Dimensionless Response of Underground Pipes Due to Blast Loads Using Finite Element Method

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ABSTRACT

Underground pipes are used for water supply, drainage, oil and gas supply, irrigation, etc. Blast constituent comprises of the ground media, intervening layer, structures, and blast. This study is aimed at determining the response of simulated empty underground pipes due to blast loads using finite element method. In this study, blast load parameters were determined using Unified Facilities Criteria (2008). Time integration technique in Abaqus/Explicit was used to solve the equation of motion. The soil and pipes materials were considered as elastic, homogeneous and isotropic. The material properties as obtained from different researchers and pipe manufacturers were used. Dimensional analysis was used to present the results. From the result of the dimensionless parameters, it was observed that depth of burial of pipes play a significant role in the response of underground pipes due to surface and underground blasts while coefficient of friction has little effect due to underground blast. Dimensionless pressure and deflection of underground pipes reduce as embedment ratios increase in surface and open trench blasts while this is not so in underground blast. Finally guidelines thus established would help in the design of underground pipes to resist effects of blasts. Consequently, the environmental risk and hazards caused by blasts will be reduced.

KEYWORDS: Environment, Dimensional Analysis, Blast, Underground Pipes, Finite Element Method.

INTRODUCTION

Underground structures are fully buried structures and partially buried structures. These can be any structures of diver's shapes, shelters, basement, silos, storage facilities, shafts, tunnels, pipes, etc. These structures are constructed of different materials such as steel, plain and reinforced concrete, timber, clay, fibre glass, etc. Underground pipes are used for various services [20]. Blast from terrorists, accidental explosion, war, accumulation of explosive gases in pipes, etc can create sufficient tremors to damage substructures over a large area. It has been reported that at blast wave of *138kpa*, reinforced concrete structures will be leveled [5, 6]. Consequent upon these phenomena are loss of lives and property while in the manufacturing industry, it leads to disruption in production, land degradation, etc. As reported by [27], it is evidently clear from the recent revelation of US cables by Wikileaks published in the New York Times that insurgent and terrorist attacks on large scale are imminent across the globe. As a result of these, there is need to study the relationship and consequences of blasts in underground structures. This is with a view to designing protective underground structures specifically pipes to resist the effects of blast [3, 22, 30].

BACKGROUND STUDY

The constituents of blast are basically the explosive, ground media, intervening layer, structural components, and blast characteristics. In studying soil-pipe interaction through modeling as shown in Figure 1a, experimental results are required in other to simulate the prevailing situations between all the constituent materials. These data are best obtained from field tests, laboratory tests, theoretical studies, work done in related fields and extension of work done in related fields [17, 20]. A lot of works have been done on dynamic soil-structure interaction majorly for linear, homogeneous, and semi-infinite half space. The response of elastic half space was first carried out by [8]. Reference [26] obtains the responses of buried circular pipes under three-dimensional static and seismic loading. Method used is the finite element based software package, SAP-80. The study is limited to determination of the displacement and slip between the pipe and the soils not considered. This study is aimed at determining the response of empty underground pipes due to surface, underground, open trench blasts and internal explosion using a-commercially-available-finite element code, Abaqus. This is with a view to providing guidelines that will assist in designing underground pipes to resist the effects of blast loads [18, 19].

METHODOLOGY

The existing model of [26] on static and seismic load on buried pipes using SAP program was validated and the result compared well with the result of Abaqus numerical code. In this study, blast load parameters were determined using [29]. The soil and pipes materials were modeled as elastic, homogeneous and isotropic as shown in Figure 1b. According to [7], the two elastic constants are enough to study the mechanics of such body. The size of the soil model is 100m by 100m by 100 deep while the pipe is 100m long and 1m diameter. The usual elastic constants and density of the materials as obtained from different researcher and pipe manufacturers were used in this study [9, 10, 11, 14, 15, 20]. Contact between the pipe and soil were clearly defined assuming that there is no slip between the soil and the pipe. Later, slip between the soil and pipe was equally considered. Non-linear geometry due to large displacements and rotations as a result of large loads was considered as well as time incrementation to ensure stability. In line with available texts [1, 2, 26], boundary conditions were defined with respect to global Cartesian axes. Blast loads were represented by pressure loads for surface blast and internal explosion while loading wave velocities were used for underground and open trench blast. The governing dynamic equation of motion is given as

$$[m]\,[\ddot{U}] + [c]\,[\mathring{U}] + [k]\,[U] = [P]; \quad \text{for } U\,(t = 0) = U_o, \text{ and } \mathring{U}\,(t = 0) = \mathring{U}_o = v_o \qquad (1)$$

where m, c, and k are element mass, damping and stiffness matrices, t is the time, U and P are displacement and load vectors and dots indicate their time derivatives [1]. Time integration technique in Abaqus/Explicit numerical code was used to solve Equation 1 [1, 7]. Contrary to our usual engineering intuition, introducing damping into the solution reduces the stable time increment, however, a small numerical damping was introduced in the form of bulk viscosity damping to control high frequency oscillations. The parameters measured are displacement, pressure, stress and strain at the crown, invert and spring-line of underground pipes buried at different embedment ratios. Consequently, dimensional analysis was used to present the results.

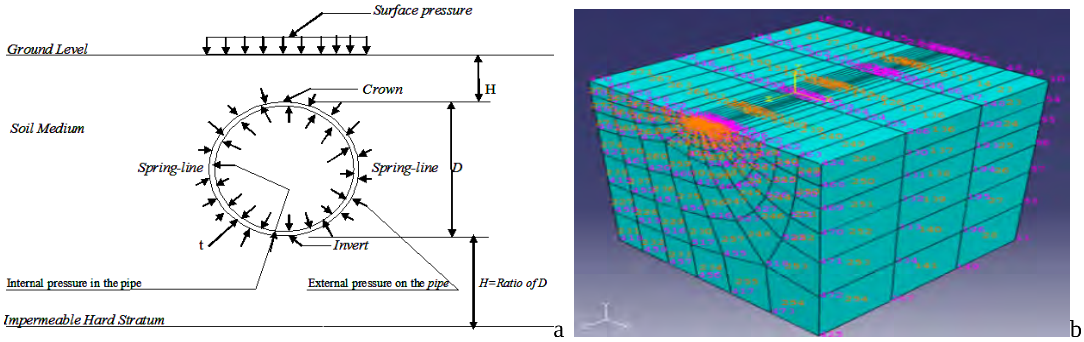

Figure 1: (a) Cross-section of underground pipe [23]; (b) Finite element model of soil medium, intervening medium and pipe [16]

RESULTS AND DISCUSSION

The results of the peak reflected pressure and peak side-on overpressure for surface blast using [29] are presented in Figures 2 while the loading wave velocity for sand and saturated clay in underground blast using analytical method are presented in Figures 3. In addition to this, the dimensionless pipe pressure and deflection against embedment ratios for surface blast are presented in Figures 4 and 5 respectively while the dimensionless pipe pressure against coefficient of friction and embedment ratios are presented in Figures 6. Pipe deflection against R/t ratios for surface blast is presented in Figures 7. Furthermore, the dimensionless pipe pressure against coefficient of friction for underground blast is presented in Figures 8 while dimensionless pipe pressure and deflection against embedment ratio for underground blast are presented in Figures 9 and 10 respectively. The dimensionless pipe pressure and deflection against embedment ratio for underground blast are presented in Figures 11 and 12 respectively. Finally, the dimensionless pipe pressure and deflection against coefficient of friction for internal explosion are presented in Figures 13. Note that in Figures 4-13, P is the surface pressure while Pcr, inv and spr are the pipe pressure at the crown, invert and spring-line respectively. H is the depth of soil cover on the underground pipe and D is the diameter of the pipe. x is the displacement at the crown, invert and spring-line of the underground pipes, P is the surface pressure (peak reflected pressure), M is the modulus of elasticity of the soil and R is the radius of the underground pipes. With the increase of R/t ratio means decrease of thickness of pipes, where R is the radius of underground pipe and t is the thickness of underground pipe.

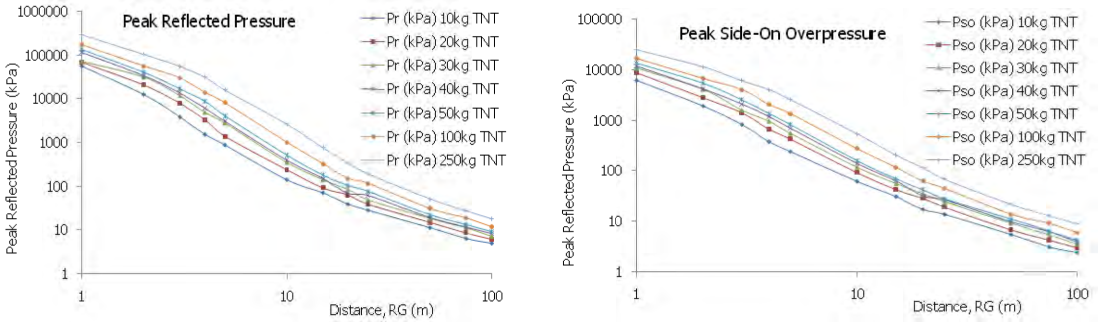

Figure 2: Peak Reflected Pressure and Peak Side-On Overpressure for Surface Blast [19, 20]

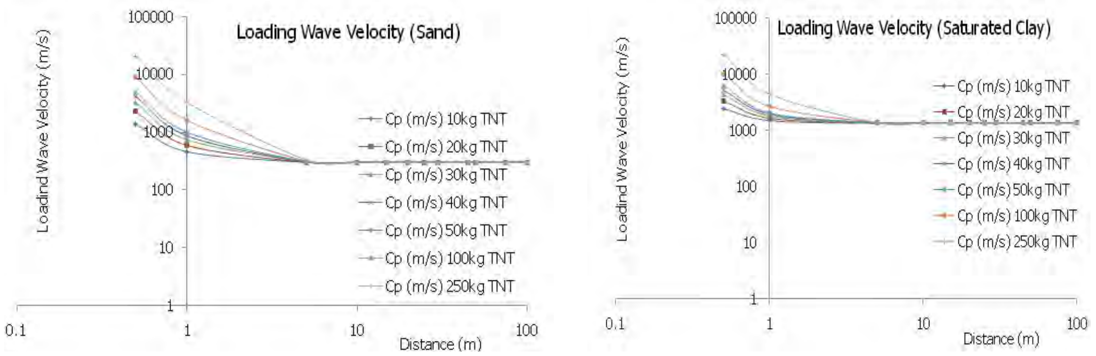

Figure 3: Loading Wave Velocity for Sand and Saturated Clay for Underground Blast [18]

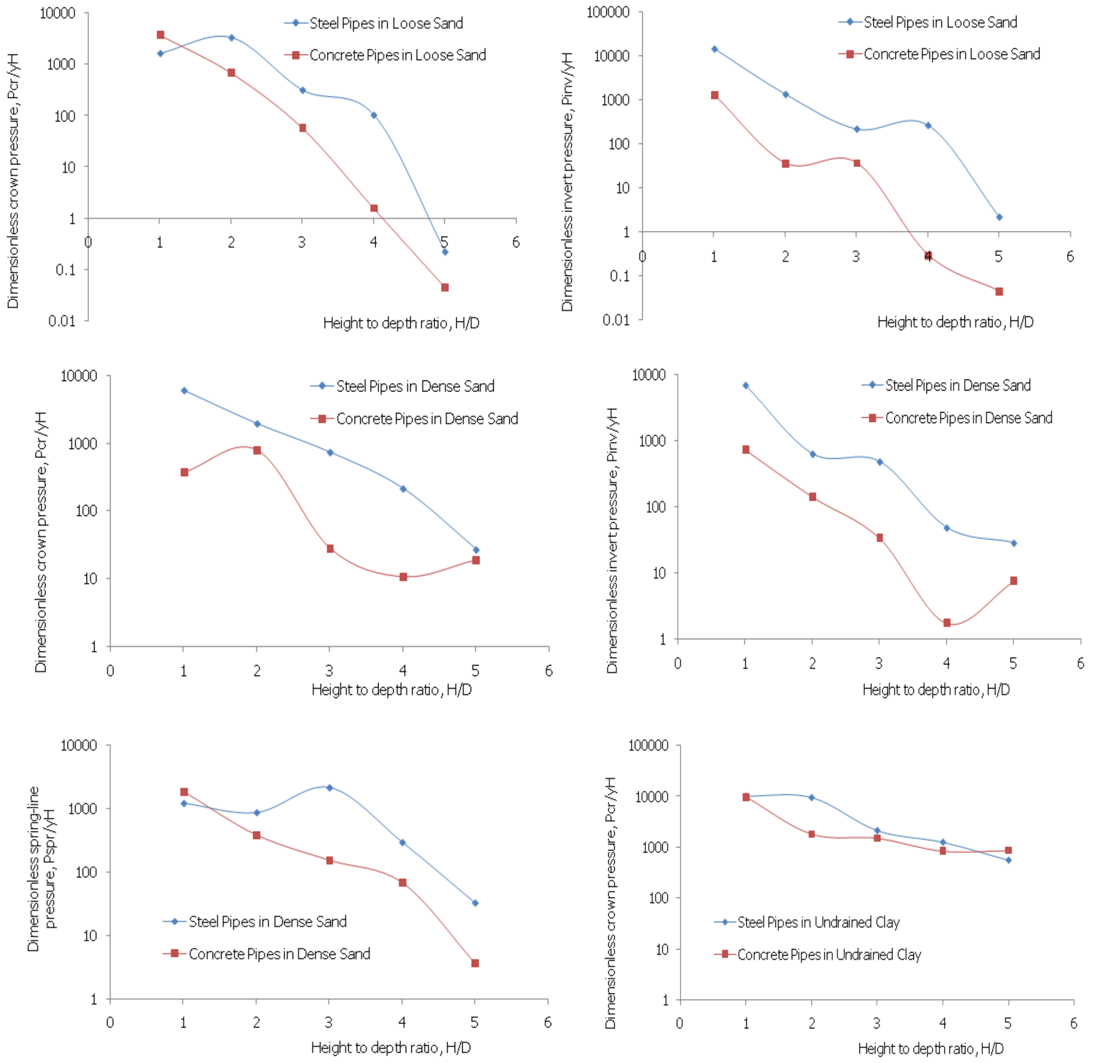

Figure 4: Dimensionless pipe pressure against embedment ratio for surface blast

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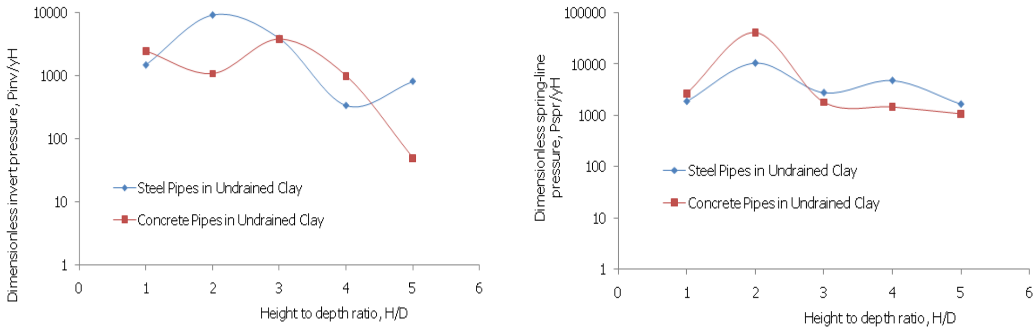

Figure 4: Dimensionless pipe pressure against embedment ratio for surface blast

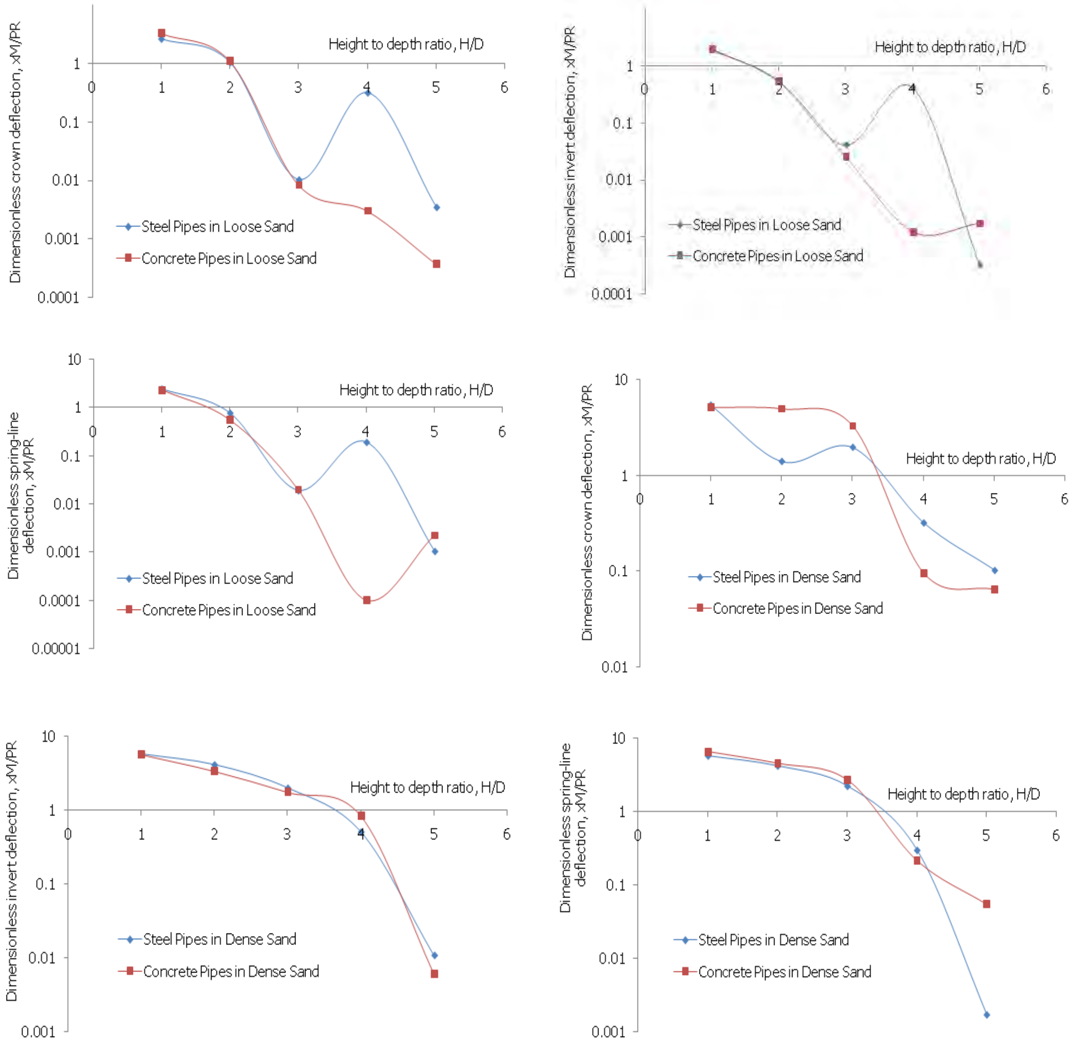

Figure 5: Dimensionless pipe deflection against embedment ratio for surface blast

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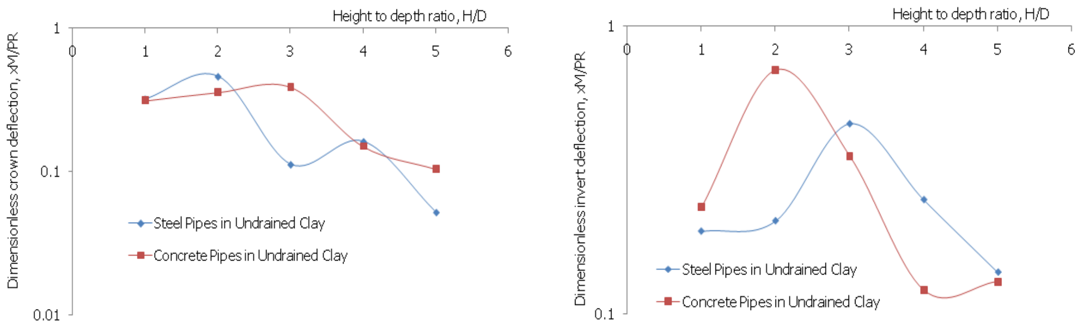

Figure 5: Dimensionless pipe deflection against embedment ratio for surface blast

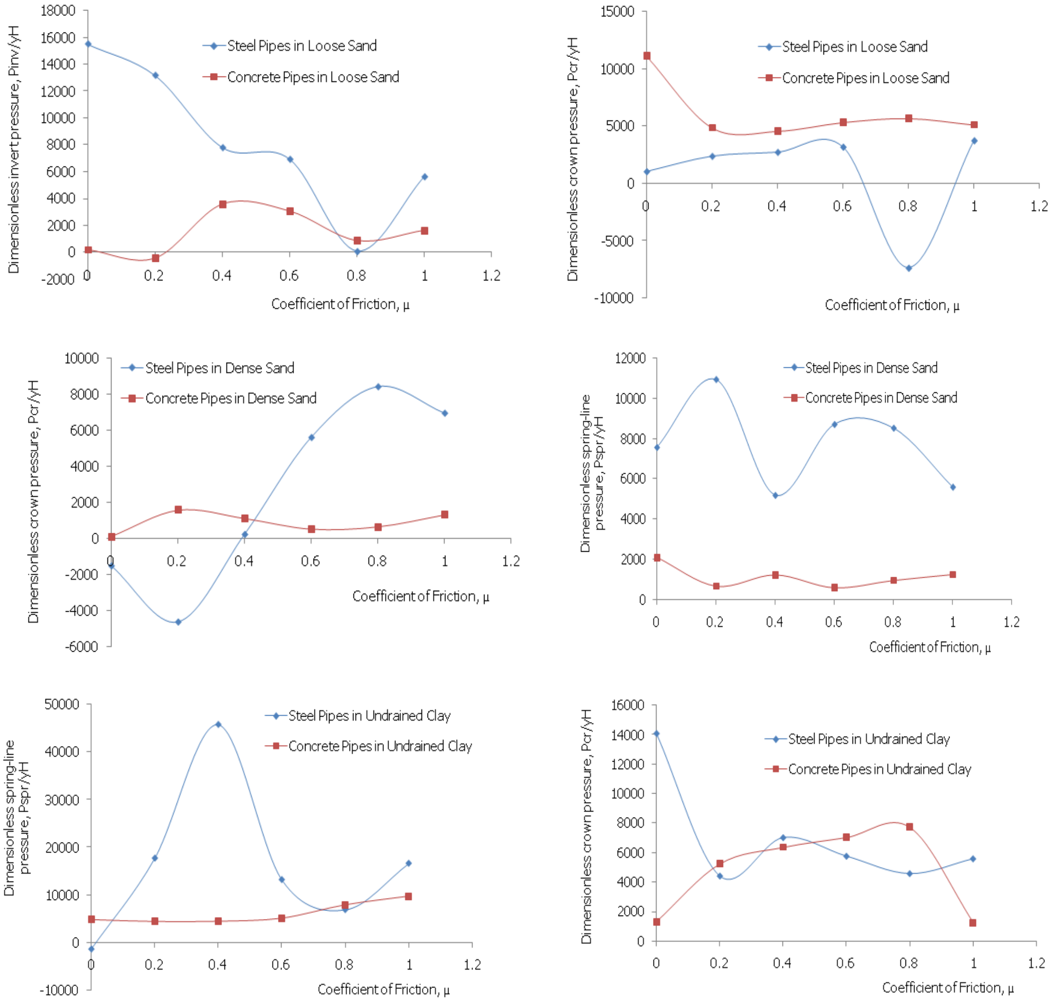

Figure 6: Dimensionless pipe presure against coefficient of friction for surface blast

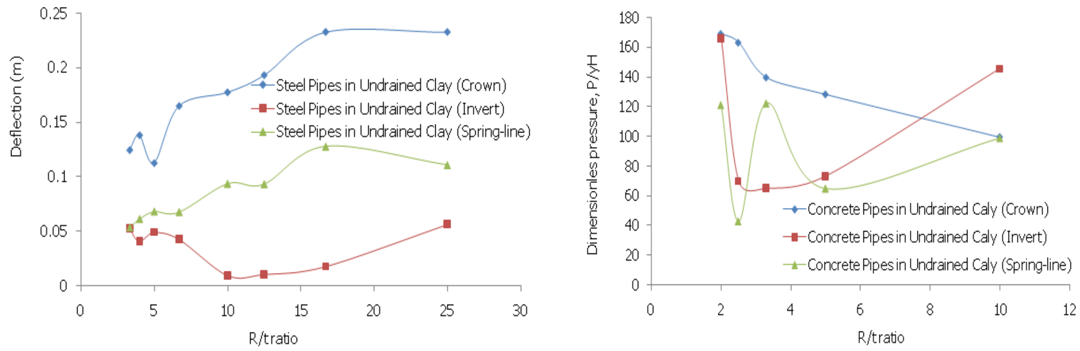

Figure 7: Pipe deflection against R/t ratio for surface blast

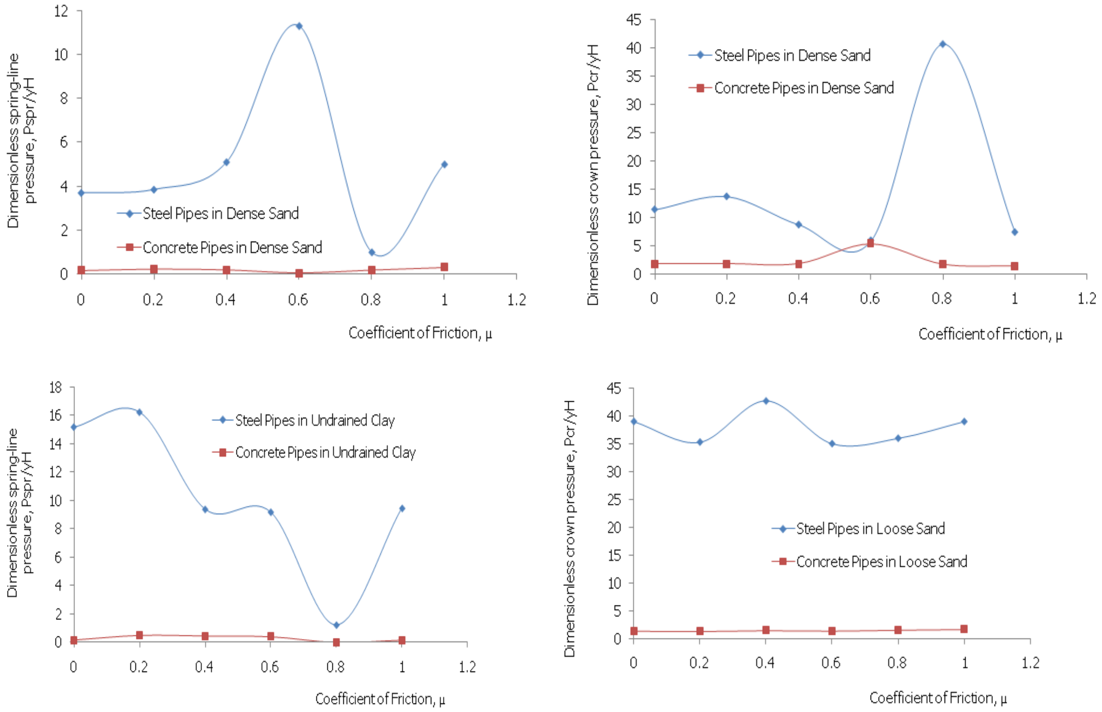

Figure 8: Dimensionless pipe pressure against coefficient of friction for underground blast

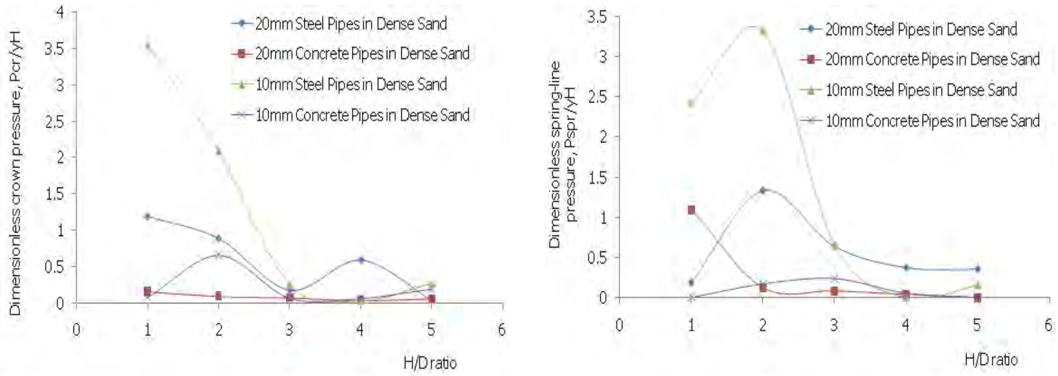

Figure 9: Dimensionless pipe pressure against embedment ratio for underground blast

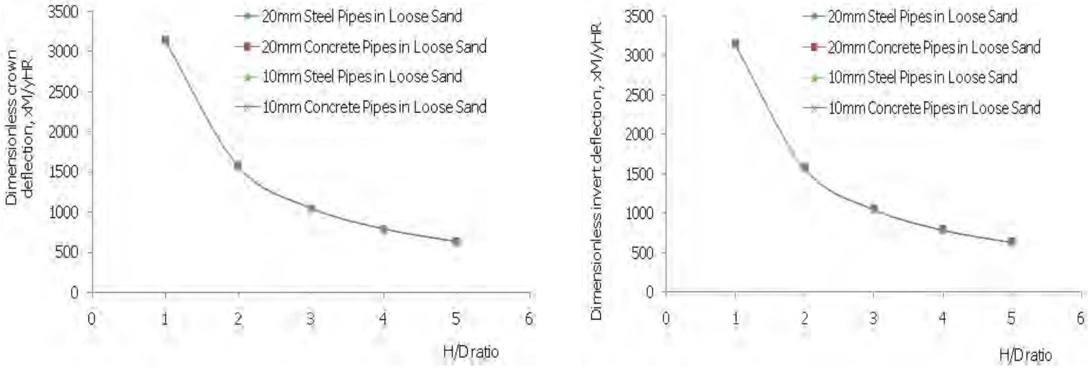

Figure 10: Dimensionless pipe deflection against embedment ratio for underground blast

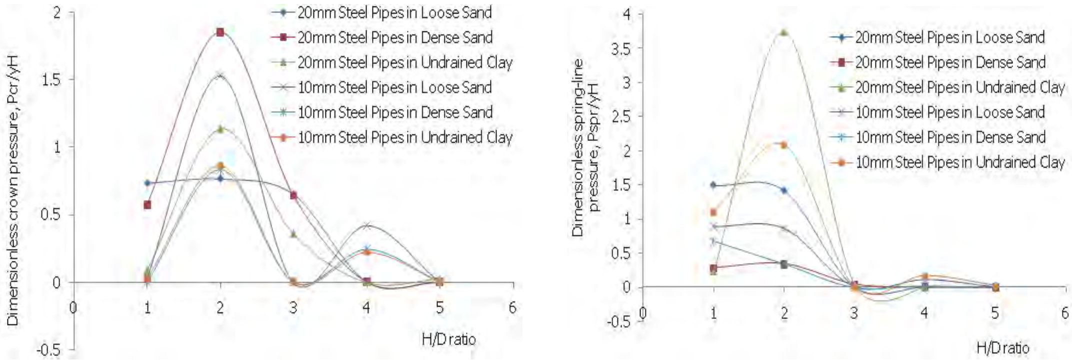

Figure 11: Dimensionless pipe pressure against embedment ratio for open trench blast

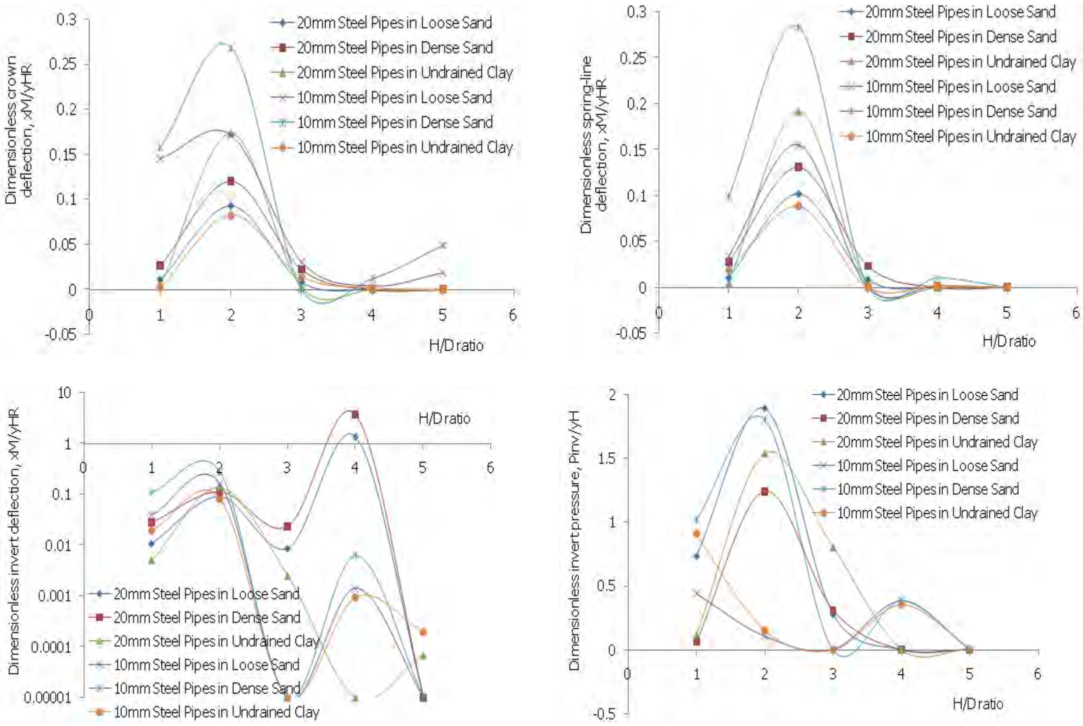

Figure 12: Dimensionless pipe deflection against embedment ratio for open trench blast

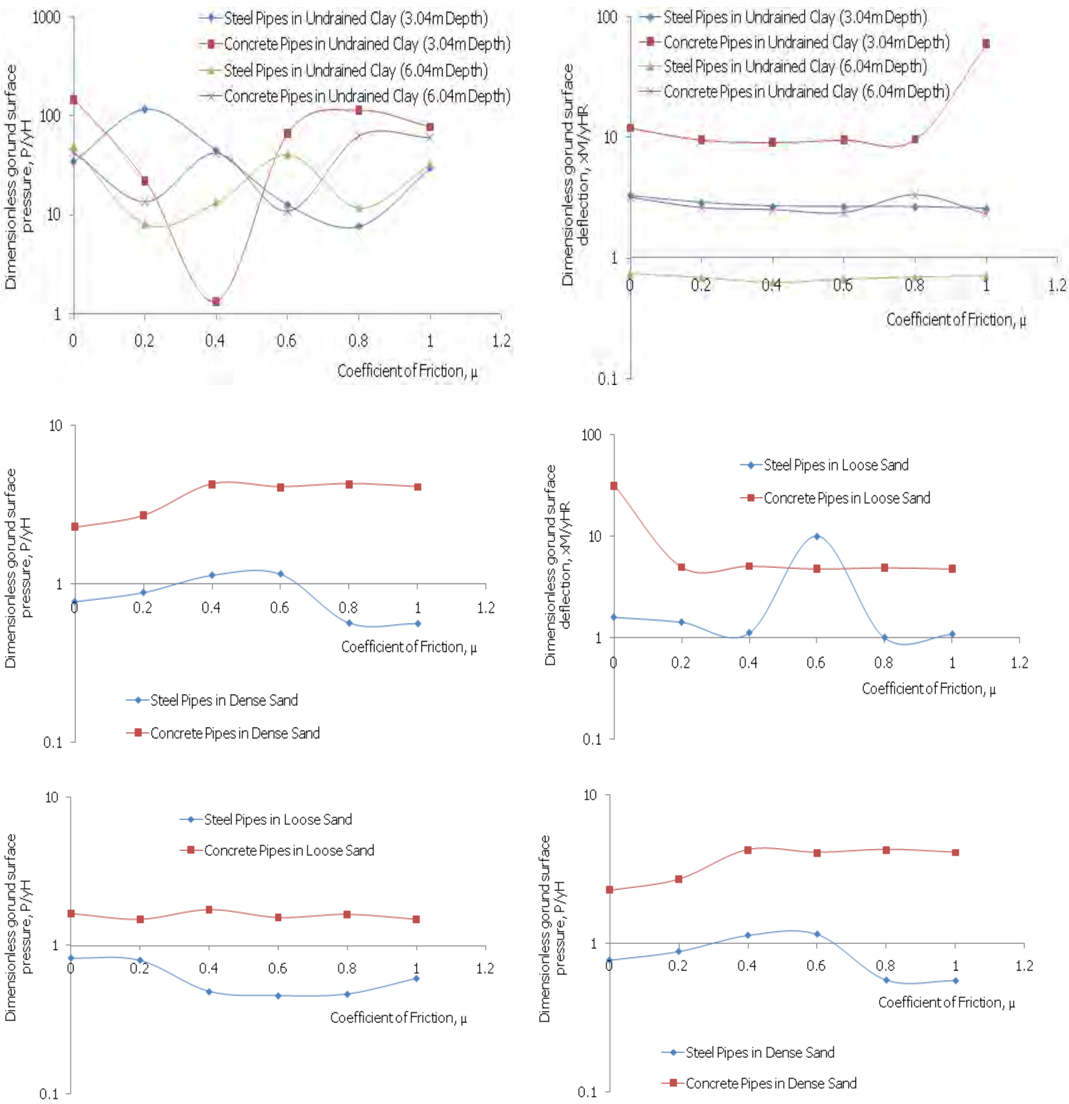

Figure 13: Dimensionless ground surface pressure and deflection against coefficient of friction for internal explosion

It is observed from Figure 2 (for surface blast) and Figure 3 (for underground blast) that energy attenuates as the distance from the explosion increases. The reduction is more in underground blast than surface blast. In underground blast, the blast energy reduces to the seismic velocity of soil as the distance from the explosive source increases [3, 14, 17, 24]. From the result of the dimensionless parameters, it was observed that depth of burial of pipes play a significant role in the response of underground pipes due to surface blast as shown in Figures 4 and 5 while coefficient of friction has little effect due to underground blast and internal explosion as shown in Figures 8 and 13 respectively. As the depth of burial increase, there is reduction in pipe pressure and deflection due to surface, underground and open trench blasts as shown in Figures 4, 5 and 9-12. The parameters reduce at embedment ration ratio of 3 in surface and open trench blasts beyond which no significant response occurred in all the ground media considered. This is not so in underground blast. In addition, coefficient of friction shows no significant changes in the response due to underground blast for concrete pipes [13, 14, 23]. In agreement with the submission of [5], increasing the burial depth of underground pipe enhances the confinement on the underground pipe due to underground blast as well as open trench blast and surface blast, hence reduces the maximum displacement, pressure, stress and strain under blast loading. According to [31], going by Australian standard, the strength of installed rigid concrete and steel pipes increases over time while the strength of installed semi-rigid and flexible pipes decreases over time. In the case of rigid pipes and semi-rigid pipes, embedment determines the magnitude of the soil load transferred to the pipe while in the case of flexible pipes, soil loads are transferred directly to the pipe. Embedment shape does not affect the magnitude in flexible pipes [5, 31].

From the results of dimensionless pipe pressure in terms of unit weight of soil and cover depth of pipe, it shows that pipe crown pressure is least at coefficient of friction of between 0.2 and 0.6. Dimensionless invert and spring-line pipe pressure is least at coefficient of friction of between 0.4 and 0.8 for loose sand, dense sand and undrained clay even though it seems not to have much effect on the response. This is in agreement with the submission of [32]. From the results of deflection against thickness ratio, it shows that as the thickness ratio increases, crown and spring-line deflection increases while invert deflections reduce in steel and concrete pipes buried in undrained clay. This is in agreement with the submission of [26].

In the case of internal explosion in underground pipes, geotechnical property of soil show no significant changes in the energy generated in underground pipes while due to dynamic nature of the blast load, coefficient of friction show no significant changes. In addition to this, earthquake parameters on the ground surface reduce as the embedment ratio increases. These earthquake parameters were higher compared to that of San Fernando earthquake of 1971 [25]. This is noticeable in loose sand and dense sand due to arching effects [4]. For buried pipes to resist effects of surface blast, burial depth must not be less than 3 [15, 16, 18, 21]. In the case of undrained clay, soil treatment in form of soil stabilization, soil improvement as well as grouting need to be carried out [12]. Results of experiment carried out by [28] have shown that tire-chips backfill could be used to reduce displacement/deflection in underground pipes. Trenchless technique could also be used to rehabilitate underground pipes damaged by blast, ageing, etc in congested or built-up areas.

CONCLUSION

This paper has highlighted the various dimensionless responses of underground pipes to surface blast, underground blast, open trench blast and internal explosion. Finite different method in Abaqus/Explicit numerical code was used to solve Equation 1. It must be noted that soil exists as a semi-infinite half space; numerical methods to be employed must incorporate the notion of infinity in the formation [14, 19, 20]. Dimensional analysis was used to present the results. Responses of underground pipes due to blast loads are graphically presented using dimensionless parameters. Other numerical software packages like AUTODYN 2D and 3D, etc. could suitably be used for blast load prediction as well as elastic linear and non-linear response of underground structures by simulation. Mitigation measures to reduce the effects of blasts were also suggested.

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