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Low-order modeling of vehicle impacts upon boulders embedded in cohesionless soil

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ABSTRACT

In this paper, a planar low-order model is presented for a vehicle impact upon a boulder embedded in cohesionless soil to examine the feasibility of using boulders as anti-ram barriers. The colliding vehicle is represented as a lumped-parameter Maxwell model, the boulder is treated as a rigid body with non-negligible mass, and the soil is represented as a system of lumped-parameter Kelvin models. The low-order model allows for the linear translation of the vehicle and boulder, along with rotational motion of the boulder. The model is validated against two full scale crash tests. Both tests were performed according to ASTM F2656-07 at an M30 rating using a 6800 kg (15,000 lb.) medium-duty sized truck. The low-order model is shown to be descriptive enough for impacts that result in small boulder motion to use in sizing of boulders for use as vehicular barriers.

1. Introduction

This paper outlines an intentionally simple model for predicting the motion of a rigid, soil-embedded object like a natural or man-made boulder embedded in soil when that object is impacted by a large vehicle. The ASTM F2656-07 crash test specification with an M30 rating is the target for validation of the model, wherein the boulder is treated as an anti-ram barrier intended to prevent penetration of the impacting vehicle through the boundary of the boulder's original location. Modeling an impact between a 15,000 lb truck and a massive boulder with low-order model is challenging in large part because the boulder's ability to dissipate crash energy is dependent upon its movement through soil, which is difficult to model under dynamic loading with simple relationships.

The goal of this study is therefore to describe the energy transfer during the vehicle-boulder collision. This transfer, from vehicular kinetic energy into boulder kinetic energy, vehicle deformation, soil kinetic energy, and soil deformation, must be accurately described with a tractable set of differential equations. While modern Finite Element Analysis (FEA) impact simulation software such as LS-DYNA® has the capability to predict the results of this type of collision, these software packages are computationally expensive, simulations can take hours or days to run, and FEA approaches can obscure an understanding of fundamental physical phenomena. When selecting a natural rigid boulder as a barrier, a designer should be able to quickly iterate through embedment depths, boulder sizes, and soil conditions anticipated at the site of installation to determine the boulder's potential as an effective barrier. Therefore, a low-order model that runs rapidly on a portable computer is needed. This study derives a novel lumped-parameter, low order model from first principles relationships, and validates this model using two crash tests. The model is found to be an accurate predictor of barrier and vehicle trajectory during a collision for small angular boulder displacements. Because crash test failure standards require small displacements for a barrier to receive a passing score, the model was found to be acceptable as a rapid design iteration tool.

The concept of a low-order dynamic model for vehicular impacts on boulders embedded in cohesionless soil is a rare topic in the literature, but more general study of vehicular impacts with objects fixed to the surrounding ground, such as guardrails, is more common. A comprehensive review of FEA-based methods for modeling vehicle impacts with guardrails is presented in Ref. [1], and gives a picture of increasing levels of complexity over the years that have led to substantial improvements in accuracy in modeling vehicle impacts. In Ref. [2], FEA was used extensively to evaluate the performance of guardrails. Similarly, Wu [3] studied the dynamic deformation of guardrails through full-scale crash tests and FEA models. Naturally, in these studies, the large plastic deformation of

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guardrails during impacts necessitated a complex model formulation.

While guardrails are commonplace on public highways, and designed to deform substantially when impacted in order to keep vehicle occupants safe, anti-ram barriers have a different focus, placing the impetus on preventing vehicle penetration through the barrier at all costs. Recent work in predicting the behavior of man-made bollards, such as the work of Hu in Ref. [4], has also required the use of detailed FEA analysis. While not designed with vehicle occupant safety as a primary concern, steel bollards are, in general, designed to deform substantially and plastically when impacted by a vehicle. In the pages that follow, the reader will find that the present study does not require an FEA approach primarily because boulders can be approximated as rigid bodies, making the use of deformable elements to model the boulder itself unnecessary.

The remainder of the paper is organized as follows: the next section provides a brief look at prior work in soil and vehicle impact modeling without FEA, to lend context to the model development. Then, these concepts are employed along with a Newtonian first-principles derivation of the dynamic equations of motion for the boulder-soil-vehicle system. Finally, results from two full-scale crash tests are presented to compare with simulations from the low-order model. Conditions under which the model is descriptive are explored in a discussion of the experimental results.

1.1. Low-order modeling of vehicle frontal impacts

Several low-order vehicle models have been developed regarding the representation of a vehicle during a front end collision. These are briefly reviewed below in an attempt to create a low-order vehicle representation for inclusion in a descriptive model of the vehicle-barrier system.

It is common practice in literature to represent a front end vehicle collision as a 1-D Maxwell model [5]. While more complex representations of vehicle impact behavior are also present in the literature, including nonlinear spring-mass-damper systems as in Ref. [6], systems of multiple spring-mass elements as in Ref. [7], wavelet theory as in Refs. [8], and regressive time-series analysis as in Ref. [9], the well-known basic Maxwell model is used in this study for simplicity. In the following sections, this model will prove to be sufficiently descriptive of the crash behavior observed when parameters are fit to a rigid barrier impact using a finite element simulation. Shown in Fig. 1, the variables in the Maxwell Model are the effective spring constant, k_v, damping constant, c_v, lumped vehicular mass, m_v, vehicle displacement, x_v, and the displacement of the contact between the Maxwell model spring and Maxwell model damper, x'. In Ref. [5], Pawlus et al. performed a series of pole impact tests for various types of vehicles and compared the predicted displacements to measured displacements when using a Maxwell model. Pawlus then fit the spring and damper coefficients from full scale crash tests and plotted the estimated displacement, speed, and acceleration compared to the actual measurements from the vehicle. Because the values obtained for the spring and damper coefficients using the method proposed by Pawlus show good agreement between predicted and measured responses of the vehicle, a Maxwell model will also be used in this work. Similar to Pawlus et al.'s work, the values obtained for the Maxwell model parameters in the present study are compared against full scale crash tests in the experiments that follow. However, because the vehicle-boulder impact under consideration in this study cannot be reliably considered analogous to a rigid pole impact, a suitable model for the soil's reaction to both static and dynamic loading is also needed.

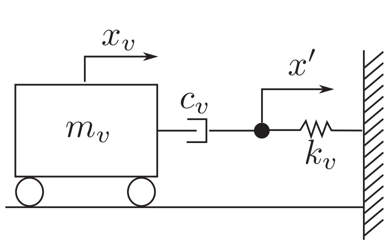

Fig. 1. Maxwell model for frontal vehicular impacts.

1.2. Static analysis of laterally loaded piles

Zhang [10] developed a computational method for predicting the displacement of a laterally loaded, short rigid pile in cohesionless soil due to static loading. For small displacements, short rigid piles were assumed to rotate about a single point. Rather than representing the soil as a system of nonlinear springs and using explicitly measured pressure–displacement curves in the prediction of pile motion, Zhang calculated the soil reaction pressure as a function of embedment depth and static forces. In Zhang's work, the predicted pile displacements agreed well with experimental data. The methodology presented does not, however, account for explicit pile translation or the effect of pile inertial properties such as mass moment of inertia, primarily because Zhang assumes static loading conditions. Nevertheless, Zhang's determination of ultimate lateral loads for cohesionless soils and the corresponding relationship between the embedment depth and the ultimate soil lateral load are used in the present study as pieces of the model for soil-boulder interaction.

1.3. Dynamic analysis for laterally loaded piles

Naggar and Bentley [11] developed a method for predicting the displacements of a laterally loaded, long elastic pile under dynamic loading. The methodology proposed incorporated the p–y method applied to a Winkler model as well as wave propagation and energy dissipation to develop static p–y curves. Then, the static p–y curves were transformed into dynamic p–y curves through the addition of dampers. The mass of the soil within the inner field was lumped against the pile due to the assumed massless area as demonstrated by Novak and Sheta [12]. In Ref. [11], Naggar and Bentley calculated the spring and dashpot constants for the soil element based on empirical data from cyclic pile head loading tests for specific soils. Those spring and dashpot constants were then used to predict the displacement of a dynamically laterally loaded pile. They also compared the predicted pile head displacements against measured pile head deflections for two cases of dynamically, laterally loaded, long elastic piles using a “statnamic” device, which incorporates both static and dynamic loading. The two cases involved a lateral dynamic load of 350 kN and 470 kN respectively. Further soil and pile conditions of the tests can be found in Ref. [13].

The methodology proposed in Ref. [11], however, determines the soil damping explicitly through experiments and curve fitting. It is the goal of this work, rather, to develop a theoretical model using a minimal number of empirical relations. Additionally, the methodology in Ref. [8] was developed for long elastic piles whereas this work is limited to short rigid boulders. The inclusion of soil damping to create a set of dynamic p–y curves as well as the lumped soil mass against the pile are used in this work in the modeling of boulder motion in soil.

2. Low-order model development

This section presents the development of a low-order model for a vehicle impact upon a boulder embedded in cohesionless soil such as sand or gravel. From this model, it is possible to not only