Finite Element Modeling and Validation of Guardrail Steel Post Deflecting in Soil at Varying Embedment Depths

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Abstract

This paper presents finite element modeling and validation of roadside guardrail steel posts deflecting in soil. The soil model was validated for posts embedded at various depths. Prior to finite element modeling, several drop-pendulum impact tests were conducted to determine the actual response of the soil-post interaction in dynamic impacts. A decrease in the depth of the post significantly increased the deflection in soil, which complicated the modeling of the soil behavior. Finite element model of the post and soil setup was developed to capture the post-soil behavior observed in the tests. Two material models, Geological Cap and Jointed Rock, were evaluated for use in the finite element model. Additionally, Lagrangian and Smoothed Particle Hydrodynamics (SPH) methods were briefly compared to determine suitability of use. It was determined that the Jointed Rock material model is better capable of capturing the soil-post interaction in cases where the post embedment was reduced and the resulting soil deformation was large.

Introduction

Accurate modeling of the deflection of guardrail posts in soil forms the basis of a typical roadside metal-beam guardrail model. This study was conducted to develop a finite element (FE) model of the W-beam guardrail post as it deflects in soil at various embedment depths. A series of dynamic tests were conducted to determine the actual post-soil response for various post embedments. Finite element model was subsequently developed for the post-soil setup and simulation analysis was performed to match the response observed in the tests. All finite element analysis was performed using LS-DYNA® software (Hallquist 2006). The details of the dynamic testing and the FE analysis are presented herein.

Dynamic Testing

To provide data for evaluation of the FE models of posts embedded in soil, a series of dynamic pendulum impact tests were performed. In these tests, steel posts were installed at various embedment depths in soil. The posts were then impacted by a gravitational pendulum and the acceleration-time response due to the impact was measured on the pendulum's body. This

enabled the researchers to quantify the post-and-soil interaction behavior at various embedment depths.

The drop pendulum had a mass of 1850-lb and was suspended from four cables. The pendulum was released from a height such that it impacted the posts at a speed of 22 mph at its mean position. The nose of the pendulum comprised of crushable aluminum honeycomb cartridges that were configured to simulate the frontal left-quarter crush of a 1979 Volkswagon Rabbit vehicle. The pendulum impacted the post at a target speed of 22 mph and at a height of 18 inches above the ground, which represents the bumper height of a small passenger car. After each test, the honeycomb material was replaced and the pendulum was reused. Figure 1 shows the pendulum just prior to impacting the post in one of the tests.

Pendulum impact tests were performed with W6×8 steel posts embedded 44 inches, 40 inches, 36 inches, and 32 inches in soil. To obtain more than one data set of post-soil interaction, two tests were performed for each post embedment. The soil around the post comprised of crushed limestone road-base material. The native soil was initially excavated from the area of testing. The road-base material was then used to backfill the excavated volume. The soil was compacted in 6-inch lifts during the backfill process. After each test, the post was removed and a 2-ft diameter hole was excavated at the post location. A new post was placed and the soil was backfilled by compacting in 6-inch lifts again. The soil specifications met the National Cooperative Highway Research Program (NCHRP) Report 350 specifications (Ross et al. 1993).
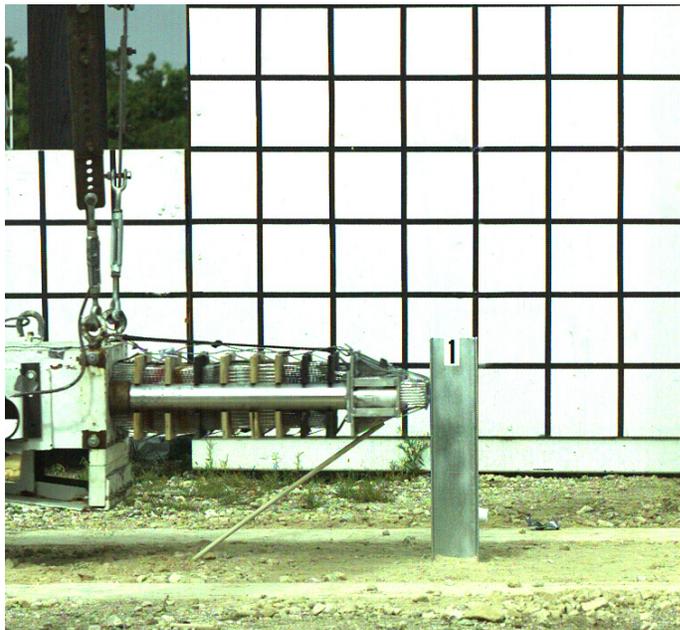
Figure 1: Typical test setup.

With the exception of one of the tests at 44-inch embedment, none of the posts were deformed after the pendulum impact. Slight bending of the post was observed at ground level in one of the tests at 44-inch embedment. This bending resulted in a permanent deflection of 4 inches about the strong axis and 3.75 inches about the weak axis at the top of the post. The acceleration-time response measured from the pendulum bogie is show in figure 2 for a test with 44-inch embedment. Remaining test data will be presented when test and simulation results are compared in subsequent sections of this paper.

Pendulum Test No. 405160-7-P1
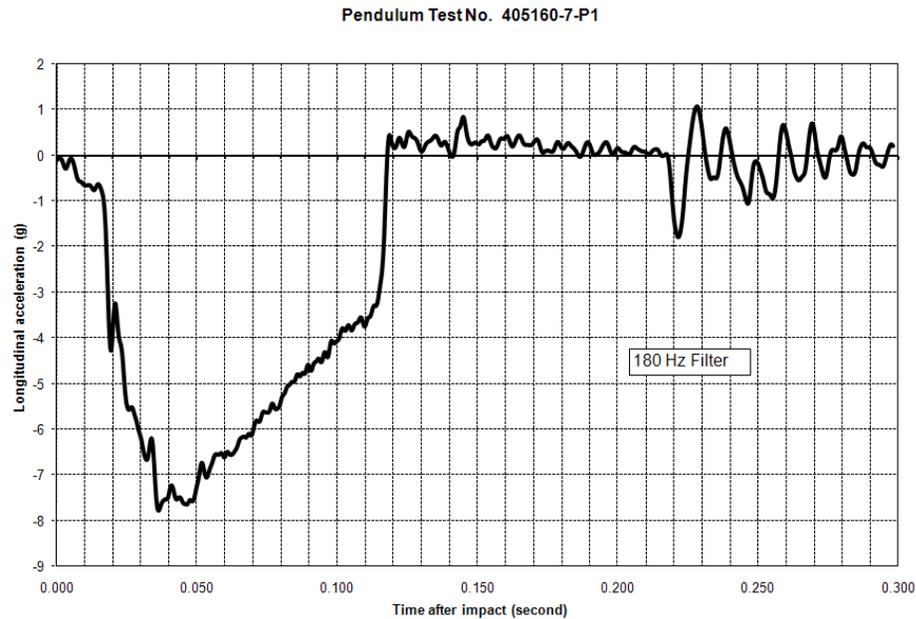
Figure 2: Acceleration-time response for 44-inch post embedment.

Modeling and Simulation

Pendulum Modeling

In previous research (Zimmer et al. 1997), the force-deflection response of the entire crushable pendulum nose was determined by impacting a rigidized pole. In this research, the researchers determined the force-deflection characteristics of individual honeycomb cartridges constituting the nose of the pendulum. The cartridges were crushed in a quasi-static load to determine the force-deflection response of each cartridge. The data was then used to model the nose of the pendulum using non-linear spring elements as shown in figure 3. A simulation was performed with the pendulum model impacting a rigid pole as in earlier tests. A comparison of the deceleration-time history measured on the body of the pendulum showed a reasonable validation of the pendulum nose (see figure 4). Thus the pendulum nose was modeled using spring elements instead of other methods of modeling honeycomb material (such as with shells or solids). This saved significant amount of computational time in running multiple simulations during the calibration of soil material properties.
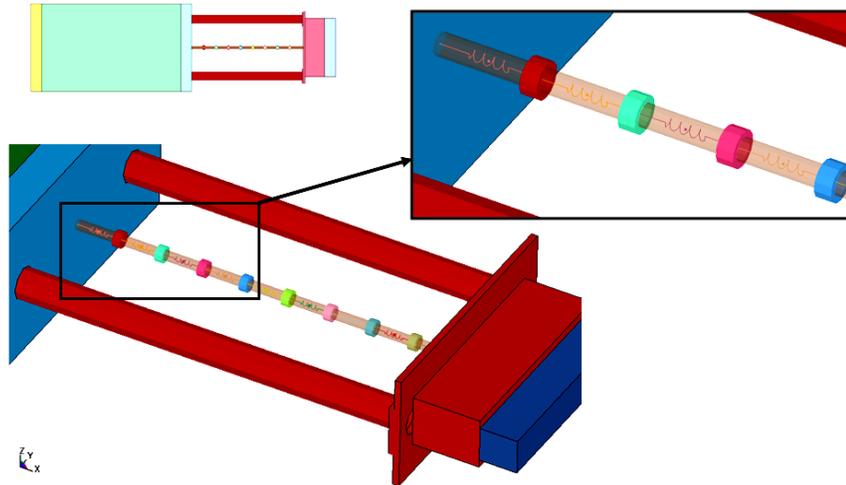
Figure 3: Honeycomb cartridges in the pendulum nose modeled with non-linear springs.
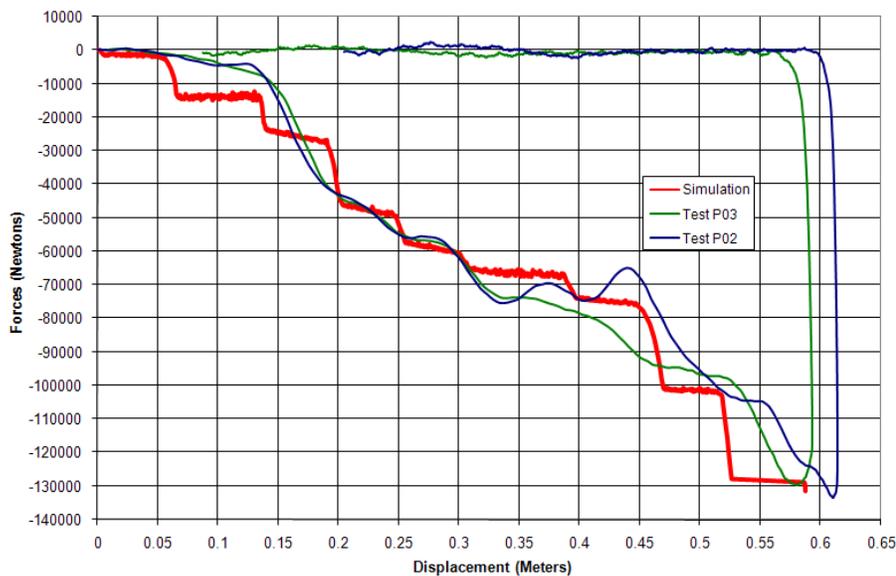
Figure 4: Force deflection comparison of the pendulum model with tests results.

Post and Soil Modeling

The researchers then developed component level finite element models of the guardrail post in soil at various embedment depths. The posts were impacted with a gravitational pendulum model as in the test (see figure 5). The W6×8 steel posts were modeled using shell elements and piecewise-linear-plasticity material model (MAT24). The soil was modeled using hexagonal solid elements forming a rectangular soil bucket as shown in figure 5. The soil bucket was modeled with a cutout built in for placing the post. A contact was defined between the post shells and the soil solids. The soil bucket was aligned with the global coordinate system such that the positive z-axis pointed upwards and positive x-axis was in the direction of the pendulum swing. The nodes on the lateral surfaces of the soil bucket were constrained using specified boundary constraints. The nodes were constrained such that only the translational degree of freedom in the direction perpendicular to the surface of the soil bucket was constrained. Thus the nodes on the bottom of the bucket were constrained only in the z-translation degree of freedom. Nodes at the edges of the bucket were constrained at more than one degree of freedom,

and nodes on the top surface were not constrained. Some sensitivity of the post and soil mesh was performed to refine the mesh and size of the soil bucket. Additional soil was added in front and behind the post and acceleration-time response of the pendulum was compared for these cases. Changes were made to the bucket size until increasing bucket size did not influence the simulation results, as shown in figure 6. The size of the bucket remained same for all post embedment depths.
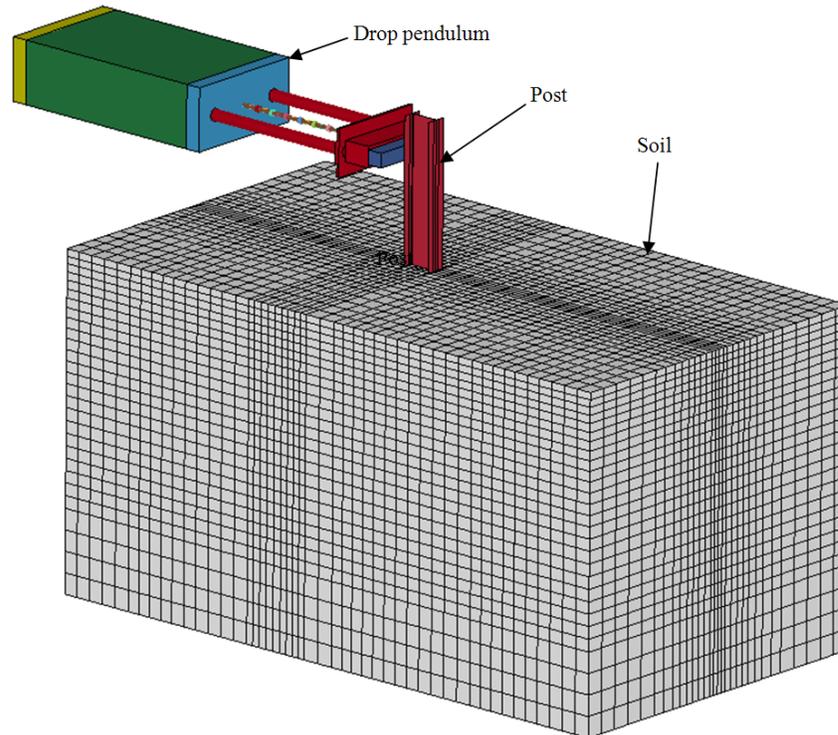
Figure 5: Finite element model of pendulum impacting post in soil.
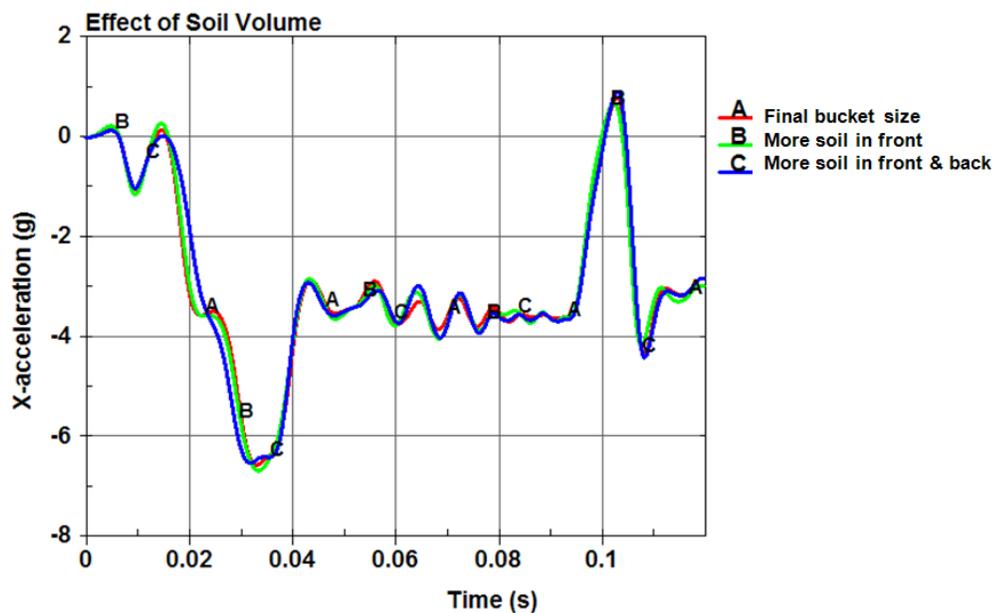
Figure 6: Soil bucket size sensitivity analysis.

Analysis with Geological Cap model:

The soil was initially modeled using the Geologic Cap material model (MAT 25) in LS-DYNA. Starting with standard soil material properties, a parametric calibration of the soil properties was performed to match the post-soil interaction between simulation and testing for the 44-inch post embedment. The researchers were able to calibrate the response of the post and soil model with test results for posts embedded at 44-inch depth as shown in figure 7a.

However, when further simulations were performed with reduced post embedment depths, it was observed that the soil material behavior started to deviate from the response observed in the tests. The acceleration-time responses of the pendulum in the simulation and tests with reduced embedment are shown in figures 7b through 7d. The results are shown for material properties calibrated for 44-inch post embedment. For shallower depths, once the post started to move in the soil, the deceleration remained more or less constant in the simulation results as opposed to a linear deceleration trend observed in the pendulum tests. The researchers then performed an extensive calibration study using the model with post embedded 32-inches in soil (i.e. minimum embedment tested), but the results of the simulation could not be improved. The parameters that were varied in the calibration exercise were the initial bulk modulus (K), initial shear modulus (G), failure envelope parameter (α), failure envelope coefficients (γ and θ), and failure envelope exponent (β) (LSTC 2009).

Evaluation of SPH technique

It was argued that as the movement of the post in soil got large, the conventional Lagrangian finite element method may be resulting in an artificially high resistance due to large distortions of the soil mesh. The researchers then investigated the use of Smooth Particle Hydrodynamics (SPH) technique for modeling the soil (see figure 8). It was expected that a 'meshless' method would eliminate any artificial soil stiffening resulting from the deterioration of the Lagrangian soil mesh.

It was observed that with the use of SPH method, the overall deceleration was reduced significantly compared to the Lagrangian mesh, as shown in figure 9. While this could be investigated further, it was also observed that even with the use of SPH modeling, the constant deceleration after the initial deceleration peak was observed for the 32-inch post embedment. This implied that the problem was less likely to be resulting from the use of a Lagrangian mesh and was more inherent in the Geologic Cap material model. Further use of the SPH modeling technique was therefore discontinued.

44-inch Embedment
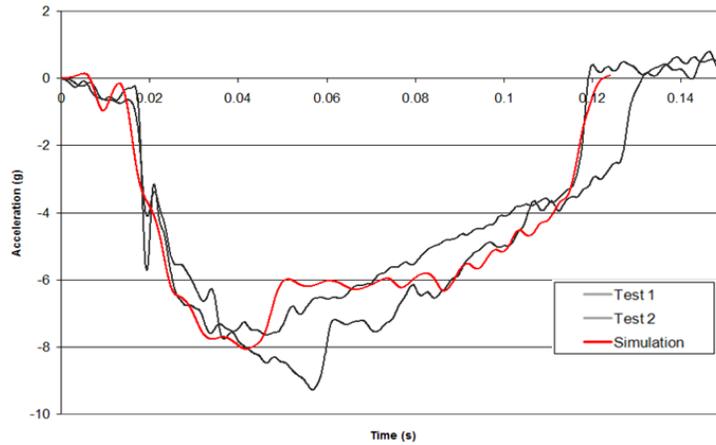
(a)

40-inch Embedment
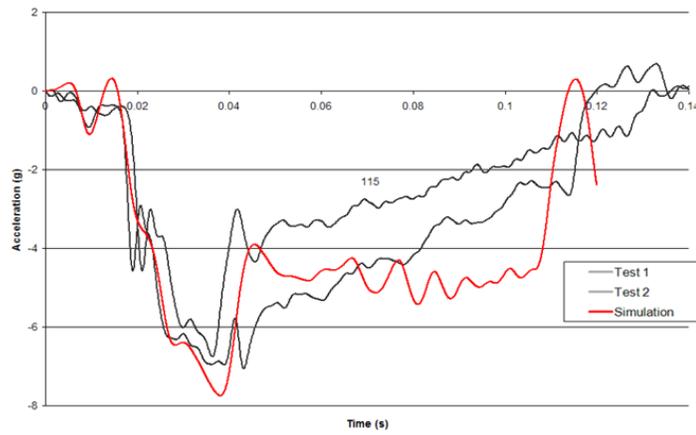
(b)

36-inch Embedment
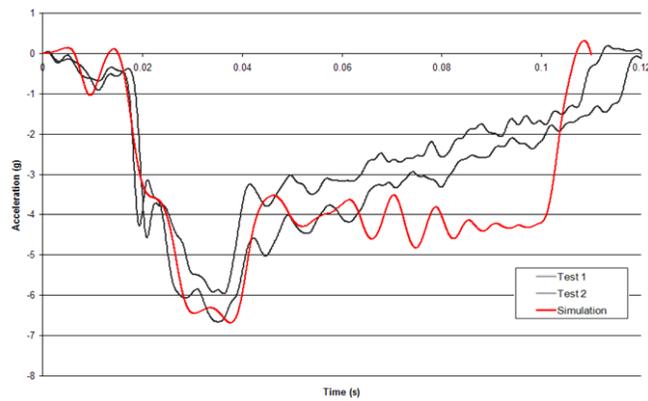
(c)
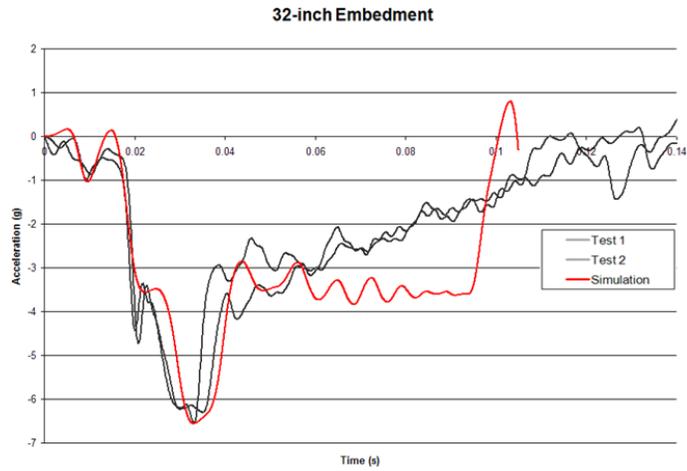
(d)

Figure 7: Acceleration-time comparison using Geologic Cap model for various embedment depths.
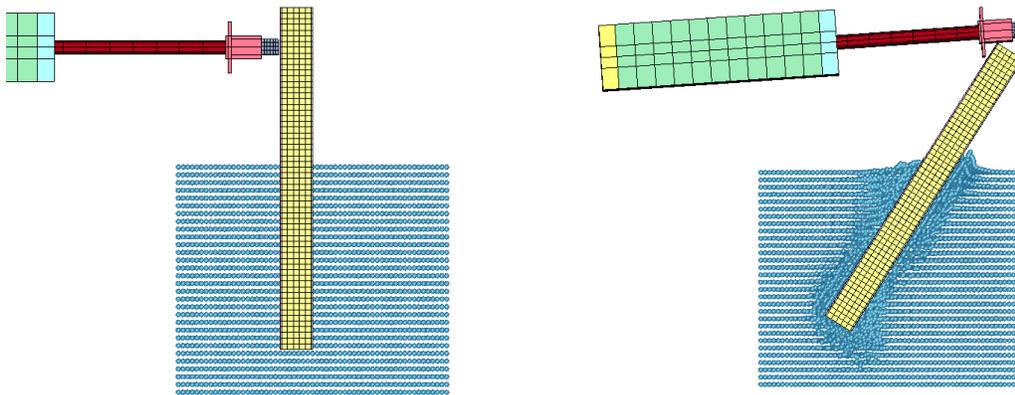
Figure 8: SPH modeling of the post and soil interaction.
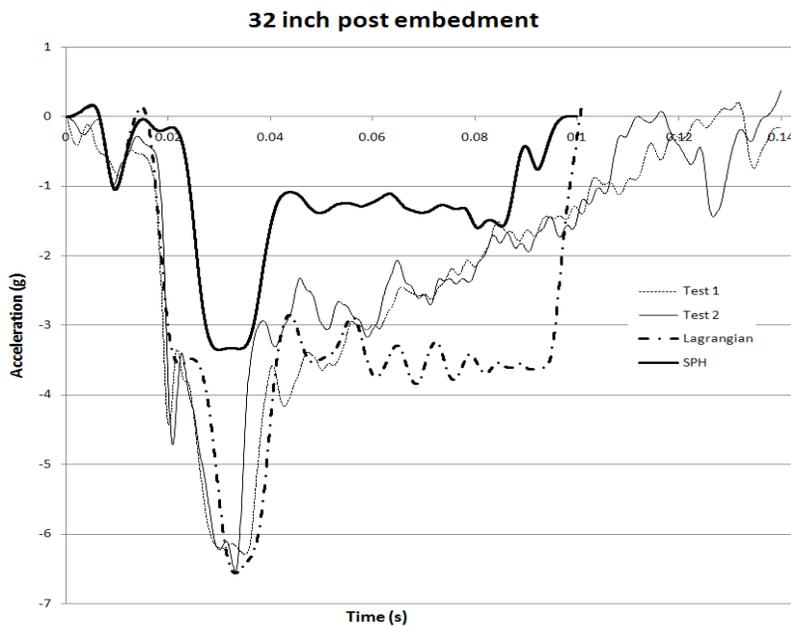
Figure 9: SPH results show same constant deceleration as Lagrangian mesh.

Analysis with Jointed Rock model:

The researchers then evaluated the use of LS-DYNA's Jointed Rock material model (MAT 198) for representing the soil material. Several parameters of the soil model were parametrically varied in an extensive calibration exercise. These included the elastic shear modulus (GMOD), cohesive value (CVAL), angle of friction (PHI), and the angle of dilation (PSI) (LSTC 2009). The calibrations were performed using the model with post embedded 32 inches in soil. Once calibrated, the material properties were used to simulate other post embedments. This material model yielded sufficiently reasonable results. The acceleration-time response measured from the simulation matched the response measured in the tests for all embedment depths of the post. Comparisons of acceleration-time responses are presented in figure 10.

44-inch Embedment
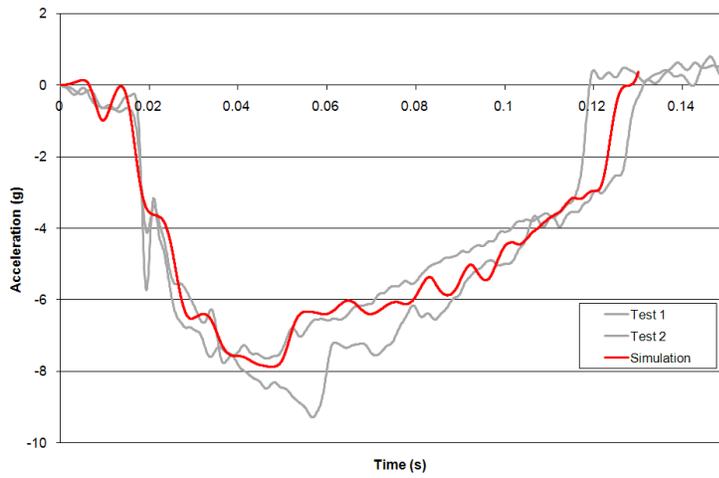
40-inch Embedment
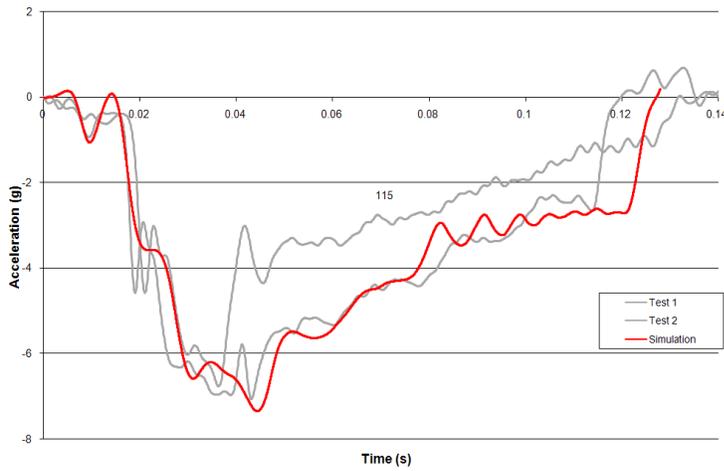
36-inch Embedment
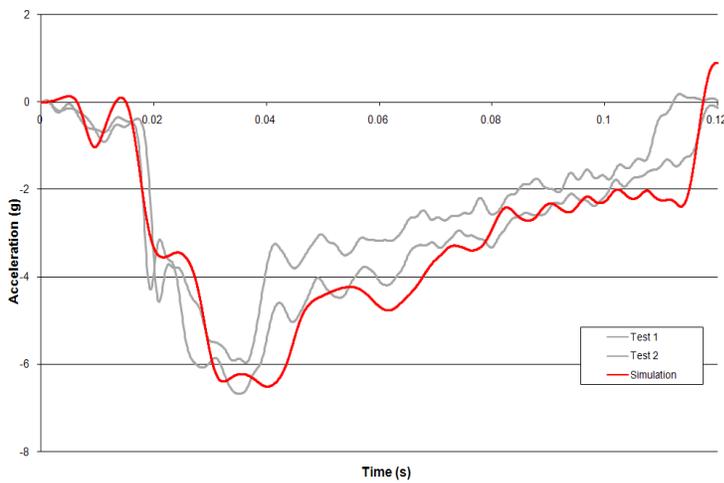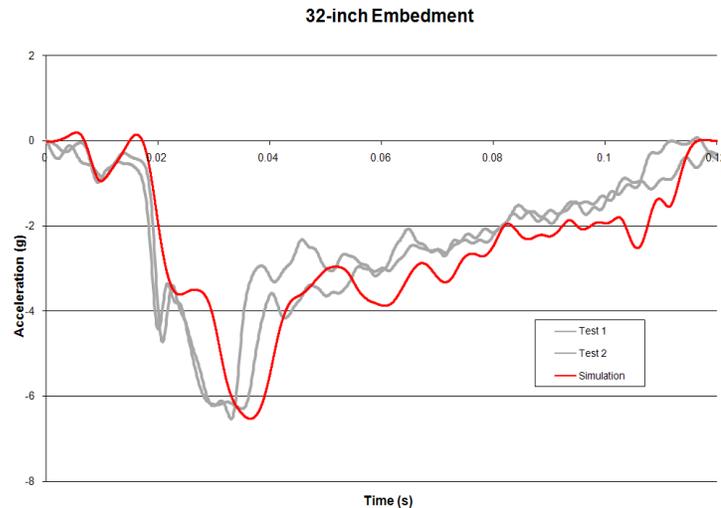
Figure 10: Acceleration-time comparison using Jointed Rock model for various embedment depths.

Conclusions

The research presented in this paper was performed to develop a finite element model of the W-beam guardrail post as it deflects in soil at various embedment depths. A series of dynamic tests were conducted to determine the actual post-soil response of guardrail steel posts installed at various embedments. Once the test data was obtained, finite element model of the post-soil setup was developed. Two material models, Geological Cap and Jointed Rock, were evaluated for modeling the soil. The Geological Cap model showed sufficient correlation with test results at the deeper embedment depth of 44 inches, which resulted in a significantly less deflection of the post in soil. However, as the embedment of the post was reduced (i.e. as post deflection increased in soil), the results of the Geological Cap model deteriorated significantly. The researchers then used the Jointed Rock material model for modeling the soil. It was determined that the Jointed Rock model was able to capture the soil-post interaction for all embedment depths. It can thus be concluded that the Jointed Rock material model is better suited to model soil behavior in cases where the post embedment is reduced and the resulting soil deformation is large.

Acknowledgements

References

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