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ASSESSMENT OF STRUCTURAL RESPONSE AND ENERGY DISTRIBUTION IN STEEL AND CONCRETE PIPES BURIED IN DIFFERENT GROUND MEDIA EXPOSED TO SURFACE BLAST

Akinola Johnson Olarewaju[1], Joseph Oladapo Olaoye[2]

[1,2]Civil Engineering Department, Federal Polytechnic Ilaro, Ogun State.

ABSTRACT

This research employs the finite element method to model surface blast loads and predict the response of empty underground pipes. The study examines various responses, including external work, energy, and viscous dissipation within subterranean pipelines. Blast loads of different magnitudes, ranging from 10 kg TNT to 250 kg TNT, are investigated. The Unified Facilities Criteria (2008) guidelines for surface blasts with commonly used explosives are utilized, considering different stand-off distances. The study assumes soil and pipe materials to be elastic, homogeneous, and isotropic, drawing on geotechnical and material properties from existing research and pipe manufacturers. Underground pipe responses to surface blasts are analyzed using the time integration technique in ABAQUS/Explicit, a finite element numerical code. The study observes the external work, energies, and viscous dissipation in underground steel and concrete pipes buried at various embedment ratios in loose sand, dense sand, and undrained clay. The findings suggest that employing loose backfill material around underground pipes may reduce the impact of blast loads on them.

Key Words: Blast, Pipes, Concrete, Steel, Soil, Explicit, Numerical, Analysis

1. INTRODUCTION

Background Study

The destructive potential of blast events is well-documented, with tremors capable of causing extensive damage to substructures across wide areas (Talmadge and Yuasa, 2011). According to Marusek (2008), the severity of destruction caused by explosions varies significantly. Blast waves with an overpressure of 21 kPa have been reported to be lethal to individuals caught in the open, while typical residential structures may collapse under an excess pressure of 35 kPa. Moreover, blast waves exceeding 83kilopascals can reduce large office buildings to rubble, and at 138 kPa, reinforced concrete structures can be completely leveled (Marusek, 2008). An example illustrating the devastating impact of such events is the Ibadan explosion of January 16, 2024, as reported by Punch on February 7, 2024. Given the profound consequences of blast-induced earth tremors, blast events can be likened to artificial earthquakes. This study focuses on evaluating the responses of simulated underground empty pipes to surface blast loads using the finite element numerical code, ABAQUS. The material properties considered, including those of the ground medium, intervening medium, and pipes, are constrained to linear, elastic, homogeneous, and isotropic materials.

The blast effects resulting from an explosion manifest as shock waves comprised of high-intensity pressure waves that emanate outward from the explosive's surface into the surrounding atmosphere. As these waves propagate, they undergo a process of decay in strength, elongation in duration, and reduction in velocity. This evolution occurs due to both spherical divergence and the completion of the chemical reaction, with some residual afterburning attributed to the mixing of hot explosion products with the surrounding air. As the shock wave expands through the air, it encounters structures in its path, subjecting them to the impinging shock pressures. The magnitude and distribution of blast loads exerted on structures by these pressures are contingent upon various factors, including the properties of the explosive (such as type, energy output, and weight), the detonation's proximity to the structure, and the reinforcement of pressure through its interaction with the ground, barriers, or the structure itself (Taylor, 1950; Longinow and Remennikov, 2003; 2009; Unified Facilities Criteria, 2008). The Unified Facilities Criteria (2008) classifies blast loads on structures into two main categories: unconfined explosions, including air and Free air burst, and surface explosions, and confined explosions, which encompass partially and completely Vented, Wilkinson and Anderson (2003), numerous warheads and munitions employ a mix of blast and fragmentation to target damage. These weapons' casings may naturally fragment or lack pre-formed fragments. During fragmentation, a significant portion of the explosive energy is absorbed, reducing the energy available for blast generation. Consequently, a cased weapon typically generates a weaker blast compared to an uncased one with an equivalent mass of high explosive (Unified Facilities Criteria, 2008). Among the six blast loading categories outlined, air burst explosions are infrequent, with free air bursts being the least common. Although these blast loading categories can be individually classified, there are no clear-cut boundaries between them. Most explosive facilities experience overlapping blast environments, requiring judgment in applying recommendations to determine blast parameters consistent with various blast-loading categories (Unified Facilities Criteria, 2008).

Energy output plays a crucial role in Abaqus/Explicit analysis. Comparing different energy components can aid in assessing whether an analysis is providing an appropriate response. An energy balance equation for the entire model can be formulated as:

$$E_I + E_V + E_{FD} + E_{KE} - E_W - E_{PW} - E_{CW} - E_{MW} = E_{total} = \text{constant}, \quad 1$$

In this equation, U represents the internal energy, (Ev) stands for the dissipated viscous energy, (Ef) denotes the dissipated frictional energy, (T) signifies the kinetic energy, (W_{ext}) represents the work done by externally applied loads, and (W_C), (W_{con}), and (W_{ma}) are the works done by contact penalties, constraint penalties, and propelling added mass, respectively. The total energy sum is (E_{total}), which ideally remains constant. In numerical modeling, (E_{total}) is approximately constant, typically with an error of less than 1%. The internal energy comprises the recoverable elastic strain energy ($U_{elastic}$)), the energy dissipated through inelastic processes such as plasticity ($U_{plastic}$), the energy dissipated through viscoelasticity or creep ($U_{viscoelastic}$), and the artificial strain energy ($U_{artificial}$).

$$E_I = E_E + E_P + E_{CD} + E_A. \quad 2$$

The artificial strain energy encompasses the energy stored within hourglass resistances and transverse shear in shell and beam elements. Elevated values of artificial strain energy signal the need for mesh refinement or other adjustments to the mesh structure. Viscous energy, on the other hand, represents the energy dissipated by damping mechanisms, which include bulk viscosity damping and material damping. Unlike the energy dissipated through viscoelasticity or inelastic processes, viscous energy is a key variable in the global energy balance. The external work performed by applied forces undergoes continuous forward integration, dictated entirely by nodal forces (moments) and displacements (rotations).

Table 1: Whole model energy output variables.

Energy Quantity
Internal energy, E_I :ALLIE = ALLSE + ALLPD + ALLCD + ALLAE.
Kinetic energy, E_{KE}.
Viscous dissipated energy, E_V.
Frictional dissipated energy, E_{FD}.
Energy dissipated by viscoelasticity, E_{CD}.
Work of the external forces, E_W.
Work done by contact penalties, E_{PW}.
Work done by constraint penalties, E_{CW}.
Work done by propelling added mass (due to mass scaling), E_{MW}.
Stored strain energy, E_E.
Inelastic dissipated energy, E_P.
Artificial strain energy, E_A.
Energy balance: $E_{TOT} = E_I + E_V + E_{FD} + E_{KE} - E_W - E_{PW} - E_{CW} - E_{MW}$.

Prescribed boundary conditions also influence the external work calculation. In energy balance output, each energy quantity can be requested and plotted as time histories aggregated over the entire model, specific element sets, individual elements, or as energy density within each element. The variable names associated with energy quantities summed over the entire model or element sets are outlined in Table 1. Additionally, Abaqus/Explicit provides element-level energy output and energy density output, detailed in Table 2.

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Table 2: Whole element energy output variables

Whole Element Energy Quantity
Elastic strain energy.
Plastic dissipated energy.
Creep dissipated energy.
Viscous dissipated energy.
Artificial energy = drill energy + hourglass energy.
Kinetic energy density in the element.
Elastic strain energy density in the element.
Plastic energy density dissipated in the element.
Artificial strain energy density in the element.
Creep strain energy density dissipated in the element.
Viscous energy density dissipated in the element.

2. METHODOLOGY

For this study, an infinite soil medium consisting of loose sand, dense sand, and undrained clay, each measuring 100 meters in length, 100 meters in width, and 100 meters in depth, was modeled. Additionally, underground steel and concrete pipes, also measuring 100 meters in length, with thicknesses of 10 mm and 20 mm respectively, and having an external diameter of 1 meter, were simulated. These pipes were surrounded by an intervening medium with an internal diameter of 1 meter and a thickness of 0.15 meters. The diagram depicting the underground pipe's response to surface blast is presented in Figure 1. A comprehensive analysis was conducted using ABAQUS/Explicit. The soil and pipe properties utilized are detailed in Table 3, drawing from various sources (Craig, 1994; Coduto, 2001; Das, 1994; FLAC, 2000; Kameswara, 1998; Gravessmith, 1985; Shacklock, 1974).

In the design and assessment of structures to withstand accidental explosions, blast pressures typically govern the structural response, as per Unified Facilities Criteria (2008), Remennikov (2003, 2009), and Longinow and Mniszewski (1996). The blasts are assumed to occur vertically above the ground at the center of the model. Initially, the blast pressures are represented as 2 x 10^6 Pa and later increased to 2 x 10^7Pa. These values correspond to blast pressures generated by a 250 kg TNT explosive detonating very close to the ground surface. The model consists of hexahedral elements, totaling 416 elements. In the analysis of blast constituents for studying the response of underground pipes to blast loads, a global stable increment estimation approach was employed. The time incrementation scheme utilized in ABAQUS/Explicit is fully automated, requiring no user intervention. Initially, it utilizes element-by-element estimates. As the analysis progresses, the stability limit is determined from the global estimator once the algorithm deems the accuracy of the global estimation acceptable (ABAQUS Analysis Manual, 2009). In this study using ABAQUS/Explicit, the computation occurs automatically, and if the accuracy is deemed unacceptable, the analysis will terminate.

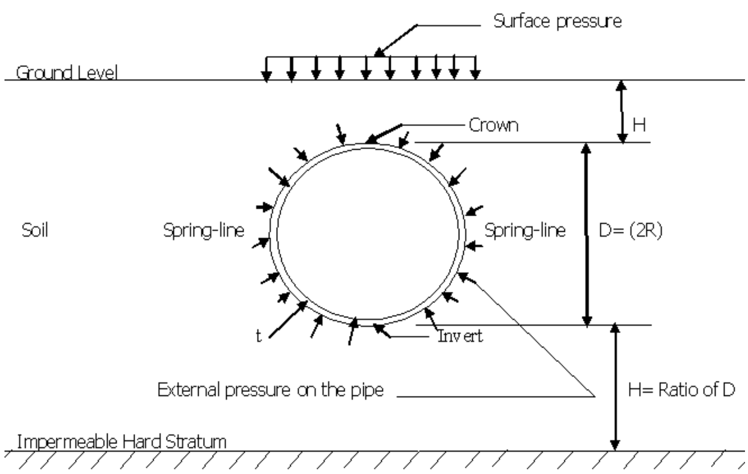

Figure 1: Cross-section of underground pipe under surface blast

Table 3: Material properties for surface and underground blast models

Material	Density, ρ (kg/m³)	Young's Modulus, E (kPa)	Poisson's Ratio, υ
Loose sand	1700	18500	0.3
Dense sand	1840	51500	0.375
Undrained Clay	2060	10000	0.5
Intervening medium	1750	19500	0.3
Steel pipe	7950	200 x 10^6	0.3
Concrete pipe	2500	28 x 10^6	0.175

The interface between the soil and pipe was defined with a 'no slip' condition, implying a perfect bond between them. This assumption suggests an ideal connection between the two materials. Both the soil and pipe materials were characterized as linear, homogeneous, and isotropic, drawing upon material properties sourced from various researchers and pipe manufacturers, as per Kameswara (1998). Boundary conditions were established in accordance with global Cartesian axes principles, following guidelines outlined in Geotechnical Modelling and Analysis with ABAQUS (2009). Analysis procedures adhered to the guidelines outlined in the ABAQUS Analysis User's Manual (2009), with variations in parameters considered. Simulated models underwent analysis by solving the governing equation of motion, as presented in Equation 3, incorporating initial conditions. This was achieved through the utilization of the time integration technique within the finite difference scheme of ABAQUS/Explicit.

$$[m][\ddot{U}] + [c'][\dot{U}] + [k][U] = [P] \quad 3$$

In the equation provided, (m), (c'), (k), (U), and (P) represent the global mass matrix, global damping matrix, global stiffness matrix, displacement, and load vectors respectively. The dots denote their time derivatives, as referenced in sources such as Kameswara (1998) and the ABAQUS Analysis User's Manual (2009). The parameters under observation include external work, energies, and viscous dissipation, all embedded within loose sand, dense sand, and undrained clay. These observations form a crucial aspect of the study's analysis.

RESULTS AND DISCUSSION

The study presents the findings of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from surface accidental explosions in 10 mm and 20 mm steel pipe and concrete pipes buried in different ground media. These results are depicted in Figures 2 to 13, respectively. Upon examination of the results, it is observed that the total energy of pipes buried in loose sand (as shown in Figures 8 and 9) reveals distinct characteristics between 20 mm steel pipes and 20 mm concrete pipes. This disparity suggests that the material properties of steel pipes, particularly in terms of stiffness and density, contribute to their ability to absorb energy compared to concrete pipes, especially when buried in loose sand. However, for pipes buried in other ground media, no significant variation in external works, energies, and viscous dissipation is evident. This indicates a consistent response across different ground conditions.

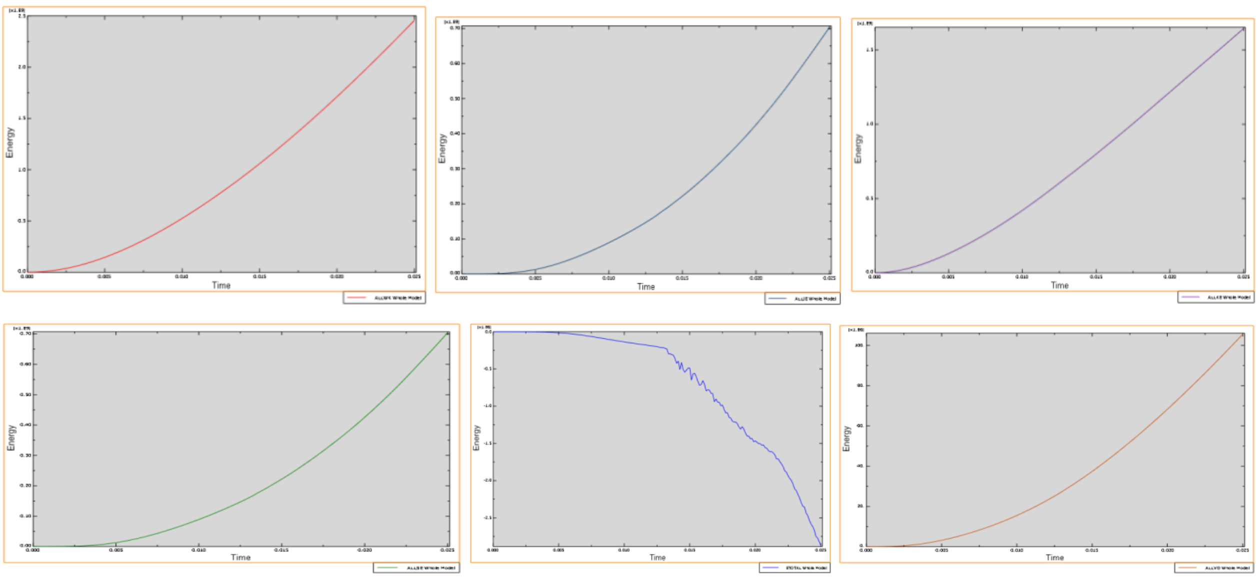

Figure 2 illustrates the various energy components generated in a 10 mm steel pipe buried in loose sand as a result of a surface accidental explosion. These components include external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation. This visualization provides insights into how different types of energy are distributed and interact within the pipe structure under these specific conditions.

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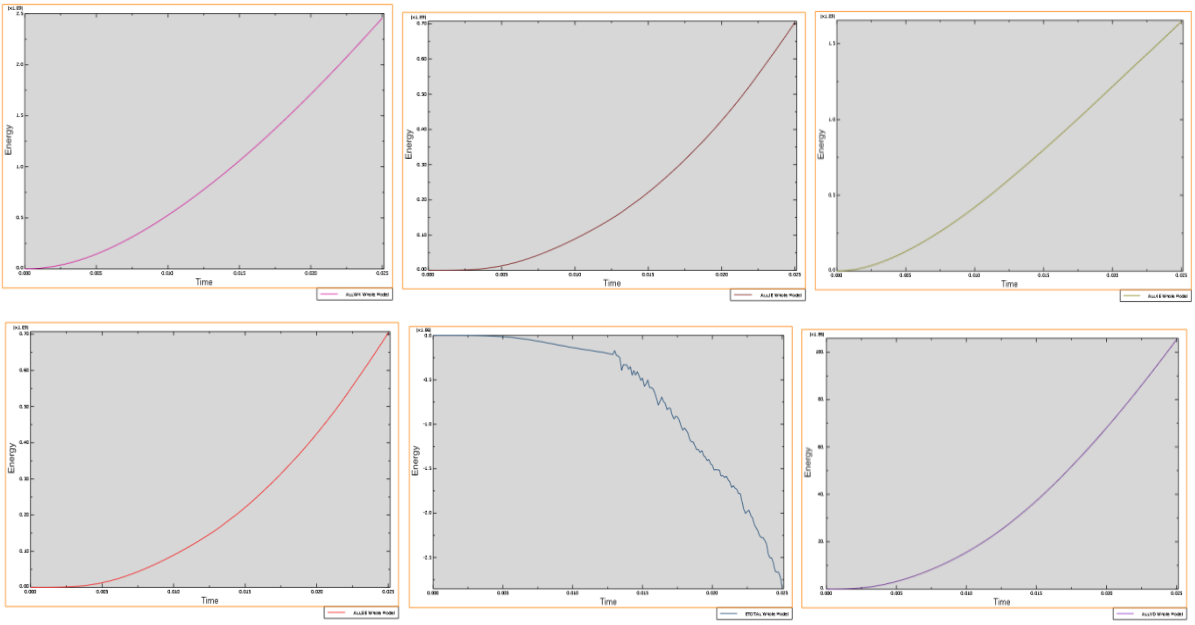


Figure 3 depicts the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 10 mm concrete pipe buried in loose sand. This visualization offers insights into the energy dynamics within the concrete pipe under these specific conditions, facilitating a comprehensive understanding of its response to the explosion.

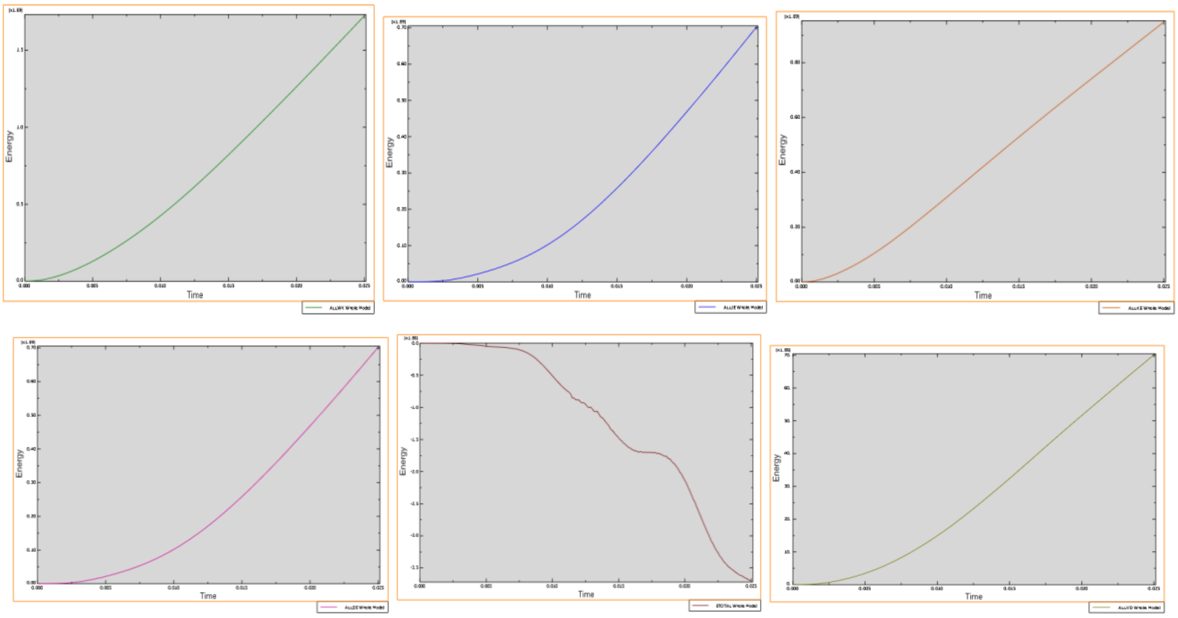
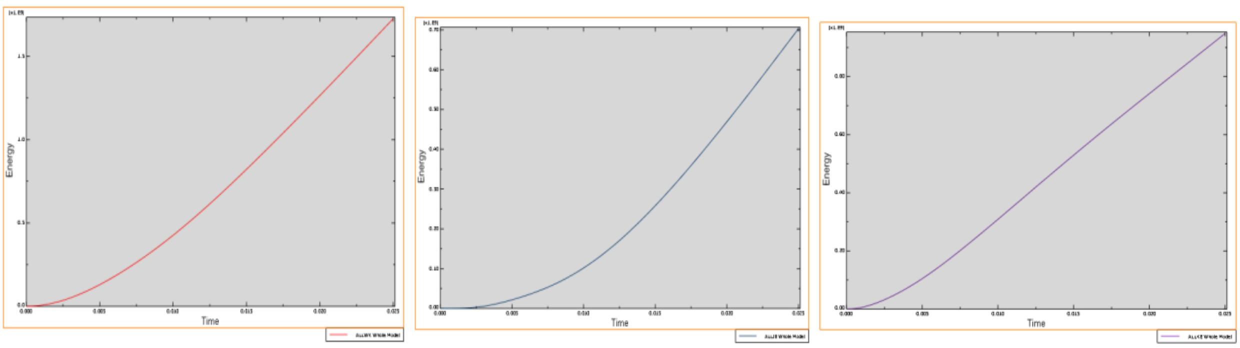


Figure 4, it was observed that the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 10 mm steel pipe buried in dense sand. This visualization provides a detailed overview of how these energy components interact within the steel pipe under the specific conditions of dense sand burial, offering valuable insights for analysis and interpretation.



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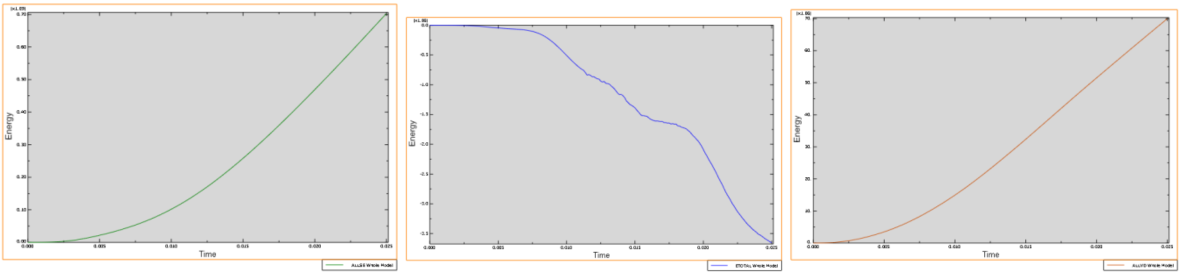


Figure 5, the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation is presented for a 10 mm concrete pipe buried in dense sand following a surface accidental explosion. This visualization offers a comprehensive depiction of how these energy components are distributed within the concrete pipe under the specific conditions of dense sand burial, providing valuable insights for understanding its response to the explosion.

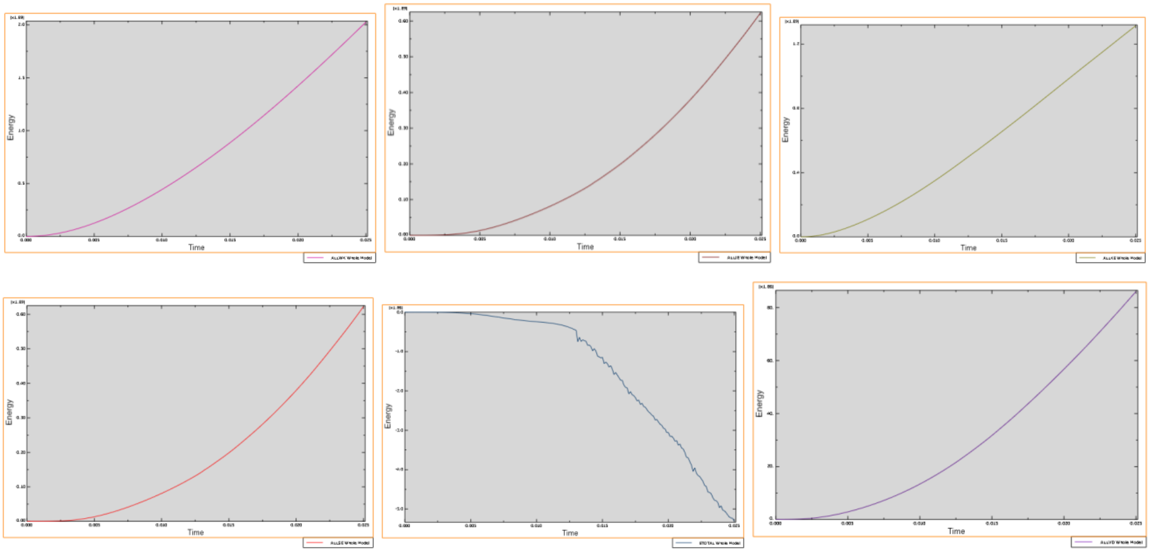


Figure 6 illustrates the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 10 mm steel pipe buried in undrained clay. This visualization provides a comprehensive understanding of how these energy components interact within the steel pipe under the specific conditions of undrained clay burial, offering valuable insights for analysis and interpretation.

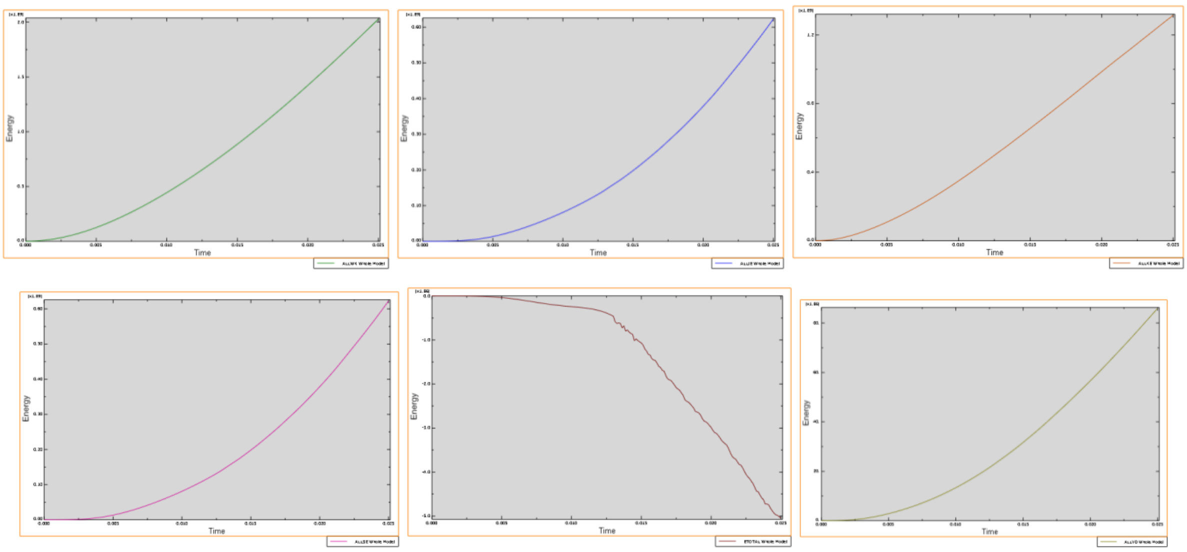


Figure 7, the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation is presented for a 10 mm concrete pipe buried in undrained clay following a surface accidental explosion. This visualization provides a comprehensive depiction of how these energy components are distributed within the concrete pipe under the specific conditions of undrained clay burial, offering valuable insights for understanding its response to the explosion.

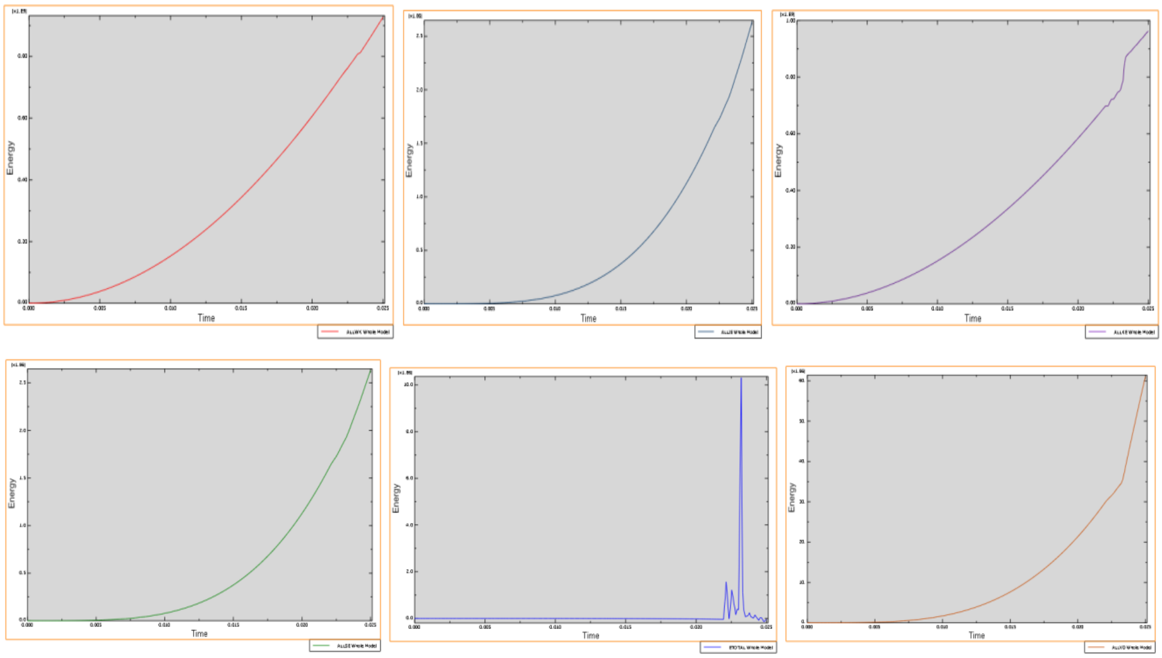


Figure 8 displays the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 20 mm steel pipe buried in loose sand. This visualization provides a detailed overview of how these energy components interact within the steel pipe under the specific conditions of loose sand burial, offering valuable insights for analysis and interpretation.

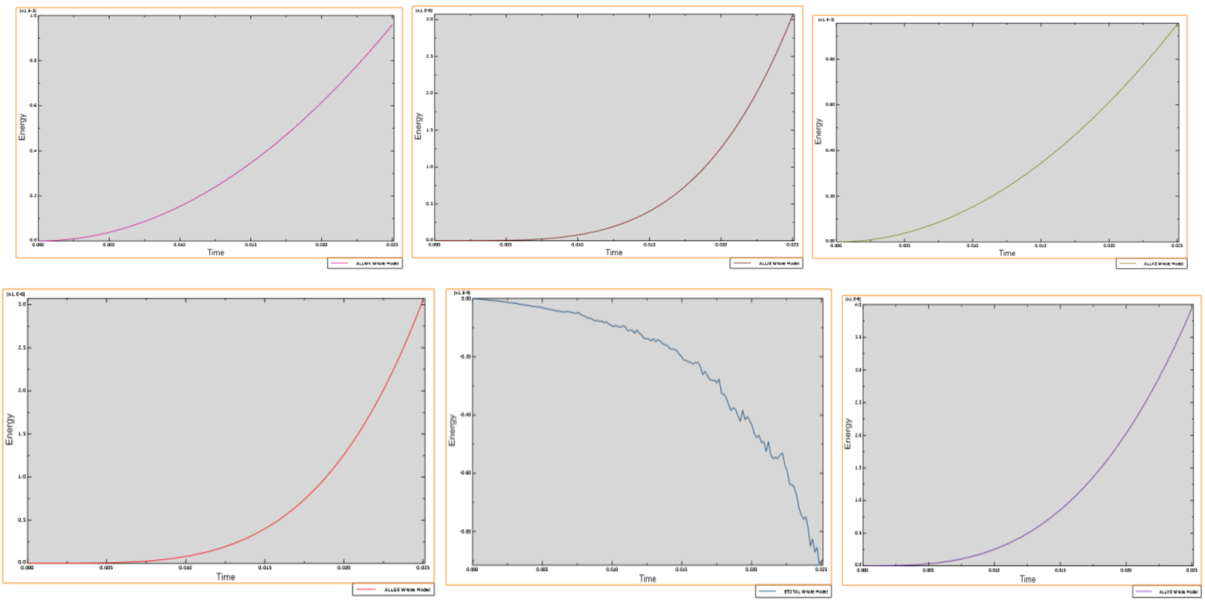
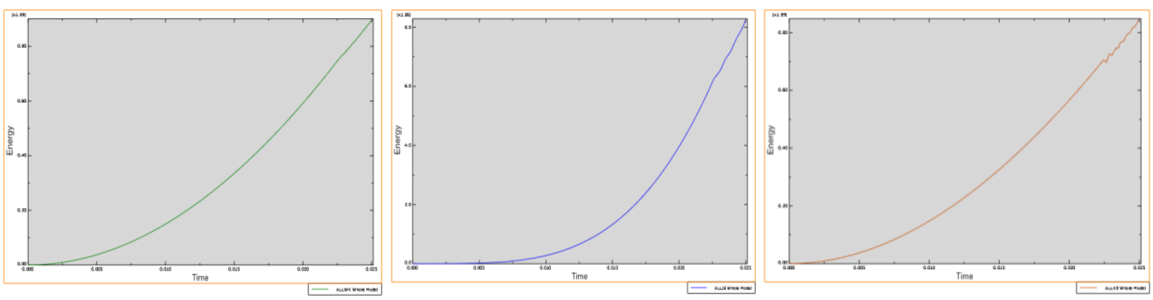


Figure 9 showcases the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 20 mm concrete pipe buried in loose sand. This visualization provides a comprehensive depiction of how these energy components are distributed within the concrete pipe under the specific conditions of loose sand burial, offering valuable insights for understanding its response to the explosion.



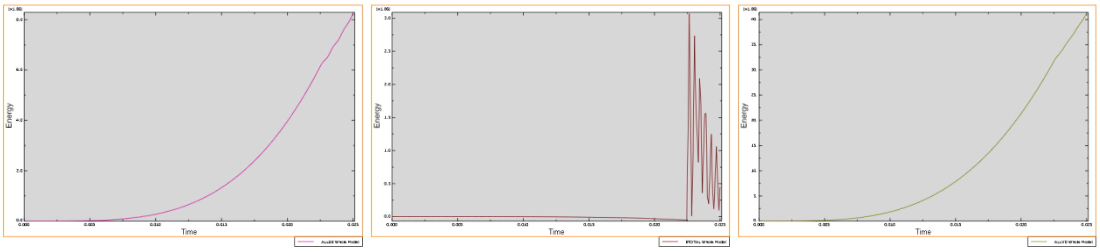


Figure 10 presents the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 20 mm steel pipe buried in dense sand. This visualization offers a detailed insight into how these energy components interact within the steel pipe under the specific conditions of dense sand burial, providing valuable information for analysis and interpretation.

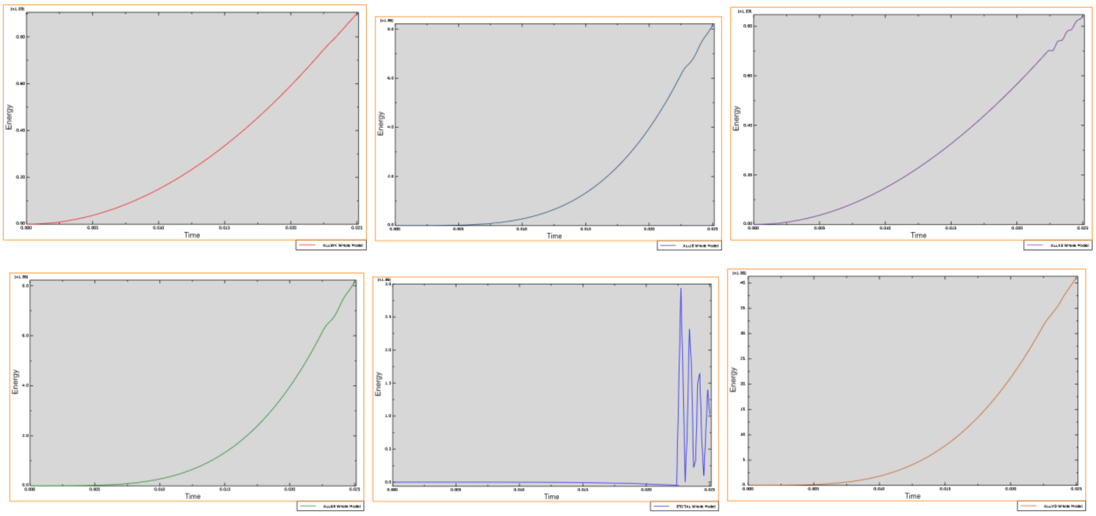


Figure 11, the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 20 mm concrete pipe buried in dense sand is presented. This visualization offers a comprehensive depiction of how these energy components are distributed within the concrete pipe under the specific conditions of dense sand burial, providing valuable insights for understanding its response to the explosion.

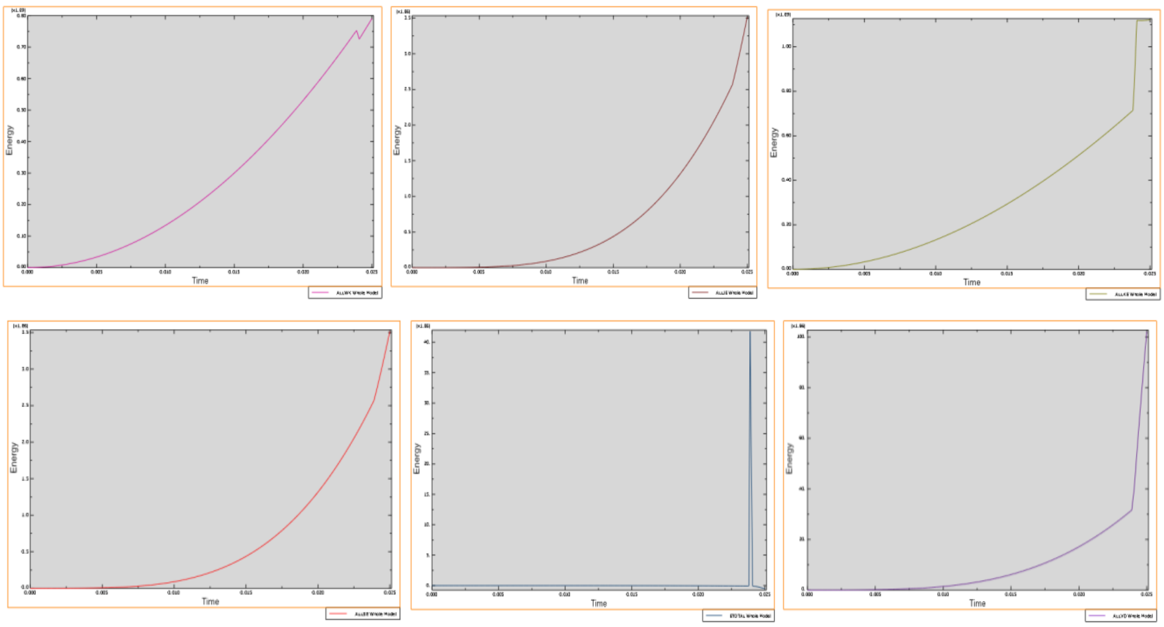


Figure 12 illustrates the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dissipation resulting from a surface accidental explosion in a 20 mm steel pipe buried in undrained clay. This visualization provides a comprehensive understanding of how these energy components interact within the steel pipe under the specific conditions of undrained clay burial, offering valuable insights for analysis and interpretation.

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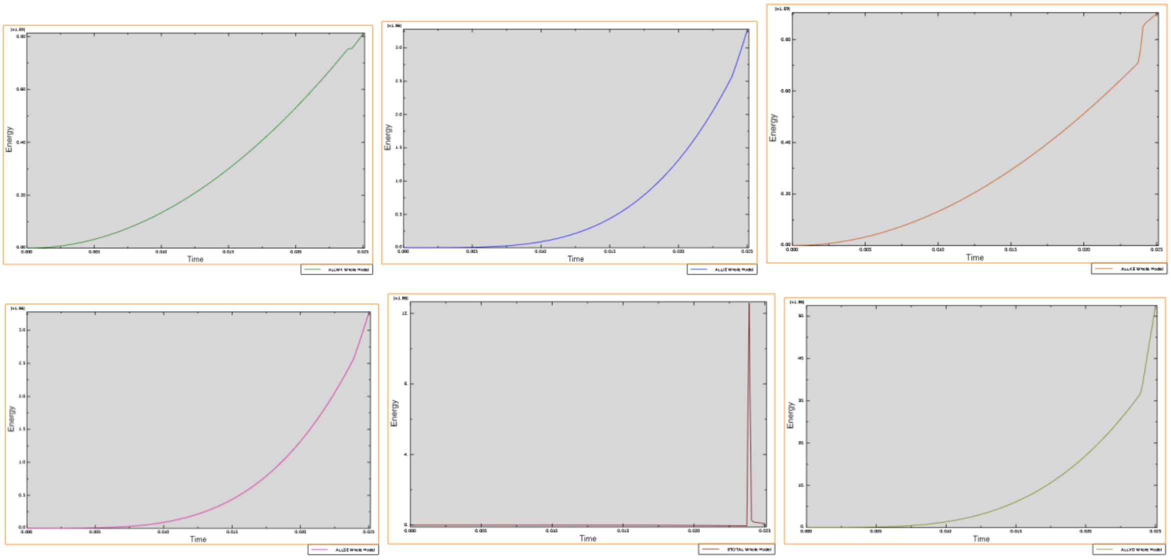

Figure 13, we observe the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dispersion resulting from a surface accidental explosion in a 20 mm concrete pipe buried in undrained clay. This visualization offers valuable insights into how these energy components are distributed within the concrete pipe under the specific conditions of undrained clay burial, facilitating a comprehensive understanding of its response to the explosion.

3. CONCLUSION

This study comprehensively investigated the distribution of external work, internal energy, kinetic energy, strain energy, total energy, and viscous dispersion generated in 20 mm concrete pipes buried in various ground media following surface accidental explosions. Our findings reveal intriguing insights into the response of these pipes under different burial conditions. Notably, pipes buried in loose sand exhibited the least response, attributed to the arching effects observed in this ground medium. This suggests that loose materials could serve as effective mitigating materials against the detrimental effects of surface blast on underground pipes.

These findings underscore the importance of considering the specific ground conditions when assessing the vulnerability of underground infrastructure to accidental explosions. Furthermore, they provide valuable guidance for the development of strategies aimed at enhancing the resilience of such infrastructure in the face of unforeseen events. Future research endeavors could delve deeper into exploring the effectiveness of various mitigation measures and their applicability in real-world scenarios.

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