Coupled Euler–Lagrange modeling of buried structure response to blast loading

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Abstract

A coupled Euler–Lagrange solution approach is used to model blast loading on a buried structure. The coupling algorithm is discussed along with a benchmark calculation.

Keywords: Blast; Buried structures; Coupled codes; Zapotec; CTH; Pronto3D

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1. Introduction

Modeling the response of buried reinforced concrete (RC) structures subjected to close-in detonations of high explosives poses a challenge due to the coupled nature of the problem. Coupling enters the problem when the structure deformation affects the stress state in the neighboring soil, which in turn affects the loading on the structure. There are many approaches for solving the coupled problem (e.g. see Mair [1] for a review of applicable approaches). The focus here is the application of a coupled Euler–Lagrange (CEL) approach.

Herein, the development of the CEL code, Zapotec, is described. Zapotec is well suited for modeling blast/structure interaction as it allows flexibility in handling different portions of the problem using either Eulerian or Lagrangian techniques. For example, the explosive and soil can be modeled as Eulerian as this approach readily handles the shock transmission and large material deformations involved. The RC structure can be modeled using a Lagrangian finite element (FE) method as this allows for detailed modeling of structure components and their response. The application of the Zapotec CEL methodology will be investigated by a benchmark calculation.

2. Coupling algorithm

Zapotec links the CTH and Pronto3D codes. CTH, a shock physics code, performs the Eulerian portion of the calculation, while Pronto3D, an explicit FE code, performs the Lagrangian portion. The two codes are run concurrently with the appropriate portions of a problem solved on their respective computational domains. Zapotec handles the coupling between domains. Both CTH and Pronto3D are well documented (e.g. see McGlaun et al. [2] and Attaway et al. [3]). The remaining discussion will focus on Zapotec.

Zapotec controls both the time synchronization between CTH and Pronto3D as well as the interaction between materials on their respective domains. At a given time t_n, Zapotec performs the coupled treatment. Once this treatment is complete, both CTH and Pronto3D are run independently over the next Zapotec time step. In general, the Pronto3D stable time step will be smaller than that for CTH. When this occurs, Zapotec allows subcycling of Pronto3D for computational efficiency. The subcycling continues until time t_{n+1} is reached, ensuring the two codes are synchronized.

The coupling at time t_n involves getting data from CTH and Pronto3D, working on the data, then passing the updated data back to the two codes. Zapotec first operates on the CTH data, a process termed material insertion. This involves mapping the current configuration (and state) of a Lagrangian body onto the fixed Eulerian mesh. The insertion algorithm determines what portions of a Lagrangian body are overlapping the CTH mesh. State data from the overlapping Lagrangian body are then mapped into the CTH mesh. Mapped data include the mass, momentum, stress, sound speed, and internal energy. In general, a CTH cell will be overlapped by multiple Lagrangian elements. When this occurs, the mapped element quantities are weighted by

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their volume overlap. The weighted quantities are accumulated for all elements overlapping a cell, after which the intrinsic value is recovered for insertion. The inserted data are then passed back to CTH as an update.

Once the material insertion is complete, the external loading on a Lagrangian material surface is determined from the stress state in the neighboring Eulerian material. Since the surface is uniquely defined, it is straightforward to determine the external force on a surface element from the traction vector, element surface normal, and area. After processing each surface element, the element-centered forces are distributed to the nodes and passed back to Pronto3D as a set of external nodal forces. Once the coupled treatment is complete, both CTH and Pronto3D are run independently over the next time step with their updated data.

3. Coupled analysis

The US Army Engineer Waterways Experiment Station conducted a series of experiments, referred to as the Conventional Weapon Effects Backfill (CONWEB) tests, to develop a consistent set of ground shock and structural response data for explosives detonated in differing soils [4]. In these tests, a 7-kg C-4 charge was emplaced 1.52 m from the structure, which was composed of a RC slab bolted to a reaction structure (see Fig. 1). Both the structure and surrounding soil were instrumented. Test 1, which was conducted in clay, will be modeled with Zapotec. This test is of interest since the structure exhibited significant deformation, allowing for a thorough examination of the coupling algorithm. The RC slab used in this test was 4.57 m long, 1.65 m high, and 10.9 cm thick, containing 1.0 percent reinforcement. The slab was bolted to the reaction structure and placed in an excavated test bed, which was then backfilled with clay.

Details regarding the Zapotec analysis can be found in Bessette [5]. Only a summary is provided here. The Zapotec problem setup is composed of three components: the explosive charge, soil, and structure. The charge and soil were modeled as Eulerian, while the structure was modeled as Lagrangian. The CTH mesh encompassed the charge and structure, having a nominal resolution of 3 cm. Soil was inserted throughout the CTH mesh, with void specified above the soil surface and within the structure's interior volume. The mesh contained approximately 1.7 million cells.

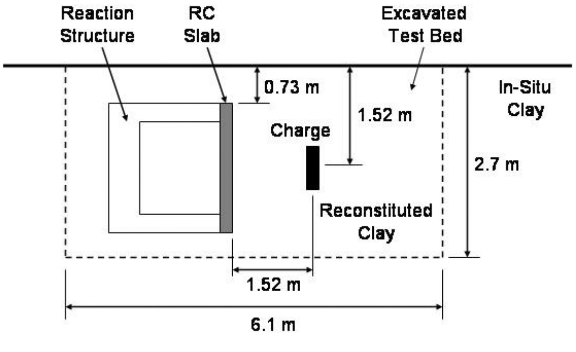

Fig. 1. Experimental setup.

A FE model of the structure was developed, which explicitly modeled the reinforcement and bolted connections using 2-node beam elements. The concrete was modeled using 8-node uniform strain hexahedral elements, having a nominal resolution of 1.9 cm. There were approximately 80,000 elements in the mesh.

In the Zapotec problem setup, the relationship between Eulerian and Lagrangian materials must be defined. This relationship includes a definition of Lagrangian materials that will be mapped into the CTH mesh as well as identifying Lagrangian surfaces that can interact with neighboring Eulerian materials. For this analysis, the concrete in the structure is mapped into the CTH mesh and the structure's exterior surface is defined as an Eulerian contact surface.

The detonation results in a shock being transmitted into the soil. Following the initial shock transmission, a cavity is formed in the soil which is composed of expanding gaseous explosive products. The cavity expands at a much slower rate as compared with the shock velocity. By 2 msec, the shock reaches the structure and it begins to respond. The combination of slab thinness and high shock transmission qualities in the clay results in significant slab deformations (see Figs. 2 and 3). In addition, the structure undergoes a rigid body motion, resulting in an interface loading arising at the rear of the structure.

The calculation was run for 20 msec, the extent of the available test data. The analysis suggests the slab will be breached. The size of the breach could not be determined; however, it was evident there would be extensive damage along the slab center as well as at the end supports near the structure centerline. This is consistent with the damage observed in the test.

Comparisons were drawn with the measured velocity at selected accelerometer locations in the structure. For brevity, only the comparison at location AHS-0 is shown (see Fig. 4). This location resides at the interior surface of the slab directly opposite the charge centroid. The slab velocity was over-predicted, with these results typical of those calculated at other slab locations. Good correlation with the data was noted for gages located in the reaction structure, suggesting Zapotec is providing a good approximation of the loading on the rear surface of the structure.

The reason for the velocity over-prediction is largely

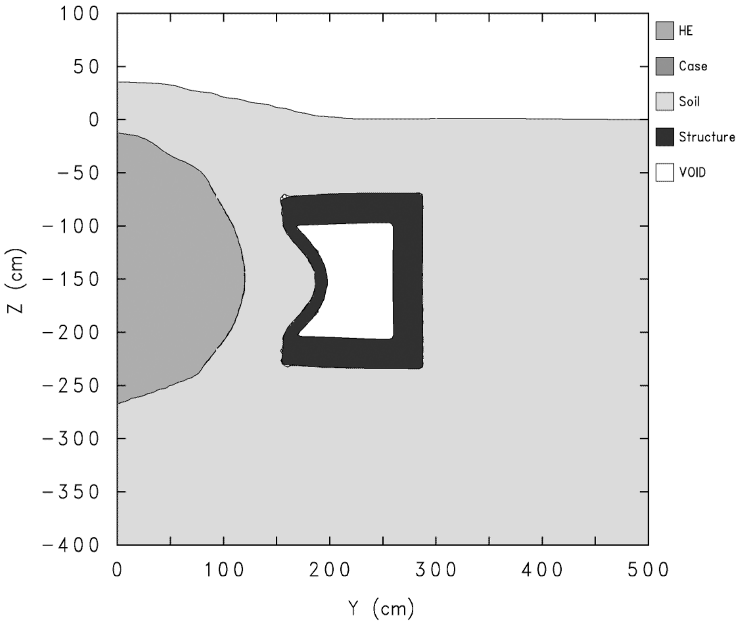

Fig. 2. Material plot at 20 msec.

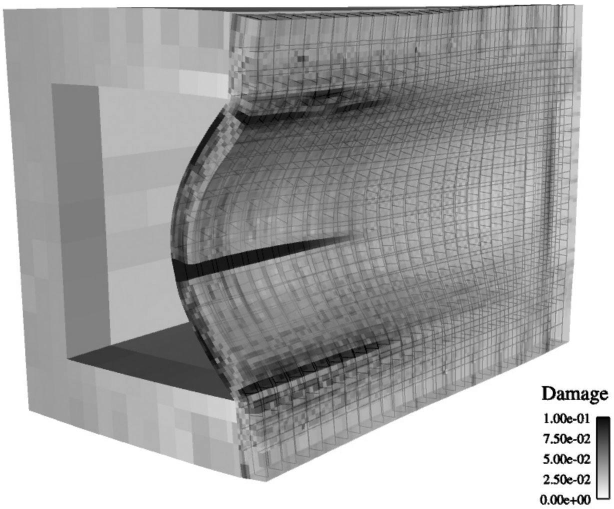

Fig. 3. Deformed structure at 20 msec.

attributed to inaccuracies in soil modeling. The soil model was developed from limited static material data, and calibrated to measured free-field impulse and velocity data. Accordingly, one can only expect an approximation of the dynamic soil response. This conclusion was tested by a parameter study to assess uncertainties associated with modeling the structure (e.g. addressing the influence of mesh resolution and constitutive modeling of structure components) and soil response. Variations in soil modeling exhibited a first-order effect on the analysis.

4. Conclusions

CEL methods are well suited for modeling blast loading on buried structures. The flexibility in choosing which portions of the problem are modeled as Lagrangian or Eulerian is the method's greatest attribute. However, the accuracy of the CEL solution is no better than the sum of its parts. This was illustrated in the benchmark, where variations in soil modeling were found to significantly affect the result.

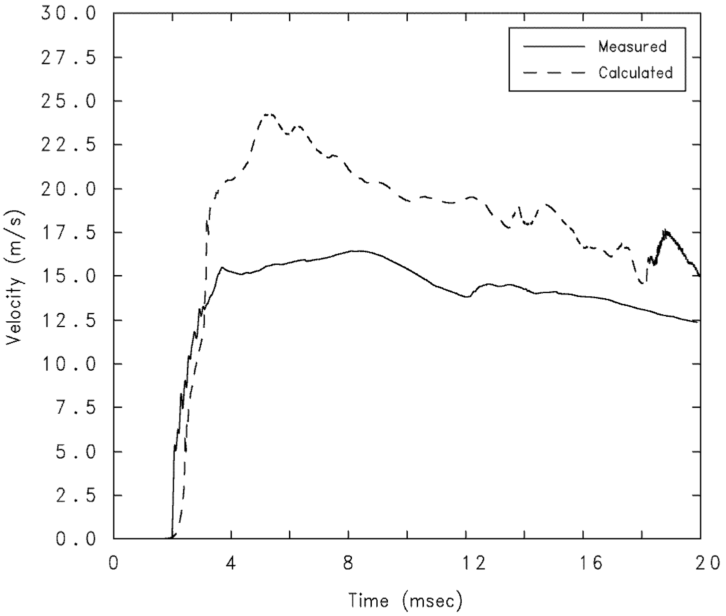

Fig. 4. Velocity at accelerometer location AHS-0.

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