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# Response of Underground Pipes to Blast Loads

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## 1. Introduction

Underground structures are divided into two major categories, fully buried structures and partially buried structures regardless of the shape of the structure. Underground cylindrical structures like pipes, shafts, tunnels, tanks, etc. are used for services such as water supply, sewage, drainage, etc. Most structures have now become targets of terrorist attack in recent years. Examples are 1995 Paris subway in France, 2004 Moscow subway in Russia (Dix, 2004; Huabei, 2009), 1995 Alfred Murrah Federal Building in Oklahoma City. The main sources of blast are: terrorist attacks, war, accidental explosion from military formations, etc. The constituents of blast comprises of: 1) rock media, 2) soils, 3) structure, 4) thin-layer elements surrounding the structure; blast loads, and 5) procedure for the analysis of interaction and responses of these constituents. In order to synchronize the interaction and responses of these variables, relevant data is required which could be obtained from field tests, laboratory tests, theoretical studies, work done in related fields and extension of work done in related fields (Ngo et al., 2007; Greg, 2008; Bibiana & Ricardo, 2008; Olarewaju et al. 2010a).

There are lots of methods available to determine the responses of underground structures to blast loads. These are: i) the analytical methods, and ii) the numerical methods using numerical tools (Ngo et al., 2007; Peter & Andrew, 2009). The problem of analytical method is that the solution allows only a small elastic response or limited plastic response and does not allow for large deflection and may lead to unstable responses. To overcome these problems, the finite element analysis paves the way towards a more rational blast resistance design. Though the drawback is the time and expertise required in pre- and post-processing for a given structural system. In structural design, the methods of structural analysis and design are broadly divided into three categories, namely, theoretical methods which can be used to carry out analysis and the use of design codes, by testing the full size structure or a scaled model using experimental methods, and by making use of model studies (Ganesan, 2000). There are different types of static and dynamic loads acting on underground pipes. In the case of static loads, there is surcharge load on the ground surface due to various engineering activities. In the case of dynamic loads, these are cyclic load, earthquake, blast, etc. Blast being one of the dynamic loads acting on underground pipes either from surface blast, underground blast, open trench blast or internal explosion is a short discontinuous event.

## 2. Background study

Under blast loading, though typically adopted constitutive relations of soils are elastic, elasto-plastic, or visco-plastic, the initial response is the most important (Huabei, 2009). It

involves some plastic deformation that takes place within the vicinity of the explosion and as a result of this one could model the soil as an elasto-plastic material. Beyond this region, the soil can be taken as an elastic material at certain distance from the explosion. Visco-elastic soils exhibit elastic behavior upon loading followed by a slow and continuous increase of strain at a decreasing rate (Duhee et al., 2009). In this study, the soil and pipes are considered as linear elastic, homogeneous, isotropic materials (Boh et al., 2007; Greg, 2008). For such materials, Kameswara (1998) has shown that only two elastic constants are needed to study the mechanics/behavior. These can be the usual elastic constants (the Young's modulus,  $E$  and Poisson's ratio,  $\nu$ ) or the Lamé's constants ( $\lambda$  and  $\mu$ ).

When explosion occurs, surface waves and body waves are generated. Consequent upon these are the isotropic component and deviatoric component of the stress pulse (Robert, 2002). Transient stress pulse due to isotropic components causes compression and dilation of soil or rock with particle motion which is known as compression or P-waves. The deviatoric component causes shearing of stress with particle velocity perpendicular in the direction to the wave propagation and these are known as shear or S-waves. On the surface of the ground, the particles adopt ellipse motion known as Rayleigh waves or R-waves (Kameswara Rao, 1998; Robert 2002). Energy impulse from explosion decreases for two reasons: (i) due to geometric effect, and (ii) due to energy dissipation as a result of work done in plastically deforming the soil matrix (Dimitiri & Jerosen, 1999; Huabei, 2009; Omang et al., 2009).

The categories of blast in this study that are applicable to underground pipes are; (i) underground blast, (ii) blast in open trench, (iii) internal explosion inside the pipes as well as (iv) surface blast (Olaewaju et al. 2010b). Blasts can create sufficient tremors to damage substructures over a wide area (Eric Talmadge and Shino Yuasa, 2011). With regards to the severity of destruction of explosion as a result of blast, it has been reported by James (2008) that typical residence structure will collapse by an overpressure of 35 kPa while a blast wave of 83 kPa will convert most large office buildings into rubbles. Accordingly, blast could be thought of as an artificial earthquake. Consequently, there is need to study the relationships and consequences of blasts in underground structures specifically in pipes. This is with a view to designing protective underground structures specifically pipes to resist the effects of blast and to suggest possible mitigation measures.

A lot of works have been done on dynamic soil-structure interaction majorly for linear, homogeneous, and semi-infinite half space soil media. This is contained in Olaewaju et al. (2010a). In this work, observations were limited to displacements at the crown and spring-line of pipe buried in a soil layer. Effect of slip between the soil and pipe was not considered. Huabei (2009) recently obtained the responses of subway structures under blast loading using the Abaqus finite element numerical software. This study is limited to the determination of the responses of empty underground pipes under blast loads. The material properties are limited to linear, elastic, homogeneous and isotropic materials. It is assumed that blast takes place far away from the vicinity of the underground pipes.

### 3. Blast load characteristics and determination

Explosive has to detonate in order to produce explosive effect. The term detonation as explained in the Unified Facilities Criteria (2008) refers to a very rapid and stable chemical reaction that proceeds through the explosive material at a speed termed the detonation velocity. This velocity ranges from 6705.6 m/s to 8534.4 m/s for high explosives. The detonation waves rapidly convert the explosive into a very hot, dense, high-pressure gas.

The volume of the gas of this explosive material generates strong blast waves in air. The pressures behind the detonation front range from 18619 MPa to 33785 MPa. Only about one-third of the total energy generated in most high explosives is released in the detonation process. The remaining two-thirds of the energy is released in air more slowly during explosions as the detonation products mix with air and burn.

According to the same source, the blast effects of an explosion are in the form of shock waves composed of high-intensity shocks which expand outward from the surface of the explosive into the surrounding air. As the shock wave expand, they decay in strength, lengthen in duration, and decrease in velocity (Longinow & Mniszewski, 1996; Remennikov, 2003; Unified Facilities Criteria, 2008). According to the Unified Facilities Criteria (2008), blast loads on structures can be categorized into two main headings; i) unconfined explosions (i. e. free air burst, air burst and surface), ii) confined explosions (i. e. fully vented, partially confined and fully confined).

According to the same source, the violent release of energy from a detonation converts the explosive material into a very high pressure gas at very high temperatures. This is followed by pressure front associated with the high pressure gas which propagates radially into the surrounding atmosphere as a strong shock wave, driven and supported by the hot gases. The shock front, term the blast wave is characterized by an almost instantaneous rise from atmospheric pressure to a peak incident pressure  $P_{so}$ . Over pressure,  $P_{so}$  is the rise in blast pressure above the atmospheric pressure. This pressure increases or the shock front travels radially from the point of explosion with a diminishing shock velocity  $U$  which is always in excess of the sonic velocity of the medium. The shock front arrives at a given location at time  $t_A$  (ms). After the rise to the peak value of over pressure  $P_{so}$ , the incident pressure decays to the atmospheric value in time  $t_o$  (ms - millisecond) which is the positive duration (Olawajun et al. 2011n).

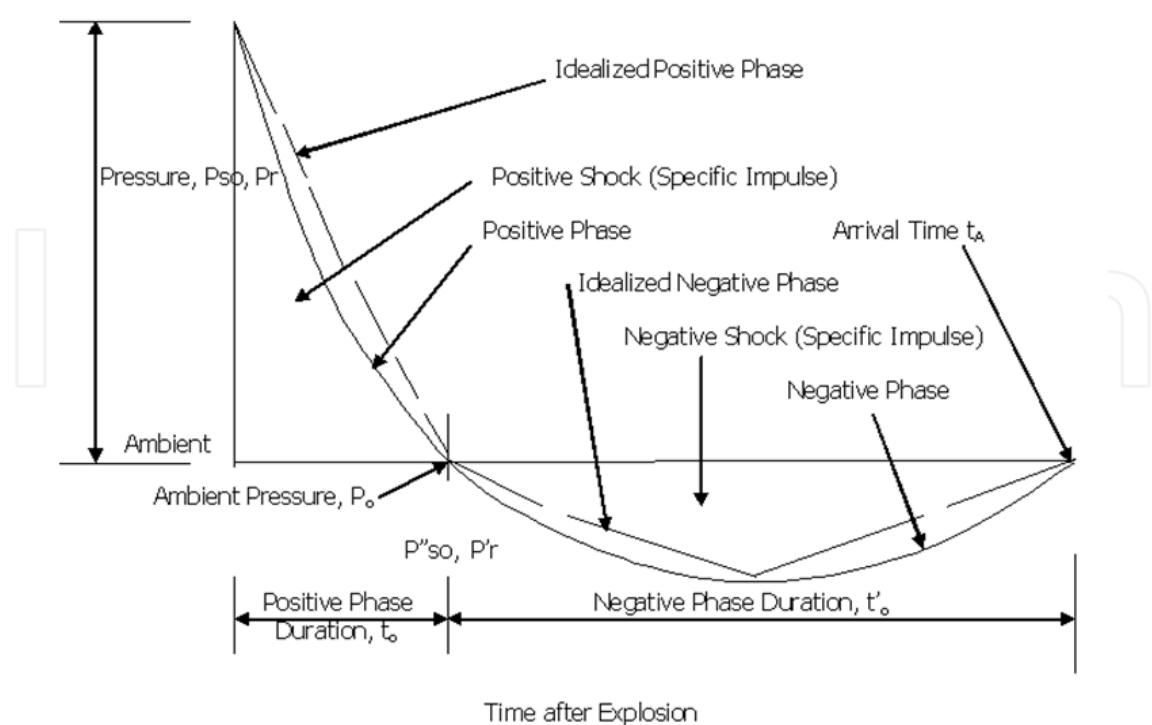


Fig. 1. Pressure Time Variation (Unified Facilities Criteria, 2008; Olawajun et al.2011 and 2011n)

The negative phase with duration  $t_0^-$  (ms) is usually longer than the positive phase. It is characterized by a negative pressure (usually below atmospheric pressure) having a maximum value of negative overpressure  $P_{so}^-$  as well as reversal of the particle flow. The negative phase is usually less important in design than the positive phase because it is very small and is usually ignored. The incident pulse density (i. e., specific impulse) associated with the blast wave is the integrated area under the pressure-time curve and is denoted by  $i_s$  for the positive phase and by  $i_s^-$  for the negative phase as illustrated in Fig. 1. An additional parameter of the blast wave, the wave length, is sometimes required in the analysis of structures. The positive wave length  $L_w^+$  is the length at a given distance from the detonation which, at a particular instance of time, is experiencing positive pressure (Longinow & Mniszewski, 1996; Remennikov, 2003; Unified Facilities Criteria, 2008). Unified Facilities Criteria (2008) allows for an increase of 20%.

In case of underground blast, most of the energy is spent in fracturing, heating, melting, and vaporizing the surrounding soils and rocks (Johnson & Sammis, 2001) with only a very small amount being converted to seismic energy. The fraction of the small amount of total energy that goes into seismic energy is a measure of the seismic efficiency of underground explosions. There are three methods available for predicting blast loads on structures. These are: empirical, semi-empirical and numerical methods. Details could be found in Peter and Andrew (2009), Olarewaju (2010), Olarewaju et al. (2010i), (2010j) and (2011p).

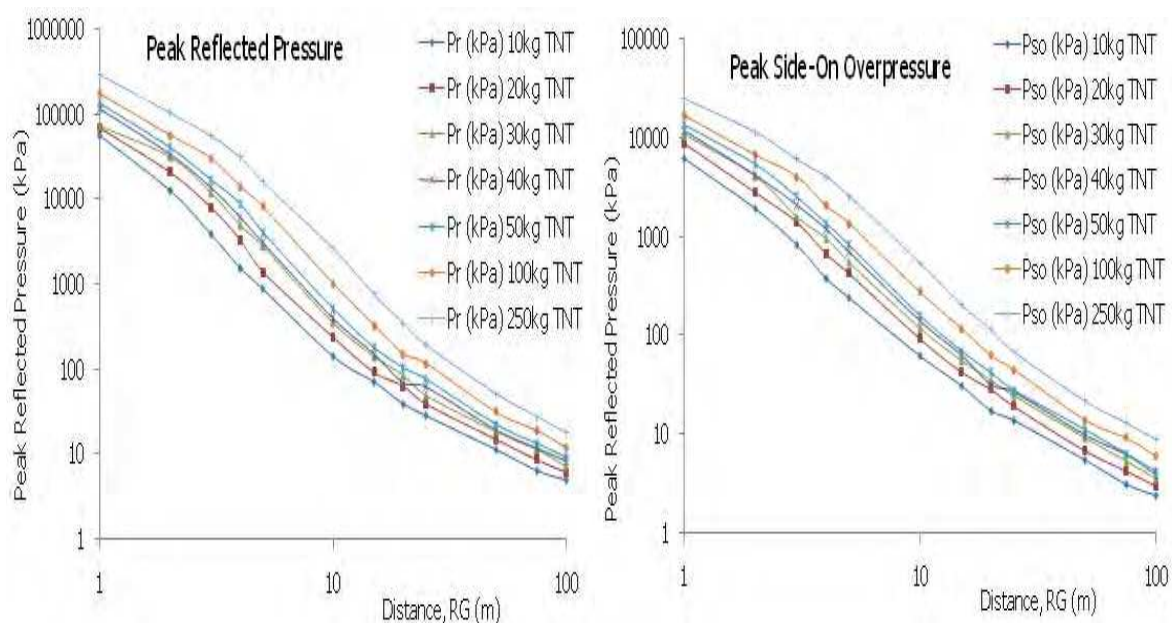


Fig. 2. Peak Reflected Pressure and Peak Side-On Overpressure for Surface Blast (Olaewaju et al. 2010c, 2010e, 2010i)



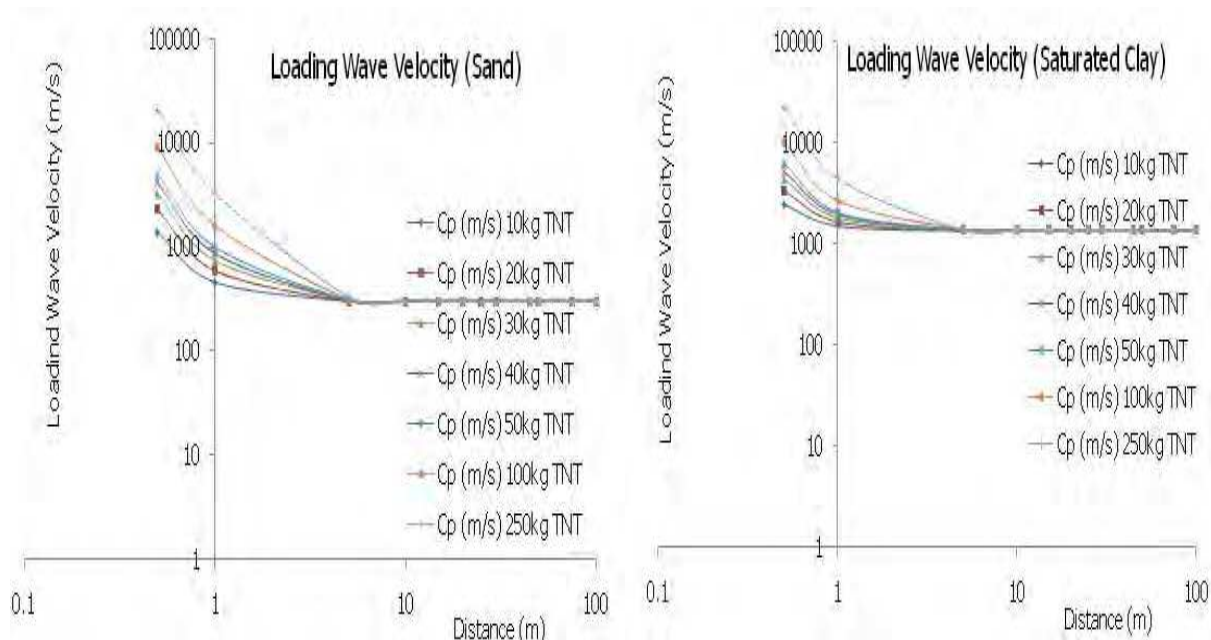


Fig. 3. Loading Wave Velocity for Sand and Saturated Clay for Underground Blast (Olairewaju, et al. 2010c, 2010e, 1020f, 2010i)

Mitigation techniques are meant to reduce the impact of blast and seismic related issues on underground structures. These techniques include: soil stabilization using mechanical and/or additive, grout, ground improvement using i) prefabricated vertical drains, placing soil surcharge and maintaining it for the required time, vacuum consolidation, stone column; ii) chemical modification (with deep soil mixing, jet grouting, etc); iii) densification (using vibro compaction dynamic compaction, compaction grouting, etc), reinforcement (using stone columns, geo-synthetic reinforcement) (Olairewaju, 2004a; 2008b; Raju, 2010; Kameswara, 1998; Olairewaju et al. 2011). Tire-chip backfill has also been used by Towhata & Sim (2010) to reduce the bending stress and moment caused by displacement of underground pipes. If the thickness of the tire-chip backfilling is increased, it can resist larger displacement caused by blast and thereby reduces the bending stress and the moment caused by large displacements. Similarly, trenchless technique can also be used to rehabilitate damaged underground pipes due to blast, aging, etc. (Randall, 1999) especially in congested and built-up areas.

#### 4. Methodology

The existing model studied by Ronanki (1997) was validated using the Abaqus numerical package and the results are compared well. From the results, the crown displacement at  $H/D=1$  is 1.31 times that of crown displacement at  $H/D=2$ . The maximum horizontal spring-line response in terms of pressure, displacement, maximum principal strain and mises for  $H/D=1$  is 1.24 times that of maximum horizontal spring-line response for  $H/D=2$ . This is in line with the submissions of Ronanki (1997) that "Embedment depth has significant effect on both the crown and spring-line response (deflection). With increase of depth of embedment of pipes, the response (deflection) decreases. The maximum crown response for  $H/D=1$  is about 1.3 times that of the maximum crown response (deflection) of  $H/D=2$ . In case of spring-line response (deflection), the maximum horizontal spring-line deflection for  $H/D=1$  is about 1.2 times that of maximum horizontal spring-line deflection of  $H/D=2$ ". These results are also in agreement with those reported by Ramakrishnan (1979) though no numerical data are presented.



Material	Density, $\rho$ (kg/m <sup>3</sup> )	Young's Modulus, E (kPa)	Poisson's Ratio, $\nu$
Loose sand	1800	18500	0.3
Dense sand	1840	51500	0.375
Undrained Clay	2060	6000	0.5
Intervening medium	1800	18500	0.3
Steel pipe	7950	200 x 10 <sup>6</sup>	0.2
Concrete pipe	2500	20 x 10 <sup>6</sup>	0.175

Table 1. Material properties for the study

The ground media considered in this study are loose sand, dense sand and undrained clay. The geotechnical properties shown in Table 1 as revealed by several researchers (Das, 1994; FLAC, 2000; Coduto, 2001; Duncan, 2001; Unified Facilities Criteria, 2008; Kameswara, 1998; etc) were used to study the response of underground pipes due to blast loads. Since the two elastic constants are enough to study the mechanics of an elastic body, the material properties used are the modulus of elasticity, E, Poisson's ratio and density of soil and pipe materials. The largest possible value of Poisson's ratio is 0.5 and is normally attained during plastic flow and this signifies constancy of volume (Chen, 1995). Huabei (2009) pointed out that undrained behavior is relevant for saturated soft soils especially clay that is subjected to rapid blast loading since the movement of pore water is negligible under such circumstance. For 10kg, 20kg, 30kg, 40kg, 50kg, 100kg and 250kg explosives, Unified Facilities Criteria (2008) was used to predict positive phase of blast loads at various stand-off point for surface blast and results are presented in Figs 2. Analytical method was used to predict the blast load for underground blast at various stand-off points and results presented in Figs. 3. According to Huabei (2009), it is not likely for terrorists to use very large amount of explosive in an attack targeting underground pipes. Soil model in the problem definition shown in Figs. 4 (a, b) of 100m by 100m by 100m depth consist of buried pipe 100m long and 1m diameter buried at various embedment ratios were study for the various categories of blast applicable to underground pipes. Parametric studies were carried out for various blasts. Blast load duration was verified and it was observed that, for response to take place in underground pipe, most especially pipes buried in loose sand, duration of blast should be greater than 0.02s (Olaewaju, et al 2011n).

5. Method of analysis

Abaqus package was used to solve the equations of motion of the system:

[m] [Ü] + [c] [Û] + [k] [U] = [P] (1)

with the initial conditions:

U (t = 0) = U<sub>o</sub> and Û (t = 0) = Û<sub>o</sub> = v<sub>o</sub> (2)

where m, c, and k are the global mass, damping and stiffness matrices of the pipes system and t is the time. U and P are displacement and load vectors while dot indicate their time derivatives. The time duration for the numerical solution (Abaqus Analysis User's Manual, 2009) was divided into intervals of time Δt = h, where h is the time increment. Finite difference in Abaqus/Explicit was used to calculate the response (Abaqus Analysis User's



Manual, 2009). Stability limit is the largest time increment that can be taken without the method generating large rapid growing errors (Abaqus Analysis User's Manual, 2009; Abaqus/Explicit: Advanced Topics, 2009). The difficulty is that the accuracy of the sensitivities can depend on the number of elements. This dependency is not seen with either analytical sensitivity analysis or with the overall finite difference method (explicit). Sensitivity analysis is not required in Finite difference of Abaqus/Explicit because. According to Abaqus Analysis User's Manual (2009), the default value of perturbation has been proved to provide the required accuracy in Abaqus /Standard.

Boundary condition of the model was defined with respect to global Cartesian axes in order to account for the infinite soil medium (Geotechnical Modeling and Analysis with Abaqus, 2009; Ramakrishan, 1979; Ronanki, 1997). Contrary to our usual engineering intuition, introducing damping to the solution reduces the stable time increment. However, a small amount of numerical damping is introduced in the form of bulk viscosity to control high frequency oscillations (Abaqus Analysis User's Manual, 2009; Geotechnical Modeling and Analysis with Abaqus, 2009). Estimation of blast load parameters could be done by empirical method, semi-empirical methods and numerical methods. The method to be adopted depends on the numerical tool available for the study of response of underground structures to blast loads. In this study, empirical method using Unified Facilities Criteria (2008) was used. The blast load parameters to be determined using this method depend on the available numerical tool. According to Unified facilities Criteria (2008), pressure is the governing factor in design and the study of the response of underground structures. Load due to surface blast was represented by pressure load with short duration (in millisecond, ms) while load due to underground blast was represented by loading wave velocity with short load duration (in millisecond, ms).

## 6. Results and discussion

### 6.1 Response of underground pipes to surface blast

The blast load was represented by pressure load (Figures 1 and 2) whose centre coincide with the centre of the explosive. The pressure load reduces to zero at 0.025s. At low pressure load due surface blast, there was no response observed on underground pipe. Due to surface blast, it was observed that crown, invert and spring-line displacement reduces as embedment ratios increases in loose sand, dense sand and undrained clay. This is shown shown in Figs. 5. Crown, invert and spring-line pressures, stresses and strains increase at embedment ratios of 2 and 3 after which it reduces as the embedment ratios increases.

For steel pipe at  $H/D = 1$ , crown and invert displacement in loose sand is the highest and least in undrained clay. This is in agreement with the findings of Huabei (2009), that increasing the burial depth enhances the confinement of underground pipe, hence reduces the maximum lining stress under internal blast loading (Huabei, 2009). The results indicate that it is necessary to evaluate the blast-resistance of underground structures with small burial depth. Materials yield easily and more at lower depth of burial (Huabei, 2009).

With small burial depth, due to low confinement from ground, displacement, pressure, stress and strain could be significantly large and underground structures like pipes could be severely damaged even with moderate surface blast, underground blast and open trench blast (Olawejaju et al 2010c). According to James (2009), the effect of varying the depth of burial of structures below the ground level is an important phenomenon to study. The depth of soil cover above the increases the over burden stresses on it, which can help in stabilizing

it with respect to its response to an externally applied impulsive action. This can help in reduction of the vibrations which occur in response to an explosive blast action.

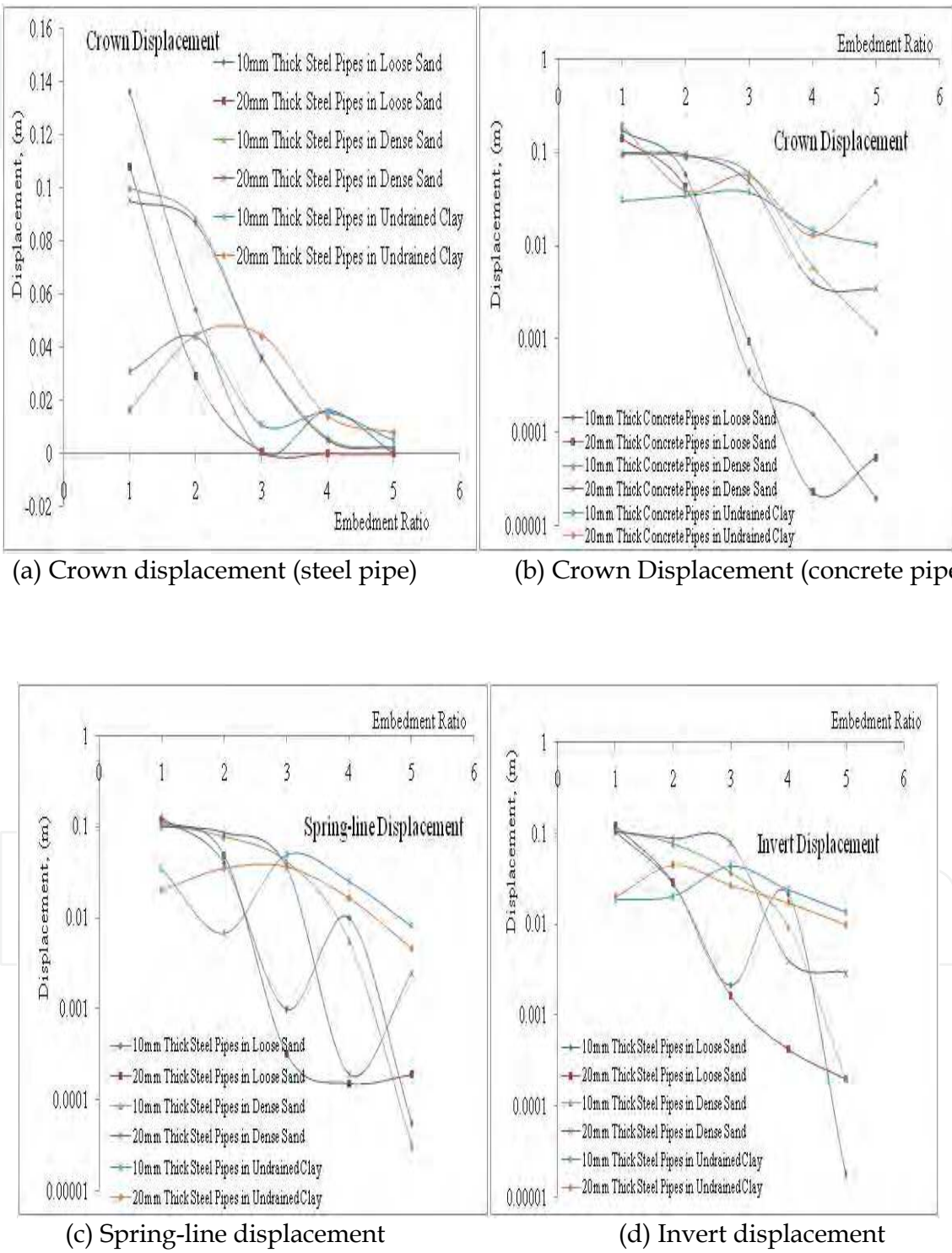


Fig. 5. Displacement in underground pipes due to surface blast

### 6.2 Response of underground pipes to underground blast

The blast load was represented by loading wave velocity (Figures 1 and 3) which reduces to zero at 0.025s. For a given loading wave velocity, crown, invert and spring-line displacements in pipes is almost constant at all the embedment ratios considered irrespective of the material properties. This is higher compared to that obtained in open trench blast. This is because, as the peak particle velocity due to underground blast travels within the soil medium, it transmits the load bodily to the buried pipes along the direction of travel. As a result of this, displacement is bound to be higher compared to open trench blast where the wave energy only impeaches on the side of the trench.

Reduction in pressure, stress and strain is noticeable at embedded ratios of 3 to 5. This is in agreement with the submission of Ronanki (1997) on the effect of seismic/loading wave velocity that, the spring-line horizontal displacement remains almost constant with increasing mode shape number. The vertical crown displacement increases with mode shape number up to a value 15, beyond that the displacement tends to be constant (Ronanki, 1997). Finally, crown, invert and spring-line pressures, stresses and strains in pipes showed wide variation as the embedment ratio increases in all the soil media considered. Though there is reduction in all these parameters as the embedment ratio increases (OlaREWaju et al. 2010f).

### 6.3 Response of underground pipes to open trench blast

The blast load was represented by pressure load (Figures 1 and 2) which reduces to zero at 0.025s. Displacement (Figs. 6) in pipes due to open trench blast is lower compared to that obtained in underground blast. In addition, virtually all the parameters observed i. e. displacement, pressure, stress and strain at the crown, invert and spring-line of pipes reduces at embedment ratios of 3 beyond which no significant changes occurred. Finally, crown, invert and spring-line displacements, pressures, stresses and strains reduce as the embedment ratio increases with a sharp increase at embedment ratio of 2 in all the ground media considered (OlaREWaju et al. 2010e). Increasing the burial depth of underground pipe enhances the confinement on the underground pipe, hence reduces the maximum displacement, pressure, stress and strain under blast loading (Huabei, 2009). Details could be found in OlaREWaju et al (2010b)

### 6.4 Response of underground pipes to internal explosion

The blast load was represented by pressure load (Figures 1 and 2) whose centre coincide with the centre of the explosive. The pressure load reduces to zero at 0.025s. The result shows that as the diameter of pipes increases, blast load parameters generated inside the pipe increases. As the thickness of pipes reduces, time history as a result of internal explosion increases in the same proportion. In addition to this, depth of burial of pipes showed no significant changes in the time history of external work and energies generated due to internal explosion (OlaREWaju et al 2010d and 2010l). Furthermore, stress components on the ground surface reduced as the depth of embedment of pipes increases. Equivalent earthquake parameters on the surface of the ground due to 50kg TNT explosion in pipe are higher than that recorded in San Fernando earthquake of 1971 (Robert, 2002). Finally, pressure changes from negative to positive within the soil medium due to dilations and compressions caused by the transient stress pulse of compression wave while velocity, displacement and stresses reduce as it approaches the ground surface. This reduction is more in loose sand than undrained clay due to arching effect (Craig, 1994). Details could be found in OlaREWaju et al. (2010d).

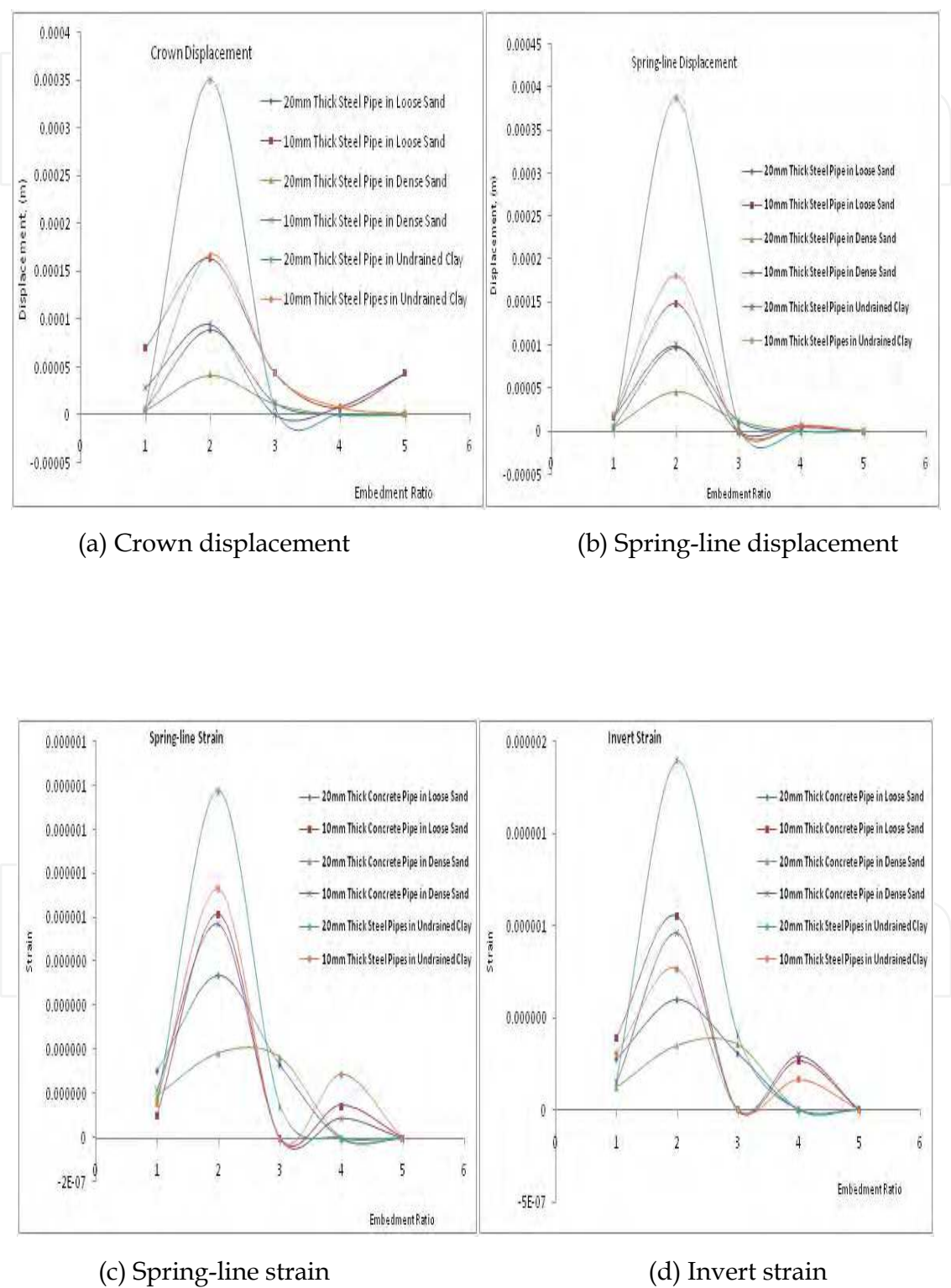


Fig. 6. Displacement and Strain in pipes in open trench blast



## 7. Parametric studies

### 7.1 Effects of coefficient of friction

Due to surface blast, displacement at the crown reduces at coefficient of friction of 0.2 to 0.4 and above in dense sand. The reverse is the case in loose sand where displacement increases as the coefficient of friction increases. Invert displacement reduces as the coefficient of friction increases. Spring-line displacement increases as the coefficient of friction increases. Due to the dynamic nature of surface blast loads, there is wide variation in the results; there is reduction in the values of crown, invert and spring-line pressures, stresses and strains for coefficient of friction of 0.2 to 0.4. This is also noticeable for the increased values of peak reflected pressure. Liang-Chaun (1978) pointed out that in cases when test data are not available, the following friction coefficient can be used: Silt = 0.3; Sand = 0.4; Gavel = 0.5m and added that the above coefficients are the lower bond values equivalent to the sliding friction. The static and dynamic coefficient of friction can be as much as 70% higher.

### 7.2 Effects of young's modulus of soil

Effects of liquefaction as observed in the varying Young's modulus for soil for surface blast and underground blast is similar to the varying Young's modulus for intervening medium. Varying the Young's modulus,  $E$  of soil, displacement became higher at  $E$  of  $1 \times 10^6$  Pa. Between Young's modulus,  $E$  of 10000 Pa and 3000000 Pa, pressure, stress and strain get to the peak value with maximum value at  $E$  of 1000000 Pa. Crown has the maximum values of stress and strain while invert has the maximum pressure. With the value of Young's modulus,  $E$  soil ranging from 0 Pa to 10000 Pa, displacement, pressure, stress and strain (Figs 7) reduce with no substantial increase. This is in agreement with the submission of Susana & Rafael (2006). From the result of the work by Huabei (2009), it showed that as Young's modulus of soil is increasing, mises stress is reducing. For the constant value of stress with increasing value of Young's modulus,  $E$  of soil, it shows that the soil has yielded.

### 7.3 Effects of young's modulus of pipes

Displacement is high at the crown but low at the invert and spring-line of pipes having low value of Young's modulus. At higher Young's modulus, the displacement at the crown, invert and spring-line became the same. Pressure and stress is low at low Young's modulus but increases as the Young's modulus increases. Large strain is observed between the values of 100Pa and 10000Pa beyond which the value of strain reduces. Low stiffness pipes are pvc pipes, clay pipes, etc while high stiffness pipes are steel pipes, reinforced concrete pipes, etc. It is evident that as the Young's modulus  $E$  of pipes increases, strain reduced due to increased stiffness but the pressure and stress increases from  $E$  of  $1 \times 10^7$  Pa. This shows that pipes of lower value of  $E$  have lower displacement, pressure, stress and strain induced in them due to surface blast compared to pipes with higher stiffness like steel and reinforced concrete pipes.

The result presented by Frans (2001) clearly shows that the low stiffness pipes suffer less from subsidence than the one with the higher stiffness. At the same time a higher deflection is observed when using low stiffness pipes. This proves that rigid pipes transfer load, and flexible pipes deform and the load is transferred by the soil. When the bed is firm, hardly any subsidence takes place hence the stiffness of the pipe has no effect either. However, when the bed is loose or soft, subsidence becomes a real issue and also the effect of pipe stiffness is significant.

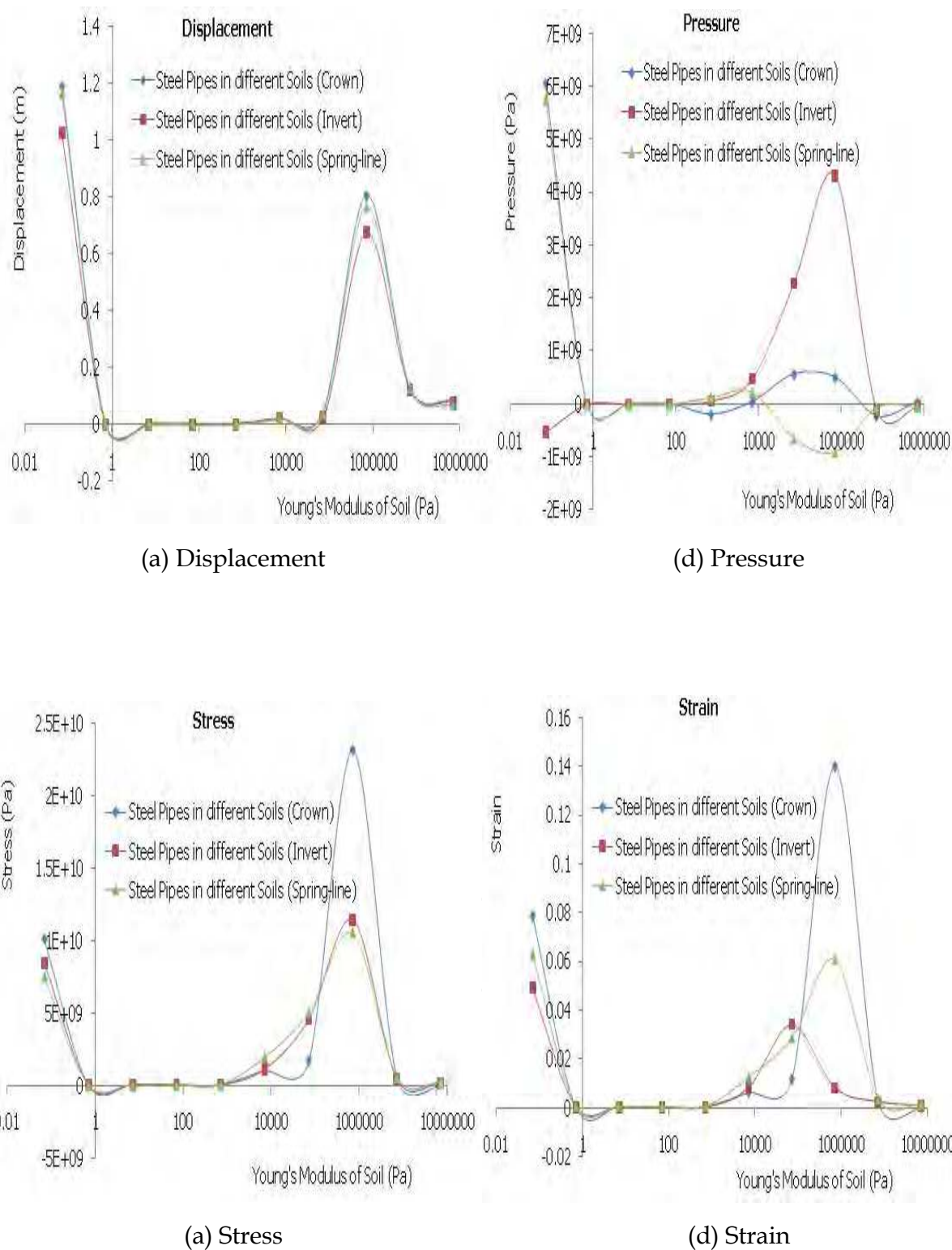


Fig. 7. Displacement, Pressure, Stress and Strain in buried pipes for varying Young's modulus of soil for surface blast

#### 7.4 Effects of young's modulus of pipes

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#### 7.5 Effects of pipe thickness

The result indicates that steel and concrete pipes show similar characteristics and behavior in thickness. In other words, as the thickness of pipes increases, displacement, pressure, stress and strain reduces. At low pipe thickness, displacement, stress and strain in steel and concrete pipes buried in undrained clay, is low at the invert but remain constant at the crown, invert and spring-line as the thickness increases. According to James (2009), the size and thickness of the structure under consideration is a major factor which can potentially influence the stresses generated on it. The reason could be attributed to the fact that smaller size structure has lower mass, making it easier to displace under blast loadings.

Higher displacements in the structure can result in larger strain deformations, causing the corresponding stresses to be lower due to energy dissipation in deforming the structure. According to Zhengwen (1997), rigid structures experience higher pressure and less displacement during the first half-wave of response, when compared with more flexible counterparts. In that case, underground pipes with smaller thickness are considered as flexible while those with increased thickness are considered as rigid structures.

### 8. Conclusions

Blast is a short discontinuous event whose duration is very small compared to earthquake. Considering the various constituent of blast, ground pipes and intervening media can be modeled. It must be remembered that soil exists as semi-infinite medium. Numerical tool to be used must incorporate the notion of infinite in the formulation. To account for the infinity of soil medium, in this study, in the absence of infinite element, Global Cartesian axis in Abaqus software was used. In other words, it shows that soil is a continuous media. To account for material damping, small numerical damping in the form of bulk viscosity was introduced. Blast and/or blast parameters can be represented or modeled using software (i. e. BLASTXW, SPLIT-X, BLAPAN, SPIDS, etc) or by using Eulerian numerical techniques

developed using finite volume and finite difference solver (i. e. SHAMRC, ANSYS, AUTODYN 2D AND 3D, etc) (Olaewaju et al., 2010i).

To represent blast load parameters, it can to be determined by empirical method using available code like Technical Manual 1990, Unified Facilities Criteria 2008, etc (Unified Facilities Criteria 2008 supersede other available technical manual). In this study, blast load parameters were estimated using empirical method, (i. e. Unified facilities Criteria (2008)) and represented in the model. Other blast load parameters applicable to the design and study of response underground pipes to blast loads that can be estimated by empirical method are: peak reflected pressure, side-on overpressure, specific impulse, horizontal and vertical acceleration, horizontal and vertical displacement, shock front velocity, horizontal and vertical velocity, duration, arrival time, etc (Olaewaju et al. 2010a; 2010i). To capture the short duration of blast load, time integration technique in Abaqus/Explicit was used in this study.

Conclusively, this study has shown the various responses of underground pipes due to various blasts scenarios. Results of parametric studies were also presented and discussed. Finally, possible mitigation measures were also suggested. Consequently, the parameters thus obtained will help in designing underground pipes to resist effects of various blast loads.

## 9. Acknowledgment

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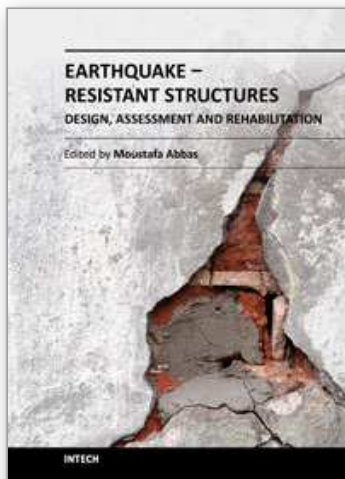
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## **Earthquake-Resistant Structures - Design, Assessment and Rehabilitation**

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This book deals with earthquake-resistant structures, such as, buildings, bridges and liquid storage tanks. It contains twenty chapters covering several interesting research topics written by researchers and experts in the field of earthquake engineering. The book covers seismic-resistance design of masonry and reinforced concrete structures to be constructed as well as safety assessment, strengthening and rehabilitation of existing structures against earthquake loads. It also includes three chapters on electromagnetic sensing techniques for health assessment of structures, post earthquake assessment of steel buildings in fire environment and response of underground pipes to blast loads. The book provides the state-of-the-art on recent progress in earthquake-resistant structures. It should be useful to graduate students, researchers and practicing structural engineers.

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