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Development and experimental validation of a numerical model for the prediction of ground vibration generated by pavement breaking

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ABSTRACT

Pavement breakers are used to break rigid pavements and obtain a suitable foundation for new top layers or to enable pavement removal. The operation of falling weight pavement breakers generates high levels of ground vibration which is potentially damaging to nearby buildings and infrastructure. A numerical model for the prediction of ground vibration generated by pavement breaking is presented in this paper. First, the impact load due to a single blow of a falling weight pavement breaker is estimated by means of a simplified model of the hammer, the pavement, and the underlying soil. The predicted impact load is in good agreement with experimental results, which have been estimated from measured accelerations of one of the hammers of a pavement breaker. Second, the response of the pavement and the soil due to the impact load is considered. In order to account for inelastic soil behaviour and slab uplifting, a non-linear model of the coupled road-soil system is developed. Predictions of ground vibrations generated by the operation of a multi-head pavement breaker are validated by comparison with experimental results. A relatively good agreement is obtained between the results of the non-linear model and measured ground vibration. Comparison with results obtained with a linear model shows that disregarding non-linear phenomena leads to significant overestimation of the ground vibration levels close to the source, whereas similar results are obtained at larger distances.

1. Introduction

Pavement breaking is commonly performed to enable the removal of rigid pavements or as a first step in road rehabilitation before pavement overlay. One of the main concerns in the operation of falling weight pavement breakers is the high level of ground vibration generated by the impacts of the drop hammers. Close to the location of operation, the peak particle velocity (PPV) in the soil can exceed 5 mm/s which is considered as the lower limit for architectural damage. For this reason, pavement breaking is considered as one of the most important anthropogenic vibration sources [1], together with pile driving, demolition activities, and blasting [2].

The fear for damage to buildings and underground infrastructure such as pipelines [3] prohibits the employment of pavement breakers in many practical situations. In order to better understand and control the risks involved, a good estimate of ground vibration levels is crucial. Up to now, such estimations are mainly based on empirical data and therefore limited to the type of equipment, pavement, and soil for which data are available. Within the frame of the present paper, a numerical model is presented which allows for predictions for a wider range of parameters. The model is validated by comparison with measurements which have been performed along the N9 motorway in Waarschoot (Belgium), where a multi-head breaker (MHB) has been used to transform the rigid pavement into a suitable foundation for a new asphalt top layer (Fig. 1). The acceleration of one of the drop hammers was measured simultaneously with accelerations of the concrete slab and the soil's surface at various distances from the source.

The outline of this paper is as follows. Section 2 deals with the prediction of the impact load due to a single blow of the pavement breaker. The load is predicted by means of a simplified model of the hammer, the pavement, and the underlying soil. The predicted impact load is compared to experimental results, obtained from measured acceleration of one of the hammers of the pavement breaker. In Section 3, the response of the pavement and the soil is predicted and validated by comparison with experimental ground vibration results. In order to account for inelastic behaviour of the soil and separation between the concrete slabs and the soil, a non-linear model of the coupled road-soil system is developed.

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Fig. 1. Multi-head pavement breaker used for fracturing of the concrete roads.

2. Prediction of the impact load

2.1. Introduction

Impact loads from sources such as pile driving [4], dynamic soil compaction [5–7], hammers and presses [8] are frequently studied using simple models consisting of rigid masses, dashpots, and springs. The impact of a rigid body on an elastic halfspace was studied theoretically and experimentally by Bycroft [9]. Chow et al. [10] have developed a one-dimensional (1D) finite element (FE) model for the simulation of pounder deceleration in dynamic soil compaction. The prediction of the impact load generated by a pavement breaker requires an accurate estimation of the flexibility of the pavement, accounting for the interaction with the underlying soil. In the following, a simplified model of the coupled system of pavement and soil is presented which allows limiting the computational cost of the simulation.

2.2. Impact model

The problem considered for the prediction of the impact load involves a hammer released at time $t=0$ from a height h, impacting the pavement at time $t_0=\sqrt{(2h)/g}$, where g denotes the gravitational acceleration. Since the drop hammer is much stiffer than the pavement [11], it is simplified as a rigid mass in the impact analysis. Before the impact ($0 \le t < t_0$), the vertical acceleration of the drop hammer $\ddot{u}_\mathrm{d}(t)=-g$, leading to an impact velocity $v_0=\dot{u}_\mathrm{d}(t_0)=-gt_0$ or $v_0=-\sqrt{2gh}$ in terms of the drop height h. During impact, the drop hammer is subjected to the impact force $f_\mathrm{d}(t)$ and the gravitational force, so that the equation of motion becomes

$$f_\mathrm{d}(t)-m_\mathrm{d}g=m_\mathrm{d}\ddot{u}_\mathrm{d}(t) \quad \text{for } t_0 \le t \le t_0+t_\mathrm{d} \tag{1}$$

which is valid from t_0 until t_0+t_d, at which the mass rebounds from the pavement and the impact ends. During impact, the drop hammer exerts an opposite contact force on the pavement, i.e. $f_\mathrm{c}(t)=-f_\mathrm{d}(t)$. Since the acceleration of the drop hammer during the impact is much larger than the acceleration of gravity, the corresponding term in Eq. (1) is omitted next. Once the acceleration $\ddot{u}_\mathrm{d}(t)$ has been computed, the contact force $f_\mathrm{c}(t)$ applied to the pavement can therefore be calculated from the acceleration of the drop hammer as

$$f_\mathrm{c}(t)=-m_\mathrm{d}\ddot{u}_\mathrm{d}(t) \quad \text{for } t_0 \le t \le t_0+t_\mathrm{d} \tag{2}$$

The contact force $f_\mathrm{c}(t)$ is related to the displacement of the pavement at the contact point $u_\mathrm{c}(t)$ through the dynamic stiffness of the system composed of pavement and underlying soil. This relation is written in the following general form:

$$f_\mathrm{c}(t)=\int_{t_0}^{t} S(t-\tau)u_\mathrm{c}(\tau)\,\mathrm{d}\tau \tag{3}$$

where $S(t)$ represents the dynamic stiffness of the coupled system [12]. When both systems are in perfect contact during the impact, $u_\mathrm{c}(\tau)$ can be replaced by $u_\mathrm{d}(\tau)$ in Eq. (3). Introducing the resulting expression for the contact force $f_\mathrm{c}(t)$ in Eq. (2) leads to the following integro-differential equation for the drop hammer displacement $u_\mathrm{d}(t)$:

$$\int_{t_0}^{t} S(t-\tau)u_\mathrm{d}(\tau)\,\mathrm{d}\tau=-m_\mathrm{d}\ddot{u}_\mathrm{d}(t) \quad \text{for } t_0 \le t \le t_0+t_\mathrm{d} \tag{4}$$

which needs to be solved with initial conditions $u_\mathrm{d}(t_0)=0$ and $\dot{u}_\mathrm{d}(t_0)=-gt_0$.

The dynamic stiffness $S(t)$ represents the stiffness of the system composed of pavement and soil. By analogy with models developed for the dynamic response of flexible foundations, a linear model of a finite sized plate coupled to a layered halfspace model for the soil can be adopted for calculating the dynamic stiffness of the coupled system. The corresponding linear dynamic soil-structure interaction problem is solved efficiently in the frequency domain using coupled finite element–boundary element (FE–BE) methods. This has the additional advantage of transforming the convolution on the left hand side of Eq. (4) into a multiplication. For this reason, an equivalent frequency domain formulation of Eq. (4) with initial conditions $u_\mathrm{d}(t_0)=0$ and $\dot{u}_\mathrm{d}(t_0)=-gt_0$ is considered here. A pseudo-force $p(t)$ is introduced in Eq. (4) to account for non-zero initial conditions in the frequency domain analysis, following a procedure proposed by Humar [13], Clouteau and Aubry [14], and Martins et al. [15]. In the present case where only the initial velocity is different from zero, the pseudo-force required to produce a change in impulse from 0 to $m_\mathrm{d}v_0$ from $t=t_0^-$ to $t=t_0^+$ is equal to

$$p(t)=m_\mathrm{d}\ v_0\ \delta(t-t_0) \tag{5}$$

where $\delta(t)$ is the Dirac delta function. Since the left hand side of Eq. (4) contains the force applied to the pavement, the pseudo-force is introduced with opposite sign to obtain the equivalent formulation of the problem with zero initial conditions $u_\mathrm{d}(t_0^-)=0$ and $\dot{u}_\mathrm{d}(t_0^-)=0$:

$$\int_{t_0}^{t} S(t-\tau)\,u_\mathrm{d}(\tau)\,\mathrm{d}\tau-m_\mathrm{d}\ v_0\delta(t-t_0)=-m_\mathrm{d}\ \ddot{u}_\mathrm{d}(t) \quad \text{for } t_0 \le t \le t_0+t_\mathrm{d} \tag{6}$$

In the frequency domain, Eq. (6) reads as

$$\hat{S}(\omega)\hat{u}_\mathrm{d}(\omega)-m_\mathrm{d}v_0=m_\mathrm{d}\ \omega^2\ \hat{u}_\mathrm{d}(\omega) \tag{7}$$

where ω is the angular frequency and a hat above a variable denotes its representation in the frequency domain. Solving for $\hat{u}_\mathrm{d}(\omega)$ and introducing the solution in Eq. (2), transformed to the frequency domain, gives the impact force:

$$\hat{f}_\mathrm{c}(\omega)=\frac{m_\mathrm{d}^2\ \omega^2\ v_0}{\hat{S}(\omega)-m_\mathrm{d}\ \omega^2} \tag{8}$$

Since the impact has a very short duration in the order of 1 ms, the corresponding impact force has a broadband spectrum extending up to a few kHz. This implies that the dynamic stiffness of the pavement $\hat{S}(\omega)$ is needed up to very high frequencies, requiring a