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Analytical Proposal to Damage Assessment of Buried Continuous Pipelines during External Blast Loading

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***Abstract*—**In this paper, transversal vibration of buried pipelines during loading induced by underground explosions is analyzed. The pipeline is modeled as an infinite beam on an elastic foundation, so that soil-structure interaction is considered by means of transverse linear springs along the pipeline. The pipeline behavior is assumed to be ideal elasto-plastic which an ultimate strain value limits the plastic behavior. The blast loading is considered as a point load, considering the affected length at some point of the pipeline, in which the magnitude decreases exponentially with time. A closed-form solution for the quasi-static problem is carried out for both elastic and elastic-perfect plastic behaviors of pipe materials. At the end, a comparative study on steel and polyethylene pipes with different sizes buried in various soil conditions, affected by a predefined underground explosion is conducted, in which effect of each parameter is discussed.

***Keywords*—**Beam on elastic foundation, Buried pipelines, External explosion, Non-linear quasi-static solution.

I. INTRODUCTION

PROTECTIVE design of buried structures, such as tunnels and pipelines is among the most important categories in design of structures. This importance comes from the massive use of these lifelines in living, from oil and gas to water and sewerage and power transmission and transportation systems. In some countries which have magnificent resources of natural gas and oil, these lifelines are considered to be the major structures related to the national economy and thus of higher importance. Because of safety and maintenance problems, most of the main transmission pipelines are buried in the ground, which implies the need to major focus on buried pipelines.

Obviously, the most harmful loadings on structures are dynamic ones such as seismic and blast loadings. Although these two types of loading have much in common [1], there are some major differences that urge separate analyses on each problem. Research on seismic design and analysis of buried pipelines has been worked out since past three or four decades and even is going on in scientific centers; on the other hand, there are only few researches on analysis and design of buried pipelines subjected to blast and explosion [2-4].

Here, both linear and nonlinear behavior of buried pipelines under blast pressures induced by external explosions is discussed analytically. As it is clear, the most challenging issues in structural mechanics such as soil-structure interaction and nonlinearity of materials are included in this study. This research offers a simple, yet robust methodology for design and analysis of buried pipelines in regions prone to be risked by any types of explosions, such as excavations, inadvertent blasts or even attacks.

II. MATHEMATICAL MODEL OF STRUCTURE AND LOADING

A. Pipeline Model

The structure discussed is a continuous pipeline, so the joints and bents are not considered in the model. The buried pipeline is modeled as an infinite beam on elastic foundation as shown in Fig. 1(a). The behavior of the pipe material is assumed to be ideal elasto-plastic during the loading, so that the strain hardening section is neglected that will lead to a more conservative solution without no significant loss of accuracy. The corresponding stress-strain relation is shown in the Fig. 1(c).

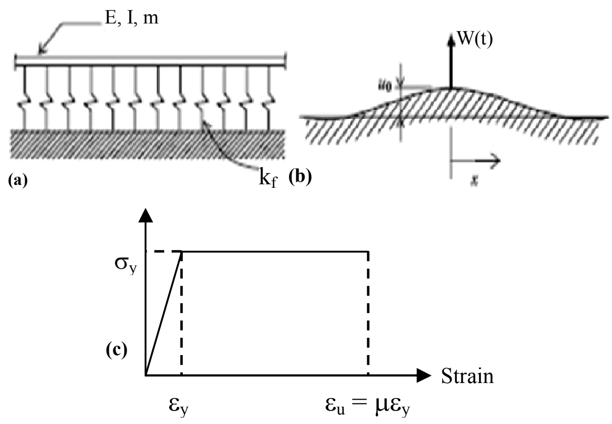

Fig. 1 Beam on elastic foundation model of the pipeline (a), applied blast force (b), assumed material characteristics (c)

E, *I* and *m* are young modulus of pipe material as a function of strain level, moment of inertia of cross-section of pipe and mass of unit length of pipe respectively, and as shown in the

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figures, μ is the strain ductility capacity of the pipe material defined as the ratio of the ultimate strain to yield strain. Here the vibration of the pipeline is modeled by a quasi-static problem, so the term m is neglected while inertia forces are neglected in this type of problems. These parameters are mentioned for different types of pipes with different materials and diameters in Table. I, II and III for the later case study.

TABLE I
SPECIFICATIONS OF DIFFERENT PIPE MATERIALS [2],[5]

Pipe material	Yield Stress, σ_y (Mpa)	Yield Strain, ε_y (mm/mm)	Ultimate Strain, ε_u (mm/mm)	Ductility Capacity μ	Modulus of Elasticity E (Mpa)
API- X60 Steel	413	0.002	0.05	25	200'000
PE	17	0.015	0.08	30	1'133.3

TABLE II
SPECIFICATIONS OF SOME REGULAR STEEL PIPES

Pipe size	Nominal pipe diameter (mm)	Pipe thickness (mm)
ST I	500	10.5
ST II	750	15.1
ST III	1500	20.0
PE I	75	8.2
PE II	100	11.4
PE III	150	16.4

TABLE III
SPECIFICATIONS OF SOME REGULAR POLYETHYLENE PIPES

Pipe size	Nominal pipe diameter (mm)	Pipe thickness (mm)
I	75	8.2
II	100	11.4
III	150	11.4

B. Soil-Structure Interaction

k_f in the Fig. 1(a), is the soil spring stiffness per unit length of the pipe. This parameter depends on the stiffness of the surrounding soil and depth of burial and of course, the position of the blast source to the pipeline, as soil behavior depends on the direction of pipeline vibration, because there are specific values for vertical bearing, uplift and horizontal direction. As it is shown in the Fig. 2, there are five possible situations for the problem. In situations that affect stand-off point A, B or C, the active soil springs that should be used are vertical bearing, lateral horizontal and vertical uplift respectively. In this paper, these three situations are discussed, thus the equations to derive the soil spring stiffness are introduced in Eqn. (1-3) based on [6]. The two other situations are combination of these situations and two types of soil springs should be modeled.

$$K_{vu} = \frac{(N_{cv} cD + N_{qv} \bar{\gamma} HD)}{\Delta_{vu}} \quad (1)$$

$$K_{vb} = \frac{(N_c cD + N_q \bar{\gamma} HD + N_\gamma \gamma \frac{D^2}{2})}{\Delta_{vb}} \quad (2)$$

$$K_h = \frac{(N_{ch} cD + N_{qh} \bar{\gamma} HD)}{\Delta_h} \quad (3)$$

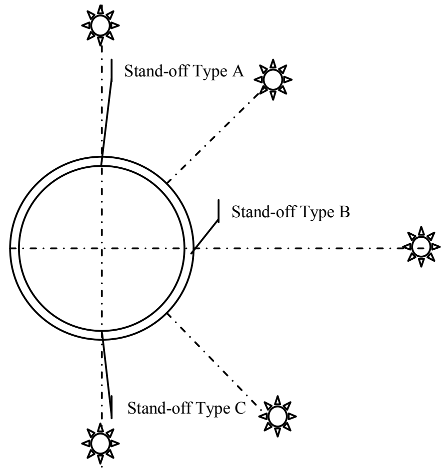

Fig. 2 Different situations for pipe and explosives under the ground surface

In these equations, K_{vu}, K_{vb} and K_h are the soil spring stiffness for vertical uplift, vertical bearing and lateral horizontal vibrations respectively, $N_{..}$ values are soil capacity factors for different situations that could be obtained from the curves introduced in [6], and:

c = Coefficient of cohesion of backfill soil
D = Outside diameter of pipe
$\bar{\gamma}$ = Effective unit weight of soil
H = Depth of soil above the center of the pipeline
γ = Total unit weight of soil
Δ_{vu} = The mobilizing displacement of soil, can be taken as:
(a) 0.01H to 0.02H for dense to loose sands < 0.1D, and
(b) 0.1H to 0.2H for stiff to soft clay < 0.2D.
Δ_{vb} = The mobilizing soil displacement, can be taken as:
(a) 0.1D for granular soils, and
(b) 0.2D for cohesive soils.
Δ_h = The mobilizing soil displacement, can be taken as:

$$0.04(H + \frac{D}{2}) \leq 0.01D \text{ to } 0.02D$$

C. Loading

On the other hand, the blast pressure loading is assumed as a point load at a point on pipeline that is a function of time as shown in Fig. 1(b). The simplified formulation of this force is given in Eqn. (4) [7].

$$W(t) = A_{aff.}.P_r.(1 - \frac{t}{T_d}) \qquad (4)$$

where $A_{aff.}$ is the area of the pipeline which is affected by the blast pressure, P_r is peak reflected overpressure, which is advised to be considered 1.5 times the peak static pressure in free field P_g for buried structures [7,8], and T_d is duration of the positive phase of blast wave. P_g is obtained from Eqn. (5) which is used exclusively for underground blast pressure [8]. In this formulation, ρ is the density of the soil in kg/m^3, C is the loading wave velocity defined as a function of seismic wave velocity in the soil. This equation also introduces the free field blast pressure as a function of n, the attenuation coefficient including soil conditions, W, equivalent TNT weight of explosives in kilograms, R which is distance between the explosives and the stand-off point in buried structure in meters and f_c, which is the coupling factor determined by the explosive depth of burial can be defined from Fig.3. The corresponding values of n are defined in Tab. IV for some types of surrounding soil.

$$P_g = 48.8 \rho C f_c (\frac{2.52R}{W^{1/3}})^{-n} \qquad (5)$$

TABLE IV
n PARAMETER DERIVED FOR SOME TYPES OF SOIL CONDITIONS [8]

Surrounding soil type	*n*
Saturated clay	1.5
Partially saturated clay and silt	2.5
Highly compacted sand, dry or wet	2.5
Medium compacted sand, dry or wet	2.75
Loose sand, dry or wet	3.0
Very loose sand, dry or wet	3.25

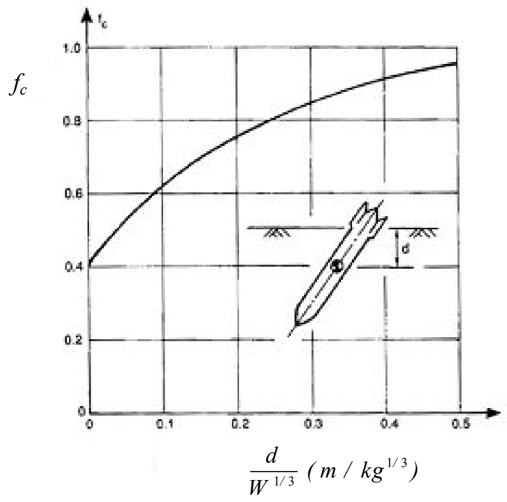

Fig. 3 Coupling factor based on scaled depth of burst [8]

As it is obvious, the intensity of loading varies with the condition of the surrounding soil in a complex manner. The surrounding soil affects the propagation and transition of pressure waves by three major characteristics: stiffness, porosity and saturation due to dissipation of wave energy in voids [9].

Here, the affected area of pipe is obtained by multiplying the pipe perimeter to the affected length of pipe, which is assumed to be equal to the length of the pipe which is within the radius of rupture, R_r of the explosive. The radius of rupture is defined as the distance from the center of an underground explosion at which the face of a buried structure would not be affected by any disruption and is defined in the early literature by the empirical Eqn. (5) (Bulson, 2003). In the equations below, D is the pipe diameter, and F factor is obtained from the Tab. 5. Because all this length is not simulated by the maximum pressure, the value obtained from this methodology, is reduced by the factor of η which here is assumed to be 0.5. Since the peak dynamic pressure decreases with the distance by the power of at least 1.5, this assumption seems to be at the safe side.

$$A_{aff.} = \pi D.l_{aff.} = 2\eta\pi D\sqrt{(R_r^2 - R^2)} \qquad (6)$$

$$R_r = 0.364 F W^{1/3} \qquad (7)$$

TABLE V
F FACTOR DERIVED FOR SOME TYPES OF SOIL CONDITIONS

Surrounding Soil Type	F
Hard rock	3.3
Soft rock	4.3
Blue clay	6.2
Loam	6.7
Gravel	6.8
Sand	7.5 - 7.8
Made ground	7.7 - 9.7

III. Governing Equation and Solution

The equation of motion for the quasi-static model of beam on elastic foundation is derived in Eqn. (8). As it is learned from seismic behavior of buried pipelines, the mass of the pipe and containing materials are not so important in the vibration of the structure [10], thus the quasi-static behavior is not far from the real problem. This formulation is based on beam on elastic foundation theory. In this equation, u is vertical displacement of the pipeline and $p(x,t)$ is the applied force per unit length of the pipe as a function of time and location. The x direction is defined in Fig. 1.

$$\frac{\partial^2}{\partial x^2}[E(u(x,t))I\frac{\partial^2}{\partial x^2}u(x,t)] + k_f u(x,t) = p(x,t) \qquad (8)$$

Substituting $p(x,t)$ with appropriate formulation shown in Eqn. (9) will lead to the closed form solution of this ordinary differential equation which is derived in Eqn. (10).

$$p(x,t) = W(t).\delta(x) \qquad (9)$$

$$u(x,t) = \frac{W(t).\lambda}{2k_f}(\cos\lambda x + \sin\lambda x).e^{-\lambda x} \qquad (10)$$

where $\delta(x)$ is Dirac's delta function of x and $\lambda = \sqrt[4]{\frac{k_f}{4EI}}$. Substituting $W(t)$ with its corresponding values in Eqn. (1) will

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yield the elastic response of the modeled buried pipeline which is defined below.

$$u(x,t)=\frac{A_{aff}.P_S.\lambda}{2k_f}(\cos\lambda x+\sin\lambda x).(1-\frac{t}{T_S}).e^{-(\lambda x)} \qquad (11)$$

According to the equation above, bending moment and thus stresses could be obtained from Eqn.s (12) and (13) respectively.

$$M(x,t)=\frac{A_{aff}.P_S}{4\lambda}(\cos\lambda x-\sin\lambda x).(1-\frac{t}{T_S}).e^{-(\lambda x)} \qquad (12)$$

$$\sigma(x,t)=\frac{A_{aff}.P_S.D}{8\lambda.I}(\cos\lambda x-\sin\lambda x).(1-\frac{t}{T_S}).e^{-(\lambda x)} \qquad (13)$$

As it was expected, maximum value of displacement, bending moment and stress happens at the point that loading is applied and the amplitude of these efforts reduces with time and distance from blast origin that satisfies the boundary conditions of the beam.

The maximum strain of pipeline in the elastic level is derived by substituting the parameters with their definitions and presented in Eqn. 14. In this equation, t is wall thickness of the pipe.

$$\varepsilon_{\max,e}=\frac{(\eta l_{aff.}).P_S}{E\,t.D.\lambda} \qquad (14)$$

As mentioned above, the moment distribution is derived by solving the elastic problem. Because the maximum value of bending moment is important and after one point of the pipeline reaches the failure point, the pipeline services may collapse due to possible leakage, the safety index Φ, is defined as the ratio of the ultimate elasto-plastic bending moment for the pipe cross-section M_{ult}, to the maximum bending moment induced by the underground explosion along the buried pipeline M_{max}. M_{ult} is the bending moment related to the maximum strain of ε_u in the pipe cross-section as it is shown in Fig. 4. The formulation of M_{ult} and Φ are carried out below, while in the formulation of Φ, $\chi(\mu)$ stands for the statement $\{\mu Sin^{-1}\frac{1}{\mu}+\sqrt{1-(\frac{1}{\mu})^2}\}$. It should be noted that for obtaining this equations, a few approximations have been used, but these considerate assumptions do not affect the outcome significantly.

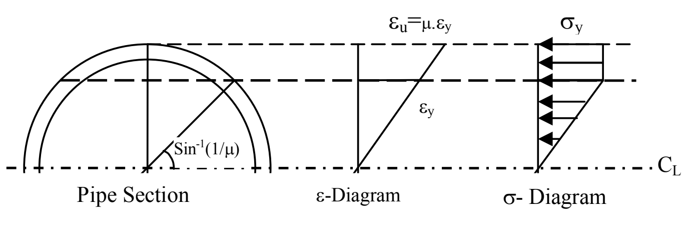

Fig. 4 Ultimate State Stress Distribution in Pipe Section

$$M_{ult}=\int_A \sigma y dA=2\int_0^{\pi}\sigma_y R^2 t Sin\theta d\theta-4\int_0^{Sin^{-1}(\frac{1}{\mu})}\sigma_y(1-\mu Sin\psi)R^2 t Sin\psi d\psi \qquad (15)$$
$$=2\sigma_y R^2 t(\mu Sin^{-1}(\frac{1}{\mu})+\sqrt{1-(\frac{1}{\mu})^2})$$

$$\Phi=\frac{M_u}{M_{max}}=\frac{4}{\pi}\frac{\sigma_y D.t.\lambda}{P_s.(\eta l_{aff.})}\chi(\mu) \qquad (16)$$

As it is understood from the definition of Φ, if the value of this parameter exceeds 1, the pipeline is safe in the specific case, and for the values lower than 1, the pipeline is vulnerable to the blast loading and it fails to resist the selected level of explosion pressure. In the former cases, it is possible to compare the maximum elastic strain obtained from Eqn. 14 with yield strain of the pipe material to see if the pipeline exceeds the elastic level it requires repair after the explosion.

A numerical survey is been conducted in the next section of this paper to examine the effect of different parameters of the problem. This study should give a brighter insight on the derived equations.

IV. Case Study

In order to examine a practical situation, an amount of 100 kg TNT is selected as the source of blast loading. It is assumed that this amount of explosive detonates in the depth of 2.5 meters under the ground surface and have a free distance of 5 meters to the subjects. Targeted pipelines of various diameters and materials in Tab.s I, II and III are buried in soil conditions shown in the Tab. V. Loading characteristics for these types of soils are calculated from the equations and data presented in this paper and shown in Tab. VI. The results of this survey for different cases are calculated and shown in Tab. VII.

TABLE VI
SURROUNDING SOIL CONDITIONS FOR STUDIED CASES

Soil type	Specification	n	c (m./s)	P_g (kPa)
A	Soft sand	2.70	66.14	437.5
B	Hard sand	3.0	83.67	175.5
C	Clay soil	2.50	47.14	210.4

TABLE VII
RESULTS FOR DIFFERENT CASES

Pipe size	Soil type	Steel pipes		PE pipes	
		Elastic $\varepsilon_{max,e}$ (%)	Safety Φ	Elastic $\varepsilon_{max,e}$ (%)	Safety Φ
I	A	0.39	13.77	yielded	1.14
I	B	0.013	42.43	1.09	3.50
I	C	0.021	25.88	yielded	2.14
II	A	0.027	20.01	yielded	1.56
II	B	0.009	61.66	0.79	4.82
II	C	0.014	37.61	1.30	2.94
III	A	0.018	29.39	yielded	2.27
III	B	0.006	90.54	0.55	7.01
III	C	0.010	55.21	0.89	4.27

V. CONCLUSION

In this paper, two direct formulas were derived for primary analysis and design of buried pipelines subject to underground explosions. These formulas were derived from the closed form solution of the quasi-static equation of motion of the pipeline modeled as a beam, therefore pipelines of greater diameters may act somehow differently and should be modeled by shell elements and it is expected that these equations suffer some losses of accuracy for larger pipe diameters.

Based on these two formulas and also the numerical study, larger diameter and thickness of pipes are the parameters that support resistance of the pipes to blast loads. Moreover, pipes made of materials with higher modulus of elasticity have better elastic behavior to the loading. Surrounding soil attributes have major effect on the response of the buried structure during and after explosion. As it was shown in the results of the numerical survey, dense sand provide more benefit for the buried pipelines prone to be affected by explosions. Another parameter involved in this survey is burial depth that in this case, it is prescribed to bury the pipes deeper under the ground, for it enlarges the distance of the blast source to the structure, and also the pipes will benefit more intense interaction with the soil.

Another major result of the numerical survey of this paper is that the elasto plastic behavior of pipelines which was modeled in this study slightly increases the load resistance of the structure. The proof is that in the cases that the strain level of the pipe exceeds elastic level, the plastic safety index defined in the text, is upper than 1 and the pipeline will endure according to the defined model. However, due to the simplifications introduced by the authors, these formulations are expected to present the upper bound damage indexes and therefore offer values in the safe side.

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REFERENCES

[1] Medearis K.G., *A Comparative Study of Structural Response to Explosion-Induced Ground Motions*, ASCE Council on Performance and Structures, 2001.

[2] D. Nourzadeh, S. Takada, K. Bargi, Response of buried pipelines to underground blast loading, Proceedings of the 5th civil engineering conference in the Asian region and Australasian structural engineering conference 2010, Australia, 2010.

[3] G. P. Kouretzis, G. D. Bouckovalasa, and C. J. Gantes, "Analytical calculation of blast-induced strains to buried pipelines", Int. J. of Impact Eng., Elsevier, 2007.

[4] Siskind DE, Stagg MS, Wiegand JE, Schulz DL. Surface mine blasting near pressurized transmission pipelines. Report of Investigations RI9523, to US Department of Interior, Bureau of Mines, 1994.

[5] Pezeshki H., Ueno J.& Takada S., "Performance and allowable fault dislocation for steel and polyethylene pipelines crossing faults". Memoirs of Construction Engineering Research Institute no.46, pp. 152-163, 2004.

[6] American Lifeline Aliamces, "Guidelines for design of buried steel pipes", ASCE, 2005.

[7] Bulson P.S., "Explosive Loading of Engineering Structures", Taylor & Francis e-Library, 2003.

[8] Smith P.D.& Hetherington J.G., "Blast and Ballistic Loading of Structures", Butterworth- Heinemann, Elsevier, 1994.

[9] Graph K.F., "Wave Motion in Elastic Solids", Dover Publications Inc.: New York, 1991.

[10] Datta T.K., "Seismic response of buried pipelines: a state-of-the-art review". Nuclear Engineering and Design 192, pp. 271-284, 1999.