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DYNAMIC BEHAVIOUR OF RAILWAY BALLAST EXPOSED TO FLOODING CONDITIONS

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ABSTRACT: Railway ballast is one of the main components in ballasted railway track systems. It is installed under the railway sleeper to absorb dynamic wheel/rail interaction forces, preventing the underlying railway track subgrade from excessive stresses, enabling the interlocking of skeleton track onto the ground and providing lateral track stability. Generally, the dynamic modelling of ballast gravels relies on the available data, which are mostly focused on the condition at a dry condition. Recent findings show that railway track could significantly experience extreme climate such as long-term flooding. This phenomenon gives rise to a concern that the ballast may experience higher level of moisture content than anticipated in the past. On this ground, a test rig for estimating the dynamic properties of rail ballast has been devised at the University of Birmingham. A non-destructive methodology for evaluating and monitoring the dynamic properties of the rail ballast has been developed based on an instrumented hammer impact technique and an equivalent single degree-of-freedom system approximation. This investigation focuses on the dynamic single-degree-of-freedom (SDOF) model of rail ballast submerged under the flood where the dependent effects of frequency can be distinguished. Based on the impact-excitation responses, the analytical state-dependent model was applied to best fit the experimental modal measurements that were performed in a frequency range of 0-500 Hz. The curve fitting gives such dynamic parameters as the modal mass, dynamic stiffness and dynamic damping constant, all of which are required for modern numerical modelling of a railway track.

Keywords: Dynamic properties, railway ballast, flood condition, climate change

1. INTRODUCTION

Railway ballast or granular media is a major track component used in ballasted railway tracks worldwide. It is mostly derived from crushed rock-based local materials from various sources such as crushed igneous rocks (granite, rhyolite, decite, basalt, quartzite or latite), crushed metamorphic rocks, crushed sedimentary rocks, crushed gravel (from river, lake), or sometimes even from waste products (such as crushed slag, chitter) [1-4]. Early railways did not place ballast as being highly significant to the makeup of a successful design of the permanent way. This position gradually changed and the performance of the ballast material is now highly regarded in the design process. Ballast is required to fulfil the task of maintaining the track in good alignment both horizontally and vertically. To provide this it must have the following characteristics:

- Durable to be able to absorb the loads imposed by the sleepers and transmit the loads to the sub-grade without undue breakdown.
- Hard wearing with high abrasion resistance in both wet and dry conditions.
- Angular with sufficient bulk density to resist movement of the track both longitudinally and laterally.
- Particle size to allow packing and transfer of the loads of the track but with sufficient void space to allow free draining to assist shedding of all moisture.

The functions or roles expected of the ballast layer have changed with time and the evolutional development of railway technology. There is some discussion of the functions of ballast in the references, “Railroad Engineering” (Ch 21) by WW Hay, “British Rail Track” (Ch 2), by the Permanent Way Institution, “A Review of Track Design Procedures” (Vol 2, Ch 4) by Jeffs and Tew, and “Track Geotechnology and Substructure Management”, by Selig and Waters [1]. The functions of ballast can be divided into two criteria:

- Primary Functions, - the original purpose of ballast; and,
- Secondary Functions, - the characteristics of the material that enable the ballast to fulfil and continue to fulfil its primary function and those functions that have

been added with technology improvements and community expectations.

The primary functions of the ballast are to provide a uniform elastic vertical support; to fix the track in position laterally and longitudinally; and to facilitate the correction of the track level and line enhancing constructability and maintainability of railway network [2-4].

Fig. 1 Ballast and capping layer [2].

The secondary functions of ballast are to allow surface water to drain rapidly; to inhibit the growth of vegetation; to compensate for the presence of fouling material, to reduce noise; to provide electrical insulation of one rail from the other; and, to moderate the effect of frost heave in cold climates and the movement due to climate uncertainties [5-8]. Railway ballast is installed under railway sleepers to transfer the quasi-static stress (already filtered by rail pads and sleepers) from axle loads and wheel loads from both regular and irregular train movements, as shown in Fig. 2. In accordance with the design and analysis, numerical models of a railway track have been employed to aid the track engineers in failure and maintenance predictions [9-12].

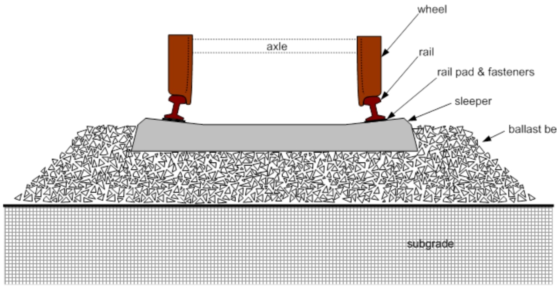


Fig. 2 Typical track structure [9].

The current numerical models or simulations of railway tracks mostly consider the track components in perfect situation or in a normal weather condition. The effect of flooding on the dynamic behaviour of railway ballast has never been investigated, although it is evident that climate uncertainty has a significant influence on railway networks that affect the serviceability and performance of railway tracks [13-20]. The primary reason is due to a lack of information, either about the dynamic characteristics of railway ballast under variable flooding conditions, or about the dynamic train-track modelling to capture the flooding conditions. This paper is the world first to present dynamic behavior of railway ballast in flooding conditions. It also discusses the experimental results obtained as part of the railway engineering research activities at the University of Birmingham (UoB) aimed at improving the dynamic performance and modelling of railway tracks globally. The proposed relationships could be incorporated into track analysis and design tools for a more realistic representation of the dynamic train-track interaction and load transfer mechanisms.

2. ANALYTICAL MODELLING

Majority of train-track dynamic simulations adopt a multi-degree-of-freedom system (MDOF) approach for modelling train and track components. MDOF system or so-called ‘multi-body simulation’ idealises the structural and mechanical components into nodes of freedom and string elements (spring and dashpot). This structural idealisation concept is very common in practice and academia in order to reduce computation time and resources. Fig. 3 illustrates the train-track simulation and track idealisation for the numerical simulation [21].

The dynamics of resilient track have been studied mostly based on a two-degree-of freedom (2DOF) model. In this paper, a SDOF-based method has been developed to help track engineers to evaluate the realistic dynamic behavior of railway ballast required for the design using the numerical simulation. An analytical solution has been used to best fit the vibration responses. Considering the SDOF system in Fig. 3, the dynamic behavior of ballast in the vertical direction can be described by the well-known equation of motion:

$$m\ddot{x} + c_p\dot{x} + k_p x = f(t) \qquad (1)$$

$$\omega_n^2 = {k_p}/{m_p} \quad \text{, or} \quad 2\zeta\omega_n = {c_p}/{m_p}$$

$$\zeta = {c_p}/{2\sqrt{k_p m_p}} \qquad (2a, b, c)$$

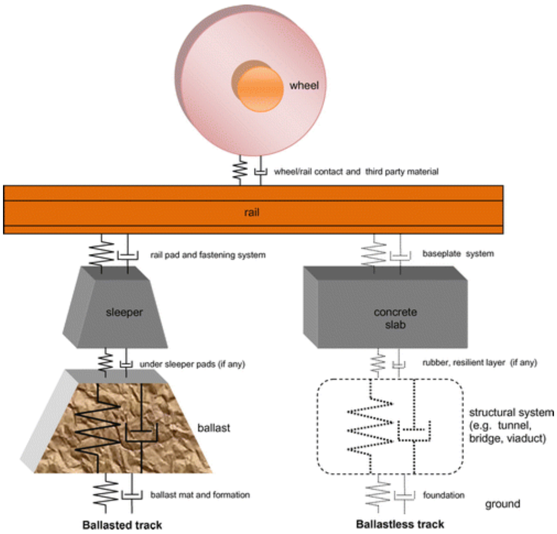
where m_p, c_p, and k_p generally represent the effective sleeper mass, damping and stiffness of ballast, respectively. By taking the Fourier transformation of (1), the frequency response function can be determined. The magnitude of the frequency response function $H(f)$ can be represented as follows:

$$H(f) = \frac{1}{m_p} \frac{4\pi^2 \beta f^2}{\sqrt{\left[1 - 4\pi^2 \beta f^2\right]^2 + \left[4\pi^2 \beta \left(\frac{c_p^2}{k_p m_p}\right) f^2\right]}} \tag{3}$$

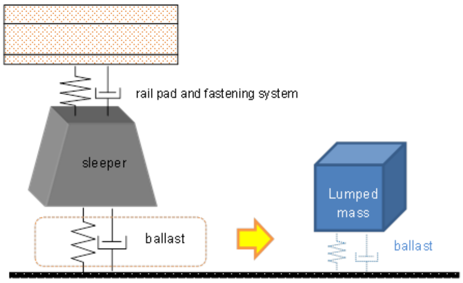
where,

$$\beta = \frac{m_p}{k_p} \tag{4}$$

This expression contains the system parameters m_p, k_p and c_p that will later be used as the curve-fitting parameters.



a) Train-track simulation



b) Ballast idealisation

Fig. 3 MDOF train-track idealisation [21]

Considering Eq. (2), the fundamental frequency of railway ballast is relatively low if the track mass is significant. This implies that significant energy is required to excite the vibration of the SDOF system. By lowering the effective mass over a representative area of ballast (similar to a falling weight method with relatively small diameter of proctor, e.g. 50mm), the fundamental frequency of the SDOF system can be lifted to a higher range and it will require relatively lower energy to excite the system in order to obtain a realistic vibration response. In this study, a block of concrete (150mm x 150mm x 150mm) is used to represent the effective mass in the system. This enables the effective use of a modal hammer to excite the system [22-26].

3. EXPERIMENTAL SETUP

Fig. 4 demonstrates the experimental setup in this study. Pilot studies (over 200 data sets) using a modal hammer (PROSIG) were carried out to evaluate the accuracy and precision of the vibration responses. The modal vibrations show excellent agreement between each test. The resonant frequency of the system is around 50-60 Hz, which are significantly above the minimum requirement for the calibrated, instrumented modal hammer (> 4 Hz). The boundary condition of the box is twice the side of the concrete block to avoid reflected shear wave. Since only vertical vibration is excited and measured, it was found that the boundary condition can be negligible and twisting and Rayleigh modes of vibration cannot be detected (as small-amplitude resonances). This pilot result allows further research into the effect of flooding condition on the dynamic behavior of railway ballast.

Fig. 4 A test setup

To measure the vibration response of the ballast, an accelerometer was placed on the top surface of the upper segment, as illustrated in Fig.

4. The mass of the upper segment is 8.2kg. It should be noted that a test rig was mounted on a “strong” or “isolated” floor, the frequency responses of which are significantly higher than those of interest for the ballast. During the tests, the floor also isolates ground vibration from surrounding sources. To impart an excitation on the upper mass, an impact hammer was employed within a capable frequency range of 0–3,500 Hz. The FRF could then be measured by using the PCB accelerometer connected to the PROSIG modal testing system, and to a computer. Measurement records also included the impact forcing functions and the coherence functions.

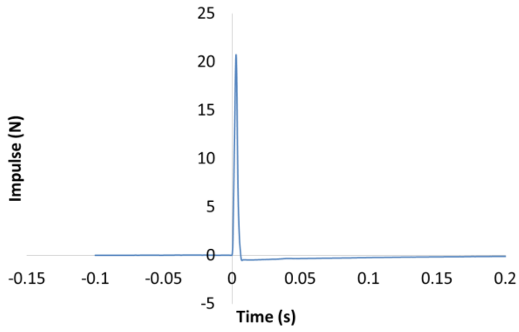
4. RESULTS AND DISCUSSION

It is important to note that railway operators do not commonly operate a train over a flooded railway track, to assure the safety of passengers and goods. This is due to the fact that the condition and integrity of railway tracks under flood condition cannot be inspected or assessed. In many cases, the flood water washes away railway ballast and also undermines the condition and load bearing capacity of subgrade and formation. Running a train on unstable track formation can cause train derailment, damage to assets and infrastructure, and failure of signalling system (e.g. switches and crossings). In addition, the track circuits and signalling could be malfunctioned and it is impossible to detect the location of the train. These issues are dangerous for train operations. The aim of this study is to establish a better insight into the dynamic characteristics of railway ballast in flooding condition. The insight will help track engineers to develop appropriate models of flooded railway ballast. Also, the dynamic model can be used for condition monitoring of railway tracks so that the track integrity can be adequately assessed in both normal and flooding conditions.

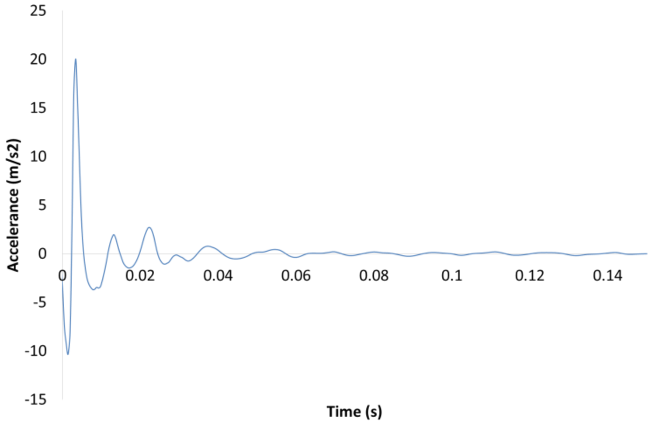
An example of the impulse, dynamic response and FRF of railway ballast in the experiments can be seen in Fig. 5. It is found that the level of water slightly reduces the natural frequency of ballast system since the stagnant water fills the pore of gravels or clogs the ballast.

The aim of this study is to establish a better insight into the dynamic behavior of railway ballast in flooding condition. The insight will help track engineers to develop appropriate models of flooded railway ballast [27-29].

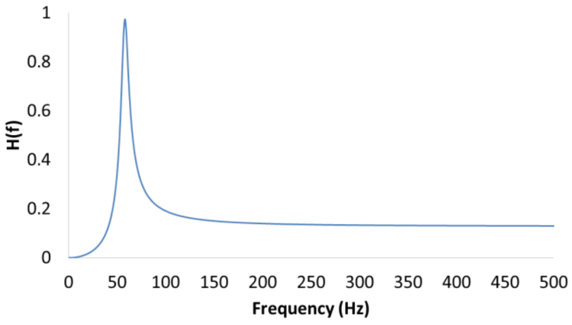
The dynamic responses of railway ballast in flood conditions can be seen in Fig. 6 (in time domain) and in Fig. 7 (in frequency domain). Fig. 6 shows that the vibrational amplitude of the representative mass is reduced with the increased level of water or flooding condition. The level of water also reduces the secondary amplitude of vibration over the time. It is clear that the flood level can also increase the energy dissipation capacity of the track when stagnant water fills the pore of gravels or clog the ballast.



a) impulse



b) accelerance



c) FRF

Fig. 5. A test result (based on the average of 10 data sets)

Fig. 7 also confirms the insight into the dynamic behavior of the ballast in flooding conditions. The dynamic receptance (H) decreases with the increment of flood level. Also, the flooding condition can also shift the natural frequency of the ballast layer (of the SDOF system). Considering that the representative mass is relatively constant, it implies that the water level can also reduce the stiffness of the system.

Table 1 demonstrates the effect of flood level on the dynamic modal parameters of railway ballast. It can be observed that the increment of flood water level will reduce stiffness of ballast, whilst increase the damping coefficient. The quality of experimental result and the best-fitting can be seen from the correlation coefficient. The error of modal parameter identification is less than 3%. However, the influence of flood water on stiffness is relatively moderate with around 30% change observed. In contrast, it is apparent that the flood water can affect the damping significantly since the change in damping can be over 70%. This insight informs that the dynamic modeling of ballast needs to be updated. Based on the experimental results, it is proposed that a model of state-dependent properties (e.g. with additional dashpot) should be adopted for flooded ballast.

Fig. 8 also confirms the insight into the dynamic behavior of the ballast in flooding conditions. It can be observed from the variation bands that the use of natural frequency alone cannot be effective in determining the integrity of railway ballast. Note that the flooding condition tends to shift the natural frequency of the ballast layer (of the SDOF system). Considering that the

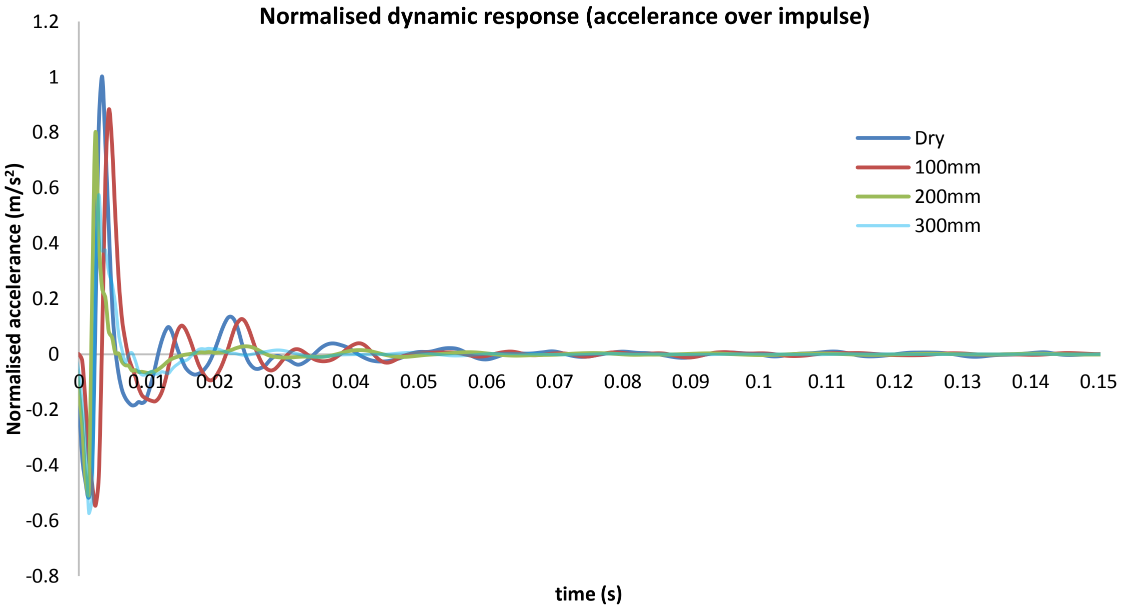


Fig. 6 Dynamic responses to impact hammer loading (normalised by the maximum impulse)

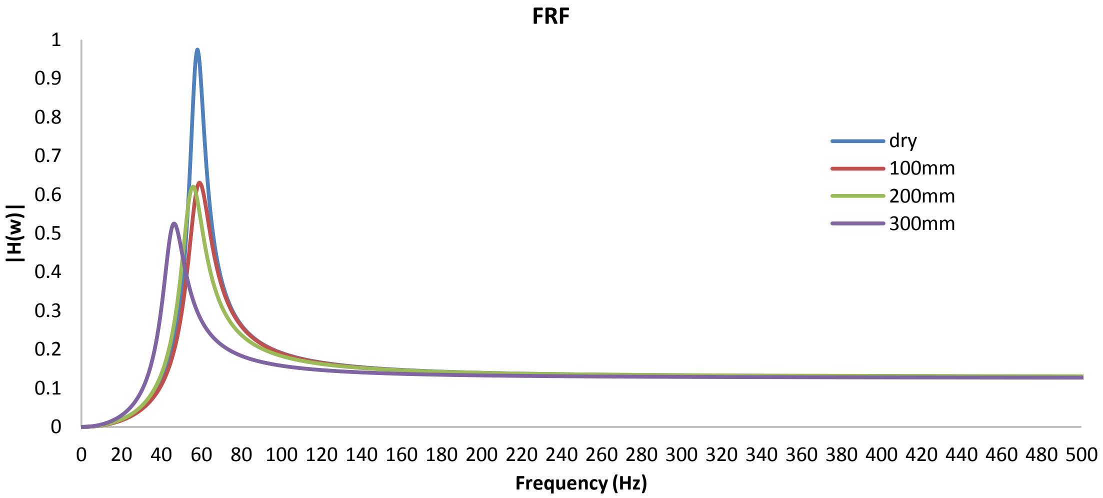


Fig. 7 Frequency response functions of flooded ballast

representative mass is relatively constant, it implies that the water level tends to reduce the stiffness of the system.

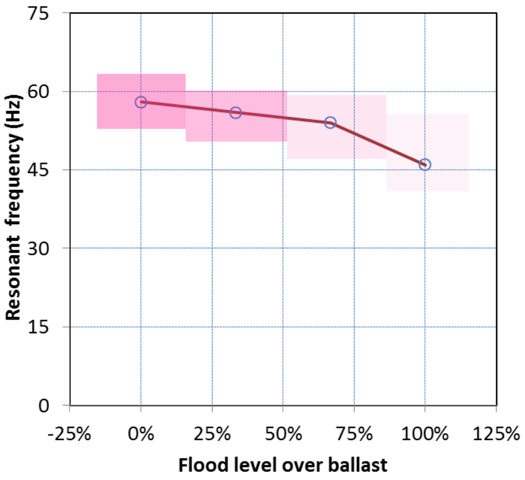


Fig.8 Natural frequency of ballast in flood conditions

Table 1. Dynamic properties of ballast in flood conditions (water temperature at 20°C).

	Stiffness (kN/m)	% ΔK	Damping (kNs/m)	% Δc	Correlation Coefficient (%)
Dry	1,036	0	0.3721	0	99.85
33%	1,009	3	0.5736	54	98.16
66%	986.2	5	0.6131	65	98.94
100%	708.4	31	0.6364	71	97.81

5. CONCLUSION

Railway ballast is one of the critical components widely used in modern ballasted railway track systems. It is generally installed under the railway sleeper to absorb dynamic wheel/rail interaction forces, preventing the underlying railway track subgrade from excessive stresses, enabling the interlocking of skeleton track onto the ground and providing lateral track stability. Current practices in numerical simulations make use of MDOF systems that adopt merely the dry ballast condition. Recent findings show that railway track could significantly experience extreme climate such as long-term flooding. Therefore, there is a need to identify appropriate models as well as to investigate the realistic dynamic behavior of railway ballast exposed to flooding conditions. This study is the world first to highlight such critical effect. Analytical and experimental studies have been carried out to address such the pressing issue. The experimental studies reveal an unprecedented insight into the dynamic behavior of the flooded ballast. The flood condition can reduce the instant stiffness of the track system, whilst also increase the damping or energy dissipation of the track. It is important to note that this study considered a flash flood case only. In reality, the flood condition can also reduce the load carrying capacity and stiffness of the subgrade layer too. Future work will highlight the modal identification and the development of new SDOF model that is more realistic and more capable to define dynamic characteristics of the railway tracks submerged under flood conditions. The influence of impulse energy as well as the track mass will also be investigated in the near future.

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