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Investigating the Factors That Reduce the Urban Gas Pipeline Vulnerability to Explosion Threats

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Abbreviations:
ALA: American Lifelines Alliance
API-5L: American-Petroleum Institute

ABSTRACT

Introduction: Buried pipelines used to distribute water, gas, oil, and etc. are considered as one of the vital arteries. The experiences of the past wars have confirmed that the invading country focuses on bombing and destroying vital centers, and that gas pipelines can be a source of serious personal and financial losses as an important transmission arteries during war in the event of damage

Methods: The vulnerability of buried urban gas pipelines to explosion was determined and the methods for reducing the vulnerability of pipelines were investigated. To this end, the three-dimensional model of the soil-pipe system in ABAQUS software was used to study the effect of factors affecting the pipe behavior, including pipe diameters, diameter to pipe thickness, internal friction angle of soil, soil type, amount of explosives, depth of buried, the distance of explosion site to the pipe burial site, has been investigated on the pipe deformation capacity according to the ALA regulation. The soil was modeled using Solid three elements and shell element. For parametric studies, analyses were performed by the finite element method using ABAQUS software 6.10.1.

Results: Studies were conducted for 4 and 12 inch diameter, diameter/thickness ratio of 26, 21 and 35, burial depth of 1, 2, 3 and 4 meters, the explosive charge of 15, 30, 45, 60 and 200 kg TNT and for soil material, hard, soft and clay sands. The results showed that proper burial depth had the most effect in reducing the vulnerability of pipelines against explosive threats. By increasing the pipe thickness and increasing the diameter and applying soft soil around the pipe, a better behavior of the pipe was observed during the explosion

Conclusion: To reduce the vulnerability of gas pipelines against explosive threats, the use of buried pipelines has a greater effect on reducing damage due to explosion compared to other parameters, and it is recommended to use this method to increase the resilience of highly important gas pipelines.

Keywords: Buried Pipelines, Non-active Defense, Soil-pipe System, Pipe Strengthening

Introduction

Given the threats that Iran faces at various times with varying intensity and severity, the need for the construction of resistant structures and facilities is considered a national necessity. Gas transmission lines are one of the most important vital arteries for energy in today's societies. The experience of security threats shows that the enemy is using all its power to destroy refineries and

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energy sources. Therefore, maintaining the function of this facility against the explosion is a major factor because gas pipes contain flammable materials, and gas leaks and subsequent fires can cause injuries and financial damage (1). In addition, the destruction of gas pipelines due to its arterial effects can put adverse effects on other vital arteries, such as power generation, and cause problems and delay in their continued operation.

Aghasi et al. investigated the effect of soil characteristics on buried steel facilities using the ABAQUS software (2). In this study, a three-phase soil model was considered as a Drauger- Pruger, and pipes of high diameter m1 with depth of burial of more than m3 were investigated. Their studies showed that by increasing the modulus of elasticity of the soil around the pipe, less displacement occurred in the pipe and the stresses created in the pipe are reduced. Olarewaju et al. (3) conducted studies to predict the effect of explosions on pipelines using the ABAQUS software. Akbardoost et al. (4) examined the impact of the explosion wave on steel pipes on the surface of the earth using the Autodyne software as a 2-D model of the pipe and examined the extent of the pipe deformation due to the explosions at different distances. Their studies showed that as the distance decreased, a large deformation in the pipe was created, so it is imperative that the distance to explosion site be observed.

Asakereh et al., in their study of the effect of the burial depth of the buried pipes in the sandy soil under explosive loading using the finite element method, investigated the effect of different parameters on the vulnerability of the pipelines. In this regard, the soil and slag repair, or the use of mobilizers and the pipes of suitable diameter, thickness, and materials and their placement in optimal depth can be suitable for reducing damages caused by explosions or other seismic waves. This study was conducted using numerical modeling of buried pipes in explosive loading soil using Explicit/ABAQUS software. By investigating the role of pipe depth in the effect of explosion on buried pipes and performing comparative work, the depth of installation could be up to 3 m (5).

Parviz et al., in a study on the numerical modeling of the effect of explosion on buried pipelines of oil and gas transmission in different soils by Eulerian-Lagrangian method, to investigate stresses and explosions under buried pipes in soil using finite element software Ls Dyna has been dealt with. In this study, five models of fluid, air, soil, pipe and TNT were used. In the following, a comparison was made between the stresses and the pressures obtained from the fluids, and the results showed that with decreasing the fluid density, the pressure on the pipe increased and higher stress and pressure were transferred to the pipe, and the volume of the fluid increases, lower stress and pressure are introduced into the pipe. By increasing the density of soil used in modeling in the explosion, more stress and more pressure are transferred to the pipe. By decreasing the density of the soil, soil behavior acts like a damper, and less stress and pressure are introduced into the pipe, resulting in less damage to the pipe.

By gaining knowledge about the soil type's function in the transfer of stress and pressure in buried pipes under explosion, it can be found that in high-density soils, due to the high stress and pressure transmission, high-strength pipes can be used, and in lower density soils due to better and more suitable soil (such as damper) and lower stress and pressure transfer, low-strength pipes can be used,which could affect the price of oil and gas transmission projects, and economically significant savings in the implementation of oil and gas pipeline projects (6).

Janalizadeh et al. in the study of the function of buried pipes under the influence of explosive load, conducted software modeling using the ABAQUS software, and studied the effect of burial depth, geometric characteristics of the pipe, pipe materials, modulus of elasticity and soil density. Comparison of variations in tension and displacement on buried pipelines indicated that with increasing depth of burial, tensions and displacements were reduced. The results showed that with increasing the depth of pipe placement in the soil, the number of displacements would decrease. Also, by increasing the amount of explosives, the amount of energy absorbed by the module increases, and if the modulus of elasticity of the steel is increased, the amount of absorbed energy will be lower (7).

In agreement with previous studies, the purpose of this study was to investigate the effects of explosions on urban gas pipelines in order to find out the link between various parameters affecting the vulnerability of gas pipelines and the introduction of factors that have the greatest impact on increasing the resistance of these lines to explosive threats.

To this end, various factors such as pipe diameter, pipe depth, burial depth, soil material, explosive mass, distance from the site of explosion, etc. are required, and the effect of each of them in reducing the vulnerability of the gas pipelines should be specified.

Materials and methods

The primary factor on which the remaining parameters should be modeled based is the issue of explosive threats and various scenarios associated with it (8).

For this reason, two scenarios are assumed in this study: **a)** the terrorist groups and the domestic and foreign enemies throw explosives using mortars or rocket launchers toward around the pipelines burial. In this scenario, the vulnerability and the resistance level of the pipes are examined **b)** in the second scenario; it is assumed that terrorists blow up a car carrying explosives on the street and near the pipe burial site.

In this scenario, vulnerability and resistance of pipelines are investigated. **Figure1** shows schematics of these scenarios.

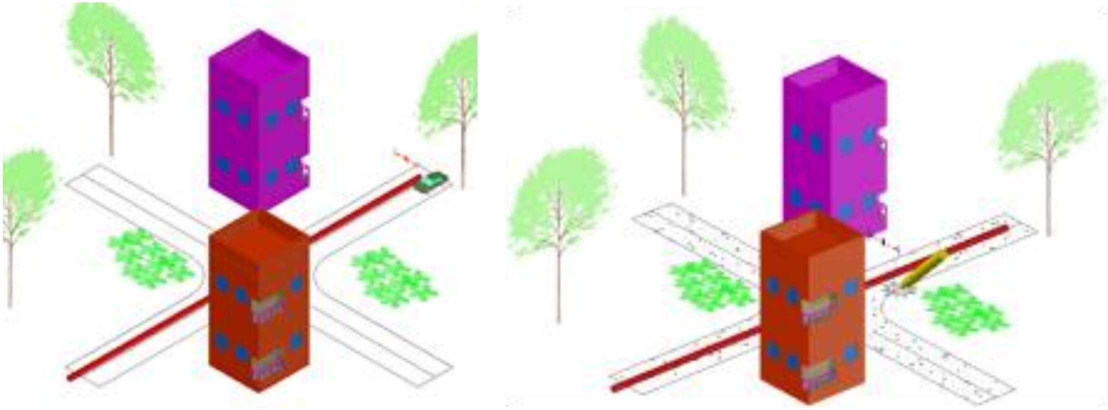

Figure 1: Direct hit (right) and indirect explosion (left) and their effects on gas pipelines

Rockets and mortars weigh about 5 to 70kg (9, 10). In our modeling weights 15, 30, 45 and 60 kg were considered. The weight of explosives in a car bomb was considered to be 200kg.

The ABAQUS software was used for modeling the effect of explosion on buried pipes in soil. This software is one of the most widely used tools for performing finite element analysis. This software provides a wide range of capabilities for simulation in linear and nonlinear applications. Problems with multiple components and different materials can be simulated by defining the geometry of each component and assigning its constituent material and then defining the interaction between components.

The analysis of the results can also be done after the completion of the processing stage, when tensions, displacements and other basic variables have been calculated (1).

The variables studied in this study included the diameter of the pipe, the diameter to pipe thickness, the internal friction angle, the soil type, the amount of explosives spent, the depth of the pipe burial, the explosion distance to the burial ground, all of which are independent variables in this study.

The deformation rate of the pipe is considered dependent variable. Among these variables, the pipe diameter and the diameter-to-thickness ratio are interrelated, and the internal friction angle of the soil and soil type are also related to each other.

In this paper, the explosion loading was defined in Dynamic Explicit Analysis and defined by Amp load definition.

Soil elements were selected as C3D8R. Soil in this study was modeled using Drauger-Pruger criterion and considering hardening and modeling was performed for four soil types with different soil mechanical properties. The pipe was modeled using S4R elements (5).

The mechanical properties of the pipe were considered to be a those of API-5L steel pipes. The Fon Mises model has been used for modeling the steel pipe elastic behavior with regard to isotropic hardness. For composite modeling, the S4R elements of the ABAQUS software were used.

The contact between the pipe and the soil is also called hard contact with a friction coefficient of 0.3. The soil dimensions were determined by sensitivity analysis to be 100 × 50 × 25 m.

The validity of the analytical method adopted has already been investigated in previous studies in this field, which is referred to by ABAQUS software to model the impact of the explosion on the soil and pipelines (11).

In addition, in future studies, using empirical relationships and manual calculations, the validity of the results can be tested.

Theory and calculations

One of the important points in explosive loading in the soil is the calculation of the maximum value of pressure at a certain distance from the explosion center, which is known as the explosive base pressure, represented by Ps.

Usually, in the authoritative references, the equation for Z is expressed in terms of the value of the equation 1 in order to calculate the maximum base pressure (8, 13).

Equation [1]: $\frac{x}{W^{1/3}} = 60\frac{f_c}{c}\left(\frac{2.52R}{W^{1/3}}\right)^{1-n}$

X (m): Maximum displacement of soil particles
W (kg): TNT equivalent mass
R (m): Distance to the target point
C (m/s): Seismic speed

n: Wavelength coefficient is selected which is proportional to the soil type and is a criterion for the energy absorption of waves energy in the soil. The value of this coefficient is obtained through an unidirectional test on an unconfined sample.

f_c: The coupling coefficient obtained by determining the depth of the explosion center from the surface of the earth is shown in **Figure2.**

By increasing the explosion of mate and land, the impact of the weapon increases. In the case of buried explosive charges and the soil around, a smaller number than one is considered (13). **Table 1**

Shows Decreasing coefficient and k factor for all types of soils

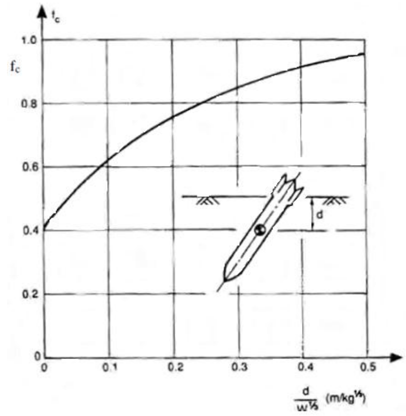

Figure 2: The coefficient of f_c (force) based on the scale (Z)

Table 1: Decreasing coefficient and k for all types of soils (14)

Soil type	k coefficient	Decreasing coefficient (n)

Saturated clay	30000	1.5
Saturated clay and layer	20000	2.5
Highly dense, dry and moist sand	10000	2.5
Dense, dry and moist sand	5000	2.75
Loose, dry and moist sand	2000	3
Very loose, dry and moist sand	1000	3.25

The amount of explosion pressure is calculated by Equation (2).

Equation [2]: $p_{so} = \frac{6.7}{z^3} + 1 \ \left(p_{so} > 10\,{}^{kg}\!/_{cm^2}\right)$ $p_{so} =$

$$\frac{0.975}{Z^1} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \quad (0.1 < p_{so} < 10\,{}^{kg}\!/_{cm^2})$$

The duration of the explosion or the positive time of the explosion is the time at which the explosion pressure is greater than the peripheral pressure.

This time depends on the velocity of the shock wave, in addition to duration of maintaining the maximum pressure and the amount of pressure reflected in the explosion.

In the TM5-1300 instruction, a graph is presented for calculating the positive phase duration that was summed up by Izadifard and Maheri inEquation 3 (16) .

Equation [3]:

$$log_{10}\left({}^{t_d}\!/_{W^{1/3}}\right) = 2.5log_{10}(Z) + 0.28 \qquad Z < 1$$

$$log_{10}\left({}^{t_d}\!/_{W^{1/3}}\right) = 0.3log_{10}(Z) + 0.28 \qquad Z > 1$$

Changes in time pressure are expressed in terms of Friedland's relationship.

The relation [4]:

$$p(t) = p_s\left[1 - \frac{t}{t_s}\right]\exp\left(\frac{-bt}{t_s}\right)$$

In this equation, b is a waveform that is a function of the maximum pressure Ps and its value is determined in accordance with the characteristics of the explosion, which is presented below. This is the phase of continuity of the positive phase. The negative phase of the wave is often much weaker and much more gradual than the positive phase, and therefore its effect in the bombing is ignored (15).

Regarding the necessity of strengthening the urban gas pipelines in non-active defense, effort was made to use diameter of 4-inch for urban pipes, 12-inch diameter for transmission pipes and 8-inch and 10-inch diameter for pipe networks in calculations. Specifications of pipes used in **Table 2** are given. Due to the variety of pipes used, several pipe samples of various thicknesses are used for modeling. Modeling for a pipe of 12 inches pressure psi250 and for a pipe of 6 and 4 inches, a pressure of 60 psi is considered. Due to the pipes used in Iran, the mechanical properties of ST-37(Standard 37) were considered for steel pipe. The steel pipe's density is 7850 kg/m^3, the Young's modulus is 210 Gpa and the Poisson coefficient is 0.3. In order to study the effect of soil on the behavior of pipes under the explosion of three types of soils, hard soils, soft and clayey sand were investigated and the depth of burial was considered1, 2,3 and 4 m. The amount of explosive charges was also 15, 20, 30, 45, and 200 kg.

Table 2: Specifications of pipes used in modeling

Number	Diameter (in)	Thickness (mm)	Diameter (in)	Thickness (mm)	Diameter (in)	Thickness (mm)
1	4	6.8	12	8.7	8	11
2	4	8.7	12	11	8	14.3
3	4	10	12	14.3	10	11
4	4	14	12	21	10	14.3

Functional level of pipe breakdown: The optimal function of pipes is selected in accordance with the ALA instruction (15,11). This level of function is the failure of the pipe and the lack of loss of the ability to maintain the contents of the pipe during the explosion. In order to achieve the desired level of function in this definition, the following should generally be true:

– **Tensile strain: limiting the tensile strain of maximum 4% for steel pipes.**

– **Pressure strain: limiting the pressure strain to the value obtained in relation (5).**

Equation [5]: $\varepsilon_{cr} = 0.88(\frac{t}{R})$

Results

In this project, we tried to define the appropriate scenario for the threat of pipelines in the first step, and in the second step, in accordance with the scenario, the type and means of threat should be identified and determined and the amount of spent explosives should be determined.

In step 3, the vulnerability that the threat tool of interest can cause to the pipeline, and, in step4, existing solutions to reduce the vulnerability of the pipelines were investigated.

In order to investigate the reduction of pipeline vulnerability in the two studied scenarios, the effect of increasing pipe thickness, increasing diameter, increasing burial depth, increasing the distance to explosion site and changing the soil material were separately investigated and analyzed.

Pipeline Vulnerability Results in Threat Scenario 1

In **Figure 3**, a schematic analysis of the explosion model software in the scenario of the direct hit of rocket (20kg) to the burial site of pipelines is illustrated.

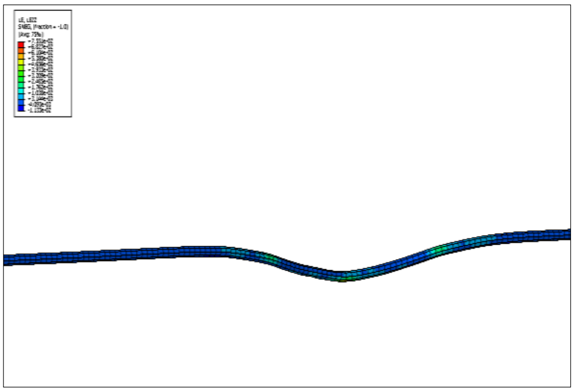

Figure 3: Analysis of the explosion model in the software

The results showed that for the charge of explosive charges of more than 20 kg for a pipe of 4 inches, 30 kg for a 12 inch pipe and 40 kg for a pipe of 16 inches, the behavior of the pipe exceeds the desired functional level and results in cracking and exploding. In the study of vulnerability reduction, the amount of rocket and mortar spent in scenario 1 was considered. In order to reduce the vulnerability and maintain the pipe function in explosions with higher charge, the following factors were considered separately:

− The effect of pipe thickness on reducing the vulnerability

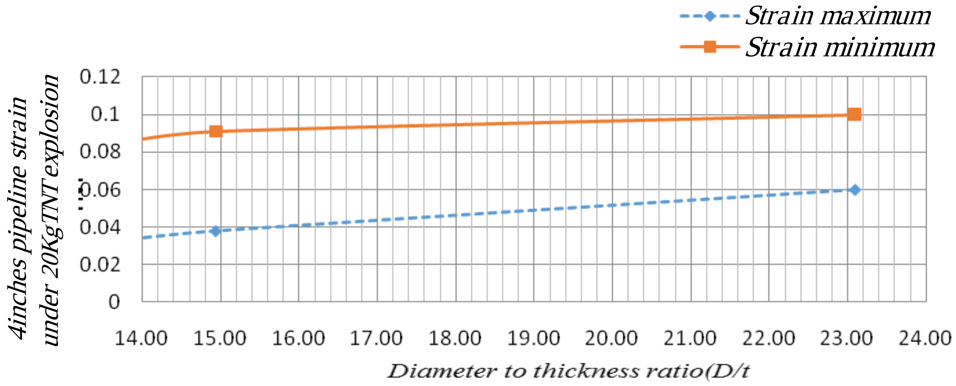

Figure 4: Effect of D/tratio to the 4-inch pipe strain and explosion per explosive charge of 20 kg explosive material.

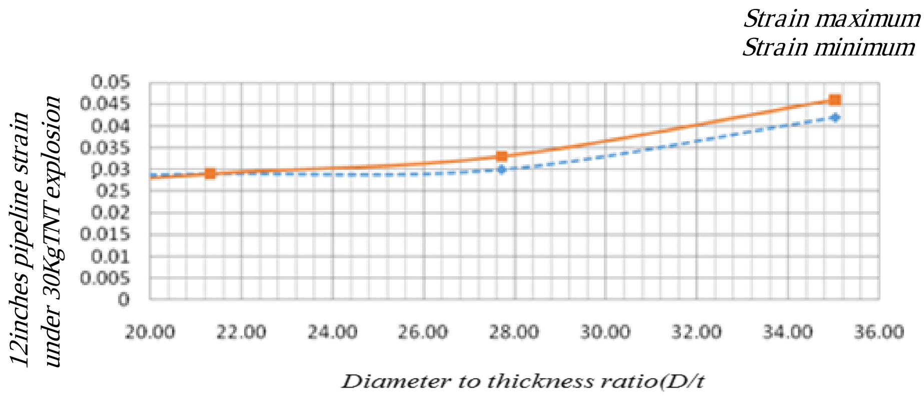

Figure 5: Effect of D/t ratio to 12-inch pipe strain due to explosive charge explosion 30 kg

As shown in **Figures 4 and 5**, the pipe behavior is improved by increasing the thickness of the pipe as it decreases with increasing pipe thickness (D/t) (Diameter to thickness) and the stability of the pipe increases against deformity. Thus, it shows a more resistant behavior against the dynamic wave of the explosion. And pressure and tensile stresses are reduced.

For a 12-inch pipe, it can be reduced by about 50% by doubling the thickness of the strain pipe and relative deformations, and will maintain the function of a 12-inch pipe under the explosion of 30 kg of explosive at a distance of 1 meter (from the explosion).

Hence, as an option for pipe strengthening, this method is not a technical solution.

− The effect of increasing pipe diameter on reducing vulnerability

In order to increase the resistance of the pipe against the explosion waves, the diameter of the pipe can be increased. As the diameter of the pipe increases, the D/t ratio increases; this improves the pipe's hardness against the explosion shock, and reduces strains and deformations in the pipe.

As shown in **Figure 6**, with a constant holding of thickness and an increase of 1.5 times the diameter of the compressive and tensile strain of the pipe is reduced by about 20%.

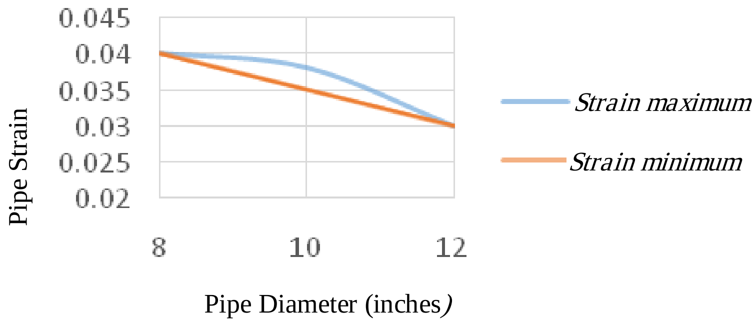

Figure 6: Impact of pipe diameter on pipe strain with depth of burial of 1 meter and explosion distance of 1 meter and TNT charge of 30 kg

The reason for this is that, as the diameter of the pipe increases, the pipe's hardness increases, but it should also be noted that the explosion wave pressure on the pipe is also increased, as the diameter of the pipe increases the pipe's interaction with the soil.

Compared to the increase in the thickness of the pipe, it can be concluded that in pipes with a diameter of about 4 inches, by doubling the diameter, the pipe functional level can be maintained for the charge of 30 kilograms of explosives, while doubling the pipe thickness, the function of the pipe for the charge of 20 kilograms of explosives is maintained.

It is therefore advisable to use the option of increasing the diameter instead of increasing the thickness in order to strengthen the pipes of short diameter because it has a greater effect on the pipe deformation and hardness of the pipe. In addition, with the same weight of steel, you can see better function.

− The effect of increasing the depth of pipe burial on reducing the vulnerability

Increasing the depth of burial is one of the ways in which it can reduce the vulnerability of the pipe to the explosion.

By increasing the depth of the pipe buried in the soil, the distance between the rocket and the increased pipe also causes the wave front to enter the pipe from the fuse, and the effective pressure enters the pipe.

As shown in **Figure 7**, the explosion-induced tensile stress decreases abundantly and results in an increase in the safety level of the pipe against the explosion. Hence, increasing the security level of pipe against threats can be a good solution.

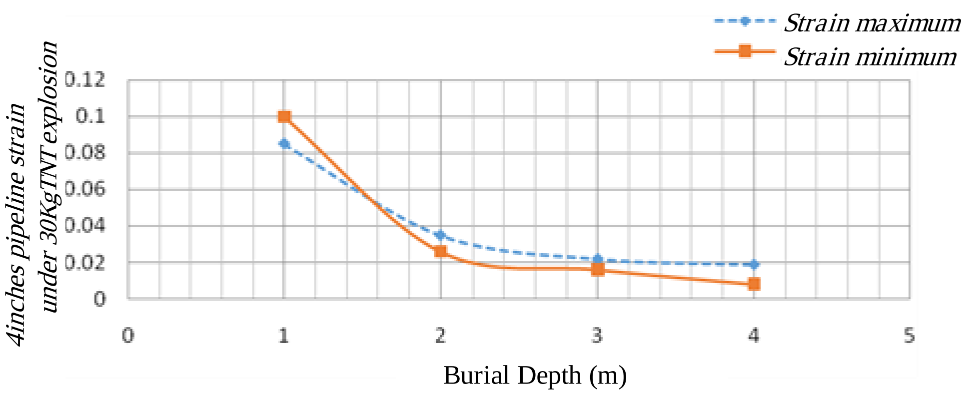

Figure 7: The effect of increasing the depth of pipe burial on the 4-inch pipe strain in explosion at 1-m distance

As the depth of the pipe bursts, the deformation and pipe strain decreases greatly, as a 50% increase in the cost of the material keeps the pipe at its optimal level.

Therefore, it is recommended that the parameter of increasing the depth of burial in the process of pipeline strengthening and reducing the vulnerability of pipelines will be given special attention.

− The effect of changing the blast distance to the pipe burial place on reducing pipeline vulnerabilities

As shown in **Figure 8**, as the distance from the pipe to the rocket increases, the distance indicator increases and the effective pressure from the explosion on the pipe decreases; however,it can be seen that by reducing distance and at very close distances of up to 1 meter, even a small amount of low explosive charges can cause a lot of stress on the pipe, causing damage and explosion in gas pipes.

In addition, as the distance of the pipe hit site to the rocket increases, the distance indicator increases and the effective pressure from the explosion on the pipe is reduced, however, the impact of explosives is reduced by increasing the distance to 4 meters.

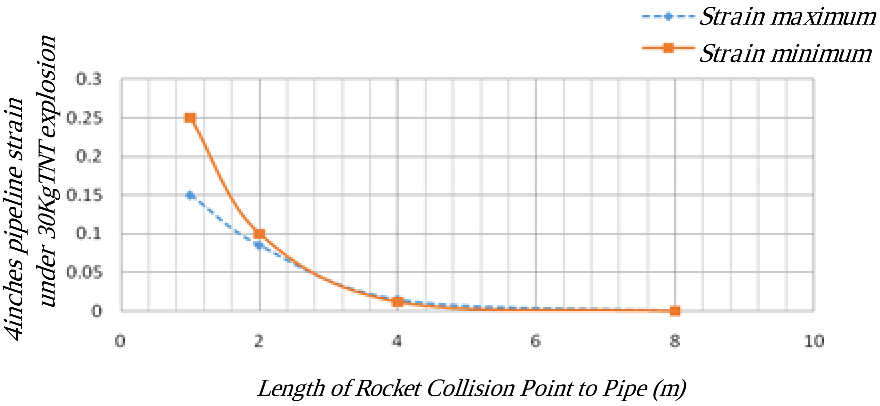

Figure 8: Effect of the Rocket Hit Site on the Strain of Pipe

− Effect of soil moisture change around the pipe on reducing its vulnerability

With the hardening of the soil around the pipes, the pipe and the soil become more explosive during the explosion, and the explosion wave propagates more rapidly in hard soil with more modulus of elasticity and more pressure is applied to the pipe.

Therefore, it is recommended to use soft soil around the pipe. This, reduces the damage to the pipe as much as possible. **Table 3** shows the soil profile used in the modeling.

Comparing the clay soil with sand shows clay soil, because of its adhesive particles, causes more damage to the pipe at the time of explosion compared to the sandy soil.

As shown in **Figures 9 and 10**, various soil parameters such as coefficient of friction, density, volumetric expansion coefficient, plastic behavior and viscosity behavior are important parameters in soil behavior that affect the behavior of the pipe differently.

Table 3: Characteristics of soil material used in modeling

Soil material	*E (MPa)*	*ρ (kg/m³)*	Soil behavior coefficients		
			friction angle	*flow stress ratio*	*dilation factor*
Soft sand	*7*	*1600*	*25*	*0.8*	*54.81*
Hard sand	*14*	*2000*	*35*	*0.85*	*44.63*
Clay	*4*	*1700*	*0*	*1*	*0*

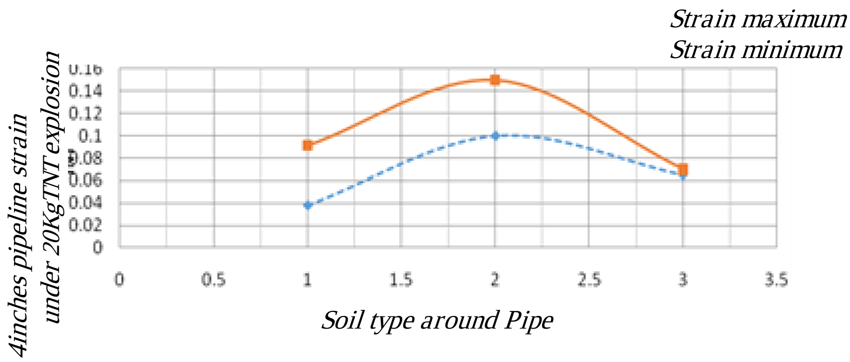

Figure 9: The effect of soil type on the behavior of a 4-inch pipe (1-sandy sand, 2-hardwood sand, 3- clayey soil)

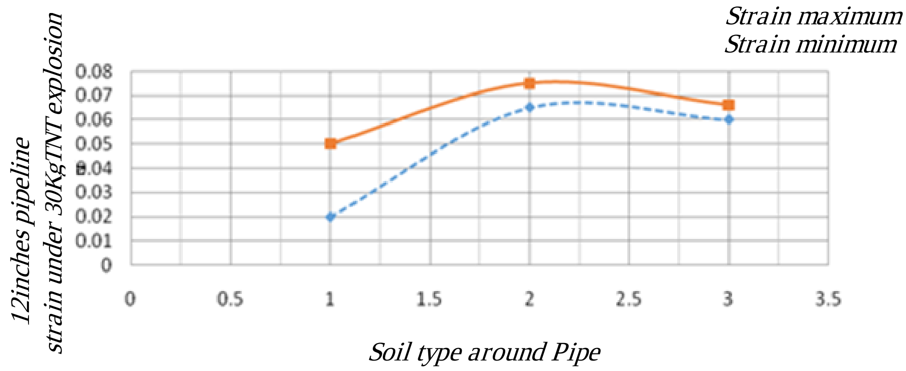

Figure 10: The effect of soil type on the behavior of a 12-inch pipe (1- soft sand, 2- hard soil sand, 3- clay soil)

As shown in **Figures 9 and 10**, hard sand soils, due to higher modulus of elasticity and friction coefficient than those of soft sandy soils and clay soils, produce relatively more interactive stresses to the pipe and, in addition, due to the higher wave transmission velocity pressure, more stress due to the explosion is exerted to the pipe; therefore, it is recommended that the soil with lower modulus of elasticity and less friction coefficient be used to exhibit the best behavior against the blast of soft sandy soils, and in the best case, about 25% Reduces the maximum tension.

Study of the vulnerability of pipelines in threat scenario 2

If we assume that the explosion cannot cause serious damage to the pipe at a distance equal to the width of a two-way street, i.e., about 6 to 8 m, and with an explosive charge of 60 to 80 kg of explosive, even if the explosive volume increase up to 200 kg, the only reasonable solution to this is to increase the depth of the pipe burial, which will have the greatest impact on reducing the vulnerability.

Conclusion

In order to control the behavior and capacity of strengthened pipes, their behavior was measured based on the purpose of the function and the response to the assumed threat scenarios in accordance with the ALA regulations.

In order to reduce the vulnerability to counteract the threat scenarios, parameters of thickness, diameter, depth of burial, rocket encounter and separate soil were studied.

By increasing the depth of the pipe buried in the soil, the distance between the racket and the pipe increases, on the other hand, it causes the wavelength of the explosion to enter the pipe further away and the effective pressure enters the pipe.

Therefore, burial depth is an important parameter, which can increase the safety of the pipe to spend on explosives up to 70%.

As the distance from the bullet or rocket hit site to the pipelines increases, the distance indicator increases, which reduces the effective pressure caused by the explosion on the pipe, but in addition, it can be seen that with reducing the distance (at very close distances of up to 1 m), even for the extremely low explosive charges, much stress is exerted to the pipe, causing a breakdown and explosion in gas pipes.

Hence, in the discussion of the extent of the vulnerability, the impact of explosives has been reduced by increasing the distance of the enclosure to 4 meters and can be ignored by the effect on the pipe.

With the hardening of the soil around the pipe, the interaction of the pipe and the soil become larger during the explosion, and the explosion wave propagates more rapidly in hard soil with more elastic modulus and more pressure is introduced into the pipe.

Recommendations

In order to strengthen the gas pipelines, it is recommended to use soft sandy soils around the pipe to reduce the damage and damage to the pipe as much as possible.

With increasing the thickness of the pipe, the hardness of the pipe increases against the explosion wave and it is more resistant to local breakdowns and less damage, but due to the excessive increase in pipe thickness and weight, there is no significant effect on the improvement of pipe function due to the movement of the front the wave caused by the explosion of motion and velocity of the soil elements is at a depth of 1 m and causes excessive stress on the pipe.

Increasing the thickness of the pipe by about 2 times reduces up to 25% of the maximum strain in the pipe.

With increasing the diameter of the pipe, the pressure of the explosion front increases on the pipe and the pipe and soil interactions also increase, and on the other hand, the hardness of the pipe increases.

Investigations have shown that increasing the pipe diameter by about 1.5 times reduces only 30% of the maximum strain in the pipe exposed to the explosion.

Hence, due to the increase in the weight of steel, increasing pipe diameter is not recommended as a desirable way to reduce the vulnerability.

Studies show that the level of explosive charges is about 30 kg for the 12-inch pipeline, which is about 20 kilograms for the pipes with a diameter of 4 inches.

In the study of the explosion scenario of explosive materials in a car on the street, if the car is assumed to be about 6 m from the pipe's burial ground, the explosion of about 200 kg of explosives will not cause serious damage to the pipe and the pipe can maintain its function.

It is therefore advisable to increase the depth of the pipe burial to 2 meters in order to increase the security of pipes against terrorist operations. In future studies, it is suggested to investigate the effect of explosion on buried pipelines in wet soils and to determine the effect of moisture on the vulnerability of gas pipelines.

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Conflict of interest

None declared.

Authors' contribution

All authors contributed to this project and article equally. All authors read and approved the final manuscript.

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