William W. Hay Railroad Engineering Seminar

Ballast Flying and Projection Phenomena: Issues and Challenges
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BALLAST FLYING AND PROJECTION PHENOMENA: ISSUES AND CHALLENGES.

Dr. Gilles SAUSSINE
For trains operated on ballasted track at speed higher than or equal to 250 km/h, ballast pick-up caused by the aerodynamic effect of the train on the track bed may be observed, and may present a risk in the vicinity of the track.

The track bed construction is not subject to any specification in the TSI INF, because there is no direct interface with vehicles; it is designed according to codes of practice of the infrastructure managers, and Annex C of the TSI INF defines the design characteristics of the track, including ‘ballasted’ or ‘non ballasted’.

Considering potential risks and the current state of the art, it recommended to cover this subject qualitatively by the following procedure: during dynamic tests up to the maximum design speed of the train, and provided that these tests are performed on a ballasted track, ballast pick-up caused by the aerodynamic effect of the train on the track bed may be observed by the applicant.

In case similar trains are already in use with the same operating conditions (train composition, maximum speed, ballasted track) without ballast pick-up observed, the entity providing the track for tests should demonstrate that the aerodynamic effect of trains at the maximum speed of the line has been taken into account in the design and maintenance of the track.

Ballast pick up remains a subject which need rolling stock and infrastructure interaction.
CONTEXT

SOME CONSEQUENCES

- Ballast flying phenomenon: aerodynamic effect induce grains motions
- Ballast projection phenomenon: due to impact on ballast bed

These phenomena need the understanding of interaction mechanisms between aerodynamic and ballast grains. But a framework is needed for risk assessment in order to limit impact on track and rolling stock maintenance.
Experiment and simulation are relevant for evaluate some mechanisms: but the variability remains the main difficulty.
THE PROBLEMS

ASSESSMENT OF THE BALLAST FLYING PHENOMENON:

- Define a relevant parameter linked to ballast flying and rolling stock properties.

- Propose a method for risk assessment which can be shared and easy to use.

REGULATE HIGH SPEED CIRCULATION DURING WINTER TO PREVENT BALLAST PROJECTION:

- Propose a method able to define the running speed which minimize rolling stock damage.

- Be able to anticipate the speed regulation by using weather forecast.
OUTLINE

ASSESSMENT OF THE BALLAST FLYING PHENOMENON:
- Example
- Aerodynamic load on track
- Ballast flying risk modeling
- Ballast risk assessment methods

REGULATE HIGH SPEED CIRCULATION DURING WINTER TO PREVENT BALLAST PROJECTION:
- Snow forecast.
- Ballast projection modeling
- The results for winter 2012/2013
Ballast flying: a sporadic phenomenon linked to rolling stock and track properties.
BALLAST FLYING

BIBLIOGRAPHY:

Wind speed measurements (2006 – Kwon – Park)

Wind Tunnel SUMKA (DB – AOA Project) test for particle dislomgement


FULL-SCALE AERODYNAMIC MEASUREMENTS UNDERNEATH A HIGH SPEED TRAIN Andrew Quinn* and Mick Hayward*, BBAA VI International Colloquium on: Bluff Bodies Aerodynamics & Applications Milano, Italy, July, 20-24 2008
From the CSTB test with a model wind gust it is possible to characterise some ballast grain motion, but it remains difficult to have a statistic: evaluate the aerodynamic load of rolling stock and propose a model able to describe ballast grains motion are to main issues to propose. The worst configuration is ballast grains on sleepers.
BALLAST FLYING

AERODYNAMIC LOAD ON TRACK:

The measurements highlight the increase of average air speed and the existence of high level out of the rail: the aerodynamic load on track has to take into account the complete flow field.

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BALLAST FLYING

NUMERICAL MODELING:

Prediction of ballast motion under aerodynamic load

**Molecular Dynamics** (Allen, Tildesley)

**Distinct Element Method** (Cundall)

**G.E.M.** (Kishino)

**Non Smooth Contact Dynamics** (Moreau et Jean)

**Principle:** time stepping approach

- External efforts applied on collection of bodies
- Contact detection
- Interaction problem solved
- Bodies position is calculated

The approach proposed is to introduce aerodynamics efforts as external effort for each bodies which has a shape digitised from real ballast grains.
Considering a moving mesh which contains the velocity of the aerodynamic field,

- For each face of considered grains, the effort is calculated by considering the corresponding velocity vectors, the face area and his orientation,
- The aerodynamic load is considered as an external load for the resolution of the mechanical problem: for each time step, the mesh move, and the contribution of external load is computed for each grains.
From the measurements and experimental test at the scale 1 in the CSTB wind tunnel during the A.O.A project :

- Similar numerical model has been created and we introduce the wind gust imposed in the wind tunnel with the same velocity profile,

- Similar behaviour has been observed: increase of air speed induce more ejections, after 3 or 4 gust on the same configuration there is no ejection,

- The numerical model has not the same grains positions, but number of ejected grains can be correlated to experiment.
A statistical analysis of grain motion under aerodynamic load has been performed: for most of the case ballast pick has been notice after rebond phenomenon.
SUMMARY FOR BALLAST FLYING RISK ASSESSMENT

**MEASUREMENTS**: rolling stock performance and track properties can be qualified from air flow profile.

**NUMERICAL MODEL**: the main tool to evaluate track capacity to limit ballast flying.

**RELEVANT PARAMETER**: A quantity which describe the flying ballast phenomenon with some limitation.

**RISK ASSESSMENT**: a method with a scientific background, already published in order to share with partners.
BALLAST FLYING

BALLAST FLYING RISK ASSESSMENT: A METHOD

The general idea is to give a level of risk for a track configuration, different type of trains and range of speed

The different type of train (UM/US, ICE3, TGV..) impose a load on track which can be characterized by air speeds

This stress can be evaluate by mean of in situ measurements and a relevant indicator

The track configuration and properties lead to ballast flying or caught ballast grains.

A numerical model or experimental setup coupled with aerodynamic field allow to evaluate the capacity of the track to limit ballast flying: we obtain the strength.

Stress

PDF of the indicator for a type of train

Stress Strength Interference Analysis

PDF of the % of ejected grains for a general load

Strength
BALLAST FLYING

BALLAST FLYING RISK ASSESSMENT: A METHOD

\[ R \in N(\mu_R, \sigma_R) \quad C \in N(\mu_C, \sigma_C) \]

These functions are defined by the following formula:

\[ f_n(x, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(x-\mu)^2}{2\sigma^2} \right) \]

We define the failure probability:

\[ P_d = P(R < C) = P(R - C < 0) = \int_0^{\infty} f_n(x) F_R(x) \, dx \]

If we define: \( Z = R - C \). Then \( Z \in N(\mu_z, \sigma_z) \) and \( Z = \mu_z + U \sigma_z \) with \( U \in N(0,1) \)

and \( \mu_z = \mu_R - \mu_C \quad \sigma_z = \sqrt{\sigma_R^2 + \sigma_C^2} \)

Consequently:

\[ P_d = P(Z < 0) = P(\mu_z + U\sigma_z < 0) = P \left( U < \frac{\mu_z + \mu - R}{\sqrt{\sigma_R^2 + \sigma_C^2}} \right) \]

The analytic solution of these equations is:

\[ P_d = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\frac{\mu_z}{\sigma_z}} \exp \left( -\frac{x^2}{2} \right) \, dx \]

The result is the occurrence probability of the stress strength scenario we have defined.
The total signal power of air speed measurements has been identified as relevant parameter by correlation analysis with ballast grains displacement ($R^2=0.82$). For 1600 measurements we performed numerical simulation with DEM modeling which allows to characterize ballast grains motions. A polynomial relationship has been found between percentage of displaced grains and ejected grains.
The PDF of Signal Power corresponding to a number of ejected grains.

We define the PDF of the strength of the track by considering that each couple (Power of signal, % of grains) follow a similar linear relation law with same slope.

\[ f(\text{Signal Power}) = A \times (\% \text{ displaced grains}) + B \]
BALLAST FLYING

BALLAST FLYING RISK ASSESSMENT : STRENGTH OF TRACK

An example for a given train at 300 km/h characterize with 53 measurements :

The stress apply by the train on the track : pdf of signal power for a speed range.

The interference between the 2 pdf gives the probability that the given train impose that X % of grains moved more than 10cm.
The consequences of ballast flying acceptable: number of impact on train, rail and the corresponding maintenance cost to limit ballast flying?

The proposed approach allow to take into account a part of mecanism of ballast flying phenomenon and take into account the stochastic aspect. A continous improvement of relevant parameter can be done.
BALLAST FLYING RISK ASSESSMENT: DENSITY OF GRAINS ON SLEEPERS

From an in situ study made by Engineering Department. Number of grains on sleepers has been recorded on different HSL: the density of grains follow an exponential law.
BALLAST FLYING RISK ASSESSMENT: THE GLOBAL FRAMEWORK

**Datas**
- Number of tolerated ejected grains: N.
- Mean and standard deviation of relevant parameter of load track for a rolling stock and range of speed.

**Strength of Track**
- From polynomial relationship: percentage of displaced grains is calculated
- From the linear relationship between Signal Power and displaced grains, the average and standard deviation of Strength is calculated

**Track Properties**
- From statistical exponential law, a probability of grains on sleeper is evaluated (P1)

**Risk Evaluation**
- From explicit formula from SSIA approach, a probability to obtain more than N ejected grains is calculated (P2)
- The risk level is the results of product of P1 and P2
BALLAST FLYING

BALLAST FLYING RISK ASSESSMENT: EXAMPLE.

Train A: 318 km/h + 2.7 km/h
Mean air speed at 7.5 cm: 29 m/s

Train C: 319 km/h + 2.4 km/h
Mean air speed at 7.5 cm: 28 m/s

Train B: 318 km/h + 3.1 km/h
Mean air speed at 7.5 cm: 34 m/s

If the mean air speed train is considered and the reference train is train B (the badest train), there is no difference in terms of ballast risk.
For different level of strength of track which is linked to number of ejected grains, it is easy for operationnal point of view to computed the risk evolution for differen rolling stock. From the network owner it is a simple way to share some rules with operators.
For a fixed risk level and a reference track corresponding to a maintenance level it is possible to evaluate for different rolling stock the speed limit which can be accepted to limit ballast flying.
The ballast flying phenomenon remains difficult to handle but some results have been found about mechanisms, or worst configuration with grains on sleepers from experimental setup.

The core problem is to find a relevant quantity which represent the main mechanism easy to handle, easy to measure and do not required a lot of running test which are expensive: the signal power is one indicator which take into account all mechanisms with some approximation.

Flying risk assessment must take into account variability of aerodynamic properties of rolling stock and track properties: the phenomenon is sporadic. We proposed and evaluate all rolling stock on French network with SSIA approach. This method is easy to share and allows discussions between train manufacturer and infrastructure manager.

The global framework proposed is the approach to be independent with a scientific background.
Snow accretion and ice falling induce track and train damage.
BALLAST PROJECTION

- Speed & number of ejected grains
  ![Graph A]

- Speed ejection
  ![Graph B]

- Ejection angle for ballast grains
  ![Graph C]

- Direction of ballast ejected grains
  ![Graph D]


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With operation condition the only way to limit train and track damage is to communicate with train board and impose limitation of operating speed.

Anticipate decision for traffic regulation:
- decrease the consequences of ballast projection
- define adapted traffic plan
- evaluate the time lost for customers
SNOW:

- The metamorphosis of dry and wet snow is the most important transformation in the accumulation phenomenon.
- This phenomenon causes a bonding or sintering of the crystals by a crystal growth caused by the presence of interstitial water following a drop in temperature.
- The metamorphosis of wet snow is probably the phenomenon that increases aggression.

Source: Meysonnier & Al (2012)
DATAS AVAILABLE WITH A 3 DAY FORECAST:

- Mean and standard deviation of temperature with 3h period,
- Rainfall or snowfall,
- The different precipitation type,
- The thickness of snow layer every day

For a high speed line different zone are linked with a meteorological station.

Source: Météo France – Christelle Robert (2012)
Some meteorological study on LGV Est produce by Meteo France:

Alert parameters:
- Mean temperature around 2° C,
- 30 mm precipitation of snow

Map on LGV Est of snowfall intensity for one day during winter 2010.

Detection rate for event with ballast projection in green. This study has been performed to find the relevant threshold about thickness snow parameter.
BALLAST PROJECTION

MODELING OF BALLAST PROJECTION

Discrete Element Approach: time stepping approach

External efforts applied on collection of bodies

Contact detection

Interaction problem solved

Bodies position is calculated

The contact dynamic approach is suitable to simulate very dynamic process without new calibration of numerical parameters (restitution coefficient or friction).
From numerical simulation parametric study ballast projection phenomenon has been characterized in terms of statistic laws of ejection of ballast grains.
The kinetic energy of ice bloc is linked to number of ballast grains ejected with a linear relation.

Ejection angle follow a similar distribution law has RTRI results, in this case a truncated law is observed.
A gaussian law of distribution of direction angle has been identified.

From these laws is possible to setup a simplified model of ballast projection in order to quantify risk of window breaking on crossing train.
BALLAST PROJECTION

TRAJECTOGRAPHY MODELING

CONDITION:
- Temperature
- Ice density
- Ice block volume
- Speed of circulation

BALLAST TRAJECTOGRAPHY:
- From kinetic energy of ice block at impact, a number of grains is obtained.
- From each statistical law, initial motion condition are introduced for each grain.
- Integration of motion of material point taking into account air flow profile.
- The grains which rich a level of kinetic energy and a specified location are considered are critical.

Risk evaluation:
- number of ballast grains

Monte Carlo simulation : N block ice falling are simulated
For each set of conditions and reference speed 40000 Monte Carlo Simulation are performed.
## BALLAST PROJECTION

### A TOOL FOR NATIONAL CENTER OF OPERATION

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**Legend:** ✓: Acceptable ✓: Tolerable X: Inacceptable

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BALLAST PROJECTION

WINTER 2012/2013: PERFORMANCE OF PROPOSED APPROACH.

REMAINING TIME BEFORE FIRST RUNNING OF TRAINS

- Proposed speed = real operating speed
- Proposed speed different of real operating speed
- Proposed speed but no limitation has been done

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Limitation of lost time with the optimization of reduction speed as a function of zone is possible:

**Proposed speed = real operating speed**

**Proposed speed different of real operating speed**

**Proposed speed but no limitation has been done**

**REMAINING TIME BEFORE FIRST RUNNING OF TRAINS**

- **10 H**
  - 12% Proposed speed = real operating speed
  - 10% Proposed speed different of real operating speed
  - 78% Proposed speed but no limitation has been done

- **3 H**
  - 10% Proposed speed = real operating speed
  - 10% Proposed speed different of real operating speed
  - 83% Proposed speed but no limitation has been done

- **0 H**
  - 8% Proposed speed = real operating speed
  - 7% Proposed speed different of real operating speed
  - 85% Proposed speed but no limitation has been done

**Gain de Minutes**

- J - 72h
- J - 48h
- J - 24h
- J - 10h

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Experience is positive: with a three day forecast it is possible to proposed some speed regulation to reduce train and track damage.

The whole set of parameters have been identified from bibliography, the snow accretion process at high speed remains difficult to handle.

From the combination of weather forecast and mechanical simulation and safety approach it is possible to propose an approach which allow to decide on objective parameters.

From an economic point of view it is possible to save 1 M€/years of maintenance and rolling stock availability.
Discrete Element Modeling combine with Experiment and Operational Objective is a relevant approach to proposition some solution for complex problem which deals with mechanics, physic. The

The ballast flying phenomenon can be assess by parameter which take into account track and rolling stock properties. The main important results is to share a methods for risk assessment and share all findings about mecanisms in order to increase the knowledge on relevant parameter. Continous improvement of our technics and finding is a key.

The ballast projection phenomenon has been the core problem of last winter on high speed line: a solution has been proposed in order to limit the effect with good results. But snow accreation remains a complex problem t

Next step :

- Improve the comparison with numerical modeling and ballas motiont on track under aerodynamic load,
- Industrialization of tools tor regulate rolling stock speed in winter,
- Share and practice : the more we share the more we progress !