VIBRATION RESPONSE IN PILE FOUNDATION EMBEDDED IN SOIL DUE TO UNDERGROUND EXPLOSION

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VIBRATION RESPONSE IN PILE FOUNDATION EMBEDDED IN SOIL DUE TO UNDERGROUND EXPLOSION

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ABSTRACT

This paper illustrates the analytical methodology to evaluate the effects of a gaseous explosion in a deeply embedded concrete chamber on existing structures and foundation in the vicinity. The explosion generates an instantaneous high-pressure wave inside the chamber, which results in stress waves in and deformation of the chamber walls. The stress waves subsequently propagate into the surrounding soil medium. The paper evaluates the dynamic effects of the explosion on the surrounding soil medium and a foundation pile in the immediate vicinity. The evaluation is divided into first constructing the analytical model and then performing the dynamic analysis using the software program ABAQUS (version 6.12). The overall model terminates in the external soil mass and measures 10 meters (m) x 6 m x 6 m, within which is located a 5-m x 3-m x 3-m chamber enclosed by 25-centimeter (cm) -thick concrete walls. The model consists of Lagrangian solids representing the air space interior to the chamber (4.5 m x 2.5 m x 2.5 m), plate elements for the chamber walls, and solid elements (C3D8R) for the surrounding soil mass. The explosive detonation is characterized by a charge equivalent to 0.50 cubic meters of TNT at the center of the interior air space. All material data are based on published literature (Nagy et al., 2009; Ambrosini et al., 2002). The solution is performed in the Explicit Domain to obtain the effects on a pile. After the analysis using ABAQUS was completed, a similar model was built and analyzed, using ANSYS software (version 13) as a check, and the results were compared. The analysis predicts excessive stresses in the concrete walls as well as the soil mass and also predicts partial loss of pile frictional resistance.

INTRODUCTION

Evaluation of the effects of potential underground explosions remains a subject of concern for mining and tunneling projects. For example, metro tunnels in urban environments are often located at significant depths below grade to avoid regions of the subsurface that are congested with existing utilities and other construction. Due to space limitations and high compensation liability for damage to existing structures, the prediction of blast-induced response in soils and embedded structures remains a vital and indispensable requirement.

This paper develops the dynamic response of a foundation pile located in the vicinity of a postulated explosion in an underground chamber. The underground chamber measures 5 m x 3 m x 3 m and is enclosed by 2-cm-thick concrete walls. The analytical model consists of a 0.5-m x 1-m x 1-m solid explosive element placed at the center of the air space in the chamber, Lagrangian tetrahedral elements representing the volume of air inside the chamber, and 3D soil elements in a 10-m x 6-m x 6-m box surrounding the concrete chamber, representing the infinite soil mass. A 0.5-m-diameter concrete foundation pile is placed in the soil mass at a distance of 3.5 m from the center of the concrete chamber.

The physics of the interaction of the soil with the chamber concrete and the foundation pile is represented by surface-to-surface contacts using the contact option in ABAQUS. The contacts between air and the chamber concrete and between air and the explosive element are considered to be frictionless. This Arbitrary Lagrangian-Eulerian (ALE) finite element formulation is analyzed for explosion-induced response in soil at various sections of the composite model to examine the possibility of caving, liquefaction of soil, and peak particle velocity of soil below the foundation level. The analysis is performed using the Explicit Technique in ABAQUS 6.12. Figure 1 and Figure 2 show the model features and dimension and the number of elements in each part. The analysis is terminated at 0.039 seconds (sec) from start due to excessive distortions in the explosive element. All of the output generated from the analysis is examined and evaluated here. Figure 3 presents the stress time history at the nodes of the chamber concrete identified in Figure 2.

MATERIAL MODEL

The material model for the air and the TNT explosive elements is shown in Table 1. Similarly, Table 2 presents the material model for the soil elements, and Table 3 presents the material model for the chamber concrete. The material data for the air and explosive elements are generic and taken from published literature. The material data for the soil and concrete are taken from the work of Nagy et al. (2009), which is based on experimental data. The equations of state for the solid elements representing the explosive, air, and soil assume that adiabatic transformations do take place under excessive heat and pressure to some extent in the soil medium, and more severely, in the air and explosive elements.

Table 1. Material model data for air and explosive elements.

MATERIAL	TYPE	PROPERTY	VALUE	UNIT
Air	Density	Mass density	1.293	kg/m^3
	EOS	Specific gas constant	287	J/(kg·K)
		Ambient pressure	101325	N/m^3
	Specific heat	Specific heat	717.6	J/(kg·K)
	Viscosity	Viscosity	$6.924 \cdot 10^{-6}$ at 100.0K	kg/(m·s)
	Initial state	Specific energy	193300	J/kg
		Ambient pressure	101325	N/m^2
TNT	Density	Mass density	1630	kg/m^3
	JWL Eos	Detonation wave speed	6930	m/s
		A	373770000000	N/m^2
		B	3747100000	N/m^2
		w	0.35	-
		R_1	4.15	-
		R_2	0.9	-
		Detonation energy density	0.0	J/kg
		Pre-detonation bulk modulus	0.0	N/m^2
	Initial state	Specific energy	3680000	J/kg
		Ambient pressure	101325	N/m^2

The equation of state (EOS) for air assumes that it is an ideal gas. Additionally, the EOS for the TNT also assumes an ideal gas, as recommended by the Jones-Wilkens-Lee (JWL) model with standard parameters.

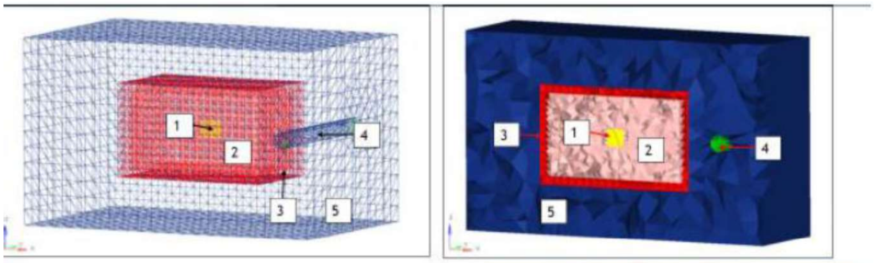
Table 2. Material model data for soil.

PARAMETER	VALUE
Young's Modulus (E)	51.7 MPa
Poisson's Ratio (ν)	0.45
Density (ρ)	1750 kg/m^3
Material Cohesion (d)	0.036
Material Angle of Friction (β)	30°
CAP Eccentricity Parameter (R)	0.3
Initial CAP Yield Surface Position (ε_V)	0.02
Transition Surface Radius Parameter (α)	0.05
CAP Hardening Behavior (Stress vs. Plastic Volumetric Strain)	2.75 MPa, 0.00
	4.83 MPa, 0.02
	5.15 MPa, 0.04
	6.20, MPa 0.08

Table 3. Material model data for concrete.

THE PARAMETERS OF CDP MODEL		VALUE	
Young's modulus E (GPa)		19.7	
Poisson's ratio (ν)		0.19	
β		38°	
Flow potential eccentricity (ε)		1	
s_{b0}/s_{c0}		1.12	
K_c		0.666	
CONCRETE COMPRESSION HARDENING		**CONCRETE COMPRESSION DAMAGE**	
Stress (Pa)	**Crushing Strain**	**Damage**	**Crushing Strain**
$15.0 \cdot 10^6$	0.0	0.0	0.0
$20.197804 \cdot 10^6$	0.0000747307	0.0	0.00007477307
$30.000609 \cdot 10^6$	0.0000988479	0.0	0.0000988479
$40.303781 \cdot 10^6$	0.000154123	0.0	0.000154123
$50.007692 \cdot 10^6$	0.000761538	0.0	0.000761538
$40.236090 \cdot 10^6$	0.002557559	0.195402	0.002557559
$20..236090 \cdot 10^6$	0.005675431	0.596382	0.00567431
$5.257557 \cdot 10^6$	0.011733119	0.894865	0.011733119
CONCRETE TENSION STIFFENING		**CONCRETE TENSION DAMAGE**	
Stress (Pa)	**Cracking Strain**	**Damage**	**Cracking Strain**
$1.99893 \cdot 10^6$	0.0	0.0	0.0
$2.842 \cdot 10^6$	0.00003333	0.0	0.00003333
$1.86981 \cdot 10^6$	0.000160427	0.406411	0.000160427
$0.862723 \cdot 10^6$	0.000279763	0.69638	0.000279763
$0.226254 \cdot 10^6$	0.000684593	0.920389	0.000684593
$0.056576 \cdot 10^6$	0.00108673	0.980093	0.00108673

The soil medium is taken to consist of dry brown clay with soil classification CL (ABAQUS, 2012). The soil behavior is modeled by an elastic-plastic Drucker-Prager cap model, as described by ABAQUS (2012). The modified Drucker-Prager/cap plasticity/creep model is intended to model cohesive geological materials that exhibit pressure-dependent yield, such as soils and rocks, and is based on the addition of a cap yield surface to the Drucker-Prager plasticity model ("Extended Drucker-Prager models," Section 23.3.1). This model provides an inelastic hardening mechanism to account for plastic compaction and helps to control volume dilatancy when the material yields in shear. Similarly, concrete has been modeled as concrete damaged plasticity (CDP), as described by ABAQUS (2012).



1. RDX - (0.5m x 0.5m x 0.5m)
2. Air - (4.5m x 2.5m x 2.5m)
3. Concrete - (5.0m x 3.0m x 3.0m , thickness 0.25 m)
4. Pile - (dia. = 0.5m , length = 5.0 m)
5. Soil - (10.0m x 6.0m x 6.0m)

Note:- Friction Contacts are simulated between the parts.

Part	Element Type	No. of Nodes	No. of Elements
RDX	C3D8R	1331	1000
Air	C3D4	5148	26071
Concrete	C3D4	3228	12818
Pile	C3D4	156	459
Soil	C3D4	3648	16807

Figure 1. Mathematical model of the infinite soil mass, concrete chamber, and embedded pile.

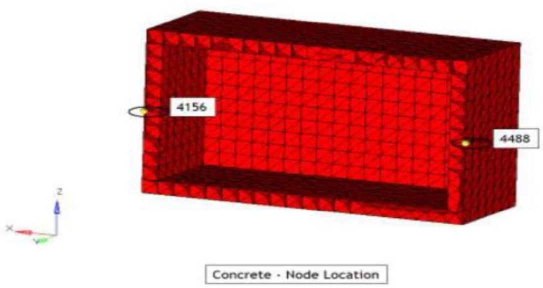


Figure 2. Concrete chamber meshed in tetrahedron element showing nodes for mapping the stress.

VIBRATION RESPONSE DUE TO UNDER GROUND EXPLOSION.

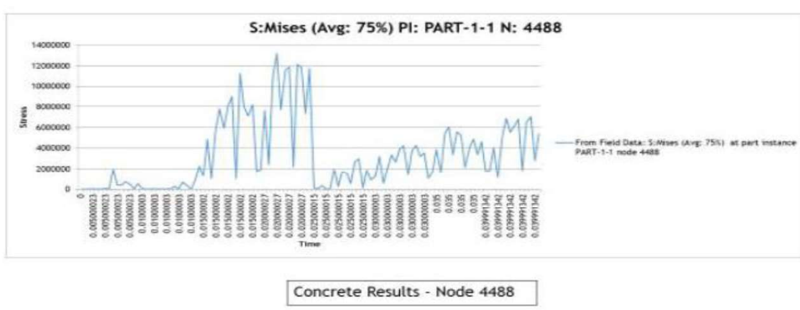


Figure 3. Stress time history for concrete chamber.

RESPONSE OF THE CHAMBER CONCRETE

Propagation of the pressure wave in the enclosed chamber is determined by the size of the chamber. For a given explosive energy, the initial pressure predicted by the JWL equation of state increases with increasing relative volume, assuming that hemispherical or cylindrical pressure pulse can be produced if the enclosure volume is sufficiently large. When the relative volume is small, these pressure pulses are not produced.

In general, the explosive loading generates stresses in the wall concrete and deformations of the walls due to incident and reflected pressure waves. With reference to Figure 3, the peak tensile stress in concrete of 12 megapascal (MPa), at Node 4458, occurs at 15 milliseconds (ms) to 25 ms after going through at least 4 to 5 load-reversal cycles. Subsequently, concrete strain hardening is observed to initiate at 26 ms and continues to rise up to 0.040 sec, with a peak stress of 6 MPa.

Because the CDP model in ABAQUS does not allow element erosion, the analysis predicts that all of the chamber concrete enters the plastic range. An independent ANSYS (version 13) analysis of the model with minor variations in material data also shows the concrete degradation phenomenon experienced under similar blast-load conditions and verifies the ABAQUS results.

RESPONSE OF THE FOUNDATION PILE

The modeled pile is one of several piles and is representative of a pile foundation embedded in the soil mass near the explosive source. The study assumes that the pile foundation consists of friction piles where the foundation load is transferred to the soil by frictional resistance at the pile-soil interface, mobilized from the pile-driving process. ABAQUS represents the pile-soil interface by surface-to-surface contact with a friction coefficient of 0.45 and incorporates penalty due to mechanical constraint. The pile stresses due to the explosive detonation are examined at two nodes, located at either ends of the modeled pile length, as shown in Figure 4. These pile stresses are presented in Figure 5 and Figure 6. The maximum von Mises stresses at nodes 14671 and 14562 are respectively 5 MPa and 6.75 MPa. Eventually, as the stress waves transmitted into the soil attenuate, the pile stresses diminish, ranging from 2.5 MPa to 3.0 MPa. The stresses sustained by the foundation pile exceed the allowable tensile strength of concrete, which is 1.99 MPa, indicating significant distress due to cracking and degradation of structural integrity.

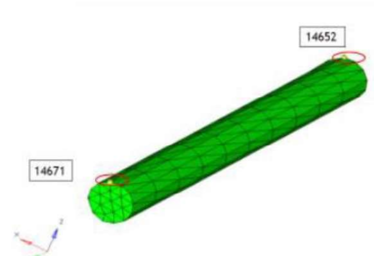


Figure 4. Concrete pile with meshing showing location of nodes.

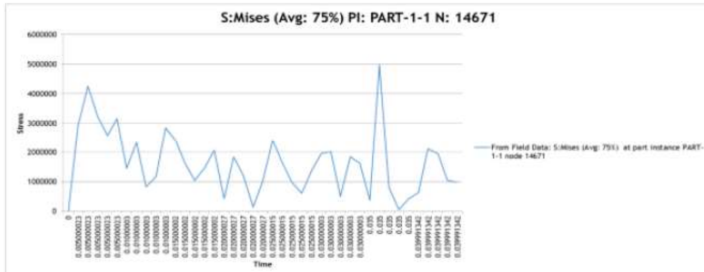


Figure 5. Pile stress mapping with time for Top Node 14671.

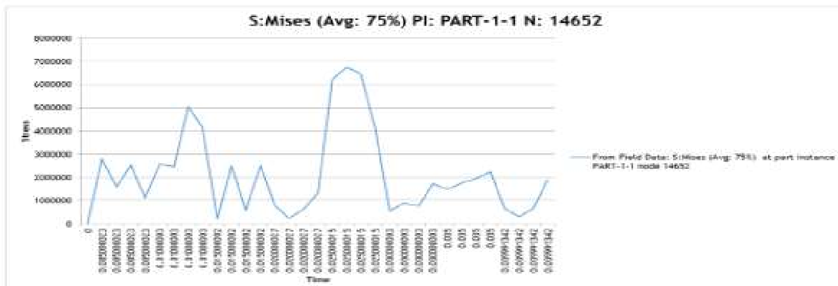


Figure 6. Pile stress mapping at End Node 14652.

RESPONSE OF THE SOIL MASS

To quantify the response of the soil mass, the authors consider the average of the stresses at two nodes (1507 and 1274) in soil adjacent to the foundation pile, as shown in figures 7, 8, and 9, which show the time history of the corresponding von Mises stresses. Based on the analysis, the average stress is calculated to be 0.23 MPa, which significantly exceeds the allowable cohesive strength of 0.036 MPa for the assumed clayey soil. This indicates shear failure in soil and loss of resistance at the pile-soil interface. The magnitude of the calculated stresses is also corroborated by the predicted deformation of soil elements adjacent to the pile. Accordingly, the analysis shows loss of interface friction over the entire modeled length of the pile and suggests the possibility of limited settlement. However, total failure of the modeled foundation pile is not expected because the blast-load duration is very short, and the pile will re-mobilize frictional resistance after a very brief loss of support.

Figure 7. Soil node location around concrete chamber.

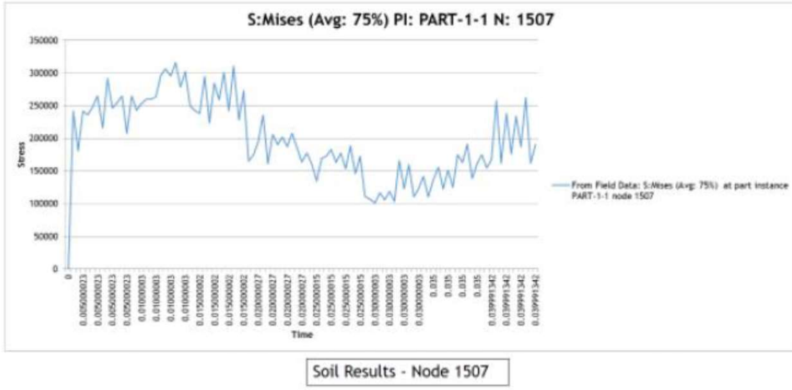


Figure 8. State of stresses in soil.

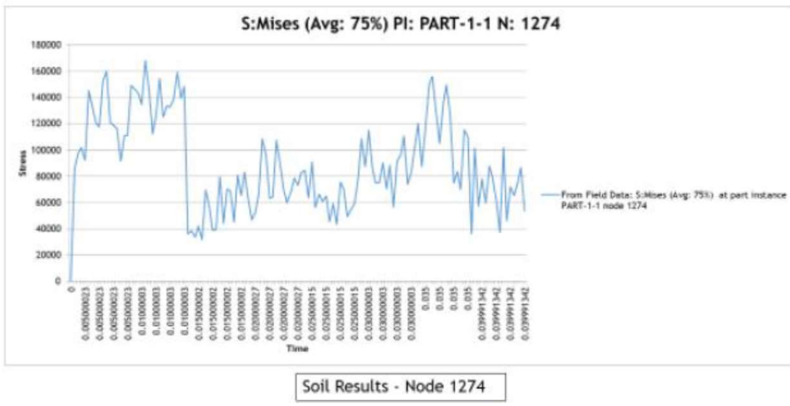


Figure 9. State of stresses in soil.

VERIFICATION OF ANALYSIS USING ANSYS

The analysis reported above is verified here using the ANSYS mechanical finite element solver (version 13.0). All of the parts used in the ABAQUS model were imported and meshed in ANSYS. All modeling parameters are the same as those used in the ABAQUS analysis, with the exception that the concrete is characterized by a compressive strength of 35 MPa instead of 15 MPa, and for convenience, sandy soil from the ANSYS Explicit Material library is used for the soil medium surrounding the concrete chamber. Figure 10 shows the model configuration in ANSYS.

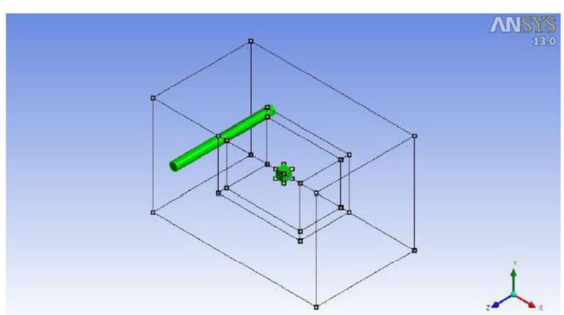


Figure 10. ANSYS model soil-pile-concrete chamber-air-explosive.

Figures 11, 12, and 13 illustrate the stresses from ANSYS in the chamber concrete and in the foundation pile, and Table 4 compares the results from ANSYS and ABAQUS. The comparison is reasonable, although some variation is to be expected due to differences in some of the parameter values. The primary reasons for the observed differences in the response quantities are attributed to the differences in the concrete characteristics and the surrounding soil type.

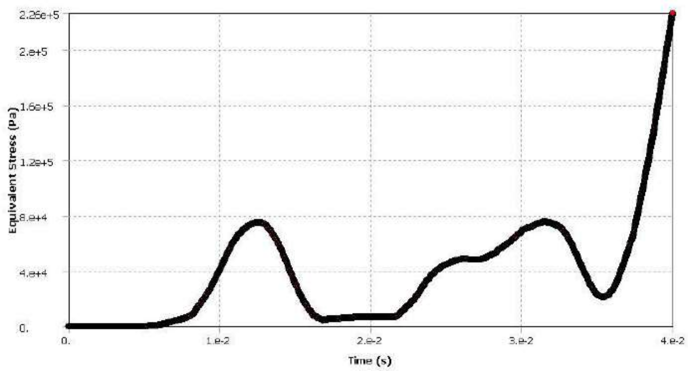


Figure 11. Soil stress (von Mises) at Time 0.04 sec.

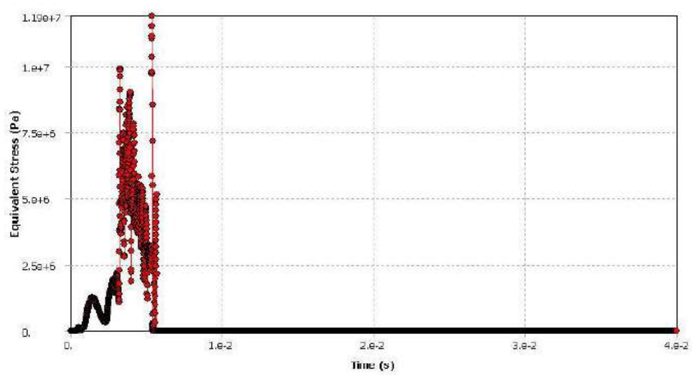


Figure 12. Von Mises stress plot at concrete chamber mid-section.

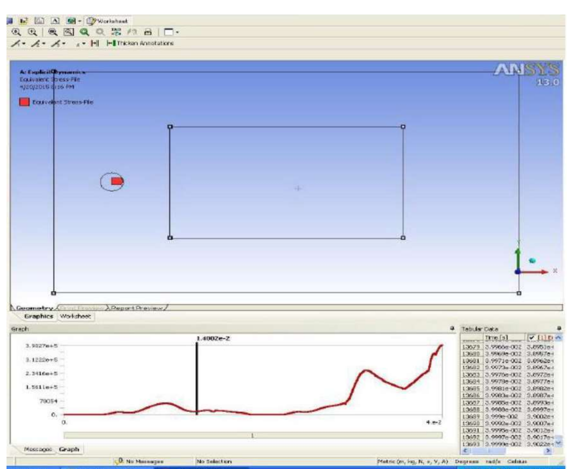


Figure 13. Location of pile stress probe point and pile stress (von Mises) graph.

Table 4. Comparison of stresses and deformations from ABAQUS and ANSYS.

PART ID	**MAX STRESS (MPa)**		**TIME OF MAX STRESS (s)**		**DEFORMATION (m)**	
	ABAQUS	**ANSYS**	**ABAQUS**	**ANSYS**	**ABAQUS**	**ANSYS**
PILE	5.0	0.2	0.035	0.035	0.008	0.012
CHAMBER CONCRETE	13.0	12.0	0.002	0.005	0.008	0.004
SOIL	0.3	0.2	0.015	0.040	0.010	0.012

CONCLUSION

The study of underground explosion inside a closed chamber illustrates the effects of wave reflection at the chamber wall in amplifying the incident blast-wave pressure. The pressure wave propagates through the chamber concrete and into the soil mass somewhat attenuated. Using the CDP material model for concrete, the analysis predicts that under the applied blast-wave loading, the entire chamber concrete sustains a plastic state. Further, the analysis also predicts a high state of stress in the soil adjacent to the concrete chamber, which exceeds the cohesive strength of the soil by a significant margin. This results in loss of frictional resistance at the pile-soil interface and consequential partial settlement of the pile.

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