Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Special Technical Proceedings ed. P Claisse, E Ganjian, F Canpolat and T Naik
ISBN 978-1-4507-1488-4 http://www.claisse.info/Proceedings.htm

Influence of Rail Pad Stiffness on Track Stressing, Life-Cycle and Noise Emission.

Konstantinos Giannakos

University of Thessaly, Department of Civil Engineering, Volos, Thessaly, Greece, <kyannak@gmail.com>

ABSTRACT

In this paper the results for the influence of the rail pad stiffness on the Railway Track stressing and its Life-Cycle is presented, as derived from a research program performed in Greece due to the appearance of extended cracking (over 60 % of the sleepers on track) in twin-block concrete sleepers during the 1980's. This implies either inadequate design and/or insufficient strength of the concrete sleepers. The existing theories for the calculation of the design loads could not justify the appearance of these cracks since the calculated actions on sleepers were much lower than the limit values. An innovative method predicting the extended cracking was developed. The adoption of very soft pads reduced the track's stressing and led to a significant prolongation of the Life Cycle of the track elements. The results of the study are presented and an approach to the noise emission as crucial sustainable parameter in railways.

1 INTRODUCTION

The track's superstructure, in the classical or conventional sense, is a multilayered construction and the terminology of the various layers according to U.I.C. (Initials in French for the International Union of Railways: **U**nion **I**nternationalle des **C**hemins de Fer) is depicted in Figure 1. In Greece during the period of 1972 until 2000, only concrete twin-block ties (sleepers) were placed on OSE (the Greek Railways Organization) tracks in operation (Figure 2).

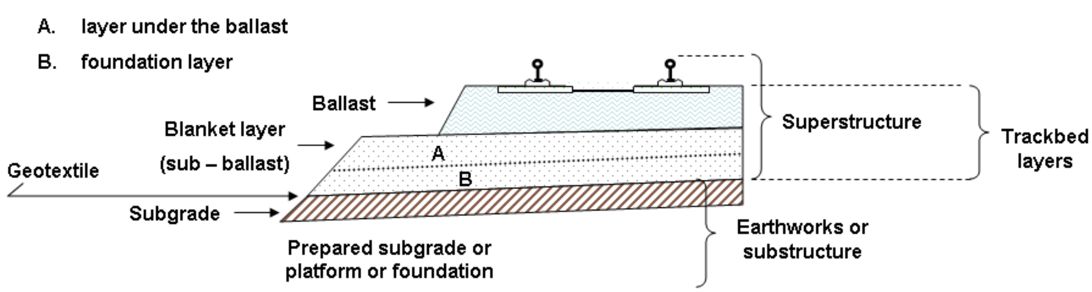

Fig. 1. Schematic Representation of the Railway Track Superstructure According to UIC [U.I.C. 1994]

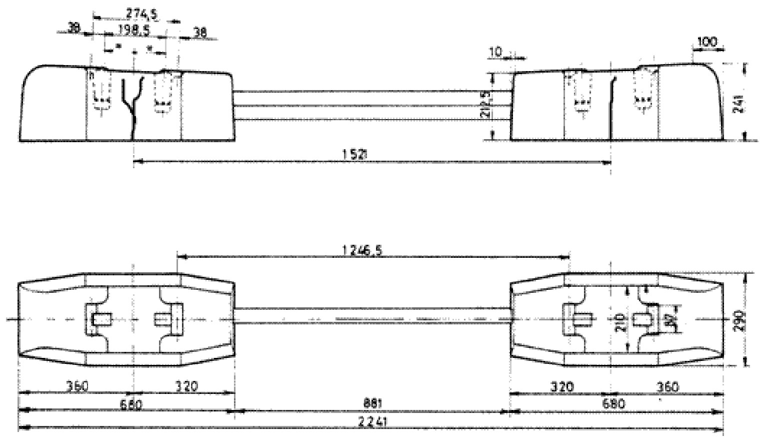

Fig. 2. Twin-block Concrete Sleeper Vagneux Type U2/U3 Laid in the Greek Railway Network, (Upper Illustration) Side View Depicting Also the Cracks that Appeared in a Percentage of 60% of the Laid Sleepers and (Lower Illustration) Ground Plan [Giannakos et al. 1990].

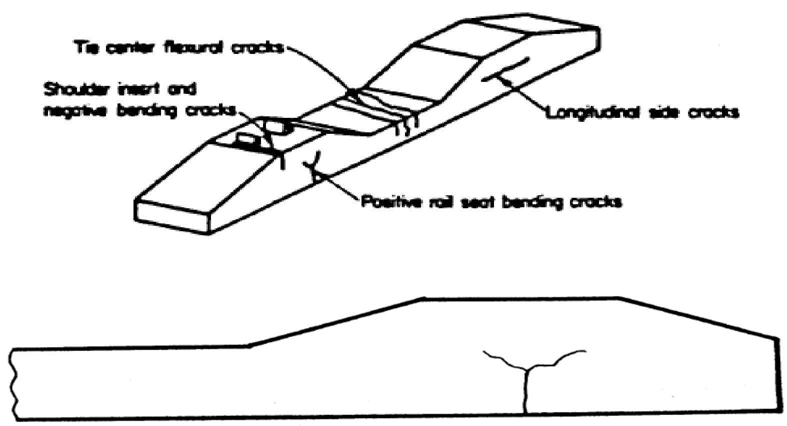

Fig. 3. Cracks Appeared in Monoblock Concrete Sleepers as Cited in Bibliography Upper Illustration in [Harisson et al.] Describing the Cases of Cracks Generally in Sleepers and Lower Illustration in [FRA 1983] for the Position Under the Rail Seat Only.

The two types of reinforced concrete twin-block sleepers, Vagneux U2, U3 with RN fastenings (of French technology), used in the Greek network, are similar to those used in the same period by the French Railways (SNCF). Of the above types U2/U3, 60% (and more) exhibited cracks in the Greek network (in lines with maximum operational speed 120÷140 km/hr at that era -it is now ≥160 km/hr- and daily tonnage ≤10,000 t/day), at a position under the rail (Figure 2) from the lower bearing area of the sleeper propagating upwards. The same type of sleepers are laid in the French network with operational speed 200 km/hr and daily tonnage 50,000 t/day, and they did not exhibit any problems at all [Giannakos 2004, 2008]. The existing, at that era, international bibliography [FIP 1987, FRA 1983, Harisson et al.] cited many cases of appearance of cracks in monoblock sleepers of prestressed concrete, as shown in Figure 3. It also included various methods that suggest respective formulas for a realistic estimation of actions on sleepers, the most broadly used being the methods in German [Eisenmann et al. 1984] and French bibliography [Alias 1984, Prud' homme 1969, Prud' homme A. et al., 1976].

2 ACCEPTANCE CRITERIA OF CONCRETE SLEEPERS– LABORATORY TESTS

According to the French standards [Norme Francaise 1989] and the standards of SNCF [SNCF 1980], the dynamic testing of sleepers was designed to correspond to three load regions. It has to be mentioned here that the exact same testing is described in the modern European Normes [EN 13230-2, 2003]. The three Regions are: (a) region R1 (Pre-cracking stage): (b) R2 region which must appear in: 125 kN≤R2≤130 kN for the U2/U3 sleeper (crack opening ≤ 0.05 – 0.1 mm after unloading). (c) R3 region which must appear in: 140 kN≤R3≤175 kN for the U2/U3 sleeper (crack opening ≥ 0.5 mm after unloading). From laboratory tests that were performed [Tasios et al., 1989 and OSE/SNCF 1988, 1989] it was confirmed that type U2/U3 Greek sleepers fulfilled the requirements of 125-130 kN for the cracking threshold and 140 - 175 kN for the failure load respectively [Giannakos 2008], for which they should be designed.

3 ESTIMATION OF THE ACTIONS ON THE SLEEPERS

The existing methods for the calculation of the actions on a railway track (in German and French bibliography) and the new method [Giannakos 2004, 2008] are described below.

3.1 Actions on Track Panel According to German Bibliography

The total load Q_{total} (static and dynamic) acting on the track, is equal to the static wheel load multiplied by a factor. After the total load is estimated, the reaction R acting on a sleeper, which is a percentage of the total load Q_{total} can be calculated [Fastenrath 1981]:

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

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

$s = 0.1 \cdot \varphi$ to $0.3 \cdot \varphi$ dependent on the condition of the track, from $s = 0.1\ \varphi$ for excellent track condition to $s = 0.3\ \varphi$ for poor track condition

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

For V < 60 km/h then φ = 1.

For 60 < V < 200 km/h then:

$$\varphi = 1 + \frac{V - 60}{140} \quad (2)$$

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%).

The reaction R of each sleeper is calculated according to J. Eisenmann [2004]:

$$R = \frac{Q_{total} \cdot \ell}{2 \cdot L} = \frac{Q_{total} \cdot \ell}{2} \cdot \frac{1}{\left(\sqrt[4]{\frac{4 \cdot E \cdot J}{b \cdot \frac{\rho}{F}}} \right)} = Q_{total} \cdot \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3 \cdot \rho}{E \cdot J}} = \bar{A}_{stat} \cdot Q_{total} \tag{3}$$

where ℓ = distance among the sleepers, ρ coefficient of quasi-elasticity (stiffness) of track

$$L = \sqrt[4]{\frac{4 \cdot E \cdot J}{b \cdot C}} \tag{4}$$

C = ballast modulus [N/mm3]

b = a "width of conceptualized longitudinal support" according to Zimmermann that multiplied by ℓ equals to the loaded surface F of the seating surface of the sleeper

3.2 Actions on Track Panel According to French Bibliography

The estimation of the reaction/action per sleeper on track the standard deviation of the dynamic component must be calculated [Alias 1984, p. 205-206, Prud'homme et al. 1976]:

$$R_{total\ \max} = \left[Q_{wh} \cdot \left(1 + \frac{Q_\alpha}{Q_{wh}} \right) + 2 \cdot \sqrt{\left[\sigma^2 \quad \Delta Q_{NSM} \right] + \left[\sigma^2 \quad \Delta Q_{SM} \right]} \right] \cdot \bar{A}_{stat} \cdot 1.35 \tag{5}$$

where: Q_{wh} = the static load of the wheel

Q_α = semi-static load due to the cant (superelevation) deficiency

$\sigma(\Delta Q_{NSM})$ is the standard deviation of the dynamic component of the total load due to Non Suspended (NSM) Masses [Alias 1984, Prud'homme 1976].

$\sigma(\Delta Q_{SM})$ is the standard deviation of the dynamic component of the total load due to the Suspended (SM) Masses [Prud'homme, 1976].

$$\bar{A}_{stat} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3 \cdot \rho}{E \cdot J}} \tag{6}$$

ρ = the total static stiffness (elasticity) of the track (as in Eqn 3)

E, J = the modulus of elasticity and the moment of inertia of the rail

3.3 Proposed Method for Actions on Track Panel [Giannakos 2004]

Both of the aforementioned methods yield results for either no cracking at all or sporadic cracks in sleepers laid on track, and they do not justify an extensive cracking as it was remarked in a percentage of 60 % (and over). The author presented a method verifying these results derived from the experience on track [Giannakos, 2004, 2009]. The reactions/actions on track panel, per sleeper, are calculated with the following equation:

$$R = \left(Q_{wh} + Q_{\alpha}\right) \cdot \bar{A}_{dyn} + \nu \cdot \sqrt{\sigma\left(\Delta R_{NSM}\right)^{2} + \sigma\left(\Delta R_{SM}\right)^{2}} \quad (7)$$

where Q_{wh} = the static wheel load, Q_{α} = the load due to cant deficiency, A_{dyn} = dynamic coefficient of sleeper's reaction, ν = coefficient of dynamic load (3 for a probability of appearence 99.7 %), $\sigma_{(}\Delta R_{NSM)}$ = the standard deviation of the dynamic load due to non suspended masses, $\sigma_{(}\Delta R_{SM)}$ = the standard deviation of the dynamic load due to suspended masses and :

$$\bar{A}_{dynam} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^{3} \cdot h_{TR}}{E \cdot J}} \quad (8)$$

where h_{TR} the total dynamic stiffness of the track given by:

$$h_{TR} = \frac{1}{2 \cdot \sqrt{2}} \cdot \sqrt[4]{E \cdot J \cdot \frac{\rho_{total}}{\ell}} \quad (9)$$

The results from this method predict an extended appearance of cracks in twin-block sleepers that was indeed observed on the Greek permanent way (60 % or even higher), as it is described below. In fib [2006] this method is used for precast concrete railway track systems.

4 INFLUENCE OF THE TRACK PANEL'S STRESSING ON CONCRETE SLEEPERS' LIFE-CYCLE

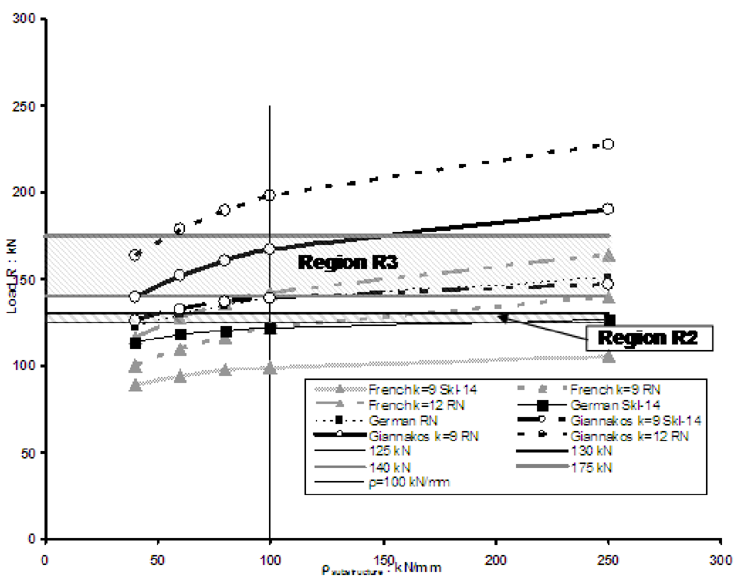

Fig. 4. Actions : (a) French, (b) German Methods, and (c) Giannakos [Giannakos et al., 2009b].

The conditions of the Greek network between the 1980s and the beginning of 1990s, consisted of very compacted, polluted ballast bed and stiff support (ρ_i = 380 kN/mm) and substructure classified according to the fluctuation of coefficient ρ_i for the seating of the track from (a) ρ_i =

40 kN/mm for pebbly substructure to the most adverse conditions of either (b) ρ_i = 100 kN/mm, which corresponds to frozen ballast bed and substructure. The rest of the parameters of the track that influence the state of actions on sleepers and possibly led to the appearance of cracks in Greece are: maximum axle load 22.5 t, nominal maximum speed V = 120 km/h which in practice was exceeded permanently for many years up to 140 km/h (this value is used), NSM = 2.54 t (three-axle bogies diesel-locomotives), UIC54 rail, 4.5mm elastic pad for RN type fastening, and 105 mm cant deficiency, twin-block concrete sleepers U2/U3 Vagneux type. The cracks appeared in the seating surface of the sleeper on the ballast in position just under the rail with an upwards direction as presented in Figures 1 and 2. From Figure 4 the value of the service load of the sleeper can be obtained for the design, applicable for fastenings of elasticity and conditions identical to those of the Greek network of the 1980s. Using the methods of cited in the French and German bibliography no cracking at all should be expected or a cracking of 1%. But the method cited in Giannakos [2004] predicts an extended cracking (as the observed 60% and over on track) since the calculated actions/reactions on track overpass the cracking as well as the failure thresholds. The appearance of the cracks (R3 region – failure threshold) in twin-block concrete sleepers of U2/U3 type led in the replacement of the sleepers from track, thus in a reduced Life-Cycle. The result was excessively high values of actions on the concrete sleepers that exceeded the limits as well as not sufficient anchorage of the steel bars in the concrete, implying that an extended cracking should expected to appear. As depicted in Figure 4, very stiff rail pads combined with conditions described in paragraph 4.2, imply increased actions and stressing of the concrete sleepers which overpass the cracking threshold at the beginning and later on the failure threshold -Regions 2 and 3 (paragraph 2)- and this situation leads directly to the replacement of the sleepers from track due to failure. Instead of being "operable" for 50 years their Life-cycle may be reduced even to 15 years as in the Greek network. This also implies a new demand for recycling of these waste materials.

5 STRESSING AND PERMANENT DEFORMATION OF SUBSTRUCTURE

For the cases of the blanket layers, subgrade, and prepared subgrade (Figure 1) that constitute the formation, dimensioning is performed with Design Loads/Actions derived by Eqn (7) 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 (7), 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 (7):

$$R = \bar{A}_{dynam} \cdot \ Q_{wheel} + Q_{\alpha} \ + (2 \cdot \sqrt{\left[\sigma^2 \ \Delta Q_{NSM} \ \right]^2 + \left[\sigma^2 \ \Delta Q_{SM} \ \right]^2}) \qquad (10)$$

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

$$\bar{p} = \bar{A}_{subsidence} \cdot \ Q_{wheel} + Q_{\alpha} \ + \frac{\sqrt{\left[\sigma \ \Delta Q_{NSM} \ \right]^2 + \left[\sigma \ \Delta Q_{SM} \ \right]^2}}{h_{TR}} \cdot C \qquad (11)$$

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

$$C = \frac{\rho_{total}}{\left(\frac{F_{sleep}}{2}\right)} \quad (12)$$

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]:

$$y_{total} = \bar{A}_{subsidence} \cdot \; Q_{wheel} + Q_{\alpha} \; + \frac{2\left(\sqrt{\left[\sigma \;\; \Delta Q_{NSM} \;\right]^2 + \left[\sigma \;\; \Delta Q_{SM} \;\right]^2}\right)}{h_{TR}} \qquad (13)$$

where: $$\bar{A}_{subsidence} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3}{E \cdot J \cdot h_{TR}^3}} \quad (14)$$

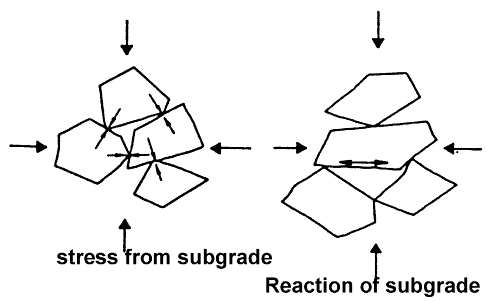

Fig. 5. Ballast Grains and Transmission of Stresses and Actions

In practice, the seating of the sleepers is supported on discrete points (points of contact with the grains of the ballast as Figure 5 depicts), and the resulting necessity to calculate the stress per grain of ballast cannot give comparative results. So it is possible to use the mean value of pressure (as derived from the Eqn (11) above) not as an absolute quantity, but comparatively and in combination with the possibility it covers [Giannakos et al., 1990 a & b]. The average pressure under the sleeper seating surface, and on the substructure's top, should be used as a "decision criterion" and not as an absolute number:

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

On the basis of AASHTO testing for road construction, the following formula is valid for the railway track too:

Decision in track geometry quality = (increase in mean stress on the ballast bed)^{m} (16)

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 frequency and consequently environmental impact and cost. In Figure 6 the curves for two kinds of very resilient rail pads are depicted but not of the same stiffness. Zw700 of Saargummi presents a higher elasticity and Zw700 of Wirtwein is stiffer. For fluctuation of the substructure stiffness from 40 kN/mm (pebbly substructure very soft) to 250 kN/mm we observe that the relatively more "stiff" pad leads to a higher mean pressure p of the order of 20% approximately. This leads to a faster deterioration of track's geometry and to the need of a more frequent and extended maintenance and environmental impact.

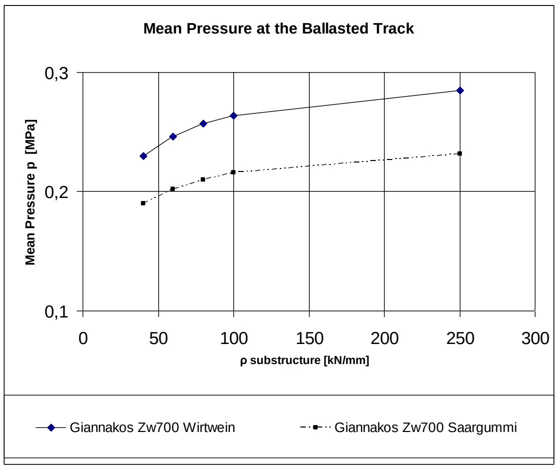

Fig. 6. Mean Pressure p, in Case of Ballasted Track with 95.5 % Certainty of Appearance

6 INFLUENCE OF THE HIGHLY-RESILIENT RAIL PADS ON THE REDUCTION OF STRESSING AND NOISE EMISSION

6.1. Reduction of Actions and Stressing

Research around the world has led to the production of a new "generation" of very resilient fastenings (e.g. German W14), that reduce the load on sleepers. In Figure 4 the values of the service load are presented for W14 fastening (Skl14 clip + Zw700 pad) . The comparison of the service load between the German W14 fastenings and the stiffer ones (e.g. French fastenings RN) shows that the load on the sleepers is significantly reduced in the case where more resilient fastenings are utilized, with the concrete sleepers staying below the cracking threshold (Region R2) and consequently their Life-Cycle should stay at 50 years. The results of the calculations are compared with the real situation of the track in the Greek network, where the monoblock concrete sleepers with the W14 fastening have not presented any cracking at all up to now (10 years in service). Figure 4 depicts these results. In practice, after almost ten years of track in operation with monoblock B70 type sleepers with W14 fastening, in Greece with operational maximum speed V⩾160 km/h, now instead of 140 km/h at the past, these conclusions are verified by the fact that there is no appearance of cracks in the Greek railway network and their excellent behavior in the track.

6.2. Noise Emission

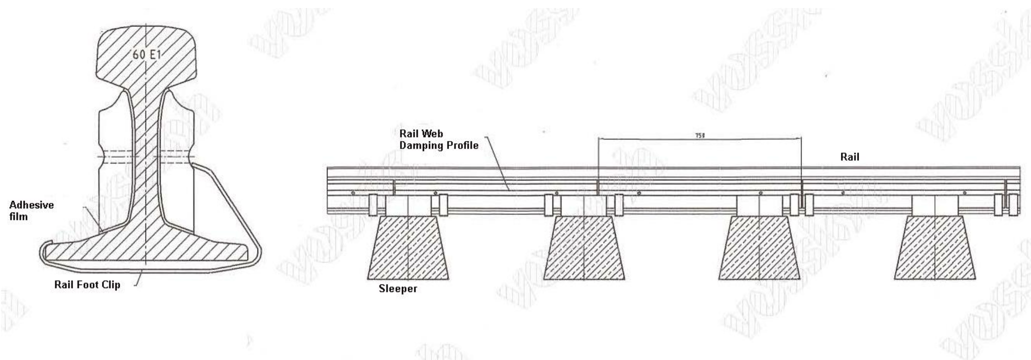

Fig. 7. Rail Dampers for the Rail Web [VFS, 2009]

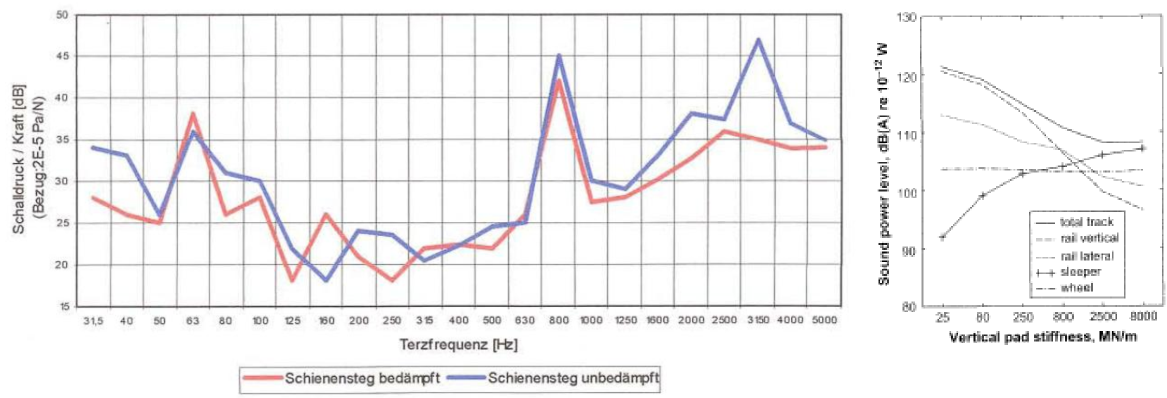

Fig. 8. (left illustration) Noise-pressure (Schalldruck) in Relation to the Frequency for Damped and Undamped Rails. [VFS, 2009] – (right illustration) Relation Between Sound Power Level in dB(A) and Rail Pad Stiffness According to TWINS Project Experimentally Validated by ERRI [Thompson, 2009]

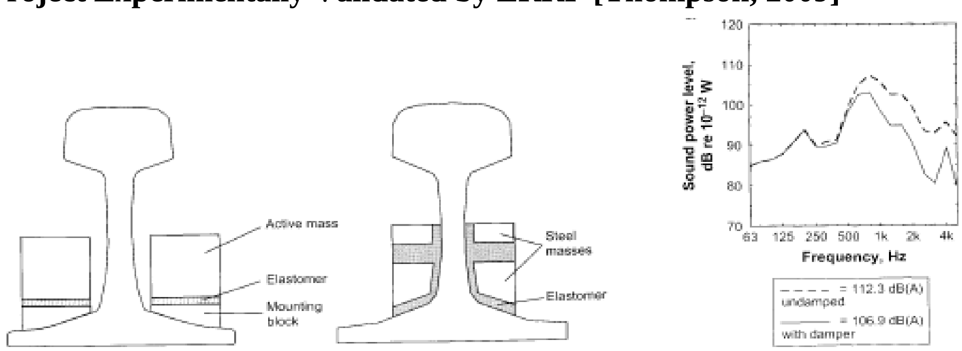

Fig. 9. Rail Dampers Developed (a) Left: in France (VONA Project), (b) Centre: Developed in EU (Silent Track Project) and (c) Right: Effect of Tuned Absorber System [Thompson, 2009]

The rail pad stiffness affects the damping of the rail and the degree of coupling between the sleepers and the rail. In the case of very resilient rail pads the sleepers are well isolated from the rail vibration, but the vibration can propagate relatively freely along the rail. Conversely, for stiff pads the rail vibration is restricted by the coupling to the sleepers and damping of the pads but the sleeper vibration is greater. This affects the balance of noise produced by the rail and the sleeper. The rail vibration amplitude decays approximately exponentially with distance along the track. The greater the damping of the track is, the greater this decay is measured. The parameter used to describe this is the track decay rate, usually expressed in dB/m. In Figure 8 – right illustration the relation between Sound Power level in dB(A) and Rail Pad Stiffness is depicted according to TWINS Project (Track - Wheel Interaction Noise Software) software experimentally validated by the European Rail Research Institute (ERRI) of the International Union of Railways (UIC). In order to reduce the noise propagation rail dampers should be used which are applied at the rail's web as depicted in Figure 7. For these rail web dampers, Figure 8 – left illustration depicts the noise-pressure (Schalldruck) in relation to the frequency for damped and undamped rails, as presented in [VFS, 2009]. These rail web dampers were developed in Germany. The results are very satisfactory in urban areas. Similar results are presented in Thompson [2009] for the rail web dampers (Figure 10 a, b) from tests in France and in EU where a reduction of 6% approximately has been observed (Figure 10 c).

7 CONCLUSION

In this paper the influence of the rail pad stiffness on the track stressing has been investigated and its implied Life-Cycle as derived from a research program in the Greek railways has been estimated. The stressing on concrete sleepers, laid in the Greek railway network with stiff pads, exceeded the failure threshold. This fact led to the development of an innovative methodology which has been proposed for the calculation of the loads acting on concrete sleepers. The results of the proposed method are verified in practice. These actions imply the estimation of the mean stress on the substructure as a criterion of decision making for the design of a track and the extension of its life-cycle. In this paper was also presented an approach of the noise emission of the track, as noise is a very important sustainable parameter in railways. The noise emission is also affected by the rail pad stiffness. For that case of the use of rail web dampers, the noise emission is reduced for approximately 6%.

REFERENCES

Alias, J., (1984), "*La voie ferree*", IIeme edition, Eyrolles, Paris

Eisenmann, J., (2004), " *Die Schiene als Tragbalken*", Eisenbahningenieur (55) 5/2004

Eisenmann, J., Mattner, L., (1984), "*Auswirkung der Oberbaukonstruktion auf die Schotter und Untergrundbeanspruchung*", Eisenbahningenieur 35, 3/1984

EN 13230-2, (2003), "Railway *applications - Track – Concrete sleepers and bearers - Part 2: Prestressed monoblock sleepers*", March 2003/ (DIN)

f.i.b. (Federation Internationale du beton), (2006), *Precast concrete railway track systems*

Fastenrath, F., (1981), "Railroad Track - Theory and Practice", Frederic Ungar Pub.Co., New York.

FRA (Federal Railroad Administration), (1983), "*Investigation of the Effects of Tie Pad Stiffness on the Impact Loading of Concrete ties in the Northeast Corridor*", U.S.A., Department of Transportation.

Giannakos K., Loizos A., (2009b), "Evaluation of actions on concrete sleepers as design loads– Influence of fastenings", International Journal of Pavement Engineering (IJPE), 2009, DOI: 10.1080/10298430903402161.

Giannakos, A., Loizos, A., (2009a), "*Actions on Railway Track Panel and Ballast - Behavior of the Hellenic limestone ballast*", 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, 29 June – 2 July, Champaign-Urbana, Illinois, USA.

Giannakos, K., (2008), "*Damage of Railway Sleepers under dynamic Loads: a Case History from the Greek Railway Network*", submitted for reviewing to the Sixth International Conference on Case Histories in Geotechnical Engineering - Arlington, VA, USA, August I l-16

Giannakos, K., (2004), "*Actions on Railway Track*", Papazissis publications, Athens

Giannakos, K., Vlassopoulou I., (1990), "Study on the «sleeper-ballast» system", OSE, Athens

Harisson, H. D., Ahlbeck, D. R., "*Railroad Track Structure Performance Under Wheel Impact Loading*", TRR 1131, 1987

Norme Francaise NF F 51-101/Decembre 1989, "*Installations Fixes Ferroviaires – Traverses et supports pour appareils de voie, en beton*"

ORE, Question D71, RP9, f.97.

OSE/SNCF Cooperation: 3/1989, "*Programme d' essays realise au centre d' essais de la Direction de l' Equipement*"

OSE/SNCF Cooperation: 6/1988, "*Comportment des traverses en relation avec les charges dynamiques*"

Prud'homme, A., Erieau, J., "*Les nouvelles traverses en beton de la SNCF*", RGCF-2.1976

Prud' Homme, A., (1969), "*Sollicitation Statiques et Dynamiques de la Voie*", SNCF/Direction des InstallationsFixes, R 080-66-03.

Regles Techniques de Conception de Calcul des Ouvrages et Constructions en Beton Arme suivant la methode des Etats Limites, Eyrolles, Paris 1980

SNCF – Direction de l' Equipement, (1980), "*Specification Technique VRE 2321 80 – 06 (B), pour la fourniture de traverses mixtes en beton arme*"

Tasios, Th. P., Trezos, K. (1989), "*Laboratory tests and measurements on OSE sleepers*" National Technical University of Athens (NTUA)/Reinforced Concrete Laboratory /Athens

Thompson, D., (2009), "*Railway Noise and Vibration – Mechanisms, Modelling and Means of Control*", Elsevier, Amsterdam, The Netherlands

U.I.C. (Union International des Chemins de Fer), fiche UIC (Code) 719R/1-1-1994 "*Earthworks and track-bed layers for railway lines*".

VFS - Vossloh Fastening Systems, Gmbh, (2009), "*System Schienenstegdämpfung zur Schallreduzierung*", Verdohl, Germany