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A generic structural pounding model using numerically exact displacement proportional damping

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ABSTRACT

Pounding damage in bridges and buildings range from minor aesthetic effects up to major structural damage inducing building collapse or bridge girder's unseating. This study proposes the Hunt–Crossley model, a generic model that can have either a linear or nonlinear force–deformation relationship, for the analysis of building pounding. This model has been extensively employed in Mechanical Engineering. There are several approximate solutions for the damping of the model and one of them has been introduced as the 'Hertzdamp' model for structural pounding analysis. The exact solution of damping constant for this model has been presented here. The performance of the linear and nonlinear Hunt–Crossley models in simulating impact force between concrete bodies is compared against other existing pounding models, namely: linear viscoelastic, nonlinear viscoelastic and modified linear viscoelastic models. The nonlinear Hunt–Crossley model best predicted the contact force while the linear Hunt–Crossley model had twice the normalized error of the Hertzdamp model, which was still only half as much as the error in other three models. Finally, a numerical simulation of pounding of bridge segments at an expansion joint is conducted with all models. It was observed that the pounding force predictions from Hunt–Crossley models are similar to that obtained in impact experiments while other models produced very different force developments. The Hunt–Crossley models do not have the discontinuities i.e. negative force, instantaneously high initial force or discontinuous transition between deformation and restitution phases of impact which are present in the other models.

1. Introduction

In past earthquakes [1–3], it has often been observed that the separation distance between adjacent structures, or adjacent parts of a structure, is insufficient to accommodate their relative displacement, resulting in collisions. The relative displacement is caused by the out-of-phase vibrations resulting from their different dynamic characteristics, different foundation properties or the spatial variation of ground motion [4,5]. Such collisions result in repeated hammer-like blows on each structure. This is an additional load which is unlikely to be catered for even in a structure designed according to modern earthquake resistant building codes.

Building pounding as an urban hazard has been observed in most of the past major earthquakes [6], while bridge damage due to pounding has also been observed frequently [5,7]. Most of the susceptible buildings have been found to be constructed before the inclusion of separation criteria in seismic codes, e.g. pre-1982 buildings in Taiwan [8] and pre-1976 buildings in New Zealand [9]. Bridges are even more vulnerable due to their long span, as the foundations of individual bents and abutments may receive non-identical ground motions e.g. due to non-uniform spatial development of soil-strata [4,5].

The recurrence of pounding damage has invited numerous experimental and numerical studies in the past two and a half decades. Different approaches have been developed in the past decades for analysis of building response with pounding, e.g. based on Lagrange multiplier solution [10] and by calculating the nonlinear soil-structure system alternately in the Laplace and time domains [11]. Several formulae were introduced for calculating impact forces [12–19] that will be elaborated in the following sections. Several works have analyzed effects of additional factors e.g. base isolation [16,18,20], soil-structure interaction [11,21,22] and spatial variation of ground motions [4,5,23–25]. Studies have also proposed and evaluated measures for mitigating and avoiding pounding damage e.g. [26–29].

Several experimental works on structural pounding have been carried out to validate the numerical models. Papadrakakis and Mouzakis [30] conducted an experiment on pounding between

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two storey RC buildings and showed that the responses could be well predicted by Lagrange multiplier method. Filiatrault et al. [31] conducted a shake table experiment on pounding between three and eight storey buildings to validate a FE program. Chau et al. [32] conducted a parametric investigation on pounding between two steel towers and predicted the relative impact velocities with the elastic Hertz theory. Similarly, Zhu et al. [33] showed the suitability of three dimensional contact-friction based models for bridge pounding at arbitrary locations. The study also measured the restitution coefficient e for the impact of bridge segments to be 0.4.

In its most basic form, pounding is an impact between two masses which can be building slabs, walls, bridge decks or abutments. The impact causes a transfer of momentum between the two structures. A number of methods have been proposed for including the pounding effects in time-history analysis of structures, which can be broadly classified into two categories, viz. stereomechanical methods (impulse momentum principle) and impact element methods.

Stereomechanical methods interrupt the time-history analysis every time an impact is observed, update the velocities of the colliding structural masses according to the impulse momentum principles of classical physics, and resume the time-history analysis. The loss of mechanical energy is incorporated by means of an experimentally determined or logically assumed value of coefficient of restitution, e, which is defined as the ratio of relative separation velocity to relative approach velocity of the colliding masses. These methods have a robust physical theory and historical research behind them, but for structural engineers their main disadvantage is the inability to estimate the impact force due to the assumption of instantaneous change in momentum of colliding masses. Thus, these models can be used for global effects on structures but not for predicting local damage. Athanassiadou et al. [23] utilized stereomechanics in parametric investigation of pounding between a row of buildings idealized as single degree-of-freedom structures subjected to spatially varying ground motion.

Impact element methods introduce a combination of gap and link elements between the colliding masses to simulate pounding (Fig. 1). The pounding force will develop only if the gap closes, i.e. the relative displacement of the masses toward each other is more than the space between them and the elastic spring is compressed. The force is calculated from the expression provided for the particular model being employed. If the contact is assumed elastic, the dashpot is omitted and the spring may be linear or nonlinear. If the models incorporate energy loss, the dashpot with equivalent viscous damping is added parallel to the spring. Experiments have found most impacts between large masses to be inelastic [34] and thus elastic models are seldom u sed for pounding analysis. The impact element method has often been used in literature because of the capability of the model to calculate pounding forces. Unfortunately, up to today the stiffness of the contact location cannot be predicted with certainty. Hence, several pounding models have been developed. A selection of the models in a study is often subjective.

Rigorous theoretical derivation exists only for elastic, nonlinear impact between spherical and cylindrical bodies and is known as the Hertz contact law [34], as shown in the following equation:

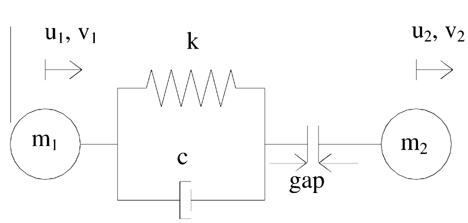

Fig. 1. Impact element model for contact force.

$$F = k\delta^{3/2} \tag{1}$$

where at any time t, F is the impact force, k is the stiffness of the nonlinear spring, δ is the relative penetration, i.e. the relative displacement of the centres of mass of the two bodies.

Although attempts have been made to include viscous and plastic energy loss in the Hertz model theoretically [35], such solutions are not yet appropriate for engineering applications. Instead, Hunt and Crossley [36] proposed a model (Eq. (2)) where the energy lost during impacts is accounted for by the damping that depends on the relative penetration and its rate of change.

$$F = k\delta^{3/2} + \zeta\delta^{3/2}\dot{\delta} \tag{2}$$

where $\dot{\delta}$ is the rate of change of relative penetration and ζ is the damping constant.

Because of its versatility, the model can be generalized as shown in Eq. (3) and such models are known as Hunt–Crossley models [37].

$$F = k\delta^{n} + \zeta\delta^{n}\dot{\delta} \tag{3}$$

Several approximate solutions for the damping constant ζ in Eq. (3) have been proposed for various mechanical engineering applications ranging from forces in ball-bearings to robotics, space docking and knee replacement simulations [37]. The solution for the damping constant in Eq. (4), derived by Lankarani and Nikravesh [38], was first proposed for simulation of structural pounding by Muthukumar and DesRoches [15], as 'Hertzdamp model'.

$$\zeta = \frac{3}{4}\frac{k(1-e^2)}{\dot{\delta}_0} \tag{4}$$

Ye et al. [17] found that the approximations involved in the derivation of the damping constant introduced significant errors and the model was ineffective in maintaining the energy loss. For example, if $e = 0.8$ is used, the energy loss in the model is equivalent to $e = 0.847$. If $e = 0.1$ was assumed, the effective e is 0.665 which is an error of 565%. A new formulation for ζ was derived, as shown in Eq. (5), and the performance was much improved. The authors acknowledged that there was still some error in the value of 'e' produced by the impact element when compared to the value assumed for the computations but the difference is very slight and much reduced from the previous formulation; effective e is 0.5769 at $e = 0.6$ and 0.0687 at $e = 0.1$ which is an error of 31%. The authors recommended that the corrected relationship is suitable for use only for the impacts with $e > 0.4$ because the deviation is only 10% at $e = 0.4$, and the relationship degrades rapidly below that.

$$\zeta = \frac{8}{5}\frac{k(1-e)}{e\dot{\delta}_0} \tag{5}$$

Ye et al. [18] has presented a modified Kelvin impact model which is identical to linear form of Hunt–Crossley model, i.e. $n = 1$. Because of the approximations involved in derivations, the damping ζ is slightly different (Eq. (6)) from that of nonlinear form (Eq. (5)). The model shows slightly better accuracy than Eq. (5) as at $e = 0.3$ the error in calculating the actual e value determined from the after impact velocities is 10% while Eq. (5) will cause 15% error.

$$\zeta = \frac{3}{2}\frac{k(1-e)}{e\dot{\delta}_0} \tag{6}$$

This study presents an exact solution for the damping constant in Hertzdamp model, which removes these errors, and makes it suitable for all values of e. Since the relationship is derived for a generic n in Eq. (3), the relationship is applicable for linear as well as any nonlinear models. Henceforth, Hertzdamp model will refer