# Railway Track Science & Engineering

International Workshop

# Ballast:
## Issues & Challenges

UIC Paris
5-6 December 2013

ABSTRACT BOOK

# RTSE 2013

# PROCEEDINGS OF THE FIRST RAILWAY TRACK SCIENCE & ENGINEERING WORKSHOP "BALLAST : ISSUES AND CHALLENGES"

5-6 December 2013
UIC
Paris,

# BOOK OF ABSTRACTS

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ISBN 978-0-9565951-9-5

# PREFACE

This Book of Abstracts contains more than 50 contributions presented at the 1st Railway Track Science & Engineering International Workshop - Ballast: Issues and Challenges, held at the Union Internationale des Chemins de Fer (UIC) in Paris on the 5th and 6th December 2013.

This workshop is organised with the aim of drawing together international experts both from industry and academia to exchange views and experiences about the challenges facing modern ballasted railway tracks. It is intended to be the first of a series of workshops dedicated to promoting such interaction on a range of topics.

The workshop presentations cover a wide range of issues and challenges surrounding ballasted tracks at all train speeds and axle weights. The four main themes are: Ballast in Practice; Ballast Physics & Characterisation; Ballast & Environment; Ballast Track Design.

We would like to express our gratitude to the four invited speakers Prof. Andrew McNaughton, Prof. Farhang Rajdai, Dr. Hideyuki Takai and Prof. Dr. Uwe Krueger for their contribution to the workshop and the time and effort they have put in.

We also thank all of the speakers and delegates for making the workshop a successful event.

We would like to acknowledge the assistance of Ms Claire Cook who has played an invaluable role in dealing with workshop registrations.

We hope you enjoy the workshop and your stay in Paris.

The Organising Committee

# Foreword

It is with a great pleasure that the International Union of Railways is organizing together with SNCF and Herriot Watt University, and hosting at its headquarters the first edition of the Railway Track Science & Engineering International Workshops.

First of all because it has always been one of UIC's core missions throughout its 90 year history to conduct, coordinate and encourage research and to disseminate to its members the most up-to-date scientific and technical knowledge.

Secondly, because in bringing together high-level scientists, industrial partners, engineering experts and infrastructure managers, this workshop is a great opportunity to unite the international railway community in exchange and cooperation.

Focusing this year on ballast, we are initiating this series of events with one of the most crucial components of the railway track.

Whereas ballast properties and quality determine track performance, the condition of ballast materials reflects the overall health of the track system. Any malfunction of the track system inevitably has an impact on the ballast in the short and long term.

Ballast behaviour under track, ballast maintenance and ballast lifetime prediction are therefore among the major concerns of Infrastructure Managers and maintenance engineers, occupying a large part of the workload and budgets.

Long empirical, ballast research now benefits from strong support from the academic community, building the knowledge on a firm scientific basis, modelling and advanced investigation techniques which reveal the surprising properties of this granular material and its ability to meet the challenges of railways since the origins and certainly for still a long time in the future.

With over 120 participants from 17 countries around the world, this event is already set to be a great success, where the latest advances of ballast research will be presented.

On behalf of UIC and of all the organization committee I wish you a very exciting workshop, fruitful exchanges and a very pleasant stay in Paris.

Jean-Pierre LOUBINOUX – Director General, UIC

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# KEYNOTE ABSTRACTS

# HS2 – HIGH SPEED RAIL FOR GREAT BRITAIN

Tim Smart

**Key Words:** *High speed; whole life; specification*

## ABSTRACT

The existing conventional rail network in Great Britain has seen sustained high growth of both passenger and freight usage in the last fifteen years reversing previous trends. This growth is expected to continue strongly, partly through a growing population, but also through changes in choice of travel mode.
Additionally, the British Government has made policy decisions that growth in passenger travel should be focussed on railways rather than another generation of road or airport building. As a result the government has set about creating a new network for long distance passenger travel between our major centres of population.
By adopting high speed rail standards, the new network creates the opportunity for better economic connectivity between our major cities as well as creating the additional capacity the country needs. It also will allow the existing railway network to focus on growth in commuter and freight traffic using the capacity released by moving into city travel onto the new high speed network.
The technical specification for the high speed network is deliberately demanding. It requires whole life engineering solutions which combine high speed, intensive operation with absolute reliability and safety. The specification will be set out along with the reasons for it.

# MICROMECHANICS OF BALLAST MATERIAL

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**Key Words:** *ballast; granular materials; micromechanics; discrete element modelling*

## ABSTRACT

The mechanical strength of ballast is fundamental to the stability of railroad bed. Since ballast is a granular material, its strength and failure properties stem from the frictional contact interactions between ballast particles. However, due to the intrinsic disorder of the ballast texture, this transition from the particle scale to the material behaviour is mediated by the complex contact and force networks, and collective particle rearrangements. In this talk, I present an overview of extensive contact dynamics simulations carried out in order to characterize the ballast texture and its link with the macroscopic strength and settlement under dynamic loading.

The simulations were carried out by means of the contact dynamics method [1]. This method is a discrete element approach for the simulation of granular dynamics with contact laws expressing mutual exclusion and dry friction between particles without elastic or viscous regularization. The particles were taken from a library of digitalised ballast grains provided by the French Railway Company SNCF. We consider two different loadings: 1) triaxial compression with homogeneous boundary conditions, and 2) axial compression between two frictional plates.

The first configuration is used to analyze the network of contacts and branch vectors joining particle centers as well as the contact force components along and perpendicular to the branch vectors [2]. By means of stress partition, we show that the shear strength is additively controlled by the contact anisotropy, normal force anisotropy (force chains) and friction anisotropy (friction mobilization). The origin of the enhanced strength of ballast, as compared to similar packing composed of spherical particles, is found to lie in its higher force anisotropy as a consequence of a large number of face-face contacts between particles. The second configuration is used to analyze the settlement and effect of the wall-particle friction at the top and bottom boundaries [3]. We show that, as a consequence of mobilized wall-particle friction, the transient deformation induced by a constant vertical load is controlled by the aspect ratio (thickness over width) of the packing as well as the stress ratio [5]. The transient deformation declines considerably for increasingly smaller aspect ratios and grows with the stress ratio. From the simulation data for a large number of independent configurations, we find that sample-to-sample fluctuations of the deformation have a broad distribution and they scale with the average deformation.

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# RESEARCH AND DEVELOPMENT ON BALLASTED TRACK IN JAPAN

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**Key Words:** *Railway track; Ballasted track; Research and Development; Simulation*

## ABSTRACT

Tokaido Shinkansen line, the first high-speed railway in the world with speeds over 200 km/h, was opened in 1964 with ballasted track. At that time, Railway Technical Research Institute (RTRI) of Japanese National Railways (JNR) developed labor-saving low-maintenance "Slab track," which uses pre-cast concrete slab/panel under rails. After the western part of Sanyo Shinkansen line, basically the track structure of Shinkansen lines were laid with slab tracks. But at this moment, 38 % of Shinkansen lines and almost all of other railway lines use ballasted tracks. In case of ballasted track, periodical track maintenance is essential, and the cost of the track maintenance accounts for about 17 % of total railway operation cost, according to governmental statistics. So, the reduction of the track maintenance cost is very important for sound management of railway companies.

At the present day, RTRI put the top priority on the development of simulation technology. We are seeking to build up a dynamic model of an entire railway system in our super computer, and to study the phenomena regarding materials or dynamics. We call this system "Virtual test line." In this system, contact mechanics between wheel and rail (Fig. 1), and analysis of ballast movement (Fig. 2) play important roles. The target of this research is to clarify the degradation of ballasted track.

At first, I show the characteristics of ballasted track and non-ballasted one like slab track, and general policy to select a specific type of track structure when a new railway line is constructed in Japan. Next, I show the outline of the research and development projects relating to ballasted track which have been conducted at RTRI.

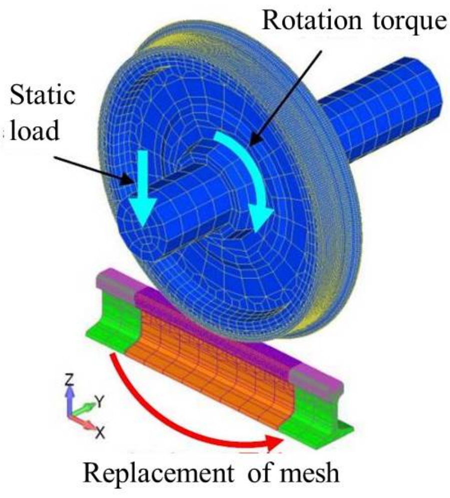


Figure 1: Wheel / rail FEM model

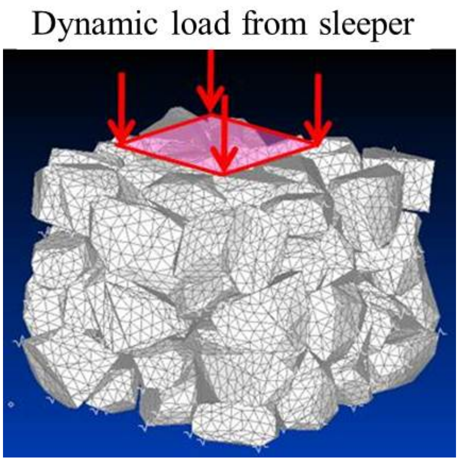


Figure 2: Ballast FEM model

# TECHNICAL PRESENTATION ABSTRACTS

# MEASURING THE CONTACT AREA AND PRESSURE BETWEEN THE BALLAST AND THE SLEEPER

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**Key Words:** *Railway; ballast; USP; full scale test; pressure paper*

## ABSTRACT

Railway ballast has several functions, including the transfer of applied wheel loads to the subgrade to stresses of acceptable magnitude. The sleeper/ballast boundary is the first stage in this load transfer process. However, the use of modern concrete sleepers and hard igneous ballast particles leads to high localised contact stresses that can damage both sleepers and ballast in a way that wooden sleepers may not have in the past. It is therefore of importance to better understand the load transfer mechanisms, the inherent variability in magnitude, the spatial distribution and area of contact positions between sleeper and ballast. The insights gained can lead to improving the performance of this interface and reduced maintenance costs. Measuring highly localised randomly placed pressures is extremely difficult. In an attempt to address this, the potential of pressure paper for providing reliable stress and contact area information at the sleeper/ballast and ballast/subgrade interfaces is evaluated.

The research makes use of the laboratory full scale tests in the Southampton Railway Testing Facility (SRTF). This apparatus represents a slice of track consisting of a single sleeper bay 650 mm wide confined by rigid sides that enforce plane strain conditions. The pressure paper is attached to the bottom of the sleeper and on the rigid sides of the apparatus, as well as on the subgrade layer represented by a 12 mm thick rubber mat. The sleeper is subsequently placed on 300 mm thick ballast layer and subjected to about 3 million cycles of 20 tonne axle load.

Particle contact pressure is measured across different combinations of sleeper type ballast gradations and under sleeper pads (USPs). This permits a comparison of the most favourable arrangements in terms of increasing the contact area and reducing the pressure.

The results obtained from the analysis of the pressure papers show several key findings: (1) that the sleeper is supported by a relatively few contact points numbering in the low hundreds with very high pressure. (2) The inclusion of USPs increases particle contact areas and reduces maximum pressures. (3) Changing a uniformly graded ballast gradation to more broadly graded ballast reduces the magnitude of contact pressure to the subgrade.

*Railway Track Science and Engineering*
*International Workshop - Ballast: Issues and Challenges*
*5 – 6 December 2013, UIC Paris*

# LOAD TRANSMISSION CHARACTERISTICS AND NATURAL MODES OF BALLAST LAYER

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**Key Words:** *Railway track; ballast; field measurement; natural frequency; spectral analysis; FEM; DEM*

## ABSTRACT

This paper details the field measurement and FE analysis carried out to clarify the transmission characteristics and reduction mechanism of dynamic loads within a ballast layer. Spectral analysis, based on the train-related dynamic loads acting on an existing ballast layer, revealed that dynamic response loads acting on a ballast layer consist of vibration components with a very wide frequency range. The measured loads on the lower surface of a sleeper (train running speed: 122.1 km/h; measurement area: 64 cm2) are applied to the central part of the ballast aggregate FE model. Figure 1 shows the von Mises stress working inside gravel of ballast. It can be seen that the stress does not act evenly throughout the gravel; rather, parts with angularities (certain contact parts) deform locally, so stress concentrates only on these parts. The stress acting on the angularity part is 1400 to 1500 times greater than the average loading stress on the ballast surface. Base on the spectral analysis of the measured data, the accelerance curve and compliance curve of the ballast layer indicate two different natural modes of the ballast layer (Figure 2). One is the first-order elastic resonance mode of the ballast aggregate at around 650 –700 Hz at which the whole ballast aggregate repeats the vertical expansion and shrinkage elastically. The other is the rigid body vibrational mode at around 40 Hz at which a mass of the track structure with an indirect additional mass given by a train vibrates simultaneously up and down due to the spring stiffness of the ballast layer. It is apparent that the ballast layer has hardly any capacity to reduce vibration components around these natural frequencies (Figures 3 & 4). A weak roadbed and excessive overburden mass theoretically cause the reduction of the frequency in the rigid body mode. Therefore, it can be inferred that the occurrence of ballast resonance with the passing-axle frequency causes the shift and the flow of ballast gravel.

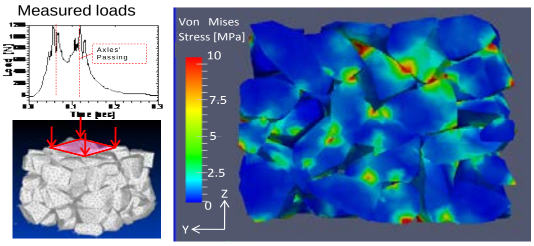

Figure 1: Stress inside ballast aggregate

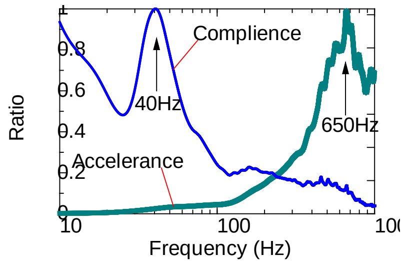

Figure 2: Compliance curve and accelerance curve of ballast layer

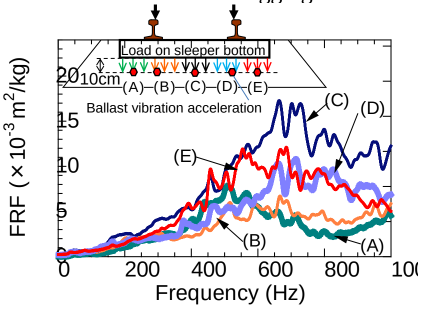

Figure 3: Frequency transfer function between stress on the sleeper bottom and ballast vibrational acceleration

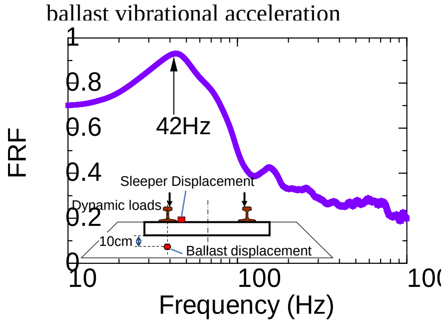

Figure 4: Frequency response function between sleeper and ballast displacement

# INFLUENCE OF FIBRE REINFORCEMENTS ON THE PACKING STRUCTURE OF GRANULAR MATERIALS

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**Key Words:** *Ballast; fibre reinforcement; grain/fibre interaction*

**ABSTRACT**

Ballast is a principal component of most railway track, on which significant maintenance effort is expended. Despite the widespread use of railway ballast, its mechanics are still not fully understood and there remains considerable potential for optimizing its performance and minimizing maintenance requirements. Previous research has shown that the use of fibres of random orientation can significantly improve the mechanical properties of sand. It is reasonable to expect that such random reinforcement will have similar effects on ballast, provided fibre dimensions are appropriately scaled to account for the much larger particle size of ballast. However, despite recent progress in the field, a detailed understanding of the micromechanics of grain/fibre interactions and of how fibre content affects the structural packing of the mixture is still lacking. In this paper, the effects of randomly oriented fibres on the packing structure of granular materials (coarse sand and scaled ballast) are investigated, as a first step towards understanding the same phenomena in full size ballast. In a departure from the existing literature, each constituent of the mixture is quantified and treated separately. The importance of understanding the structure of fibre reinforced materials when comparing the mechanical behaviour of specimens is highlighted and micromechanics-based explanations for the observed behaviour are presented.

# CHALLENGES ON THE SIMULATION OF VIBRATIONS INDUCED BY VERY HIGH SPEED TRAINS

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**Key Words:** *Railway track; dynamics; high speed; computational methods; critical speed*

## ABSTRACT

The dynamic amplification effects of the response due to a moving load on the surface of an elastic solid has been a topic of research for more than a century [1-3]. However, if in the beginning of the last century the problem has only theoretical interest, this is not true anymore. Indeed, the recent advances on the rolling stock, which can now reach speeds of more than 500 km/h, brought this kind of problems for the engineering practice, mainly for the railway engineering of high speed [4, 5]. Actually, the increase of the traffic speed that is expected to reach during the next years could give rise to the appearing of this kind of problems in several regions where the railway lines cross alluvionar regions with soft soils.
In the present communication, departing from the theoretical formulation of the critical speed problem of a moving load on the surface of an elastic solid, the problem is approached for the railway engineering. Since the mechanical soil behavior is quite far away from the elastic approach, it is shown that non-linear methodologies are needed for the simulation of the dynamic response of railway tracks when subjected to very high speed traffic, i.e., when the circulation speed is high in comparison with propagation speed of the waves in the ground [4]. However, due to the complexity of the problem, involving a vast three-dimensional domain with non-linear response subjected to moving loads, several challenges are found, for which the engineering practice should give an efficient answer [6]. To reach that target it is indispensable the development of efficient and accurate numerical models, without undesirable numerical complexity that could put them in a non-applicable level for practical situations.
The communication presents not only simplified approaches for the estimation of the critical speed of railway tracks but also comprehensive approaches where the effects of the soil non-linearity can be taken into account, without forgetting the demands of the time of computation. Moreover the theoretical background is discussed with the presentation of case studies where the proposed methodologies are applied and numerical and measured results are compared.

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# UIC PROJECT "UNDER SLEEPER PADS IN TRACK"

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**Key Words:** *Under Sleeper Pads; ballast degradation,*

## ABSTRACT

After gathering positive results from several railway companies, the UIC decided to launch a second project on the topic of Under Sleeper Pads (USPs). Between 2010 and 2012, members from 12 countries all over Europe and Japan worked on one of the biggest projects seen in recent years carried out by the UIC. Measurements in the Laboratory and theoretical studies complemented the intensive on-site measurements on various test tracks in Europe. The project name — 'Under Sleeper Pads in Track' or 'USPs in Track' — aimed to develop a new track model to understand why tracks with USPs give a better performance.

Tracks with USPs have many advantages, for example, less settlement, bettertrack geometry quality, less ballast wear, less rau corrugation and a reduction of vibrations with soft USPs. An economic evaluation fulfilled the working programme with the result that USPs normally have a positive influence on the life-cycle costs (LCC) of the permanent way. The results are presented in the 'USPs in Track — Summary Report' and the UIC leaflet 'Recommendations of the Use of USPs' — both of which are due to be published by the end of 2013. The aim of the leaflet is to support non-experienced railway engineers when installing USPs for the first time. Based on the study work, USPs have positive effects on the service life and the maintenance of the track:

- Longer lifespan of the track components especially ballast (the aim is a lifespan of the whole track of at least 40 years)
- Less maintenance due to the better track quality and the reduction of forces in the ballast (less tamping, less ballast cleaning and less grinding of tracks in tight curves due to the reduction of long pitch corrugations)

In some cases (such as vibration mitigation) it is technically possible to install the cost effective under sleeper pad solution instead of other more expensive options (e.g. under ballast mats).

In special cases the use of USPs enables a reduction of the ballast thickness.

# IMPACT OF GEOMETRIC AND PETROGRAPHIC CHARACTERISTICS ON THE VARIABILITY OF RAILWAY BALLAST ATTRITION TEST VALUES

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**Key Words:** *ballast; attrition tests; repeatability, particle shape, angularity; petrography*

## ABSTRACT

Attrition tests such as the Los-Angeles test, the impact test and the Deval test ("wet attrition test") provide information on railway ballast quality. However, the test values are subject to large variability. As important economic decisions depend on these values, the reasons for variability are investigated.

An extensive test series with eleven rock types and three test methods (LA-test, impact test and Wet attrition test) and an in-depth analysis of particle geometry (using advanced machine vision techniques) and petrography are carried out. The impact of these characteristics on the test results is investigated.

The deviation of the petrographic composition within a given sample turns out to have a considerable impact on the test results, whereas the influence of the respective deviation of particle geometry is relatively small. The latter effect only comes into play with petrographically homogeneous rock types.

Due to the large deviation of particle shape and angularity the sample mass (as given in standards EN 1097-2, EN 13450, and BS 812:1951) is not found to be representative. The necessary number of test repeats to exclude the effect of deviation of particle petrography and geometry is estimated.

Some of the result parameters according to the standards do not allow to discriminate between the amount of abrasion and fragmentation occuring during the LA- and the impact test. Additional result parameters for the estimation of the fragmentation are proposed.

# LARGE SCALE MODEL TESTS ON CYCLICALLY AND DYNAMICALLY LOADED BALLASTED TRACK

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**Key Words:** *Ballasted track; high speed; experimental tests; cyclic and dynamic loading*

## ABSTRACT

Ballast is a key element in common railway track superstructures. Ballasted track has been used for more than a century but has been disputed for its ability to fulfil the requirements of modern high speed traffic. One of the concerns in discussion is its ability to withstand the dynamic loading of a railway system with increased traffic speed. Major topics are the – irregular - long term deformations and the track stability resulting from the repeated loading.

Commonly the design of ballasted track is a matter of operating experience while a constitutive modeling is restricted to research. In this context, experimental investigations are the appropriate way to deal with a dynamically excited granular material. Ballast is a granular material consisting of partly unconstrained large particles. Single surfacial ballast particles could exhibit large rotations and movements. A behaviour that is going to be even more likely for a dynamically excited track section. Vibrations in a ballasted track show a very complex loading situation: The main vibrations originate locally from the loaded sleeper. However, another source are the adjacent sleepers and track sections which distribute a heterogeneous straining of the track section investigated. Furthermore, the loading is not a harmonic excitation but a sequence of vibration load cycles with different amplitudes. For a dynamic loading, the ballast particles are pushed aside laterally. Hanging sleepers pushed on the ballast surface can increase the settlement rate of a ballasted track. Ballast on a shake table has been used to explain track degradation. However, it can only be the representative model for the ballast on an excessively vibrating bridge deck.

Basically, two situations have been investigated separately in large scale tests at the BAM: The ballasted track on subgrade and the ballasted track on bridges. For both scenarios an experimental set-up and load sequences have been developed to deal with the fundamental load schemes. Cyclic loading - which is inertia free – has to be distinguished from dynamic loading. To differentiate between the two types of loading tests started with a pure cyclic loading that was intermitted with sequences of dynamic loads. A sudden increase in displacement then indicates the impact of a dynamic loading. Apart from the phenomenological insight, the obtained findings can be used to quantify limiting values for dynamic loadings. If the vibration is applied directly on the sleeper the limiting value is best fitted by RMS floating values of the particle velocity. On excited bridge decks this limit is given by the magnitude of the vertical acceleration. For the latter value the physical meaning lies evidently in the proximity to the gravitational acceleration. Finally, for the dynamically excited bridge decks the investigation is extended to lateral track displacements.

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# DYNAVOIE : A REDUCED TRACK MODEL ALLOWING LONG 3D SIMULATION OF TRAIN/TRACK INTERACTION

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**Key Words:** *Track dynamics; 3D FEM; train-track interaction*

## ABSTRACT

Current procedures for the design and maintenance of railway infrastructure [1] are still quite empirical and the need for predictive dynamic models of the ballasted track is very clear, especially to be able to respond to the current trend towards more and heavier trains running at higher speeds with lower track maintenance costs. Currently two approaches are common: track computations limited to taking into account the sleepers and the ballast as equivalent loads applied at the passage of a train and dynamic model where the trains are represented in some detail and the track is only represented by equivalent springs. The objective of the DYNAVOIE software discussed here is to open a third approach considering coupled simulations where both the train and the track can be modeled in detail.

The classical track layout is composed of rails discontinuously supported by sleepers, supported by a ballast layer, granular sub-layers and a platform. In other track systems, the rails can be directly connected to concrete slabs. Transition zones between different track systems are naturally subject to significant dynamic phenomena and are thus of major interest. To allow modeling of all these configurations, a finite element modeling approach is retained. Since fairly long track segments are needed for proper predictions of train/track interaction, keeping a full model of the track would lead to excessively large FEM models. The first characteristic of the proposed approach is thus to use periodic computations to generate a reduced slice model that allows reproduction of both static and dynamic track behavior. A first aspect of the presentation will therefore be to illustrate how the validity of this reduction is established.

The use of an underlying detailed FEM model implies that all mechanical quantities of interest (acceleration, stress, …) are available in any position of the modeled track. This feature is quite important for the development of degradation criteria for different constituents of the track and subsequent predictions of settling.

The trains apply dynamic excitations on the track in vertical and transverse directions. Longitudinal solicitation can then be added due to train traction or braking. As a first step, the applications are currently focused on simple vehicle models and thus on vertical loads associated with the rail/wheel contact that is modeled using a simple contact model.

Sample computations of configurations described in [2] are thus used for illustrations. In particular, one discusses the ability to introduce parametric studies on quantities of interest in long track models for which a detailed 3D simulation without reduction would not be accessible.

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# EFFECT OF THE SPREADING OF THE AXLE LOAD THROUGH THE BALLAST ON THE DYNAMIC RESPONSE OF SHORT SPAN RAILWAY BRIDGES

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**Key Words:** *Railway bridges; ballast; high speed; dynamic response; load spreading*

## ABSTRACT

One important effect of the ballast in dynamic of railway bridges is to spread the train axle loads. This can lead to large reductions of the bridge response, especially for short span bridges. For this reason, Eurocode prescribes to distribute the axle loads over three adjacent sleepers. In this paper, the axle load distribution is first studied using a plane finite element analysis and based on that, a triangular load distribution is proposed. Then, numerical simulations are performed to compare the effect of this load distribution with the Eurocode one. Both simply supported bridges and bridges with integrated backwalls, all with span lengths less than 10m, are studied. For the later bridges, the effect of the support stiffness on the dynamic response is also studied.

# IDENTIFICATION OF HIGH SPEED RAIL BALLAST FLIGHT RISK FACTORS AND RISK MITIGATION STRATEGIES

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

## ABSTRACT

With the development of high speed rail (HSR) systems around the world during the past 50 years, one of the observed phenomena that occur at the train-track interface is the “ballast flight”, a phenomenon where ballast particles become airborne during the passage of a train. This phenomenon occurs when a combination of both mechanical and aerodynamic forces generated mostly by the passage of the train cause a ballast particle to overcome gravity. Factors affecting ballast flight include aerodynamic conditions, track response, ground effects and atmospheric conditions. Damages to the railhead, train body, and adjacent structures as well as injuries to maintenance staff have been reported in the literature to result in a major maintenance cost and safety concern for HSR systems with ballasted track. Previous studies have used laboratory wind tunnel tests and large-scale field tests to verify the various causes and mechanisms of ballast flight, and theoretical models have been developed to simulate the phenomena. However, there are only few existing practical risk models formulated according to certain field and/or analytical occurrences and used to assess the risk of ballast flight under different HSR operating conditions. For example the French National Railways (SNCF) and the Spanish Railway Administration (ADIF) have developed models to assess the flying ballast. A comprehensive literature review is needed to identify all the risk factors relevant to potential HSR operational conditions in the U.S. This would enable the development of a risk model to assess the ballast flight risk. The purpose of this article is to present the framework developed by the University of Illinois at Urbana-Champaign to perform a full evaluation of risk factors that may contribute to ballast flight in the United States where HSR is now emerging. This findings will likely to provide a basic strategic development plan for ballast flight risk for HSR operations in the United States. The scope of the work will include an identification of operating and infrastructure conditions that may lead to ballast flight, a development of risk assessments and methodologies for HSR planners and operators in North America, thus allowing the development of safe HSR systems.

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# TRACK SERVICE LIFE – DRIVEN BY BALLAST QUALITY

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**Key Words:** *ballast; track service life; track quality*

## ABSTRACT

The whole maintenance demand of track is driven by its initial quality. However, due to a small contact area between sleeper and ballast (3 to 5 per cent) initial settlements by cracking of ballast are unavoidable. As long as the ballast stones cannot bear the concentrated forces cracking will occur, until more and more stones come into contact and thus contact area is increased. Unfortunately these initial settlements are not similar but differ sleeper by sleeper – and these differences form the initial failures, causing dynamic forces, increasing the failures, increasing the forces, and so on and finally causing maintenance demand.

Thus ballast causes maintenance. Moreover ballast is the critical element in track regarding track service life. Rails can easily be changed if necessary, sleepers, even wooden ones show sufficient service lives (if track drainage is working properly), but as soon as ballast bed is polluted to a certain amount and/or ballast is rounded track no stable high quality track can be obtained by maintenance. Thus ballast cleaning is required. Unfortunately this is a costly operation. In practise the residual service life of track is already small when this ballast cleaning would be required. Therefore this maintenance action in general (if draining system works and there is a sound sub-layer) cannot be justified economically and thus track service life has reached its end. Just high speed lines and heavy haul lines form an exception.

Moreover within the life cycle costs of track depreciation forms the dominating cost component. Thus an increase of service life must be the main target.

Therefore the wear process in ballast must be analysed in detail. It contains ballast cracking, ballast rounding, and abrasion of ballast. Cracking leads to local settlements of track and thus vertical alignment failures. Furthermore cracking also produces fines, which pollute the ballast bed, increases its stiffness and hinders dewatering of track. Rounding destabilises track as track after a tamping action deteriorates quite fast. Abrasion again forms fines in the ballast bed. The consequences of ballast wear are therefore vertical alignment failures and pollution of ballast bed. A polluted ballast bed must not be tamped, as the tamping action would even worse the situation. Therefore in such cases no maintenance action is executed unless the poor riding quality thus does not require a speed restriction. However, higher stiffness of track results in higher forces for all components. This will lead to problems with fasteners (loose fastenings), can result in sleeper cracking and in rail contact fatigue (squats). In principle two solutions exist to better the situation: firstly to increase ballast quality, secondly to reduce forces in ballast.

1st: Comparing different ballast quality in different countries show the impact to track service life as in France basalt ballast can be tamped 28 times, while Austrian granite ballast stands the operation and 15 times tamping. But weak limestone ballast is crashed after 10 times tamping. However, this does not mean that tamping destroys ballast but the total traffic loads which form the demand of tamping and the tamping and the cracking after tamping together limits the ballast service lives. The consequences are a reduction of track service life by 20 per cent and service life of turnouts by 33 per cent comparing granite ballast with weak limestone ballast.

2nd: decreasing of forces in the ballast can be realised by increasing the contact area between concrete sleepers and the ballast in implementing sleepers with under sleeper pads. This is the standard solution in Austria for track and turnouts since 2009 showing very promising results, as e.g. a reduction of track deterioration by two third.

# THE ASSESSMENT OF SUPPORT STIFFNESS ON RAILWAY CROSSING DYNAMICS

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**Key Words:** *track stiffness; ballast; crossing; numerical modelling; dynamic forces; P2 force*

## ABSTRACT

Railway switches and crossings are one of the most costly items to produce, install, operate and maintain for railway infrastructure managers. The non-linearities generated by varying rail profiles, sudden change of curvature and also varying support conditions make them highly susceptible to high dynamic loading and therefore accelerated degradation and component fatigue. Faults can develop, for example crossing casting fatigue cracks and particularly voiding under bearers as tamping activities are restricted around the moving part of the S&C. With the help of modern simulation tools and techniques, it is possible to accurately predict the impact forces that may be generated from a range of vehicles, considering running conditions and wheels state, and investigate the interaction with the various crossing designs and support conditions they are in.

As part of the European Framework 7 Project SUSTRAIL, The University of Huddersfield and Politecnico di Milano are working together on the investigation of the dynamics performance of switches and crossing under freight traffic condition in the context of future traffic demand, i.e. higher tonnage and/or higher speeds. Improved performance can be achieved from geometrical modifications to the crossing shape as well as from changing the vertical support stiffness provided to switch and crossing panels. For the purpose of these studies the University of Huddersfield designed a series of modelling tools and techniques that allow the prediction of the vertical dynamic load at the crossing in a range of frequencies relevant to the type of different damage types experienced by the crossing: material wear and fatigue in the contact, component fatigue and the ballast layer deterioration. The tool is based on a dynamic analysis of the wheelset interaction with the crossing geometry using detailed cross sections surveys and measured support stiffness. The vertical and lateral motion of the wheels are derived and used as input to a fast multibody model of the wheel and track interaction so that dynamic impact forces are produced in a wide frequency range taking into account the response behaviour of the track construction. This includes layers such as the ballast stiffness, the presence or not of resilient baseplate or under sleeper pads and their variation along the track.

In the project, comparisons are made of crossings installed on conventional ballasted track and other innovative designs including resilient baseplate and under sleeper pad. The impact of sleeper voids on the force levels is also assessed and results are further related to the degradation of the ballast layer.

# HIGHER SPEED BRIDGE APPROACHES

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**Key Words:** *Railway track; ballast; high speed; experimental tests; displacement transition limits*

## ABSTRACT

Bridge approaches can receive sudden impact loading due to a change in the vertical stiffness between the bridge deck and approach embankment leading to frequent settlement of the approach bank. This may create large acceleration at high speed leading to riding discomfort. Proper design of approach banks can include provision of wider sleepers at approaches, an approach slab or providing tapering stone to simulate gradual rise in approach stiffness
The rails are obviously continuous over discontinuities in the support to the track. Thus the bridge deck, bearings and substructure with the track resist jointly the longitudinal actions due to traction or braking forces as well as the effects of thermal variations and deflection of the deck under vertical traffic loads LM 71. They are transmitted partly by the rails to the embankment behind the abutment and by the bridge bearings and the substructure to the foundations. Relative displacements of the track lead to interaction phenomenon, which results in additional stresses to the bridge and the track. Theoretically this is a serviceability limit state for the bridge and an ultimate limit state for the rail. The expansion length LT between the thermal fixed point and the end of the deck, number of spans and length of each span, position of fixed bearings and the thermal fixed point are basic parameters affecting the combined response of the structure and track.
For rails on the bridge and on the adjacent abutment the permissible additional rail stresses due to the combined response of the structure and track to variable actions should be limited to 72 N/mm2 in compression and 92 N/mm2 in tension. The bridge beam edge rotations at an abutment are required obviously being less than 20/0 and double limit values are imposed at intermediate supports. More severe limits impose EN 1991-2. Due to traction and braking, the relative longitudinal displacement □2 shall not exceed 5 mm for continuous welded rails without rail expansion devices or with a rail expansion device at one end of the deck and 30 mm for rail expansion devices at both ends. For vertical traffic actions produced by non-classified model LM 71, where required SW/0 the longitudinal displacement □3 shall not exceed 8 mm when the combined behaviour of structure and track is taken into account. The vertical displacement of the upper surface of a deck relative to the adjacent construction or another deck abutment □4 due to variable actions shall not exceed 3 mm for a maximum line speed at the site of up to 160 km/h and only 2 mm over this value.
The low-maintenance characteristics of slab track concepts are being applied, although still at a moderate volume. The slabs may be prefabricated or poured on site. Increased service life, high lateral track resistance, no shaking of ballast particles are the further advantages of such structures.The long-term monitoring of the part of the modernized line, specifically in the tunnel and its adjacent areas in contact with the classic superstructure through transition areas, where the ballastless track was applied and continuous recording of changes in the development of the geometric parameters of the rail during operation would be presented. The monitoring allows to obtain information not only about the structural quality of the ballastless track and its transition areas but also enables to consider the profitability from the point of view of costs for ballastless superstructure maintenance and repairs compared to the most of the line with the classic superstructure. The further solutions of transition areas arrangement would be presented in the eventual contribution, which could satisfied the above high speed requirement.

# SHORT AND LONG TERM BEHAVIOUR OF THE TRAIN-TRACK SYSTEM AT AN UNDERPASS TRANSITION ZONE

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

## ABSTRACT

The railway experience in conventional and high speed lines shows that when track characteristics change abruptly, namely in embankment-bridge or embankment-underpass transitions, the evolution of the degradation process of the track is considerably faster than usual. These zones require frequent maintenance operations in order to restore the geometrical quality of the track. This work presents an experimental and numerical study of an embankment-underpass transition located at the Northern line of the Portuguese railway network. The experimental component of this study involved track receptance tests in three distinct zones along the transition: over the embankment, over the transition and over the structure. Moreover, several parameters were monitored, such as the rail displacements, the accelerations of the sleepers and the dynamic loads along the transition zone, for the passage of an Alfa Pendular train at 220 km/h. The numerical component involved the development of a 3D model in LS-DYNA program and a 2D model in ANSYS program. The train-track interaction was included in both models by means of contact algorithms applied to the wheel-rail interface. The dynamic models were calibrated by adjusting the experimental and calculated receptance functions. The calibrated models were applied to the prediction of the dynamic response of the transition zone for the passage of Alfa Pendular train and excellent agreement was obtained between numerical and experimental results. Subsequently, the calibrated and validated models were used to simulate the evolution of the deformed track profile in the transition zone by means of a computer tool that enables to account for the permanent deformation of the track-subgrade materials. This study allowed the assessment of the long term dynamic behaviour of the train-track system at the transition zone.

# MECHANICAL BEHAVIOUR OF A MICROBALLAST UNDER MONOTONIC AND CYCLIC TRIAXIAL LOADINGS

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**Key Words:** *railway track; microballast; triaxial loading; cyclic weathering; size effect*

## ABSTRACT

Ballast constitutes an essential component of the complete railway system, which controls, to a large extend, the global behaviour of the track.
Although various aspects of the mechanical behaviour of ballast have already been addressed, based on the use of the triaxial apparatus, some issues remain unclear and deserve to be further investigated.
Within this context, we present, in this communication, the results of an experimental study aimed at better understanding the mechanical behaviour of a microballast (scale 1/3 with respect to real size ballast) tested under monotonic and cyclic loading in the triaxial apparatus.
The influence of parameters such as the specimen size with respect to grain size (100 and 300 mm diameter specimens have been tested), the amplitude and frequency of cyclic loading, on the microballast behaviour observed are presented. Also, the weathering process of microballast grains submitted to very large numbers of cycles (3.5 millions of cycles have been applied in a specific test) with creation of fine particles is presented and discussed.
Conclusions are finally given concerning the results obtained and perspectives for further research are proposed.

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# DYNAMIC & CYCLIC BEHAVIOUR OF BALLAST IN THE LONG TERM AS DETERMINED IN CEDEX'S TRACK BOX

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

## ABSTRACT

The 6 cylinder servo-hydraulic loading system of CEDEX's track box (250 kN, 50 Hz) has been recently implemented with a new piezoelectric loading system (±20 kN, 300 Hz) allowing the incorporation of low amplitude high frequency dynamic load time histories to the high amplitude low frequency quasi-static load time histories used so far in the CEDEX's track box to assess the inelastic long term behavior of ballast under mixed traffic in conventional and high- speed lines.

This presentation will discuss the results obtained in the first long-duration test performed at CEDEx's track box using simultaneously both loading systems, to simulate the pass-by of 6000 freight vehicles (1M of 225 kN axle loads) travelling at a speed of 120 km/h over a line with vertical irregularities corresponding to a medium quality line level.

The superstructure of the track tested at full scale consisted of E 60 rails, stiff rail pads (> 450 kN/mm), B90.2 sleepers with USP 0.10 N/mm$^3$ and a 0.35 m thick ballast layer of ADIF first class. A shear wave velocity of 250 m/s can be assumed for the different layers of the track sub-base.

The ballast long-term settlements will be compared with those obtained in a previous long-duration quasi-static test performed in the same track, for the RIVAS [EU co-funded] project, in which no dynamic loads where considered. Also, the results provided by a high diameter cyclic triaxial cell with ballast tested in full size will be commented.

Finally, the progress made at CEDEX´s Geotechnical Laboratory to reproduce numerically the long term behavior of ballast will be discussed.

(The research leading to this presentation has received funding from the European Union Seventh Framework Programme under grant agreement nº 265754)

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# A THEORETICAL MODEL OF BALLAST COLMATATION

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**Key Words**: *Ballast permeability. Ballast colmatation. Permanent Way.*

## ABSTRACT

Ballast of old railroads built without subballast or geotextile protection are subjected to colmatation as a result of the water flow that carries soil particles into crushed stone voids over many years, a common case on Brazilian railroads. Even frequent winds carrying soil particles can produce a similar result, clogging voids and reducing permeability coefficient. This phenomenon modifies the structural behavior according to the usual stresses and strains forecast models. In this paper it is proposed a theoretical model of water flow, from the subgrade to the ballast upper part, taking into consideration the sleeper vertical movement generated by rail flexural, pumping water into the ballast porous medium. The sleeper and ballast gap, as a free space for pumping water reduces the ballast permeability coefficient. There is an approach of the behavior of the new ballast state, influenced by colmatation, which minimizes the elasticity theory suitability when studying efforts on the permanent way. Some former studies and results were also considered to evaluate this proposed model.

# THE INTERACTION BETWEEN BALLAST AND UNDERLYING LAYER IN RAILWAY SUB-STRUCTURE

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**Key Words:** *Railway substructure; physical model; cyclic loading; migration of fine particles; interface ballast/sub-soil; mud pumping; interlayer creation*

## ABSTRACT

In France, during the maintenance campaign of ancient tracks, a new layer namely interlayer was identified. It is suspected that this layer was formed mainly by the interpenetration between ballast and sub-soil. This interlayer can play an important role in the overall behavior of railway tracks. On the other hand, mud pumping which is characterized by the upward migration of sub-soil fine particles through the ballast voids has been known to be the worst degradation phenomenon for the railway sub-structure. Basically, these two phenomena (interlayer creation and mud pumping) are both related to the migration of particles and the interaction between ballast and sub-soil layers.

In order to investigate these phenomena, experimental tests using a physical model (550 mm in internal diameter and 600 mm in height) that consists of a ballast layer (160 mm thick) overlying a sub-soil layer (220 mm thick) were carried out under different conditions in terms of water content, loading and sub-soil dry unit mass. The physical model was equipped with various sensors and devices allowing water content pore water pressure, axial displacement to be monitored. Visual observations were also made using a digital camera. The analysis of the ballast settlement through the particles movement, the global displacement and the sub-soil settlement showed that the sub-soil state can strongly influence the ballast behavior: the larger the initial dry unit mass of sub-soil, the lower the permanent axial displacement. This suggests that in order to understand the overall behavior of railway sub-structure, it is important to take into account the interaction between different layers.

The presence of water was found to be the most crucial factor for the stabilization of ballast/sub-soil interface and for the migration of fine particles. In unsaturated state, both ballast and sub-soil settlement occurred, but without migration of fine particles. Under near saturated state, the ballast/sub-surface interface moved up, and the pumping level depends on the sub-soil dry unit mass. In the case of low dry unit mass of sub-soil, cyclic loadings generated high pore water pressures, resulting in sub-soil liquefaction during the unloading process. Excess pore water pressure dissipation took place, bringing fine particles upward. This corresponds to the mud pumping phenomenon. In the case of high dry unit mass of sub-soil, there was just the interpenetration of ballast and sub-soil, resulting in a mixture layer namely interlayer.

# BALLAST-GEOGRID INTERACTION ANALYSIS USING DEM

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**Key Words:** *Ballast; geogrid; discrete element method; DEM*

## ABSTRACT

Geogrid is an appealing product to stabilise railway ballast by preventing its deformation. The interaction between geogrid and ballast is investigated using the discrete element method (DEM) in which the ballast is considered as an assembly of interacting objects. These objects, the particles of the ballast, are represented by clumps of overlapping spheres (Fig.1). In order to obtain interlocking between the geogrid and the ballast, these clumps can reproduce irregular shapes with a certain accuracy which depends on the number of spheres overlapping. Geogrids are modelled by bonding an array of spheres together using bonds that can transmit forces and moments. The mechanical parameters of the spheres and bonds are adjusted by performing simulation of basic loading tests on geogrid: single rib pull test and in-plane rotation test. These simulations showed the importance of modelling accurately the geometry of the geogrid in DEM to get realistic deformation patterns (Fig.2).
The efficiency of the geogrid is analysed using DEM simulations of the standard pull-out test (Fig.3) and loading of geogrid-reinforced ballast in confined and unconfined conditions. Compared with laboratory tests, the results of the DEM simulations show that even simple particle shape models can reliably reproduce the interaction between the geogrid and the ballast. Realistic deformation pattern of the geogrid are also obtained.
DEM offers the possibility to analyse the ballast-geogrid interaction at the scale of the stones giving access to the contact forces between the stones and the geogrid, stones displacement and geogrid deformation, information hardly observable experimentally during loading.

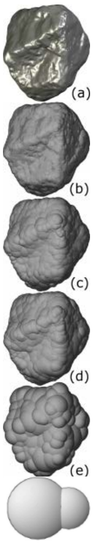

Fig.1

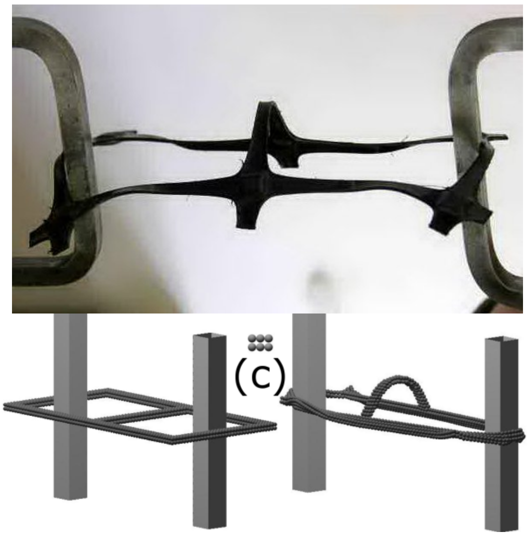

Fig.2

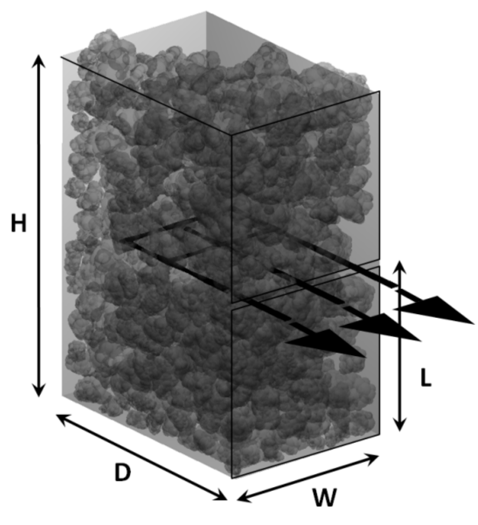

Fig.3

# NEOBALAST: SEEKING FOR THE BALLAST OF THE FUTURE.

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

**ABSTRACT**

During the last decades a lot of research/design/construction/monitoring concerning slab track solutions have been done. In almost each study a comparison with ballasted track appeared as one of the key points leading to interesting conclusions about what should be "the track of the future".
What it seems logical is that the last goal of railways engineers should be to combine the main advantages of the ballasted track and those from the slab track in order to develop an innovative new track system providing the best possible performance. A decade ago the ballast-less track was seen as a far better solution than ballasted track, yet much more expensive, but time and real tests have proved that it is not exactly this way and ballasted track still has big chances for the future.
Thus, ballasted track properties –such as high maintainability at relatively low cost, convenient values of elasticity, high drainage capacity, excellent Noise &Vibrations (N&V) behaviour, etc.- should be merged with slab track strengths - low maintenance requirements and hence, high availability, better fixing of geometry, high durability, etc - to obtain the best possible solution.
Furthermore, new challenges have arisen in the time being as high quality ballast - as a natural resource it is - has started to be scarce and not always an available material. As a result, in some specific locations and projects, long transport routes must be done in order to get the right material, which results in an increase of not only cost, but of the environmental burdens associated to track construction.
This occurs in a context where EC policies have increased its strictness in environmental issues, whereas sustainable and durable solutions are each time more encouraged by the EC. In this sense, there has been an increasing awareness of noise and vibration related problems in the last years. For this reason, there should be a migration for the existing situation -mitigation- where countermeasures are adopted to comply with the new N&V demands to a new scenario -prevention- where the track system is designed to cope with N&V future demands.
Solutions like precast ballast, modified ballast with in-situ polymers or geo-grids have been developed to improve both LCC (Life Cycle Cost) and LCA (Life Cycle Assessment) and performance. Nevertheless, further tests should be carried out to demonstrate that these new solutions are feasible from a technical-economical-environmental point of view. NEOBALAST is an innovative project with a focus on developing the “ballast of the future”, as the believe that there is much room for improvement in ballasted track is shared, but at the same time ballasted track still has a long and brilliant future. This enhanced ballast aims to conjoin the advantages of ballasted track –and even improve them-, whilst achieving durability, very low maintenance and other properties until now only featured by slab track. As an excellent performing ballast, NEOBALLAST will give solution to the scattering of high quality ballast quarries, but at the same time it is designed to improve significantly the N&V behaviour of the whole track system. NEOBALLAST project is at a laboratory demonstration stage. A first battery of tests is currently being done. The first preliminary results obtained from the tests already done have shown interesting and very positive results, which leads to an optimistic expectation for the upcoming tests and promising future for NEOBALLAST.

# EVALUATION OF RAILWAY TRACKBED BALLAST USING NDT

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**Key Words:** *Railway track; ballast; GPR, Impulse Response*

**ABSTRACT**

The increase in freight and passenger rail travel has driven demand for more efficient and rapid investigation of railway trackbed ballast.
Current work on ballast contamination and degradation is investigated by Network Rail (UK) using impulse radar (GPR) (Musgrave, 2013) – based on the work of Selig and Waters (1994). It is proposed to discuss refinements and options to the Selig and Waters approach.
One of the current approaches to evaluating the stiffness of railway ballast is to use a Falling Weight Deflectometer. Whilst this is very effective, it requires the rails to be unclipped from the ties – thus, it is intrusive and expensive. It is proposed to discuss the option and possible role of using an Impulse Response (IR) generated by using a 12lb instrumented hammer to excite railway trackbed ballast composed of variously fouled ballast, with response measured using a geophone.
The overall objective is to generate discussion which might deliver both cost savings and a greater insight into the behaviour of ballast using NDT techniques.

# BALLASTED TRACK AT HIGH SPEED: STATE OF THE ART AND PERSPECTIVES FOR OPERATION AT HIGHER SPEEDS

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

**ABSTRACT**

A review of ballasted track investigations and feedback from experience at high speed was carried out for High Speed 2 Limited, in view of potential implementation for very high speed.
A review of research on the mechanics of ballasted track, including subgrade is presented first, with a particular focus on ballast itself. In particular, experimental tests and numerical modelling (e.g. discrete element modelling) are detailed. Tamping mechanics and optimization potential are also considered. This is followed by an analysis of dynamic phenomena involving the platform (Rayleigh waves) with a view to characterizing their physical occurrence in practical situations, as well as preventive measures in current practice of high speed line construction.
Ballasted track settlement and deterioration are then reviewed, both starting from reduced or full scale tests, and also from the feedback from operation on French high speed lines. Sub ballast layer properties as well as transition zones specifications are also considered.
Ballast flight phenomena are then analysed, both from their occurrence in practice as well as recent modelling and including feedback from experience from 360km/h running tests. A presentation of the developed risk assessment methods results for different speed and/or train configurations is also given. Protective measures on track also of use for ice fall are also given.
Ballasted track optimisation in view of very high speed is addressed in a last section. Different potential improvements in track and subgrade technology are reviewed as well as the results of experiments on real tracks. Potential for optimisation of maintenance of ballasted track is also given. Finally, the increase of track loads at 360km/ tests in France, as well as lessons gained from the short term observation of track behaviour during the world speed record runs are also discussed.

# THE INFLUENCE OF THE BALLAST PARAMETERS ON TRACK LATERAL ALIGNMENT

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**Key Words:** *Railway track; ballast; hysteresis characteristic; computational methods*

## ABSTRACT

Track geometry deteriorates with traffic and needs to be regularly restored by tamping or other methods. As the deterioration is mainly in the vertical direction this aspect has been more widely studied and models developed but track lateral deterioration is not as well understood. The development of lateral track irregularities potentially increases the risk of track buckle. The research work presented in this paper aims to develop a better understanding of the influential parameters relating to different ballast conditions that influence lateral track deterioration. The track lateral position may not be fully restored after vehicle passages due to the residual and frictional characteristics of the sleeper-ballast interface and even the failure of this interface which causes sliding Kish et al. [1]. Unlike the stiffness and damping values provided by rail pads and fastenings, the ballast layer has highly nonlinear characteristic and is assumed to have a relatively constant stiffness and constant value. This research aims to study the stiffness and damping values provided to the sleepers by the ballast in order to have a better understanding of the track lateral behaviour with time and loading. The non-linear characteristic of the lateral resistance is shown has been determined from experimental programs in different researches[2][3]. The sleeper-ballast stiffness is determined by this non-linear relationship and the dynamic forces changes, thus this stiffness changes with respect to the different dynamic vertical load. A vehicle-track lateral dynamic interaction model, that predicts the track lateral deterioration, has been established and validated against measured track data in the UK. The vehicle-track lateral interaction can be effectively modelled based on two main parts, which are the vehicle-track interaction model and the track lateral deterioration model. The vehicle-track interaction model is an existing Multi-body System (MBS) model in this case VAMPIRE. The outputs from the Vampire simulation are then used as the inputs to the Finite Element (FE) track model. Sensitivity analysis is carried out to investigate the influences of different conditions of ballast layer. Improving the strength of the ballast layer will effectively reduce the track lateral deterioration and risk of lateral sliding failure.

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# THE USE OF FALLING-WEIGHT DEFLECTOMETERS IN DETERMINING CRITICAL VELOCITY PROBLEMS

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**Key Words:** *Railway track; ballast; high speed; experimental tests; computational methods*

## ABSTRACT

The performance of track is highly dependent upon trackbed condition and stiffness. This is well recognised in the international railway industry with trackbed stiffness seen as a key factor in the deterioration and whole life cost of railway tracks, and ultimately the safety of the line at high line speeds or where heavy-axle load application is required.

One method for determining the trackbed stiffness is the Falling-Weight Deflectometer (FWD). Although this technique is widely used in pavement applications, URS have been operating the only rail-based Falling-Weight Deflectometer (FWD) on problem sites in the UK over the past 15 years. Problem sites have typically been characterised by either high deflection of the trackbed layers or sites exhibiting critical velocity problems.

URS' Rail FWD generates a pulse-load through dropping a weight onto a bespoke loading beam placed on an unclipped sleeper. The loading beam transfers the pulse-load into the sleeper which in turn transmits the load to the trackbed. Geophones are then used to measure displacement of the ballast surface at set intervals away from the loaded sleeper. Peak deflections and time histories are recorded.

Through measuring the time-history of the wave generated by the FWD it is possible to calculate the surface wave-propagation velocity (critical velocity), from which it the permissible velocity of a given section of track can be estimated. Previous research undertaken by URS (formerly Scott Wilson) has indicated that limiting the linespeed typically to two-thirds of the critical velocity is necessary in order to control risk and also provide track where maintenance can be undertaken sustainably.

Critical velocity and trackbed deflection are likely to find increasing prominence on many rail networks, as asset owners seek to improve linespeeds to meet timetable demands, or to increase axle-loads in order to meet the needs of freight operators. Case-studies of recent investigations undertaken using the FWD are presented, including:

Midland Mainline between London St. Pancras and Derby in the UK – Assessment of likely impact of proposed linespeed improvement over sections of soft ground. Results have shown that although much of the track is able to support the proposed increase in linespeed, several sections may require intensive maintenance in the short-term, and improvement of ground conditions in the longer-term in order to sustain the increased linespeeds.

Alberta, Canada – Investigation of a 130 mile long section of track largely underlain by Muskeg (peat) deposits, where increases in both axle load and traffic density are proposed. Reports have suggested that the subgrade is failing to support the existing 25mph linespeed and FWD investigation has been undertaken to determine trackbed stiffness and critical velocity in problem areas of the track section.

# FIELD BALLAST GRANULOMETRY ASSESSMENT THANKS TO IMAGE ANALYSIS

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**Key Words:** *ballast; geoendoscopy, image analysis, in situ grain size distribution*

## ABSTRACT

The ballast is the main component of railway structure. It plays a role of drainage, force transmission, security level in terms of lateral resistance. The degradation of track geometry induce an evolution of the initial gradation and angularity due to fouling or numerous maintenance operation.
The usual process for Track or Ballast renewal is based on some investigations about the track geometry and substructure and the efficiency of maintenance operations. However, the properties of ballast layers are not assessed because they are hard to provide especially on the field.
Once the renewal decision has been taken, one of the most important information in order to save money is the evaluation of ballast gradation directly in the field. As a matter of fact, ballast gradation information helps evaluate the ballast part which can be reemployed. The most usual way is to sample ballast on the track by special trains or manual operation which are costly and heavy to manage.
A new in situ ballast gradation valuation based on image analysis is presented in this article.
The images are provided thanks to the coupled use of panda® penetrometer and geoendoscopy. This new geotechnical investigation technique has been widely used on the French rail network and allowed to gather a large database of ballast images at different levels of degradation. Moreover, previous works on image analysis made it possible to assess sandy material gradation thanks to geoendoscopic images.
This article shows how ballast gradation can be assessed thanks to 5mm X 5mm geoendoscopic images.

# NUMERICAL MODELLING OF RAILWAY BALLAST AT THE PARTICLE SCALE

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**Key Words:** *Railway track; ballast; numerical modelling; computational methods*

## ABSTRACT

Ballast is traditionally used to support railway tracks as it is relatively inexpensive and easy to maintain. However, the increasing demands being placed on ballasted track in terms of faster, heavier, tilting and more frequent trains mean that a better understanding of its mechanics, and the way in which it resists lateral and vertical loads and movement, is required.

Railway ballast is an ideal subject matter for discrete element modelling (DEM). The relatively large size of the grains in comparison to the depth of the ballast layer means that there are relatively few grains to model. Furthermore, the inherent heterogeneity of the ballast mechanical behaviour is best studied at the grain scale, at which the effects of grain shape (form and roundness and roughness) and size distribution can be properly investigated. However, representation of the irregular shape of ballast stones presents a modelling challenge. The simplest approach is to represent particle shapes with an agglomeration of spheres, but large numbers of spheres are required to capture angularity with this method. Alternative methods use polyhedral elements, which can represent angularities well, but which can be computationally intensive and complicated. The approach adopted in this paper uses the potential particle method (Houslby, Harkness), which is an efficient method for modelling slightly rounded polyhedral particles of moderate complexity.

A library of particles for the DEM modelling has been developed to be representative of ballast by means of a shape study of real ballast particles using image analysis. Assemblies of the representations of ballast have then been systematically tested in triaxial simulations that have varied parameters of (1) initial void ratio, (2) inter-particle contact friction and (3) contact stiffness. These tests have been compared to physical tests on 1/3 scaled ballast to better understand the influence of varying each parameter on the results and to gain insights into the most appropriate parameters for obtaining realistic behaviour. The results show the most appropriate sets of parameters to gain realistic behaviour but also highlight difficulties in the numerical modelling where further research could be productive such as a better understanding of the contact stiffness model.

The intention is to expand the modelling to real models of track and to investigate further factors such as particle angularity and gradation in the observed behaviour.

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# A FULL-SCALE EXPERIMENTS AND INVESTIGATION OF EFFECT OF FLOODING ON TRACK PERFORMANCE

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**Key Words:** *Full-scale; flood; experimental tests; soil suction; subgrade*

## ABSTRACT

The new demand for faster and heavier train service needs good support from the underlying substructure; which is why designing new tracks along with improvement of the existing tracks are deemed important. The performance of the railway track depends on the behaviour of underlying subgrade materials; track performance, maintenance and stability are all depended on the variation and magnitude of subgrade stiffness. Recently, the railway tracks in the UK experiencing repeatable flooding events; therefore, maintenance cost increases extensively. Despite clear evidence, the enormous effects of flooding to the railway foundation have rarely been investigated. This research focus on investigation including softening of subgrade materials due to decreases of suction by wetting and regain of subgrade strength after drying due to increases of suction. Large scale tests were performed using the Geopavement & Railway Accelerated Fatigue Testing (GRAFT-I) facility at Heriot-Watt University together with suction measurements using the filter paper method.

# BALLAST BEHAVIOUR SEEN FROM A GEOTECHNICAL POINT OF VIEW

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**Key Words:** *Railway track; ballast; experimental tests; evolution of stiffness*

## ABSTRACT

Cyclic large scale triaxial tests (specimen with diameter 0.8m and height 0.8m) on ordinary ballast will be presented. The results include the evolution of stress dependent stiffness and settlement with ongoing numbers cycles. The sensitivity of settlement depending on the stress amplitude will be discussed also. Results are compared with measurements on real tracks under dynamic loading (stationary using a special vehicle as well as passing trains).
A simplified model for a ballast track uses these results and others in order to identify some basic mechanisms of the behaviour of the ballast under and between the sleepers. Among others, one result shows the significance of initial stress on the evolution of settlements.
The results are gathered during a long period of research. They can and should be used for a validation of constitutive relations for ballast and numerical models of ballast tracks using FEM, DEM and etc.

# ACOUSTIC PROBING OF THE BALLAST: A GRANULAR POINT OF VIEW

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**Key Words:** *granular media; elastic wave propagation; acoustic measurements; effective medium theory*

## ABSTRACT

Probing the mechanical properties of the ballasted bed of railway track remains a challenging task. Non destructive testing by acoustic velocity measurements has been identified as a genuine method to achieve this major objective both for engineering and maintenance purpose. However, interpretation of such measurements in the ballast relies upon strong assumptions that the ballast layer could be effectively considered as a continuous medium. Considering the coarseness of the ballast itself and the relatively small number of granular layers involved here, it is unclear whether the effective medium approaches apply in the ballasted bed.

In this communication, we will briefly review the sound propagation in granular media and critically test the applicability of the effective medium theory in model granular layers. To this end, we measure the time-of-flight velocity V of transmitted longitudinal ultrasonic pulses through the granular packing [1, 2] whose thickness H ranges from 5 to 40 grain size d. The granular materials consist of glass beads of 1.5 mm or micro ballast of 1-2.5 mm, confined under pressure P = 180 kPa. The ratio of the standard deviation to the configuration-averaged value (20 experimental runs) is measured for the sound velocity V and the packing density □, respective fluctuations for both V and □ decrease with increasing the sample size L. Moreover, for small L, the fluctuations in V strongly depend on the confining pressure P. Our results are consistent with the fluctuation of linear elasticity observed in numerical simulations on the small scale of a granular medium via coarse-graining [3]. The effects of the particle shape are also studied using micro ballast particles. This work shows that acoustic measurements may be very efficient for monitoring the ballast.

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# IMPROVING BALLASTED TRACK LATERAL RESISTANCE: THE US EXPERIENCE

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**Key Words:** *Ballast lateral resistance; track lateral stability; maintenance works/policies; track stabilization; track buckling/lateral shift safety limits; lateral resistance measurements*

**ABSTRACT**

A key aspect of track lateral stability is the provision of adequate lateral resistance to the rail-tie structure by the ballast. With the increased tendency for higher axle loads and very long trains, maintaining high lateral ballast strength becomes more important. When lateral resistance is reduced, such as when ballast is worked or degraded, the track can not only lose alignment and surface, but can become buckling prone in the presence of high thermal forces. Current methods to restore ballast strength after track work is through mechanical compaction either by dynamic track stabilization (DTS), or through traffic (tonnage) induced consolidation. US research has confirmed the benefits of DTS, however data on traffic/tonnage consolidation have not shown the expected equivalent benefits.

This presentation will offer a review of the fundamentals of ballast lateral resistance, its measurement and key influencing parameters, provide a test/data summary of US measurements to date, present analysis results on influence of lateral resistance on track stability, and offer insights on additional research needs for improving lateral ballast strength.

# FFU - SYNTHETIC SLEEPER TECHNOLOGY

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**Key Words:** *synthetic sleeper, long life time*

## ABSTRACT

In the 1970tes JR Japanese Railways after many years of maintenance observation realized that around 70% of installed sleepers from wood have a very short life time, this because the existing weather influences where leading to moldering and rotting of wood. JR decided to develop alternative material so that life time of sleepers can be increased and track behavior advantages of wooden sleepers can be reached.

The letters "FFU" stand for "fibre-reinforced foamed urethane", the material used in Japan to develop a synthetic sleeper. Back in 1978, a company called Sekisui was awarded several prizes in Japan for this technological development, which initially went under the name of "Eslon Neo Lumber FFU".

FFU synthetic sleeper is from a material that has the same material properties as natural timber and can be handled and processed as easily as it can. The synthetic material has virtually the same specific mass as the natural one, yet a very considerably longer service life than the latter, and its weathering proper ties are also superior.

In 1980, the Railway Technical Research Institute (RTRI), working in cooperation with the Japanese railways, laid sleepers made of this material on two experimental sections of track in Japan. Following on from a period of five years of practical experimentation, in which all the specified requirements were fulfilled, FFU has since then been used by the Japanese railways as a standard product on steel structures, under points and crossings and in tunnels in combination with both ballasted and ballast less track. In 1996, the RTRI removed the first synthetic sleepers from the experimental track sections and subjected them to a new series of tests. Extrapolating the results recorded at that time, FFU would be expected to have an in-situ service life of more than fifty years.

Since 2004, railway sleepers made of FFU have been in use in Europe on railway bridges with open load-bearing structures made of steel as well as under points and crossings. In September 2008, Munich's University of Technology wrote the final report on a research project into such sleepers, drawing positive conclusions. 2011 DB AG – German Railways installed first time FFU on a 60 m long bridge in Vilsbiburg. 2012 DB AG used FFU for two 60.000 t/day switches in Wurzburg. Since them further projects of DB are carried out with FFU. Pro Rail installed it first time in September 2012 on 3 bridges. In 2014 first switch and bridge projects will be implemented with FFU in Switzerland, Also Network Rail in 2014 will start first experiences on bridges with regular but also longitudinal sleepers with a cross section profile of 40/40 cm.

In 2011, 30 years after the first field test, RTRI again did laboratory test with sleepers removed from first field test. This 30 years old and under regular train operation used sleepers showed that the technical figures have been decreased a little. The conclusion of this test was that RTRI wrote a letter to JR – Japanese Railway operator - that they can still use these FFU sleepers for the next 20 years.

Latest positive result from TU Munich happened in July 2013 for the test of FFU slim sleeper with heights of 10cm for the use on LRT track and 12 cm for regular trains for an axel load of 22.5 t and a speed up to 200 km/h.

# BALLASTLESS TRACKS – SOME OBSERVATIONS

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**Key Words:** *Girder rail, elastic ballast, failure modes, optimum criteria, ballast free LR55 track;*

## ABSTRACT

Ballasted tracks are still not right after 170 years? Girder rails (bullhead and Vignoles) fixed to sleepers (ties) and set in crushed aggregate ballast became the track norm for railways in the 1840's. This replaced various earlier methods including stone block with rails as beams, and the Brunel continuously supported squat rail. This track form was adequate then, when trains had low axle weight and ran at slow speeds.
Now mass production makes the installation cost of ballasted track low. Heavier trains running at high speed means that the cost of maintenance and the deterioration of ride quality is the ongoing problem. There appears to be no solution near, despite major expenditures on research and development. Girder rails are intrinsically unstable because of the high load carried on top and the small footprint in support. Analysis of girder rails on sleepers presented earlier in 2013 by Causse and separately by Hohnecker, indicates that central to the poor performance of ballasted track are two conflicting mechanisms. Firstly the rails are too stiff, which also leads to fatigue problems like corrugations and gauge corner cracking. Secondly the ballast is too elastic with inadequate damping. These finding are based on both physical experiments and calculations.
This paper considers how these intrinsic problems can be address. It examines the characteristics of a rail track with less stiff rails and a hysteresis elastic/damped foundation, and how it may be realised for railway operations. At least one such track form will be discussed, which has had over 17.5years of service, not needing any maintenance with a minimum of wear and no corrugations. This replaced Vignoles railed track that failed after 6 months.
The paper concludes by proposing a generic track type that addresses the problems found in existing ballasted tracks.

# TRACK GEOMETRY DEGRADATION UNDER EFFECT OF THE TRAIN'S DYNAMICS

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**Key Words:** *Track geometry; train dynamics; temporal evolution; track maintenance; track irregularities*

## ABSTRACT

Nowadays, the ballasted track is submitted to more and more solicitations, because of the increase of the train traffic, the load and the speed of the trains. These solicitations trigger degradation of the track geometry, making the irregularities of the track geometry evolve. To maintain a good level of the quality of the track, maintenance operations are needed. This study aims at identifying which are the portions of the track which evolve more, and in what extend it affects the train dynamics.

To observe the track irregularities, a high speed track has been measured very precisely and frequently. Four geometric criteria are computed to indicate the state of the track. The evolution of these criteria in the time is observed. First, we observed that the track geometry changes faster in curves than in alignment. Besides, maintenance operations better the quality of the track, but do not erase all the track irregularities.

On the other hand, the train dynamic response is simulated with a multibody software on the measured track. We can now observe the evolution of robust indicators of the train dynamics and detect the portions where the dynamic indicators are the highest. These portions are compared to the track portions where the evolution of the geometry is the biggest.

As a conclusion, we characterized the evolution of the geometry on a measured track, observing the evolution of irregularities and the influence of maintenance operations on the track geometry. Robust indicators on the train dynamics are computed, introducing uncertainties in the measures of the track geometry. Portions where the geometry has the biggest evolution are located and compared to the portions where the dynamic response of the train has the highest amplitude.

# NUMERICAL PREDICTION OF TRACK SETTLEMENT IN RAILWAY TURNOUT

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**Key Words:** *Turnouts, train-track interactions, numerical simulation*

**ABSTRACT**

Turnouts (switches & crossings, S&C) are critical components of a railway track requiring regular maintenance and generating high life cycle costs. Main drivers for the high maintenance costs are the needs to repair and replace switch rails and crossings as these components are often not sufficiently stable in track geometry and rail profile over time. Dynamic wheel–rail contact forces with high magnitudes, and associated track geometry degradation, are often generated in the switch and crossing panels due to the discontinuities in rail profiles. One critical contribution to track geometry degradation is track settlement. It is a phenomenon where the horizontal level of the ballasted track substructure reduces in height over time when subjected to traffic loading. Due to the design of the turnout and the variation in track support conditions, the load transferred into the track bed is not uniform and the resulting differential settlement leads to track irregularities. Poor quality in track geometry induces higher dynamic wheel–rail contact forces and increases the degradation rate resulting in further track settlement, and possibly to increased wear, plastic deformation and rolling contact fatigue of the rails. Thus, it is important to understand how settlement evolves under repeated loading to support product development of S&C with a more uniform load distribution on the ballast that leads to a more stable track geometry.
An iterative procedure for the prediction of settlement in turnouts is presented. For a given traffic situation, wheel–rail contact forces are calculated using the commercial software GENSYS (module I). The space-dependent properties of the simplified moving track model that is applied in the vehicle dynamics software have been tuned using a finite element model of a turnout. The contact pressure distributions at the interfaces between sleepers and ballast are then determined by applying the calculated wheel–rail contact forces from step I on the rails of the finite element model (module II). For each vehicle passage, the contribution to the accumulated track settlement (module III) is dependent on the calculated distribution and magnitude of the sleeper–ballast contact pressure. The accumulated track settlement at each sleeper is accounted for when updating the loaded track geometry (module IV) that is used as input in the next iteration where a new set of wheel–rail contact forces is calculated, etc. The different steps of the iterative procedure are demonstrated in a numerical example.

# DISTINCT ELEMENT SIMULATIONS OF THE SLEEPER-BALLAST RESPONSE UNDER THE ACTION OF TRAFFIC

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**Key Words:** *Railway track; granular material; Voronoï tessellation; cyclic loadin; polygonal particles*

## ABSTRACT

A microscopic analysis of the ballast-sleeper interaction system is performed using Distinct Element simulations, both under monotonic and cyclic loadings, in order to analyze the mechanical response of the system. The 2D ballast-sleeper model is constructed from the generation of irregular polygons by Voronoï tessellation, leading to a grading of particles close to real ballast dimensions. A preliminary analysis with different boundary conditions and different material characteristics is conducted under monotonic loading for validation of the model; then cyclic loadings are developed. The ballast response is characterized in terms of particles displacements, contact forces, and sleeper settlements. Under monotonous loading, the results show that different loading force amplitudes produce different contact force chains, with contact force magnitudes not strictly proportional to the external loading force, due to the elasto-plastic model used for the contacts and to the rearrangement of the particles. The boundary conditions applied to the lateral walls of the system (fixed or stress controlled walls) have an influence on the system response and shows the advantage of ballast confinement. The influence of different geometrical and mechanical parameters under cyclic loading is analyzed both at the microscopic and macroscopic scales. The size and the angularity of particles influence both the sleeper settlements and the contact force network. Different mechanical characteristics of particle contacts (friction angle, elastic stiffness) produce different displacements and contact force patterns. More generally, the simulations show that the microscopic parameters of the particles have a large influence on the macroscopic response of the system.

# ANALYSIS OF BALLAST TRANSPORT IN THE EVENT OF OVERFLOWING OF THE DRAINAGE SYSTEM ON HIGH SPEED LINES (HSL)

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**Key Words:** *ballast transport, natural disaster, risk analysis, drainage overflowing, physical model, railway track structure*

## ABSTRACT

Ballast is an essential component of a railway track structure. The interactions it has with the environment must be well understood so as to characterize how ballast and track environment impact on each other. For high-speed lines (HSL), the impact is more important than for 'classic' lines due to the combination of high-speed with high-rates of usage. Therefore, the consequence of an incident involving HSLs would be significant.

The transport of ballast caused by the overflowing of the longitudinal drains is a prime example of the interactions between environment and the track. In such conditions, water as well as debris flow on the structure and may drag the ballast off the track foundation. This may create problems for the infrastructure and can create a significant risk for the rail traffic, so called "Sarry risk". As an example, a violent thunderstorm happened in the area near to the village of Sarry in September 2000, on the Paris-Lyon HSL. It led to an incident which could have had important consequences in terms of the safety of the rail traffic if the problem had not been noticed in time. SNCF, responsible for the maintenance of the infrastructure, outlined a wide range of initiatives to define and understand the "Sarry risk".

In order to manage this risk, research has been undertaken in collaboration with EPFL (Ecole Polytechnique Fédérale de Lausanne) to study the phenomenon of ballast transport on a physical model at a 1/3 scale. Three thresholds for ballast transport were studied: the initiation of transport, the linear transport and the intense ballast transport resulting in structural failure. Systematic tests have been conducted for ballast transport, both in normal (low longitudinal slope without obstacles) and in severe conditions (high longitudinal slope with obstacles, on a smooth concrete platform) in order to study different kinds of physical configurations. The presence of obstacles (e.g. catenary column, bridge pier, manhole) on the structure increases the risk of ballast removal.

This research aimed at identifying and quantifying the two criteria characterizing the removal of ballast and its transport: water level and flow velocity. These criteria are now used in the determination of the risk-level. This approach aims to reduce the vulnerability of railway infrastructure to the overflowing of the adjacent hydraulic structures. The results of this research have improved the understanding of the phenomenon of ballast transport and the accuracy of the calculations made to detect the sites where there exists a risk of drainage overflowing.

# EVOLUTION OF RAILWAY TRACK SETTLEMENT AFTER BALLAST TAMPING

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**Key Words:** *Railway track settlement; ballast; tamping; settlement speed*

## ABSTRACT

Ballast is an essential part of the railway track system. Among other important functions, it enables the correction of track geometry errors by means of tamping. From the geometry quality control point of view, ballast is the most important track component. Traditionally ballast material consists of coarse-grained and uniformly graded crushed rock aggregate made of high-quality rock material. In the extremely severe loading environment of ballast, the breakage and attrition of the grains are inevitable, which gradually leads to settlements of the track and deviations in track geometry. The degradation of the ballast of the Finnish railway network is largely due to traffic loading and tamping.

On newly built or recently tamped tracks, sleepers are expected to have nearly optimal contact on ballast bed and the track has smooth geometry. The smoothness requirements of modern railway track geometry are becoming even stricter along with increasing train speeds. Track geometry quality is monitored with special track inspection cars from 2 to 6 times per year in main lines of Finnish rail network. Due to cumulative traffic, which in Finland is usually mixed traffic with both high-speed passenger trains and heavy freight trains, track geometry slowly weakens over time which turns up as errors in track inspection. At certain stage tamping operation is required to correct errors and attempting to restore the initial track geometry. The period between two sequential tamping operations is called tamping cycle. Track settlement speed determines the length of tamping cycle and is highly dependent on ballast quality. Important factors of settlement are also other track structure properties and traffic volume of the track.

In a research project at the Laboratory of Earth and Foundation Structures of the Tampere University of Technology, in co-operation with Finnish Transport Agency, the settlement speed of railway track after tamping was studied by performing long-term in-situ measurements at test sites with varying properties. This paper reveals the results from the in-situ measurements and compares the results with the information, such as ballast grading and traffic volume, gathered at the test sites. Also seasonal changes in settlement speed and the state of sleeper support based on track stiffness measurements are evaluated site-by-site.

# TRANSITION ZONES: BACKFILL CONSTRUCTION, DYNAMIC TRACK CHARACTERIZATION AND IN SERVICE FIELD MEASUREMENTS

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**Key Words:** *railway transition zones, backfill design and construction, deformation modulus, non-destructive dynamic characterization, field measurements*

## ABSTRACT

Over the life-cycle of railway ballasted tracks, its initial geometric quality continuously changes and degrades, which induces variations in dynamic axle loads of trains inducing the degradation of ballast material and other track components. This well-known behaviour of the ballasted track requires frequent maintenance operations which reduces the availability of the line. Some studies report that this behaviour is more noticeable at the transition between track sections with different support conditions, such as transitions to bridges or other structures, because of the associated abrupt changes in the track vertical stiffness. To maintain similar levels of safety and service quality as open track, considerably more interventions are usually required at these locations. To address this problem, many railway infrastructure administrations have suggested different designs and recommendations for the construction of transition zones. However, some studies based on the maintenance records of existing high-speed lines indicate that no solution was yet found to mitigate track degradation at transition zones.

In this study, various aspects of transition zones to bridges and underpasses in a new Portuguese railway line are addressed. First, to characterize the track substructure, the design and construction of backfills ("technical blocks") are analysed, involving conventional laboratorial and cyclic load triaxial testing on granular materials and in situ mechanical characterization of supporting layers. Then, some results of dynamic track characterization at transitions using non-destructive tests are presented and analysed. Measurements of track response at different sections of transition zones, as trains passed by, are also presented and discussed. So far, the obtained results seem to indicate that the design of transitions in that line was successful in minimizing settlements and achieving a gradual stiffness increase as approaching a bridge.

In addition, the influence of using Under Sleeper Pads (USP) at an experimental transition zone to an underpass was also investigated and some results are presented. It was verified that USP influence the dynamic behaviour of the track, increasing its vertical flexibility and amplifying both rail displacements and sleeper accelerations.

# DEGRADATION AND CHARACTERIZATION ANALYSIS OF RAILWAY BALLAST GRAINS

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**Key Words:** *railway ballast; degradation; characterization; experimental tests.*

## ABSTRACT

The ballast layer is composed by cubic grains in the granular fractions between 22.0 and 63.0 mm and is one of the most important elements of the railway track related to the mechanical and hydraulic properties, and to the maintenance efficiency. The knowledge of the ballast physical characteristics is important for the long term track stability. Along the time, due to the traffic and maintenance procedures, the ballast material is subjected to degradation by means of wear and breakage phenomenon. In order to represent the ballast degradation, laboratory tests were performed. This paper presents results of ballast material degradation submitted to the Los Angeles Abrasion and full-scale railway infrastructure tests, aiming represent the process of grains degradation. In order to evaluate the degradation evolution through the roundness index, an image-based process was used. The objective was to evaluate the degradation evolution in terms of grains wear and breakage along the imposed efforts. Furthermore, a hundred ballast grains were scanned and characterization data are also presented. From the characterization study, the geometric indexes obtained provided values for the different grains shapes tested. The degradation study showed the granulometric deviations in the ballast material granular fractions, different degradation trends related to the breakage process and a fair representation of the wear degradation through the image-based method related to the roundness values. The process of the ballast degradation is also discussed focusing on the material granular fractions.

# BALLAST CHARACTERIZATION ON FRENCH RAILWAY NETWORK

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**Key Words:** *Ballast characterization, ballast specification, life cycle, gradation*

## ABSTRACT

Ballast characterization on French Railway Network. The technical conditions before 1985 were basic. For the construction of the first high-speed line between Paris and Lyon in 1979, the closest quarries were chosen. But the fast degradation of the track geometry revealed that ballast quality criteria were insufficient. After 3 years of R&D, SNCF has published new technical specifications. This presentation sums up the development of the technical conditions in France and compares the ballast life cycle according to the hardness. In a second part, the life cycle of the ballast railway will be estimated in connection with its gradation.

# EXPERIMENTAL CHARACTERISATION OF THE DYNAMIC BEHAVIOUR OF BALLAST

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**Key Words:** *Railway track; ballast; experimental tests; dynamic behaviour; ballast stiffness*

## ABSTRACT

The understanding of the dynamic behaviour of ballasted track requires improved knowledge of the dynamic characteristics of the ballast layer. Better understanding of the behaviour of this layer will lead to improved prediction of low frequency noise and ground vibration. There will also be benefits for more resilient track design and effective maintenance. Laboratory observations of controlled ballast samples offer an opportunity to greatly improve knowledge and modelling of ballast dynamics. A lab-based experimental method to measure the dynamic stiffness and damping of ballast is presented. Measurements have been carried out covering frequencies between 30 and 700Hz and a wide range of preloads. The effects of the geometry of the ballast layer, ballast gradation and under sleeper pads (USPs) are considered. Results are presented to illustrate the frequency dependence of ballast stiffness and the effects of preload, ballast depth, gradation and USPs. The implications of the test results for the dynamic behaviour of track are outlined.

# DEM MODELLING SERVING SCIENCE AND ENGINEERING AT SNCF

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**Key Words:** *Railway Ballast; DEM; computational methods*

## ABSTRACT

The maintenance cost of ballasted railway track remains of major interest for infrastructure manager. One of the origins of this cost is the geometrical degradation of the track structure which is commonly named as track defects. These defects mainly come from the non homogenous behaviour of track components which remains difficult to handle both from the engineering and fundamental point of view.

The ballast granular layer is an essential component of the system which allows restoring the track levelling by means of industrial processes, like tamping and dynamic stabilization. The macroscopic behaviour of this coarse granular media is governed by interaction between the grains, i.e. by the micromechanics. The research works from the last decade have shown that the granular science specificity needs to link between mechanic, physic and statistic to get a better understanding of granular media. The adaptation of this fundamental knowledge to the railway track is an ongoing work at SNCF.

This paper deals with the capacity of DEM to provide some solutions to increase the knowledge of ballast behaviour in order to give prescription to the track manager or simplified model for engineering application. The numerical method currently used by SNCF Innovation and Research Department is the Contact Dynamic approach which allows simulating a large collection of irregular polyhedral particles. The CD method is based on implicit time integration of the equations of motion and a non-smooth formulation of mutual exclusion and dry friction between particles. This method requires no elastic repulsive potential and no smoothing of the Coulomb friction law for the determination of forces. For this reason, the simulations can be performed with large time steps compared to molecular-dynamics simulations.

In the proposed communication, we present numerical simulations of railway ballast under maintenance process, lateral resistance, or triaxial tests. These simulations have been performed at different scale in order to identify the micro-mechanical parameters which play an important role on the ballast behaviour or to exhibit some recommendation at the track scale. The study of the mechanical behaviour of the ballast during tamping has been done at different scale in order to show the influence of the main parameters (frequency, speed) on the compaction and to evaluate the homogeneity of compaction process at the track scale. We show that a modulation on frequency can increase the final solid fraction at the end of the process and the influence of speed penetration of tamping tines on ballast stone breakage. These conclusions have been validated with a full scale track model by means of high performance computing using parallel numerical computation. Another important topic strongly linked to the safety of commercial running of trains is the lateral resistance of track. The numerical simulations are a relevant tool to analyse the block shape influence of ballast behaviour and identify the role of ballast blanket shape or thickness of ballast layer.

DEM and Contact Dynamic approach offer numerous perspectives like multiphysic simulations with deformable bodies in order to investigate the behaviour of interface of ballast and sub-ballast layer or characterize the influence of shape with highly discretized grains shape which is strongly related to the topics of ballast wearing.

# ON THE USE OF AN HIGH PERFORMANCE HYBRID FEM/DEM MODELLING APPROACH FOR AN IMPROVED SIMULATION OF RAILWAY TRACK

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**Key Words:** *Discrete Element Method; Finite Element Method; hybrid model; Non-Smooth Contact Dynamics; 3D railway track modelling; Soil Structure Interaction; LMGC90*

## ABSTRACT

Discrete Element Methods (DEM) seem particularly well relevant to study ballast as a coarse granular material. Numerous studies using this modelling approach have been performed over the last decade to improve the understanding of the physical behaviour of this particular granular material and to optimize common restoration procedures like tamping process. Discrete element models classically used in such studies take into account the polyhedral shape of the grains. Even if such models make possible to perform rather realistic simulations of the ballast – despite the choice of a poor bulk behaviour to model grains (rigid bodies) and the application of poor boundary conditions (rigid foundations) –, the influence of the resulting lack of deformability of the system on its global behaviour has to be studied. The originality of the work concerns the modelling approach based on the coupling between the standard Discrete Elements Method and the Finite Elements Method where the long term purpose is to develop an accurate FEM/DEM railway track model making possible to provide more realistic responses of the system and better understand physic phenomena involved by studying the ballast behaviour itself – both under dynamic and cyclic loading actions – or its interactions with the other track components. The field of our study will be focused on the influence of soil conditions or on the role of Under Sleeper Pad (USP) on the ballast behaviour for different load conditions. First results are briefly given in this paper on those topics while the main part is dedicated to the strategy developed to succeed in performing accurate and efficient hybrid FEM/DEM simulations from which depends the feasibility of this type of modelling approach. It takes place in the particular framework of the Non-Smooth Contact Dynamics (NSCD) method proposed by Moreau and Jean. One of the critical aspects we have to deal with when using DEM is the computation time which is strongly related to the number of bodies in the collection, the complexity of the bulk behaviours involved or coupling effects on contact problem in presence of large scale bodies. Simulations of railway track – even using poor grains modelling strategy – are from this point of view very expensive. Here is presented a complete numerical strategy based on the use of a more realistic FEM/DEM model designed to minimize as much as possible computational costs. Thanks to an adapted contact approach developed in the software LMGC90, soil is modelled as a poor meshed finite element object with a linear behaviour (elasticity) able to represent dynamic behaviour while grains are modelled as rigid bodies. Non linearity due to permanent plastic deformation of soil at contact locus is introduced thanks to a contact law miming the plastic behaviour and allows to control the local penetrations of the grains in the ground (stamping). The whole strategy and the description of the contact law are presented in this paper as well as first comparative results of the simulation of a representative portion of railway track under quasi-static vertical load. Further studies will be dedicated to the whole understanding of the substructure action and track structure changes on the ballast dynamic response.
All the simulations are performed thanks to the open-source LMGC90 software.

# ANALYSIS OF TRACK-TRAIN INTERACTION IN TRANSITION ZONE WITH VARIED VERTICAL STIFFNESS USING 3D FINITE ELEMENT MODEL

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**Key Words:** *Railway track; ballast; track transition zone; Video Gauge System tests; finite element methods*

## ABSTRACT

Transition zones in railway tracks are locations with discontinuity in the vertical support, such as at bridges, culverts and tunnels. In such a transition zone, the vertical support structure is varying, which cause the discontinuity of stiffness and irregularity of track, the different settlement peace and the different styles of wave propagation. These changes will first cause geometry difference in the transition zone and cause further increase of the dynamic forces. This can result in rail damage, especially in the rail foot. As a result, a special transition track system should be set to reduce the discontinuity of track to make the stiffness changes gradually between two track systems. By doing that the vibration of train and track could be reduced and the passengers could be safe.
To solve the problem of railway transition zone, the dynamic effect of the transition should be analysed, including the displacement, acceleration and stress distribution of each part of transitions. Therefore, a 3D finite element model is developed. In the model, the transition is constituted by one section of ballast track and one section of slab track which is stiffer in the vertical direction. The ballast track consists of the rails, sleepers, ballast and soil, while the slab track consists of rails, concrete slab, mortar layer, support concrete and soil. The model uses 3D solid elements with an exception of fasteners and rails which were modelled by spring and beam elements respectively. The vehicle is composed by 1 body, 2 bogies and 4wheels connected by suspensions simulated by spring elements. To get better understanding of the interaction between vehicle and track system, simulations have been performed when the vehicle is travelling in both directions namely and from ballast track to slab track and from the slab track to the ballast track.
To verify the model, a series of measurements were performed in a transition area in the Netherlands. The measurement system is Video Gauge System, which could measure real-time displacements of track components by using targets tracing by video cameras.
Using this model the transition zone phenomena have been studied by analysing of the rail/sleeper displacements and the stress distribution in ballast due to moving vehicle.
The results of the analysis are presented and discussed.

# MODELLING CRITICAL VELOCITIES FOR HIGH SPEED TRAINS

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**Key Words:** *Railway track; ballast; high speed; numerical methods; critical speeds; resonant velocities; Rayleigh waves*

**ABSTRACT**

It is know that as trains pass over soft soils a point can be reached whereby the train speed will exceed the Rayleigh ground wave velocity, so called *critical velocity* issues. If track structures are present, such as stiffened embankments, this critical velocity may increase due to interaction between the Rayleigh wave velocity in the track structure and the one in the subgrade leading to dispersive behaviour. It is also known that there is more than one critical velocity and indeed there may be many depending on the track and train system. Approaching the Rayleigh wave velocity will lead to the development of a Ground Mach cone increasing the transient track deflection when compared to the static case. A resonant condition may also develop leading to very high transient track displacements, including track uplift. In the past these sites were few in number as the train speeds were relatively low, however as train speeds continue to increase Rayleigh wave problems and resonant track conditions will become more of an issue. In order to develop the most cost effective solution strategy it is necessary to understand the development of the dynamic interaction and hence determine the most cost effective mitigation strategy. The development of critical velocities is studied in the current work using a 3-dimensional finite element program in which the train and track are coupled. The development of both the Ground Mach cone and the Resonant Train-track Velocity with train speed through both transient sleeper deflection and displacement contour plots of the overall surface behaviour is presented.

# DEM SIMULATION OF RAILWAY BALLAST OEDOMETRIC TEST

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**Key Words**: ballast; oedometric test; discrete element method; polyhedral particles

## ABSTRACT

Railway ballast is used worldwide in the structure of permanent way to transfers load from sleepers to subsoil. Understanding of the ballast behaviour is therefore important for safe design and maintenance of the railway tracks. Many experiments were performed to obtain its mechanical parameters and there are also several attempts to simulate the measured behaviour by some computer models.

This contribution presents simulation of the large oedometric test of railway ballast in which the ballast is poured into cylindrical container and compressed. Measured data were taken from dissertation of W. L. Lim. Simulations are performed using the discrete element method (DEM). In most of the applications of DEM, particles of spherical shape are employed because of the simplicity and computer time savings. However, it has been showed that shape of elements is of importance. For that reason, the ballast simulation use (convex) polyhedral particle shapes that seem to be closer to real ballast grain shapes.

The polyhedrons are generated pseudo-randomly as Voronoi cells created on randomly placed nuclei; repulsive normal force between two polyhedral particles in contact is linearly dependent on the intersecting volume. Normal direction is obtained through least-square fitting of an intersection of polyhedral shells by a plane. Shear strains are calculated by standard incremental algorithm, shear force is then estimated using Coulomb friction model. Important aspect of ballast behaviour is its crushing. This phenomenon is incorporated into the model through splitting polyhedral grains into two separate parts when some phenomenological stress criteria is fulfilled.

The influence of involving polyhedral particles and ballast crushing into the simulation, which can help to represent ballast behaviour including nonlinear rheological properties, is commented in the paper conclusions.

**Acknowledgement:** The financial support received from the Czech Science Foundation under Project No. P105/11/P055 and from Czech Ministry of Education, Youth and Sports under Project „IRICoN“ No. CZ.1.07./2.3.00/20.0176 is gratefully acknowledged.

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