if-it-exists}} + \frac{1}{\rho_{sleeper}} + \frac{1}{\rho_{concrete-slab}} \tag{13}$$

(ii) for ballasted track:

$$\frac{1}{\rho_{total}} = \frac{1}{\rho_{rail}} + \frac{1}{\rho_{pad}} + \frac{1}{\rho_{sleeper}} + \frac{1}{\rho_{ballast}} + \frac{1}{\rho_{substruct}} \tag{14}$$

For Transition Zones between ballasted and ballastless track Eqn (13) -appropriately adapted- should be used.

Typical values for Ballasted and Ballastless Track stiffnesses derived from measurement data from Germany are provided in Giannakos (2010) of the present Conference. .

STATIC AND DYNAMIC STIFFNESS COEFFICIENTS OF THE PADS AND THE TRACK

General

Track is a multilayered structure of "springs" and "dampers" in parallel arrangement consisting of: rail, elastic pad, sleeper/tie, ballast, substructure (Fig. 9). The more elastic the whole structure is, the less reaction/action is exercised on the sleeper, since the load is distributed to more (adjacent) sleepers along the rail. Elastic pad and substructure are the most resilient (elastic) from the five constitutive layers of track and they contribute the greater percentage of the total stiffness of the structure. Elastic pad –resilient element existing only in railways- possibly offers more than 50% in the total stiffness coefficient. The compatibility of the load-deflection curve of the pad with the corresponding curve of the clip of the fastening, is of utmost importance and constitutes the high technology element in the railway track. For this reason the influence of the pad stiffness, static and dynamic needs to be investigated.

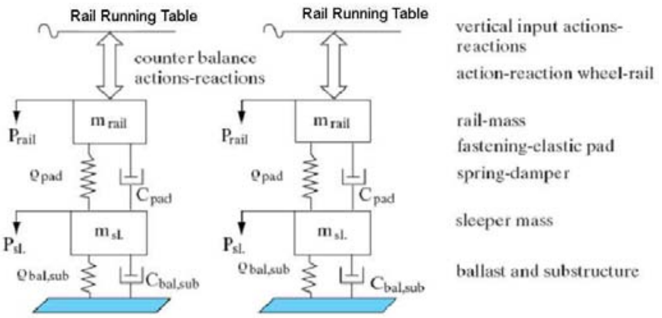


Fig. 9. Track as a multilayered structure of "springs" and "dampers"

Static and Dynamic Stiffness Coefficients of the elastic pads

For the parametric investigation the W14 Fastenings with Zw700 Wirtwein pad for ballasted track and Ioarv300 with Zw104/22.5 for Slab Track, both of Vossloh Gmbh are used, which are laid in the Hellenic Railway network and are among the most resilient fastenings all over the world. For the Embedded Track the DFF21 fastening of Vossloh Gmbh with Zw700 Saargummi pad is used and in the ballasted track the W14 fastening with Zw700 Saargummi pad is used.

As described below, Zw700 Wirtwein and Zw700 Saargummi pads have different stiffness coefficients. The Load – Deflection curves of these fastenings were used to determine the coefficient ρ (or c) for the pads (and also the fastenings).

The investigation yielded results depicted in Fig. 10. In the upper illustration the static stiffness coefficients of the pads are presented for a range of the stiffness coefficients of the substructure (Ballastless Track) between 86 kN/mm and 250 kN/mm.. The lower illustration depicts the dynamic stiffness coefficients of the pads (Giannakos 2004) or coefficients of track stiffness c_G according to the "List of Requirements for Slab track Construction" of German Railways (Anforderungskatalog, 2002, 2 seite 1) for the cases of Slab Track, Transition Zone, and Ballasted Track.

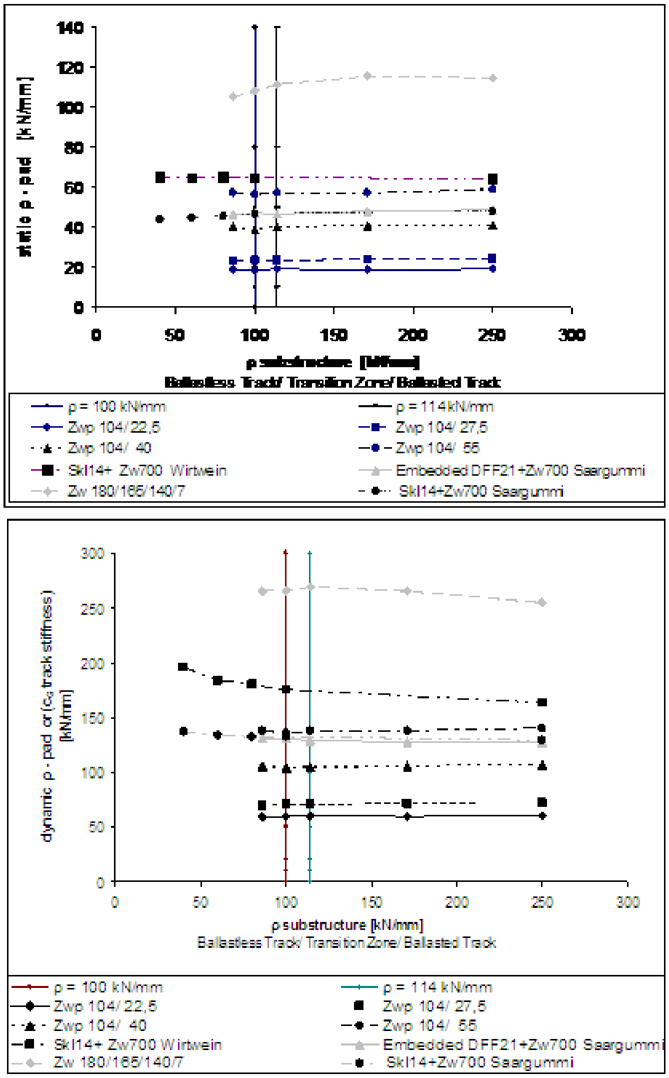


Fig. 10. Coefficient of pad stiffness ρ (upper illustration) static and (lower illustration) dynamic

For the Embedded Track the aforementioned "List of Requirements" is not applicable, but the same range of subgrade stiffness is used. For the case of Ballasted Track the the static coefficient of stiffness for the substructure ranges from 40 kN/mm to 250 kN/mm. Figure 11 depicts (upper illustration) the coefficient of total dynamic stiffness of track ($\rho_{dynam}=h_{TR}$) and (lower illustration) the coefficient of total static stiffness of track ρ, for the Ballastless Track, the Transition Zone and the Ballasted Track (see Giannakos, 2004).

From Fig 10 (lower illustration) it is derived that for the Slab Track section of the permanent way (pad Zw 104/22,5), the dynamic coefficient of the pad (Giannakos, 2004) covers the following requirements of the "List of Requirements for Slab track Construction" (Anforderungskatalog, 2002, 2 seite 1) :

$$\rho_{dynamic-pad} = c_G = 64 \pm 5 \quad kN/mm \qquad (15)$$

This dynamic stiffness coefficient of the pad refers to the pad laid in a track with specific characteristics/parameters and it is different from the dynamic stiffness coefficient of the individual pad measured at the laboratory. More details about this pad dynamic stiffness laid in a track with specific characteristics/parameters are cited in Giannakos (2002, 2004).

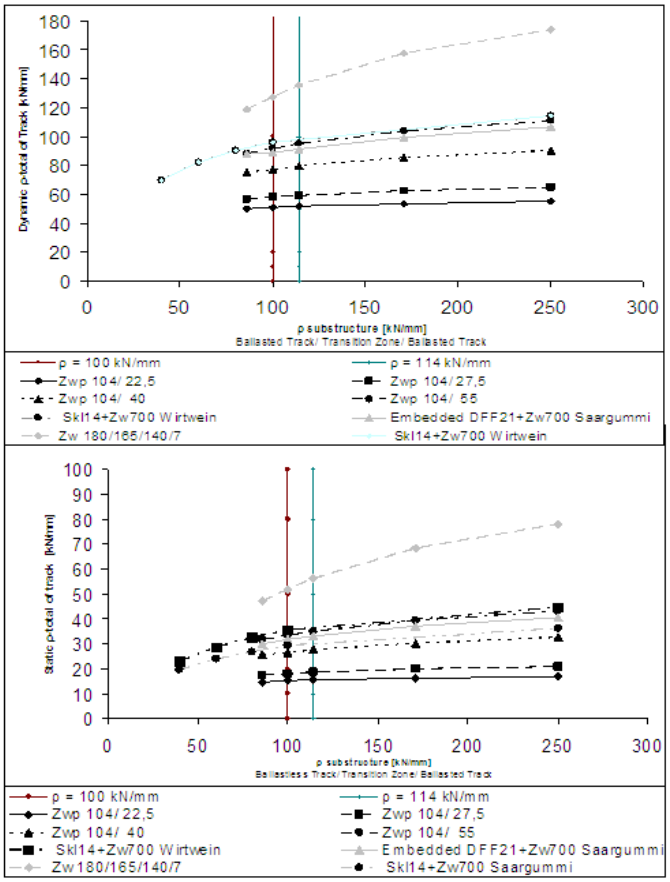


Fig. 11. Coefficient of total track stiffness ρ (upper illustration) static and (lower illustration) dynamic

For the ballasted track in the "List of Requirements for Slab track Construction" of the German Railways (Anforderungskatalog, 2002, Anhang 2.1 seite 3 – 4), an example calculation for the stiffness coefficient c_G *(gleissteifigkeit)* is cited. In this example instead of ρ (or c), the sum of the inverse ρ_i of the substructure and of the pad (for C=0.15 N/mm^3 that is $\rho_{substructure}$= 43 kN/mm (as in Table 1 of Giannakos, 2004) is taken into account. Obviously, this happens in order to facilitate calculation,. In fact results are derived slightly more adverse and consequently to the safer side in comparison to the use of ρ_{total} from Eqn (13), which would be more accurate but a slightly more complicated.

In the present paper the calculations are performed with the use of the more accurate ρ_{total} according to Eqn (13), that is of the coefficient of the total static stiffness of track accurately calculated. In this case for comparability reasons the results for $\rho_{substructure} = 40$ kN/mm $\cong$ 43 kN/mm are used which are valid. Consequently it is derived:

$$\rho_{total\text{ - }dynamic} = h_{TR} = 67{,}76 \text{ kN/mm} < 78 \text{ kN/mm} \qquad (16)$$

It is a result similar to the example cited in the "List of Requirements for Slab track Construction" of German Railways (Anforderungskatalog, 2002, Anhang 2.1 seite 3 – 4).

In the case of the Embedded Track the requirement of the "List of Requirements (Anforderungs Katalog)" is not fulfilled, since the Embedded Track is not included in the region of application of the "List", and in this case (Giannakos, 2009a):

$$\rho_{dynam-pad} = c_G = 127.83 - 130.80 > 64 \pm 5 \quad \text{kN/mm} \qquad (17)$$

Static and Dynamic Coefficient of the Track's total Stiffness

Parametric investigation using the Load – Deflection curves of the elastic pads and ranges of stiffness coefficients as above, uielded results for the coefficients of total static stiffness $\rho_{total\text{-}stat}$ of track as well as the coefficients of total dynamic stiffness of track $\rho_{total\text{-}dynamic}=h_{TR}$ (Giannakos, 2004, 2007). These results are depicted in Fig. 11. In the lower illustration the coefficient of the total static stiffness of track $\rho_{total\text{-}stat}$ in Ballastless Track, Transition Zone and Ballasted Track is presented and in the upper illustration the coefficients of the total dynamic stiffness of track $\rho_{total\text{-}dynamic}=h_{TR}$ in Ballastless Track, Transition Zone and Ballasted Track.

In Figs 10 and 11 the vertical curves for (a) $\rho = 100$ kN/mm and (b) $\rho = 114$ kN/mm are depicted which represent the stiffness coefficient of substructure for ballasted track/slab track (ρ=100) and slab track (ρ=114). For New Constructed Lines NBS (Neubaustrecke) in Germany these values are the most representative according to the existing German bibliography.

Parametric investigation shows that Ballastless Track presents coefficient of total dynamic stiffness of track approximately 50 % smaller than the Ballasted Track in the case of Slab Track and almost similar to the Ballasted Track in the case of the Embedded Track. It must be noted that even though the Ballastless Track is much more rigid (stiff) than the Ballasted Track due to the bearing concrete slab, after the appearance and the use of the highly resilient fastenings of advanced technology with the corresponding compatible elastic pads its overall response becomes much softer. Moreover it is observed that there is no significant amplitude of fluctuation of the total track stiffness coefficient for relevant subgrade stiffness fluctuation from very "soft"/flexible of 40 kN/mm in the case of gravelly subgrade to very rigid of 250 kN/mm in the case of rocky tunnel bottom in the case of Ballasted Track and from 84 kN/mm to 250 kN/mm in the case of Ballastless Track (see also Giannakos et al., 2009b).

ACTIONS ON THE TRACK PANEL

In Giannakos (2010) the calculations have been performed, for confidence percentage (possibility of appearance), according to the three methods mentioned above. It was found that the Actions (Loads) on the track superstructure in the case of Ballastless Track have negligible fluctuations around the level of 150 kN for subgrade stiffness varying from 84 kN/mm to 250 kN/mm (in the case of a tunnel's rocky bottom) for the Slab Track case. This should be compared to the actions of about 170 kN in the case of the Ballasted Track with fastening W14 and subgrade stiffness from very flexible 40 kN/mm of gravely subgrade to 250 kN/mm. The level of 170 kN is also similar to the magnitude of the actions in the case of Embedded Track.

CALCULATION OF ACTIONS ON SUBGRADE WITH 95.5% LEVEL OF CONFIDENCE

Even though bibliography suggests (Eisenmann, 1988, Esveld 2001) that regarding the substructure load the sum of the mean load +1 standard deviation should be taken, and for the case of the ballast between 1÷3 (P = 68.3% ÷ 99.7%) standard deviations depending on the speed and the necessary maintenance work, it has been found that a confidence percentage of 95.5 % is more appropriate (t=2 or 2 times the standard deviation, see Giannakos, 2004, 2010).

Applying Eqn (5), the actions on the track panel are derived in relation to the fluctuation of the subgrade's stiffness, with confidence percentage 99.7 % (3 times the standard deviation of the dynamic component of the load). This parametric investigation, in comparison to the methods cited in German and French bibliographies, is presented in Giannakos (2010) at the present Conference. As it is stated above, for the stressing of the subgrade the actions taken into account covers a possibility of appearance of 95.5 %, that is 2 times the standard deviation of the dynamic component of the load, as in Eqn (8).

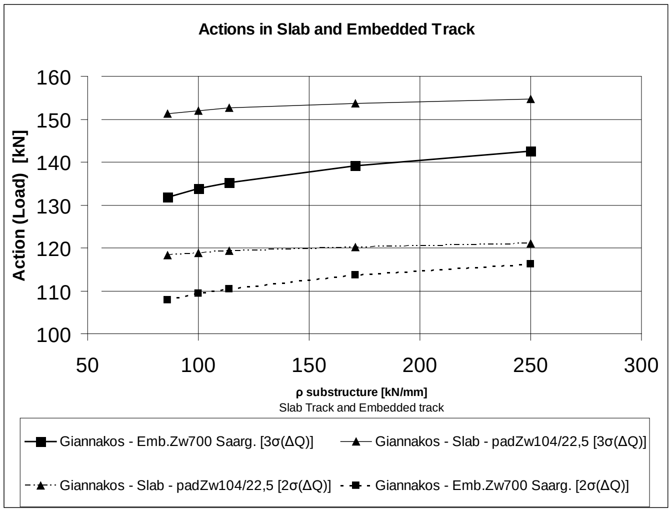


Fig. 12. Actions on track, in case of Ballastless Track, comparison for 95.5 % and 99.7% certainty of appearance

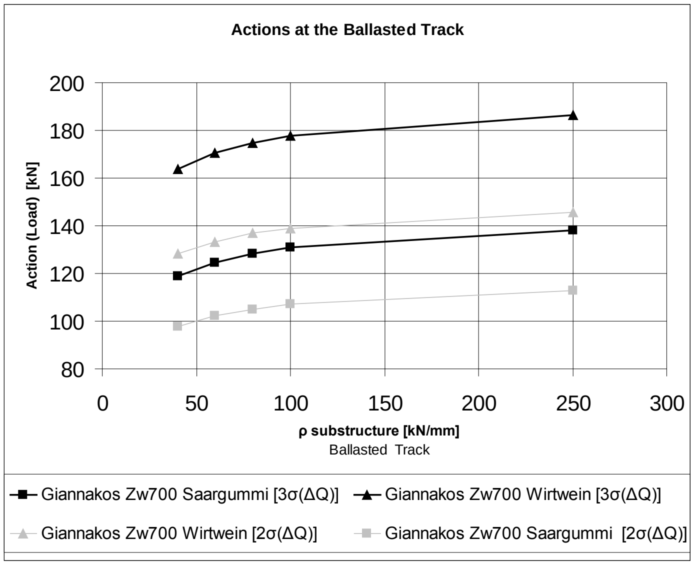


Fig. 13. Actions on track in case of Ballasted Track, comparison for 95.5 % and 99.7% certainty of appearance

The parameters for the calculations were:

- For Slab Track the maximum axle load is 22.5 t, maximum speed 250 km/h (155.38 m/h), Non-Suspended Masses (NSM) 1.5 t (two axle bogies), rail running table coefficient k=9 (average non ground rail surface), maximum cant (superelevation) deficiency 160 mm.
- For the Embedded Track case, the following should be taken into account: maximum axle load is 22.5 t, maximum speed 120 km/h (74.58 m/h), Non-Suspended Masses (NSM) 2.54 t (three axle bogies), rail running table coefficient k=9, maximum cant (superelevation) deficiency 110 mm.

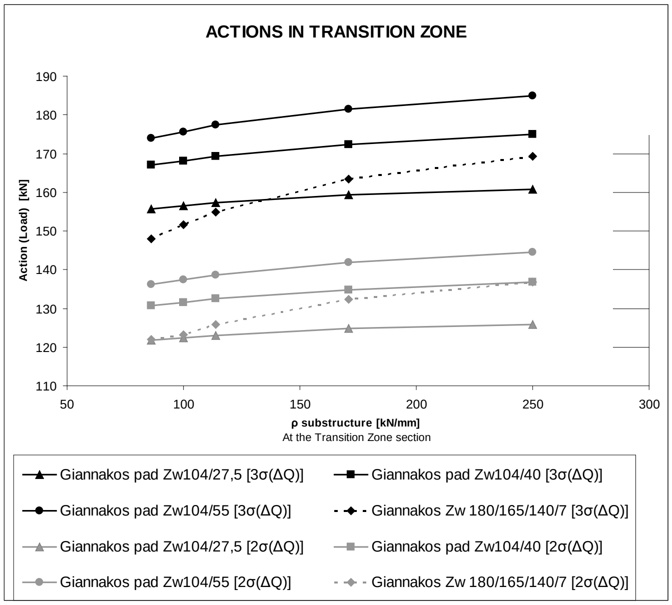


Fig. 14. Actions on track, in case of Transition Zone between Ballasted and Ballastless Track, comparison for 95.5 % and 99.7% certainty of appearance

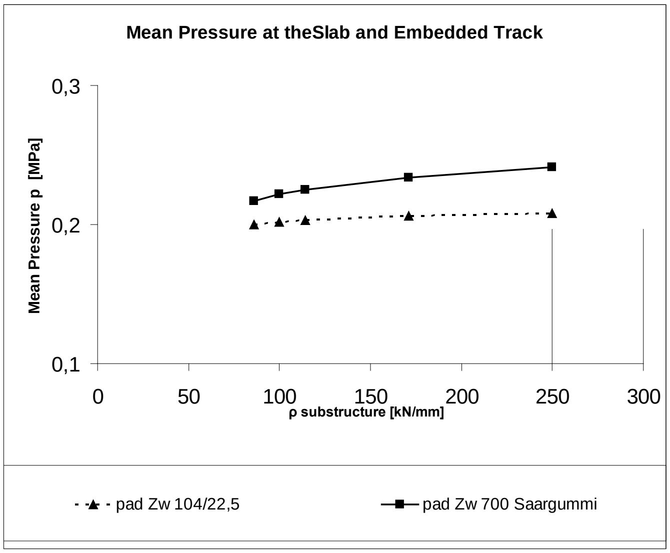


Fig. 15. Mean Pressure $\overline{p}$, in case of Ballastless Track with 95.5 % certainty of appearance

In Figs 12, 13 and 14 the graphic comparison of the results of the Eqns (5) and (8) is depicted in relation to the fluctuation of the subgrade's stiffness coefficient ρ_{subgr}, for the cases of the Ballastless Track, the Ballasted Track and the Transition Zone between them.

FORMATION STRESSING AND REQUIREMENTS

Track maintenance and renewal are planned, always taking into consideration local conditions, based on a resultant of control data from measuring systems, visual observation and economic data. Each track, as in every construction, has a predetermined life cycle during which maintenance works are necessary for the provision of the basic, minimum standards of quality and safety as mentioned above. For conventional superstructure, that is rail, fastenings, sleepers and ballast, there is an optimum life-cycle from an economic point of view. The mean stress on the formation (magnitude of the pressure on the contact surface) plays a major role in the maintenance needs and planning and consequently on the costs.

It is characteristic that in international bibliography, the average stress on the contact surface between sleeper-ballast is used to examine the stressing on the seating of the track. On the basis of AASHTO testing for road construction, the following formula is valid:

Decrease in track geometry quality =
(increase in stress on the ballast bed)^m
where m = 3 to 4.

When the pressure on the ballast is increased by 10%, then we have 1.3 to 1.5 times more rapid decrease in the track's geometry, and a corresponding increase of the maintenance cost.

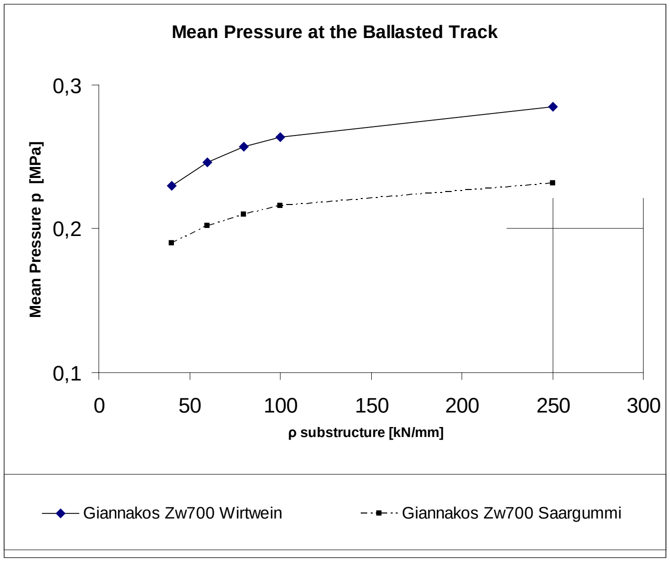


Fig. 16. Mean Pressure $\overline{p}$, in case of Ballasted Track with 95.5 % certainty of appearance

During the study for the dimensioning as well as the selection of the individual materials that constitute a railway track, the "weak links" are the ballast and the substructure. According to bibliography the key parameters for the definition of the track's vertical stiffness and deformation are the quality of substructure and elastic pad, both of which characterize the subsidence (or the stiffness) of a track, that is the distribution of loads between the sleeper that carries the axle and the adjacent sleepers (Eisenmann, 1988, 1981, 1980). Among them it is the substructure (formation) of the track that presents residual deformations: subsidences and lateral displacements, directly connected to the deterioration of the so-called geometry of the track, which can be nevertheless described much more specifically as quality of the track. The slighter the residual deformations and the slower their alteration over time is, the better the quality of the track.

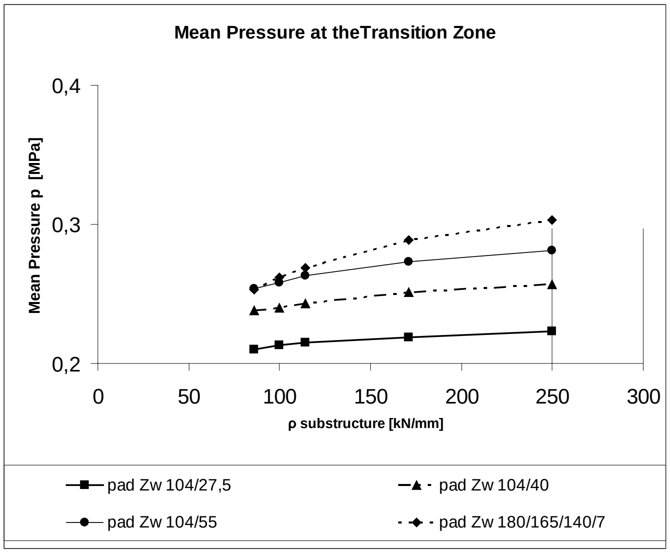


Fig. 17. Mean Pressure $\overline{p}$, in case of Ballasted Track with 95.5 % certainty of appearance

Minimizing or diminishing the subsidence in these two layers practically minimizes the permanent deformation of the track. In order to achieve that, the mean pressure on the formation layers should be minimized and –more specifically- kept under some precise values. In the present paper the influence of the actions and the stress on the subgrade (and prepared subgrade) is examined. These layers constitute the Formation of the Track (Fig. 5, 7, 8), which in the case of Ballasted Track is just underneath the ballast-bed and in the case of the Ballastless Track it is just under the Cement Treated Base (CTB) as depicted in Fig. 6

It is imperative to reduce as much as possible the development of vertical, primarily, as well as lateral displacements on to formation layers. On the contrary the total subsidence of the track structure should acquire a high value, in order to distribute the load Q_{total} at a longer distance from its acting point and consequently to a greater number of adjacent sleepers. This should minimize the action/reaction on each sleeper. The above two requirements are contradictory. The solution is the adoption of very "soft" fastening pads contributing a high value of subsidence in a resilient behaviour that secures non-permanent deformation and consequently excellent preservation of the geometry/quality of the track.

For a given quality of ballast material, as far as the part of the deformations caused by the ballast are concerned, this is accomplished by the correct combination and usage of heavy track machinery (ballast regulator, tamping machine, dynamic stabilizer). For the layers underneath the ballast a very well-executed construction is required: crushed stone material in the upper layer, 100% Proctor compaction or 105% Proctor modified (Giannakos, 1999). According to the demands of the German Railways (DB) the requirement for the modulus of elasticity E_{v2} (taken from the second load step in a plate loading test) is: $E_{v2} \geq 120$ N/mm^2 both for the blanket layer just beneath the ballast bed (in the case of Ballasted Track) and for the Frost Protection Layer just beneath the Cement Treated Base (CTB) in the case of Ballastless Track.

Applying Eqn (9) the mean pressure is derived in relation to the fluctuation of the subgrade stiffness, with confidence percentage 95.5 % (2 times the standard deviation of the dynamic component of the load). The results of the Eqn (9) are depicted in Figs 15, 16 and 17 for the cases of Ballastless and Ballasted Track as well as for the Transition Zone between them.

The permissible compressive stress on the formation (blanket layer, subgrade) can be established using the following equation (Esveld, 2001):

$$\bar{\sigma}_z = \frac{0.006 \cdot E_{v2}}{1 + 0.7 \cdot \log n} \qquad (18)$$

where: E_{v2} modulus of elasticity taken from the second load step in a plate loading test

n number of load cycles (usually 2 million cycles)

For 2 million cycles and E_{v2}=120 N/mm^2, then the permissible compressive stress for the blanket layer (or Frost Protection Layer for slab track) should be (see also Esveld, 2001, p. 95, 258) :

$$\bar{\sigma}_z = 0.13307 \text{ N/mm}^2 \qquad (19)$$

The pressure on the formation, assuming a distribution cone of 45 degrees and a layer thickness of 25 cm underneath the lower contact surface of the sleeper, can be estimated as follows:

Sleeper seating surface S_{sleep}=1100 mm x 259 mm≈ 285,000 mm^2

Surface on the top of Formation $S_{Form} \approx$1600 mm x 759 mm = 1,214,400 mm^2

Relation S_{sleep}/ S_{Form}=0.235

Consequently $\bar{p}_{Form} = \bar{p}_{Sleep} \cdot 0.235$ (20)

And its maximum possible value (from Figs 13 to 15) is:

$$\max \bar{p}_{Form} \approx 0.3 \cdot 0.235 = 0.0705 \text{ N/mm}^2 < 0.13307 \text{ N/mm}^2$$

in the case of the quality of formation described above with E_{v2}=120 N/mm^2. In the limit a formation quality of E_{v2}=80 N/mm^2 could be accepted (with permissible compressive stress $\bar{\sigma}_z$=0.089 N/mm^2 derived from Eqn 18).

CONCLUSIONS

The parametric investigation performed in this paper showed that for the dimensioning of the top layers of the formation/ substructure of the railway track and especially the blanket layer in the case of Ballasted Track and the Frost Protection Layer in the case of Ballastless Track, a very good quality should be aimed during the design and the construction. For the Ballastles Track case an excellent quality of the top of the substructure with E_{v2}=120 N/mm^2 is not expected to present any problems at all. For the Ballasted Track a quality of E_{v2}=80 N/mm^2 is not expected to present a problematic behaviour.

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