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INTERACTION BETWEEN SUPERSTRUCTURE AND SUBSTRUCTURE IN RAILWAYS

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ABSTRACT

The railway track superstructure undertakes the forces that develop during train movement and distributes them towards its seating. The track panel (sleepers with their fastenings or slab with the fastenings) plays a key role in terms of load distribution, while at the same time it ensures the stability of the geometrical distance between the rails. Earthworks and ballast (if it exists) undergo residual deformations, settlements and lateral displacements, directly influencing the deterioration of the so-called geometry of the track, which can be nevertheless described much more specifically as quality of the track. In this paper, a parametric investigation of the stiffness of the substructure of the railway track and of the elastic pads of the fastenings is presented. Moreover, conclusions are drawn for the magnitude of the acting forces. A methodology is also suggested for the calculation of the actions and stresses that strain the layers of the track structure as well as for the mean pressure on the seating surface of the sleepers (or the slab) and the total settlement of the structure.

INTRODUCTION

The track's superstructure is a multilayered construction consisting of: (a) the rails, which support and guide the train wheels, (b) the sleepers (with their fastenings) which distribute the loads effected by the rails and retain the distance between them (gauge), and (c) the ballast in the case of the classic ballasted track (Figure 1) or the concrete slab in the case of the more recently developed Slab Track (Figure 2). In the case of the ballasted track the superstructure also includes the blanket layer (sub-ballast) which consists of sand and gravel adequately compacted. It contributes to further load distribution and protects the substructure's upper surface from penetration of the ballast particles.

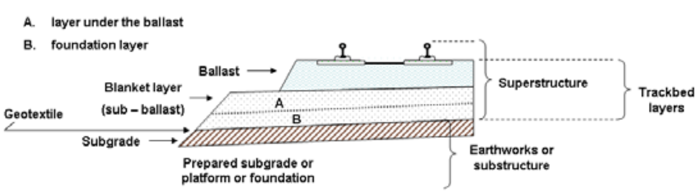
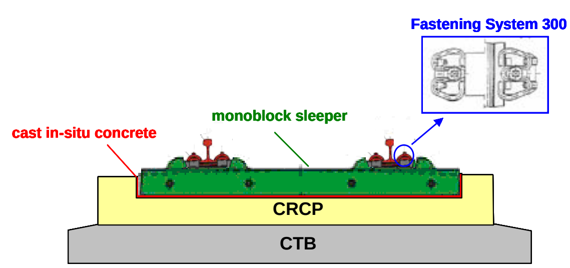


Fig. 1. Cross section of classic Ballasted Track with twin block concrete sleepers.

.The use of ballastless track is necessary as Slab Track in the case of High-Speed Lines (V>200 km/h or 124.30 m/h), 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 slab. 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 (Tsoukantas, 1999).



CRCP=Continuously Reinforced Concrete Pavement

CTB = Cement Treated Base

Fig. 2. Cross section of Rheda type Slab Track with monoblock concrete sleepers.

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 the ballast-bed with a concrete floor for functional reasons (i.e. 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.). In this case an embedded track is constructed which must also secure small or zero maintenance needs for the railway track. Its main difference from the slab track is the low speed of train circulation.

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 and the ballasted track sections. In the Transition Zones, the total stiffness (elasticity) coefficient of the multilayered structure must change gradually in order to secure a smooth stiffness transition, resulting in a smooth variation of the acting forces on the track.

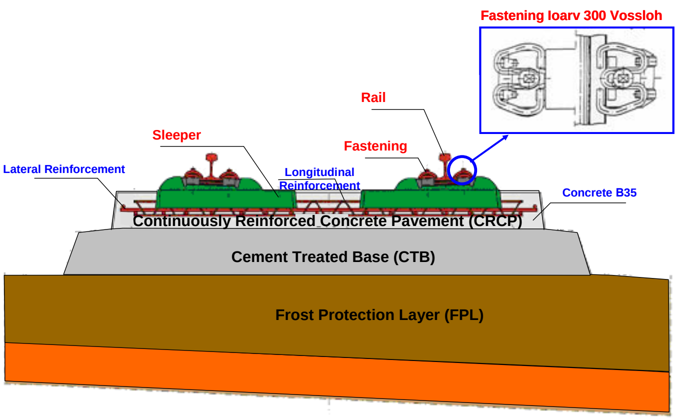


Fig. 3. Cross section of Rheda 2000 Slab Track with monoblock concrete sleepers

The acting forces are a decisive factor for the dimensioning of the railway track both for ballasted and ballastless track, as well as of its elements and layers. This paper presents an investigation of the interaction between superstructure and substructure in the permanent way and consequently the factors influencing the dimensioning of the superstructure of the track in all cases: Ballastless Track, Transition Zone, and Ballasted Track. This is performed for the first time in Greece in the case of: (a) the use of Rheda 2000 type Slab Track (Figure 3) at the High-speed network (V>200 km/h) of the Greek Railways (Giannakos, 2008a), 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).

CALCULATION METHODS FOR THE DESIGN LOAD OF A RAILWAY TRACK

In general, in order to calculate the stresses and strains on the different layers of the track and due to the random nature of the moving loads, a probabilistic approach is adopted. This approach has been utilized for the calculation of the Design Load and 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 presented 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 developed by the author (Giannakos, 2004, 2009c), after a ten-year research program in order to define the causes for the appearance of cracks in more than 60% of concrete twin block sleepers in the Greek Railway network.

In this paper Q is the load acting on the track panel and R is the reaction/action on a sleeper after the distribution of the load to the adjacent sleepers.

(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

Equation (1) gives the most adverse results among the equations cited in the French bibliography for the dimensioning of the elements of the track superstructure and substructure (Prud'homme et al., 1976). In practice Eqn (1) gives 10% higher value for the reaction R than other corresponding equations cited in the French bibliography (Alias, 1984, RGCF, 1973). This equation is applicable for the most adverse conditions of track stiffness (rigid, undeflected structure), for k=12 which is the most adverse coefficient of the rail running table of rail, for the case of non-ground rail, and for speeds higher than 120-140 km/h. For speeds smaller than 120 km/h and in lines of less importance k could be taken equal to 25 (Giannakos, 2004).

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

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

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

$$Q_{total} = Q_{wheel} \cdot (1 + t \cdot \bar{s}) \quad (4)$$

and Q_{wh} is the static load of the wheel,
$\bar{s} = 0.1 \cdot \varphi$ to $0.3 \cdot \varphi$ depending on the condition of the track, that is
$\bar{s} = 0.1\ \varphi$ for excellent track condition
$\bar{s} = 0.2\ \varphi$ for good track condition
$\bar{s} = 0.3\ \varphi$ 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:

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

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):

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

where:

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

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

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:

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

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.

DEFINITION OF TOTAL TRACK STIFFNESS FOR DIFFERENT CASES OF PERMANENT WAY

The above equations have been applied in the cases of ballastless track, transition zone and ballasted track. For the determination of the spring constant (stiffness) of the Slab Track, Table 1 is valid for Ballasted and Ballastless Tracks as derived from measurements in the German railway network (Leykauf et al., 1990). For Slab Track the classic Rheda type slab track was used.

Table 1. Relation between ballast coefficient C and stiffness coefficient ρ (or c) in a line equipped with rails UIC60 and monoblock sleepers (ties) of prestressed concrete B70 and concrete plate/slab (Leykauf et al., 1990)

	Bearing Capacity of Subgrade					
	Ballasted Track			Ballastless Track		
	poor	good	very good	Concrete slab		
C [N/mm^3]	0.05	0.10	0.15	0.30	0.35	0.40
ρ [kN/mm]	14	29	43	86	100	114

The seating surface of the sleeper is F=5700 cm^2 and the distance between two consecutive sleepers is 60 cm. Bearing in mind that ρ=C·F/2 (Giannakos, 2004), the value of ρ for ballasted track calculated for the cases of Table 1, is (Giannakos et al., 2009b):

$$\rho = C \cdot \frac{F}{2} = 0.05 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 14.25 \approx 14 kN/mm \quad (7a)$$

$$\rho = C \cdot \frac{F}{2} = 0.10 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 28.50 \approx 29 kN/mm \quad (7b)$$

$$\rho = C \cdot \frac{F}{2} = 0.15 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 42.75 \approx 43 kN/mm \quad (7c)$$

$$\rho = C \cdot \frac{F}{2} = 0.30 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 85.5 \approx 86 kN/mm \quad (8a)$$

$$\rho = C \cdot \frac{F}{2} = 0.35 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 99.75 \approx 100 kN/mm \quad (8b)$$

$$\rho = C \cdot \frac{F}{2} = 0.40 \frac{\frac{1}{1000} kN}{mm^3} \cdot \frac{5700 \cdot 100 mm^2}{2} = 114.0 = 114 kN/mm \quad (8c)$$

In a Rheda type Slab Track (Figure 2) the sleepers used are a type of B70 with seating surface of $F=5700\ cm^2$. Consequently for the concrete plate functioning as subgrade underneath the seating surface of the monoblock sleepers (B70), the following will also be valid:

$$\rho = C\ F/2 \tag{9}$$

This implies that the coefficients of spring constant (stiffness coefficient) for the Slab Track should be calculated in a similar way from Equation (9). In this case the value of slab stiffness is similar to the stiffness of a substructure consiting of ballast and frozen soil as cited in Giannakos (2004, 2009c). The methodology described above models both the concrete slab (Betonplatte) and the underlying layers. Eisenmann (1994) cites that in the Newly-Constructed Lines (NBS-Neubaustrecke) in Germany the Ballast Coefficient C may be equal to the value even of $C=0.60\ N/mm^3$ (this implies $\rho=171$ kN/mm), which has been measured on site and for this reason it has also been taken into account in the parametrical solution/investigation that follows.

Eisenmann (1979) cites that the mean value of concrete slab subsidence is 0.23 mm (fluctuating between 0.17 and 0.31 mm). This is a result almost identical to the results calculated with the method Giannakos (2004). Consequently the coefficient of total static elasticity (stiffness) of track ρ_{total} for Slab Track (with concrete sleepers embedded in its structure) is given by the following equation:

$$\frac{1}{\rho_{total}} = \frac{1}{\rho_{rail}} + \frac{1}{\rho_{pad1}} + \underbrace{\frac{1}{\rho_{pad2}}}_{if-it-exists} + \frac{1}{\rho_{sleeper}} + \frac{1}{\rho_{concrete-slab}} \tag{10}$$

The aforementioned methodologies was applied for the Slab Track case using equations (7) to (10) and was subsequently used for the parametric investigation presented in the next paragraphs. 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.

This methodology was also applied in the case of Embedded Track, using respectively equations (7) to (10). The following were used: 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.

ESTIMATION OF THE ACTIONS ON THE TRACK

The aforementioned methods were programmed in a computer code and parametric investigations were performed varying the stiffness of the substructure. The results are depicted in Figs 4, 5, and 6 A clear comparison among the results derived by the three aforementioned methods can be performed in the three figures. The parameters (speed etc.) were used as described above for the stiffness.

In Figure 4 the actions on the track superstructure in the case of Ballastless Track are depicted, with fastening Ioarv300 and elastic pad Zw104/22,5 kN/mm for Slab Track and DFF21 fastening with Zw700 Saargummi pad for Embedded Track.

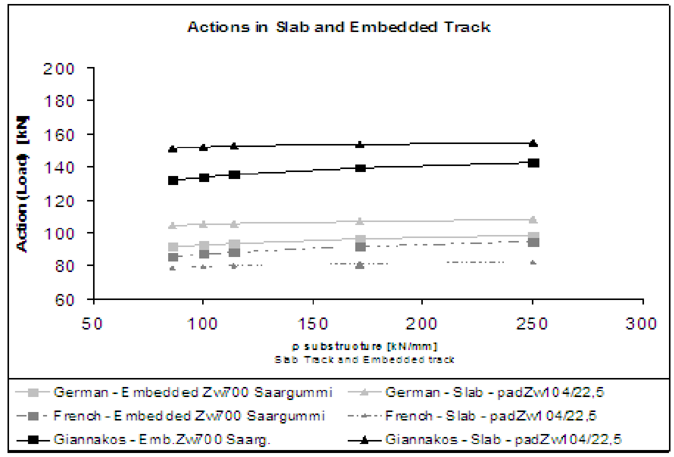


Fig. 4. Actions on track panel in the case of Ioarv 300 Fastening with pad Zw104/22,5 kN/mm (Slab Track) and in the case of DFF21 Fastening with pad Zw700 Saargummi (Embedded Track).

In Figure 5 the actions on the track superstructure are presented in the case of the Transition Zone are depicted, for the Slab Track case with fastening Ioarv300 and elastic pads Zw104/27,5 – Zw104/40 – Zw104/55 and for the Embedded Track case with fastening DFF21 h and elastic pad Zw180/165/140/7.

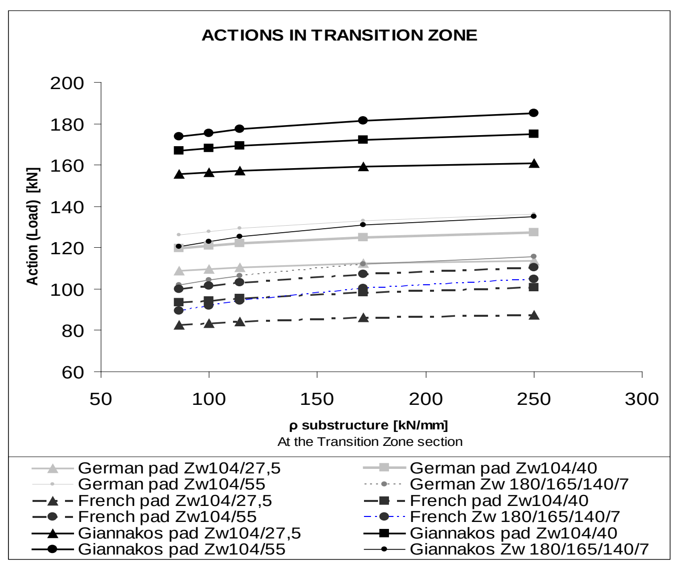


Fig. 5. Actions on track panel in the Transition Zone in a Slab Track (Ioarv 300 Fastening with pads Zw104/27.5 – Zw104/40 – Zw104/55) and an Embedded Track Section (with Skl14 and pad Zw180/165/140/7).

In Figure 6 the actions on the track superstructure in the case of the Ballasted Track are also depicted, with fastening W14 and two types of elastic pad: (a) Zw700 Wirtwein and (b) Zw700 Saargummi, having two different Load-Deflection curves and –consequently- different behavior under circulation.

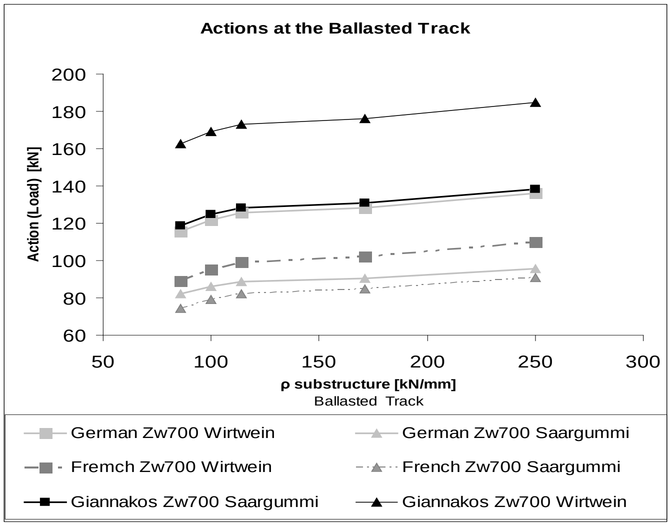


Fig. 6. Actions on track panel in the case of W14 fastening and pads: (a) Zw700 Wirtwein and (b) Zw700 Saargummi, in the Ballasted Track section.

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.

MEAN PRESSURE ON THE SEATING SURFACE OF SLEEPER AND SUBSIDENCE

The aforementioned actions should be taken into account for the dimensioning of the track panel but also for the dimensioning of the layers that constitute the multi-layered structure of the Permanent Way, in the region where Ballastles and Ballasted Tracks with the intermediate Transition Zone are consecutive. For the cases of the blanket layers, subgrade, and prepared subgrade (terminology according to code UIC, 719R) dimensioning could be performed with Design Loads/Actions derived by Eqn (5) with 2 times 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, Giannakos et al., 2009d):

$$R = \bar{A}_{dynam} \cdot \left(Q_{wheel} + Q_{\alpha}\right) + (2 \cdot \sqrt{\left[\sigma^2\left(\Delta Q_{NSM}\right)\right]^2 + \left[\sigma^2\left(\Delta Q_{SM}\right)\right]^2}) \qquad (11)$$

and the average pressure under the sleeper seating surface should be calculated by the following equation:

$$\bar{p} = \bar{A}_{subsidence} \cdot \left(Q_{wheel} + Q_{\alpha}\right) + \frac{2 \cdot \sqrt{\left[\sigma\left(\Delta Q_{NSM}\right)\right]^2 + \left[\sigma\left(\Delta Q_{SM}\right)\right]^2}}{h_{TR}} \cdot C \qquad (12)$$

where: $\bar{A}_{subsidence} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3}{E \cdot J \cdot h_{TR}^3}}$ (13)

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

$$C = \frac{\rho_{total}}{\left(\frac{F_{sleep}}{2}\right)} \qquad (14)$$

the rest of the parameters as above.

For the pressure on the ballast bed the same equations should be used (Giannakos et al., 2009d) in the case of ballasted track.

The average pressure under the sleeper seating surface should be used as a "decision criterion" and not as an absolute number:

$$\bar{p} \leq 0.30 \qquad N / mm^2 \qquad (15)$$

We should use the average pressure as a "decision criterion" because there is no uniform support of the sleeper on the ballast, or uniform compaction of the ballast and the ground and there are faults on the rail running table, imperfections on the wheels etc. Undeflected (stiff) seating (e.g. in the case of a concrete bridge, rock at the bottom of a tunnel as substructure) with great axial load (e.g. 225 kN) leads to faster deterioration of the ballast and therefore, to deterioration of the geometry of the track. In such cases, the phenomenon can be prevented by placing rubber sub-mats in order to smooth out the great differences in the stiffness of the substructure, during the transition from an embankment into a tunnel or a concrete bridge.

In the bibliography it is suggested (Eisenmann, 1988) 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. The most important issue, though, is that since the publication (ORE D117, Rp2, Rp4) of ORE's research, (Office des Recherches et Etudes of the U.I.C.), it has been established that the material of the sleepers (wood, concrete) gives almost identical values of settlement of the track. Furthermore, since the residual settlement is a percentage of the total subsidence during the passing of the loads (Hay 1982), it can be extrapolated that in this case there will be an almost identical performance in the deterioration of the geometry of the track (see also FIP, 1984)..

FACTORS INFLUENCING THE SUPERSTRUCTURE AND SUBSTRUCTURE OF THE PERMANENT WAY

But in reality, the seating of the sleepers is supported on discrete points (points of contact of the sleeper with the grains of the ballast) as Figure 7 depicts, (see also Eisenmann et al., 1980) and the resulting necessity to calculate the stress per grain of ballast cannot give comparative results to the rest of the bibliography. So it is possible to use the mean value of pressure not as an absolute quantity, but comparatively and in combination with the possibility it covers (Giannakos et al., 1990 a & b).

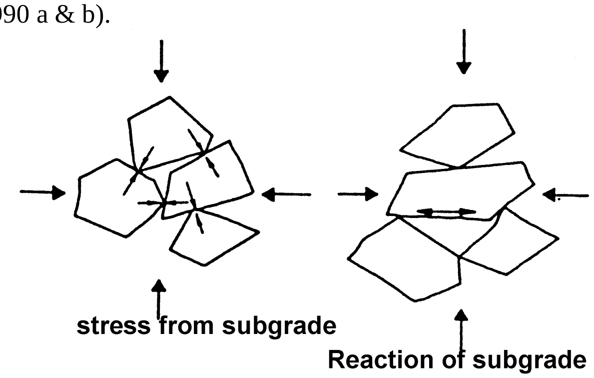


Fig. 7. Ballast grains in the ballast bed and transmission of stresses and actions

The subsidence y should be calculated by the following Equation (Giannakos, 2009c):

$$y_{total} = \bar{A}_{subsidence} \cdot (Q_{wheel} + Q\ ) + \frac{2\left(\sqrt{\left[\sigma(\Delta Q_{NSM})\right]^2 + \left[\sigma(\Delta Q_{SM})\right]^2}\right)}{h_{TR}} \quad (16)$$

The experimental confirmation, as cited at the end of the previous section, which has been also verified through calculations (Giannakos et al., 1990 a, b), means that in relation to the sustaining of the geometry of the track, the material of the sleeper has no significant influence. We will observe the same frequency of maintenance interventions whether using a wooden sleeper or a concrete sleeper, as far as the material of the sleeper is concerned and without taking into account the fastening influence. The above experimental data as well as the mean value of pressure $\bar{p}$ and subsidence y for different types of sleepers that predict the superstructure/ substructure behaviour in the permanent way are verified through calculations. (Giannakos et al., 2009d).

It is therefore imperative to reduce as much as possible the development of subsidence, primarily, but also that of lateral displacements. In the Greek network during the 1970's and the 1980's appeared cracks on twin-block concrete sleepers and an extended investigation program begun. In the frame of this investigation, a new approach for the actions on sleepers and the ballast has been developed, by taking into account the real conditions of the line (maintenance etc.) which led to the increase of the demands in the specifications for the railway ballast, as well as the specifications for the subgrade and the substructure (Giannakos, 2008b).

Heavier concrete sleepers, in relation to the wooden ones, hinder the settlement of the track that is caused by vibrations (Giannakos et al., 2008b). With those sleepers no peaks are observed, which characterize the amplitude of vibration in the resonance area, and whose creation leads to destabilization of the ballast. Moreover, the reduction of the participating Non Suspended Masses in the system's motion and the use of a "softer" pad, i.e. pad with small ρ (ρ< 100 kN/mm and/or 80 kN/mm), leads to a reduction of the stressing of the ballast. The average pressure on the ballast-bed (Eqn (12)) is much higher than the permissible stress 0.30 MPa (Eqn (16)). In some cases it is almost double. So the method predicts the degradation of ballast (Giannakos, 2008b) as well as the development of great subsidences leading to high permanent deformations. This leads to the deterioration of the so-called geometry of the track.

During the study for the dimensioning as well as the selection of the individual materials constituting a railway track, the "weak links" are the ballast and the substructure as well as the soil. Minimizing or diminishing the subsidence in these two layers practically minimizes the permanent deformation of the track.
Therefore it is obligatory to (see also Giannakos, 2004, 2009c, d):

(a) minimize the actions by:
- Using very resilient fastenings and pads compatible to the clips
- Grinding the rail running table normally
- Reducing the Non-Suspended Masses of the vehicles

(b) use ballast of high quality and hardness and
(c) construct a high quality substructure of the permanent way, with 100% Proctor or 105% Modified Proctor.

Table 2. Results of the performance of 4 types of sleepers (Giannakos 2009d)

Types of sleeper & fastening	Action (kN)	Average pressure (MPa)	Subsidence y (mm)	Surface of sleeper Mm^2
Wooden + "K"	261.9	0.505	1.166	275,000
TwinblockU3 + RN	264.7	0.751	1.044	185,800
TwinblockU31 + Nabla	228.3	0.598	1.468	197,200
Twinblock U41 + Nabla	228.3	0.503	1.468	243,600

Experiments verify that the track subsidence is independent of the sleeper material (wood, concrete). Since the calculated pressure at the "interface" between the sleeper and the ballast, that is the seating surface of the sleeper, agrees well with the average measured values. This method can safely be used as a criterion for the behaviour of the ballast-sleeper system. Table 2 cites the calculation results for 4 types of combinations of sleepers and fastenings. The method (Eqn (5)) also provides a quantifying reasoning of the real situation observed on track. These results guided Greek Railways Organization to modify the technical specifications for ballast and, practically, to exclude limestone ballast from railway use.

CONCLUSIONS

In this paper a new method for the estimation of the actions on the track superstructure is presented. A parametric investigation is performed with this method and results are compared to the methods in German and French bibliography. The main factors influencing the dimensioning of the layers of the multi-layered structure of the permanent way are highlighted. Measures to minimize the actions and permanent deformations of the superstructure and substructure are presented including:

(a) Use of very resilient fastenings and pads compatible to the clips
(b) Grinding the rail running table normally
(c) Reducing the Non-Suspended Masses of the vehicles
(d) Use of ballast of high quality and hardness and
(e) Construction of a high quality substructure of the permanent way, with 100% Proctor or 105% Modified Proctor.

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