Transactions on the Built Environment vol 32, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

Trenching by explosives nearby an existing pipeline: charge size charts

F. Lagasco, G. M. Manfredini, G. P. Vassallo
D'Appolonia S.p.A., Genoa, Italy
EMail: dappolonia@PN.ITnet.it

Abstract

Trenching by explosives in the vicinity of an existing pipeline can induce structural damage in the pipeline walls. Charge sizes defined on the basis of optimum trenching effectiveness must be verified on the basis of their impact on the existing nearby pipelines. An effective Structure Medium Interaction (SMI) approach, implemented in a 2-D code, is proposed to model the blast design scenarios. Stress and particle velocity decay is governed by exponential laws calibrated to fit experimental data by means of empirical parameters. Wave propagation filtering through the backfill around the pipeline is obtained by scaling stress and velocity on the basis of standard relationships governing the transmission phenomenon at the boundary. The methodology presented is aimed at producing design charts relating limiting charge to distance, medium, backfill and pipe characteristics. Design charts proposed can be readily used by practicing engineers to verify structural integrity of existing pipelines for the effects of nearby blasts.

1 Introduction

Along the main pipeline routes it is often required to accommodate additional lines due to the increased market demand of gas and oil. Trenching new routes by explosives at short distance from existing lines requires the evaluation of possible damage to the existing structures. The importance of this kind of analysis is due to the fact that internal pipe pressure generates a hoop tensile stress usually in the vicinity of yield. Thus, an additional stress may cause damage.

The present paper examines a typical case of a pipeline placed in a trench backfilled with granular material, such as crushed rock, excavated in the base rock medium. The trench of the new pipeline is obtained by firing explosive charges, placed in shallow boreholes at suitable depth to provide maximum trenching effectiveness. The required charge size is a function of type of explosive, strength of the excavated material and trench dimension and it is well addressed within specialised Demolition Manuals. On the other hand, simple means to evaluate the integrity of structures in the vicinity of explosion sources are not readily available. Methodology on how to obtain design charts and an example of design chart for a specific geometry and site, are presented in this contribution.

2 Modelling

State of the art analysis tools, including non linear finite element or finite differences computational capabilities, although very powerful, do not afford reliable estimates of the structural shock effects within reasonable times. Decoupling procedures used to model structure-medium interaction effects were found to provide a satisfactory approximation to the full non linear formulations [1]. In these simplified approaches a decoupled force, consisting of interface stress modified by the SMI model, is directly applied to the structure. Empirical expressions for stress attenuation, based on experimental peak velocities are available in the literature and give a reliable definition of the decoupled exciting force. The methodology adopted in this paper has been implemented in a 2-D lumped mass beam element code. The program models free-field load histories at nodal points of the structure and accounts for interaction effects by means of a non-linear SMI model. It also includes engulfment of the structure by the ground shock wave and limiting structural capacity indicator.

2.1 Underground explosion

Explosions beneath the ground surface produce a radially expanding shock wave propagating through the soil. Exponential pressure time histories (Figure 1) rapidly decaying from the explosion source have been the object of extensive research and basic results are given in Protective Design Manuals, such as TM5 [2]. For the present work the following expressions were employed to model particle velocity V(t) and the pressure P(t) time histories:

Transactions on the Built Environment vol 32, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

$$t<t_a \quad P(t)=V(t)=0 \tag{1}$$

$$t_a \le t \le t_p \quad P(t)=\gamma\rho c f\left(\frac{R}{W^{\frac{1}{3}}}\right)^{-n}\left(\frac{t-t_a}{t_r}\right)$$

$$V(t)=\gamma f\left(\frac{R}{W^{\frac{1}{3}}}\right)^{-n}\left(\frac{t-t_a}{t_r}\right) \tag{2}$$

$$t>t_p \quad P(t)=\gamma\rho c f\left(\frac{R}{W^{\frac{1}{3}}}\right)^{-n} e^{-\alpha\left(\frac{t-t_a-t_r}{t_a}\right)}$$

$$V(t)=\gamma f\left(\frac{R}{W^{\frac{1}{3}}}\right)^{-n}\left(1-\beta\frac{t-t_a-t_r}{t_a}\right) e^{-\beta\left(\frac{t-t_a-t_r}{t_a}\right)} \tag{3}$$

where:
α, β, γ = empirical parameters;
f = coupling factor for near-surface explosions;
ρc = acoustic impedance of the medium;
ρ = density of the medium;
c = sound velocity of the medium (or seismic wave velocity);
R = distance from the source of the explosion;
W = weight of the explosive charge;
n = attenuation factor;
t_a = shock wave arrival time;
t_p = time at peak of the pressure time history;
$t_r = t_p - t_a$

The arrival time t_a, from the instant of the detonation to the instant at which the ground shock reaches the monitoring point at a distance R, is calculated according to:

$$t_a=\int_0^R \frac{dr}{c_p} \qquad c_p=c+s\left[f\gamma\left(\frac{R}{W^{\frac{1}{3}}}\right)^{-n}\right] \tag{4}$$

where:
c_p = loading wave velocity;
s = equation of state variable.

As soon as the stress wave reaches the structure, the wave engulfs it and gives rise to a rigid body motion combined to a deformation of the external walls. The overall motion and the resulting structural stress are affected by charge weight, mass and deformability of the structure, interface shear friction and soil characteristics. SMI model imposes continuity of both stress and displacement between the soil and the structure. Normal interface stress σ_i is then determined as a function of the normal incident free-field stress σ_n and relative velocity/displacement between the soil (V_n, D_n) and the structure ($\dot{y}$, y):

$$\sigma_i = \sigma_n \rho c_p \left(V_n - \dot{y} \right) + \frac{\rho c_p^2}{l_c} (D_n - y) \tag{5}$$

where:
l_c = characteristic length.

2.2 Effect of backfill

The backfill material (BF) surrounding the pipeline filters the stress wave reaching the interface through the base soil/rock (R). Transmission of the incident stress wave is modelled by means of the standard theory for elastic plane waves [3]. Incident and transmitted particle velocity and stress are described by the following relationships:

$$v_{BF} = v_R \frac{2 \rho_R c_R}{\rho_R c_R + \rho_{BF} c_{BF}} \tag{6}$$

$$\sigma_{BF} = v_{BF} \rho_{BF} c_{BF} \tag{7}$$

In addition to that resulting by crossing a material with lower acoustic characteristics, ground shock attenuation rate is also a function of the degree of compaction caused by passage of the stress wave. This effect is directly accounted for by means of an appropriate attenuation coefficient resulting from experimental data on different soils [4].

2.3 Effect of depth

In trenching operations, charges are placed in shallow boreholes drilled to a depth selected for maximum effectiveness. In the analyses, a ground shock coupling factor is employed to quantify the enhancement of the compressive shock wave as a function of the higher confinement provided by a higher depth. A relationship between depth of burst, measured at the center of the charge, and charge size is shown in Figure 2 for different values of the coupling factor. For combinations of charge weight and depth plotting below the $f = 1$ curve, peak velocity and pressure histories have to be reduced using the appropriate coupling factor.

3 Configuration scenario and analyses

3.1 Configuration scenario

Numerical analyses have been performed with reference to the geometrical configuration shown in Figure 3. The explosion source consists of C-4 charges at a depth of 1.2 m + D/2, being D the pipe diameter. Scaled distances are obtained by simply varying the distance between the center of the charge and the impacted area of the structure. The width of the trench and therefore of the backfill cross section is taken as 40 centimeters greater than the pipe diameter for all cases. Geomaterials considered in the analyses are a soft rock and a granular backfill surrounding the pipeline. Their physical properties are reported in Table 1. The finite element model is composed of 24 nodal points, with three degrees of freedom, connecting 24 structural elements (Figure 4). Load time histories are directly applied to nodal points.

3.2 Analyses

The system of equation of the structural motion is solved by a central finite difference scheme. The resulting nodal displacements and rotations are used to calculate element end elastic moments, shears and thrusts to update the system of nodal equations for the next cycle of solution. Damping is treated as an internal force for each element. This approach damps out numerical oscillations associated to the axial and flexural response modes without reducing global response.

By using an iterative process, different sets of simulations have been developed to find out the charge size potentially causing a predefined limiting condition for the most critical element of the pipeline model. The selected limiting condition, computed with reference to the combined axial load and bending moment capacity of the section, is reached whenever the stress state equals the yielding stress of the steel pipe, according to:

$$\left(\frac{N+N_i}{A}\right) \pm \left(\frac{M}{W}\right) \leq \sigma_y \qquad (8)$$

where all quantities are per unit length of pipe wall:

N = element thrust;
M = element bending moment;
Ni = element hoop force due to internal pressure;
A = section area;
W = section modulus.

4 Design charts

The similitude law governing the explosion phenomena can be used to construct linear predictive curves in a Log-Log diagram. Scaled distances $R^2/(D\,W^{1/3})$ are plotted in Figure 5 against scaled thickness $t^2/(D\,W^{1/3})$ for different values of internal pressure. The parameters considered in the simulation analysis include pipe geometry, in terms of external diameter and thickness, internal pressure, charge weight and distance from the structure. Extension of the simulation range is given by:

$$0.021\,\mathrm{m} < t < 0.031\,\mathrm{m}$$

$$0.6\,\mathrm{m} < D < 1\,\mathrm{m}$$

$$100\,\mathrm{bar} < p < 200\,\mathrm{bar}$$

Curves given in Figure 5 were obtained with reference to yielding of steel. The configuration implied a coupling factor equal to 1. For near-surface explosions the appropriate coupling factor *f* has to be accounted for to scale predicted values.

At constant internal pressure, knowing the geometry of the pipe, a relation between R and W is obtained. By appropriately varying the two parameters, the burst scenario can be optimised with respect to design constraints. On the contrary, by introducing distance, R, charge size, W and pipe characteristics, the allowable internal pressure is obtained and can be compared with operational values.

5 Conclusions

A two-dimensional structural model has been applied to predict effects caused by rock trenching with explosives on nearby existing pipelines. Design curves have been generated to allow the designer evaluate the compatibility of the charge size employed for trenching with the strength of the existing pipeline. The proposed chart covers a range of significant engineering parameters and can be extended to other cases of practical interest.

References

[1] Drake, J. L., Frank, R. A., Rochefort, M. A., A simplified method for prediction of the ground shock loads on buried structures, Proc. of the International Symposium on the Interaction of Conventional Munitions with Protective Structures, Mannheim, West Germany, 1987.

[2] TM5-855-1, Fundamentals of protective design for conventional weapons, Headquarters Dept. of the Army, Wash. DC, 1986.

[3] J., Henrych, The dynamics of explosion and its use, Elsevier Publishing Company, New York, NY, 1979.

[4] J., L., Drake, E., B., Smith, S., E., Blouin, Enhancement of the prediction of ground shock from penetrating weapon, Proc. of the 4th International Symposium on the Interaction of Non-Nuclear Munitions with Structures, Panama City Beach, FL, 1989.

Table 1. Material property constants

ROCK	
Seismic wave velocity	2500 m/sec
Density	2400 kg/m^3
Attenuation coefficient	1.5
BACKFILL	
Seismic wave velocity	500 m/sec
Density	2200 kg/m^3
Attenuation coefficient	2.5
STEEL PIPELINE	
Young Modulus	2.1 10^6 Kg/cm^2
Density	7800 Kg/m^3
Yield stress	4570 Kg/cm^2
Percentage Critical Damping	2

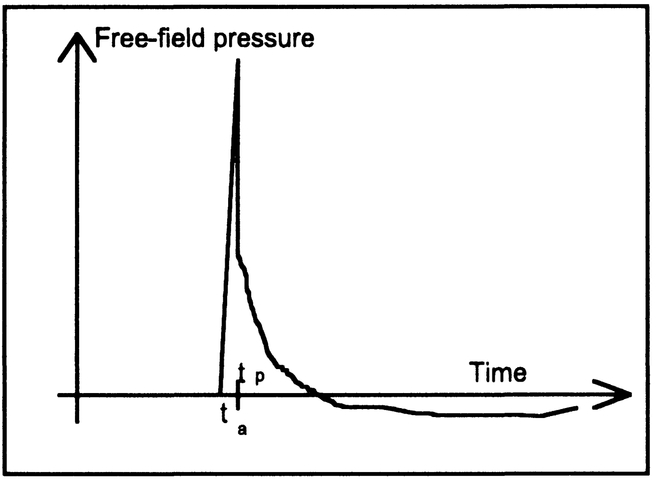

Figure 1. Exponential type free-field pressure history at a given site produced by a ground blast

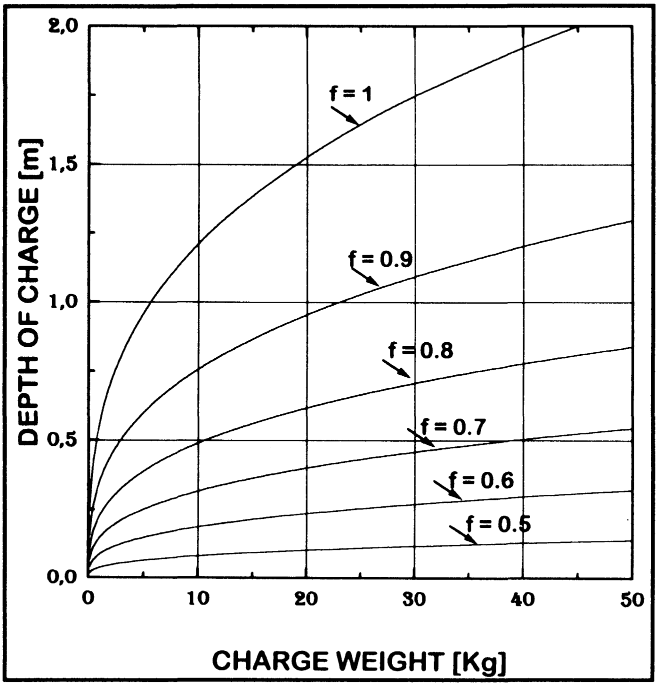

Figure 2. Ground blast coupling factor as a function of depth of burst and charge weight

Transactions on the Built Environment vol 32, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

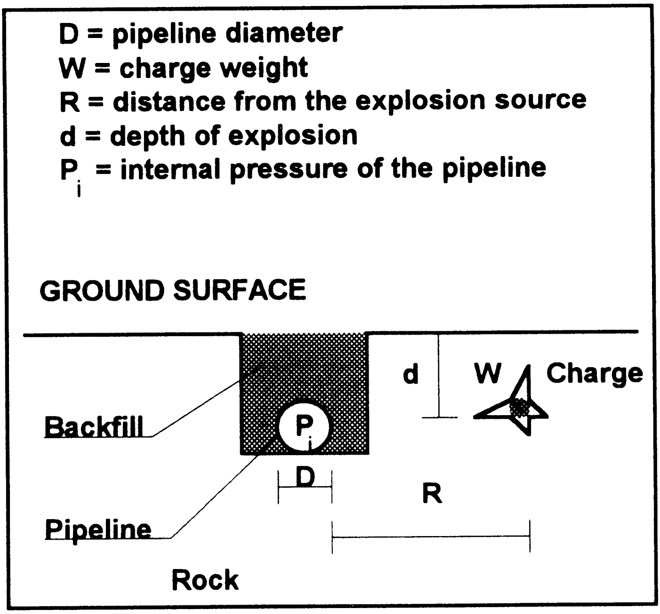

Figure 3. Geometrical configuration of the burst scenario

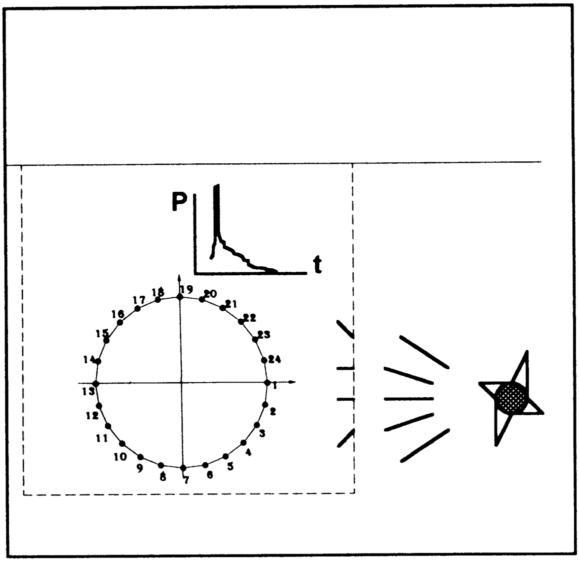

Figure 4. Finite element model of the pipeline

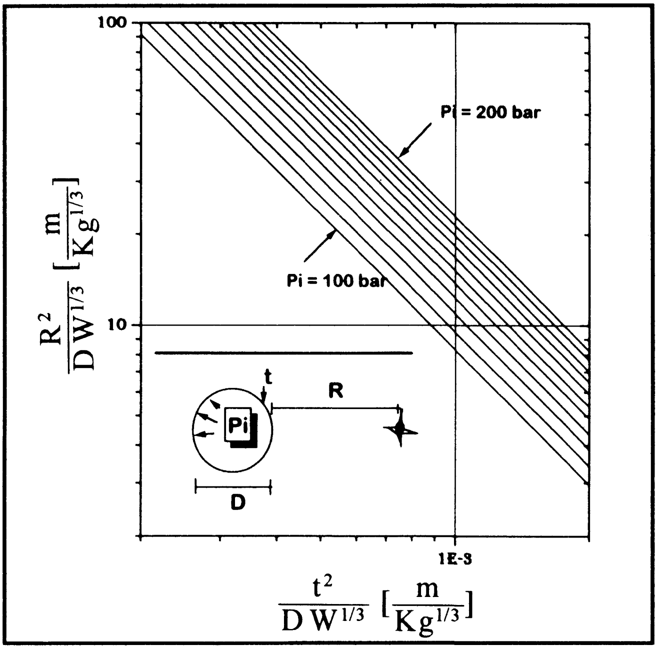

Figure 5. Design chart to evaluate integrity of pipelines for a nearby blast