RELATIONSHIPS BETWEEN PIPE STRESS, GROUND PARTICLE VELOCITY AND SCALE FACTORS IN BLASTING DOLOMITE

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ABSTRACT

An increase in construction and quarry operations has necessitated blasting activities in areas once considered rural and in the close proximity of transmission pipelines.

A method to determine the maximum allowable bending stress by the formulas outlined by the Battelle Memorial Institute report of October, 1962, and the assumed stress comparison with actual measured data is presented.

A direct relationship between pipe stress and ground particle velocity is shown, and a method to predict stress by relating stress to charge weight and distance from the shot point is discussed.

INTRODUCTION

The rapid growth of urban areas in locations that were only farm land Just a few years ago, has increased the necessity of relating ground particle velocity to stress when blasting activities occur in the vicinity of high pressure transmission pipe lines. Blasting operations in the Upper Midwest has been encountering the need to take into consideration the close proximity of pipe lines more than any previous time.

There is an inherent danger when blasts occur near high pressure pipelines, more so than blasting near other types of man-made structures. When failure occurs to structures and water or sewage pipelines, normally only physical damage is the result. Failure to a high pressure line will most likely result in the loss of human life. Since the blaster and his associates are the closest to such activities, if they value their life, they must take care to preserve it by understanding or at least have a fear of the energy available to them in the form of commercial explosives. The resulting transcient seismic ground motion has a potential to cause damage and must be controlled to the best of our abilities.

The relationships which will be presented here are applicable in different rock and soil types but the specific data and case histories relate only to blasting in dolomite similar to that located in the metropolitan Chicago area.

Our firm has experienced an increase in the concern on the part of both the pipeline operator and the quarry-construction industry to arrive at a satisfactory solution when blasting is to take place close to a pipeline, since neither party wants to seem uncooperative and disruptive to a necessary industry.

In the early 1960's work was undertaken by the American Gas Association Pipeline Research Committee to establish limits for charge size (pounds per delay) and distance from a blast to high-pressure gas transmission lines. The primary research found that there had been no case of pipeline failure due to blasting activities when prudent measures were taken by the blaster. Only when explosives were detonated directly adjacent to a pipeline were failures recorded.

Even though this be true, there always is concern for the safety of human life and installations when blasting occurs and questions arise which must be answered to assure those who question safe blasting procedures out of ignorance. Those persons who operate natural gas utilities or transmission pipelines, (along with the explosive user) are not always aware of the information available to them to understand the relationship between excessive pipe stress and ground vibration from blasting; therefore the method outlined here will insure job safety.

Even though the assumed pipe stresses are conservative, it will be shown that actual measurements are required due to the variables in the formulas.

BASIC CONSIDERATIONS REGARDING VIBRATION

We normally report the level of vibrations in terms which are functions of amplitude and frequency, be it either ground particle velocity or energy ratio. An assumption is made that the motion is sinusoidal and thereby the amplitude can be related to pressure, the critical radius (radius surrounding a bore hole in which the rock is fragmented) the rocks' modulus of elasticity and the distance from the blast.

Amplitude can be represented as :

$$A = a^2 P_o / kr$$

a = Critical radius
P_o = Pressure
k = Modulus of elasticity
r = Distance from blast

Frequency of the vibration is a relationship of sound velocity and critical radius, written as :

$$f = C/a$$

C = Sound velocity of the medium
a = Critical radius

A shot fired in limestone gives use to higher frequencies than in shale or soils and also since the modulus of elasticity of limestone is greater, the resulting wave amplitude would be less than that in shale or soil.

A high sound velocity rock produces higher frequencies therefore than a low-velocity medium and high frequencies which are present in low velocity rock or soils, attenuate rapidly with increasing distance.

The vibration waves' potential for damage decreases with increasing time and distance but the rate at which the wave is damped decreases as r/a increases.

The geologic environment is the most variable parameter, since its presence gives rise to the departure from the ideally elastic and infinite medium. Geology will control to some degree the frequency, amplitude, and other quantities characterizing the ground motion from a blast.

The prime concern is the measurement or determination of the maximum value of the ground motion, regardless of the direction of wave travel or type. Depending upon the distance the pipe is from the blast, the direct, refracted, and reflected waves will arrive at varying times and the direct wave since it travels the shortest distance will normally carry the most energy but will not necessarily produce the maximum movement at the pipe.

Of the many criteria that has been advanced to limit the amount of vibration allowable to man made structures, Particle Velocity is presently the most common. Particle Velocity is equal to 2~nfA.

The United States Bureau of Mines and other experimenters have equated the amplitude of ground motion to the square root of the explosive weight divided by the distance from the shot point, times a constant relating to: 1. Average overburden, 2. Deep overburden and 3. Rock.

$$A = KW^{\frac{1}{2}}/r$$

K = Site constant
W = Weight of the explosive
r = Distance from blast

The constant, according to Morris (2), is 0.03 for rock; 0.4 for soil.

The scale factor is the inverse relationship of the amplitude by which a single regression line can be drawn to represent vibration from a wide range of charge sizes when plotted on log-log paper versus the resulting maximum ground particle velocity.

$$SF = r/W^{\frac{1}{2}}$$

There will be scattering of data but this only indicates the uncertainties when using emperical formulas to express the magnitude of ground motion as a function of charge weight and distance.

ASSUMING ALLOWABLE PIPE BENDING STRESS

To be able to predict if the stress produced in a pipeline by nearby blasting activities is sufficient to cause failure one must assume.

1. Soil displacements can be adequately predicated by the equations described in the previous section.

2. The pipeline is subject to movement equal to those of the surrounding soil.

These two assumptions result in a very conservative predicted stress.

Two types of pipe stress will be discussed

1. Longitudinal Bending Stress

2. Circumferential Bending Stress

For blast in rock, which we are mainly concerned with, longitudinal stresses are predominant, while circumferential stresses effect pipelines in blasts detonated in soils or thick overburden.

1. Longitudinal Bending Stress

   Two assumptions made to predict longitudinal stresses are :

   a. The pipe is a long elastic beam on an elastic foundation.

   b. The displacement profile is the same as that produced by a concentrated load.

$$\text{Longitudinal Stress} = S_L = (KDW^{\frac{1}{2}}/2r)(kE/I)^{\frac{1}{2}}$$

K = Site factor
D = Pipe diameter, nominal outside
W = Single charge weight (lbs/Delay)
r = Distance from blast
k = Soil Modulus
E = Pipe Modulus
I = Moment of Inertia of the pipe:
0.0491 D[exponent 4]-(D-2t)[exponent 4]
t = Pipe wall thickness

2. Circumferential Bending Stress

   Here the stresses imposed by the soil displacement are expected to be such that the bending causes the pipe to be deflected out-of-round.

   While it is normally assumed that the soil would provide side support for the pipe walls, the assumption made in the prediction equation is that the "side support is small in comparison to the magnitude of the applied load." In addition, the pipeline is assumed to be unpressurized.

$$\text{Circumferential Stress} = S_C = 4.26(KEtW^{\frac{1}{2}}/rD^2)$$

K = Site factor
E = Pipe Modulus
t = Pipe wall thickness
W = Single charge weight (lbs/Delay)
r = Distance from Blast
D = Pipe diameter, nominal outside

The above function is critical in soil and is not recommended for distances less than 100 feet.

In calculating the stresses from the equation presented, the results will vary to a large extent upon the choice of the site factors and soil constants as well as the ranges of the other variables over which the relations apply.

DETERMINATION OF ALLOWABLE PIPE STRESS

The assumed allowable pipe bending stress is the difference in the allowable stress according to the American Petroleum Institute (API) specifications and the pipeline location (Design Factor) minus the calculated longitudinal pressure stress divided by two.

The following pipe data is needed to calculate allowable pipe stress.

Pipe Diameter, nominal outside	D - inches
Pipe wall thickness	t - inches
Specified Minimum Yield Strength (SMYS)	S - pal
Maximum Operating Pressure (MOP)	P - psl
Design Factor (A/.72; B/.607 C/~50; D/.40)	F

This data can be supplied to you by the gas transmission company or local utility which operates the pipeline.

To solve for allowable pipe stress.

$$S_A = 0.75 \times S \times F$$
$$S_L = P \times (D-2t)^2 / D^2-(D-2t)^2$$
S_B = Allowable Pipe Bending Stress
$$S_B = (S_A-S_L)/2$$

CASE HISTORIES

The following two cases are examples of data gathered from field work on an installation of a sewer line and the proposed expansion of a quarry.

Case 1

A 48 inch sewer line was to be installed, crossing two high pressure gas lines, and the transmission company wanted insurance that failure would not occur as the blasting operation approached the pipes.

A. Pipe Data

1. 30 inch Main Line Loop

Pipe Diameter .... D = 30 inches
Pipe Wall Thickness .... t = 0.344 inches
SMYS .... S = 52,000 psi
MOP .... P = 850 psi
Design Factor .... F = 0.6

Allowable Pipe Stress

$S_A = 0.75 \times 52{,}000 \times 0.6 = 23{,}400$ psi

$S_L = 850 \times (30-.688)^2 / 30^2 - (30-.688)^2$

$= 17{,}897$ psi

$S_B = (23{,}400 - 17{,}897)/2 = 2{,}751.5$ psi

2. 22 inch Main Line

Pipe Diameter .... D = 22 inches
Pipe Wall Thickness .... t = 0.25 inches
SMYS .... S = 52,000 psi
MOP .... P = 850 psi
Design Factor .... F = 0.6

Allowable Pipe Stress

$S_A = 0.75 \times 52{,}000 \times 0.6 = 23{,}400$ psi

$S_L = 850 \times (22 - 0.50)^2 / 22^2 - (22 - 0.50)^2$

$= 18{,}065$ psi

$S_B = (23{,}400 - 18{,}065)/2 = 2{,}667.5$ psi

The pipeline company requested that the allowable pipe stress for both pipes be held to 2,500 psi.

The pipeline company required both pipes to be monitored by strain gauge methods and seismic particle velocities measurements were taken to correlate, particle velocity, bending stress and the distance to the shot point and pounds per delay interval (Scale Factor).

A curve of the scale factor versus particle velocity was maintained for each shot and changes in loading procedures were made as the blasting approached the pipes (Figure #1).

The maximum pounds per delay interval varied from 25.0 to 2.7 pounds per delay interval as the blasting proceeded from 100 to 5 feet of the pipelines.

The maximum particle velocities reached a high of 9.85 inches per second and the bending stress 1,785 psi.

The formula for assuming longitudinal bending stress was projected for both the 30 and 22 inch pipeline.

The site factor K was 0.03 since blasting was in dolomite while the soil modulus was projected to be 20,000 pounds per square inch. This factor had been selected since the soil was a sandy clay which was water saturated. The water table in the area was quite high and the pipelines intersected the sewer line in a low lying area.

Figure #2 shows the assumed bending stresses for both diameter pipes, and its relationship to the measured bending stress.

Figure #3 plots the actual maximum particle velocity versus the bending stress recorded by the strain gauges.

The limiting bending stress (2,500 psi) was never recorded but the last blast which was five feet from the 22 inch diameter pipe did have a measured particle velocity of 9.85 inches per second. The strain gauge recorder malfunctioned due to water shorting out the electrical connections. A projected stress though from Figure #3 is 3,300 psi which is above the 2,500 psi allowed but below the 5,335 psi calculated bending stress.

Case 2

A pipeline company has an easement through the property owned by a stone company which operates a quarry on the property. The stone company plans to expand their operation and approach the easement.

Particle velocity measurements had been made at nearby residents and a knowledge of the blasting procedures used was available. The quarry owner wanted to keep the same drill pattern, hole size, and pounds per delay, therefore, the distance he could approach pipeline depended on the pipes' characteristics.

The pipeline company was approached and a plot with their easement, and pipe data was supplied to us for evaluation.

The pipe characteristics were

Pipe Diameter	D = 34 inches
Pipe Wall Thickness	f = 0.281 inches
SMYS	S = 52,000 psi
MOP	P = 770 psi
Design Factor	F = 0.6
Pipe Modulus	E = 30×10^6 psi

Allowable pipe bending stress was assumed to be

$$S_A = 0.75 \times 52,000 \times 0.6 = 23,400 \text{ psi}$$

$$S_L = 770 \times (34 - 0.562)^2 / 34^2 - (34 - 0.562)^2$$

$$= 22,716 \text{ psi}$$

$$S_B = (23,400 - 22,716)/2 = 342 \text{ psi}$$

The distance was found to be 82 feet, with a scale factor of SF = 5.8.

The scale factor versus particle velocity curve of previous blasts showed that a maximum particle velocity of 3.2 inches per second could be expected when the pipe stress approached the limiting criteria.

Both the quarry and the pipeline company accepted the assumptions, but plan to undertake strain gauge test once the pipeline is approached to within 100 feet.

CONCLUSION

The predictions which are made regarding the potential for damage to pipelines by blasting is sufficient to give the blaster and the pipeline operator a guide but the assumption must be used with the upmost care.

The best protection for both parties will be for strain gauge test to be made along with particle velocity measurements to assure the pipelines integrity and personnel safety at the point when the particle velocity is equal to one half assumed allowable bending stress.

The potential for failure is great, when one is working with explosives around high pressure pipelines and the transcient nature of the seismic ground waves should not be allowed to influence one to disregard this hazard by thinking that since the external pressure last only a second or two, nothing will happen.

For operations which are planned for start-ups in the future, and a pipeline is in the area, strain gauge test made on the pipe along with particle velocity measurements of single hole blast at varying distances from the pipeline would be the best check on the estimate of pipe stress, decay of soil displacement with distance and the relationship between charge weight, bending stress and particle velocity.

TABLE 1

SEISMIC VELOCITIES IN SUBSURFACE MATERIALS

Soil Type	Velocity ft/sec Minimum	Maximum
Top soil :		
Light dry	600	900
Moist foamy silty	1,000	1,300
Clayey	1,300	2,000
Semiconsolidated sandy clay	1,250	2,150
Wet Loam		2,500
Clay, dense wet	3,000	5,900
Rubble or gravel	1,970	2,600
Cemented sand	2,800	3,200
Sand clay	3,200	3,800
Cemented sand clay	3,800	4,200
Water-saturated sand		4,600
Sand	4,600	8,400
Clay, clayey sandstone		5,900
Loose rock talus	1,250	2,500
Weather-fractured :		
Rock	1,500	10,000
Shale	7,000	11,000
Sandstone	4,250	9,000
Granite, slightly seamed		10,500
Limestone, massive	16,400	20,200

TABLE 2

SUMMARY OF SOIL FACTORS

Site Factor (K)		
Deep overburden	0.40	
Rock	0.03	

Soil Constant (k), psi	Minimum	Maximum
Top soil :		
Light dry	262	590
Moist, loamy silty	812	1,370
Clayey	1,420	3,370
Semiconsolidated sandy clay	1,510	4,150
Wet loam		5,600
Clay, dense wet	8,850	34,100
Rubble or gravel	6,400	11,100
Cemented sand	9,700	12,600
Sand clay	10,000	13,900
Cemented sand clay	17,800	21,700
Water-saturated sand		22,500
Sand	26,200	87,000
Clay, clayey sandstone		45,000
Loose rock talus	1,750	7,000
Weather-fracture		
Rock	3,100	140,000
Shale	63,000	156,000
Sandstone	23,500	160,000
Granite, slightly seamed		160,000
Limestone massive	390,000	590,000

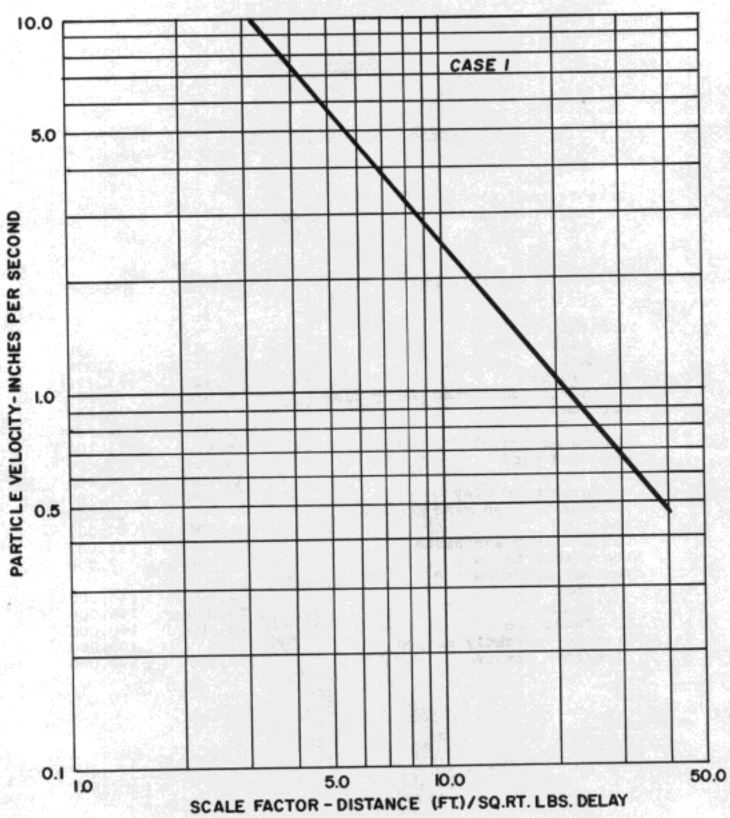

FIGURE-I

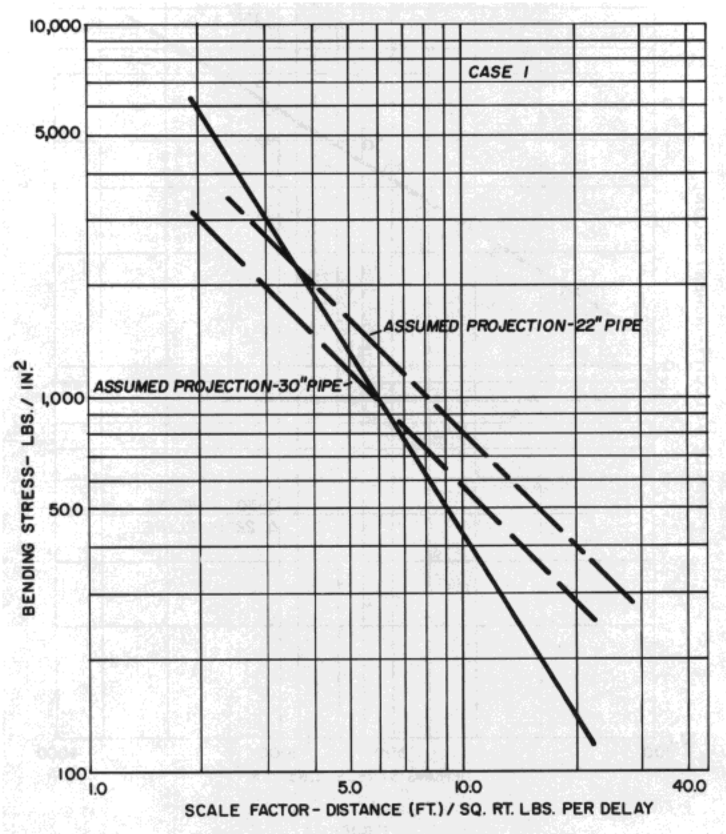
10,000
5,000
1,000
500
100
1.0
5.0
10.0
40.0
CASE I
ASSUMED PROJECTION-22" PIPE
ASSUMED PROJECTION-30" PIPE
BENDING STRESS- LBS./ IN.²
SCALE FACTOR- DISTANCE (FT.) / SQ. RT. LBS. PER DELAY

FIGURE-2

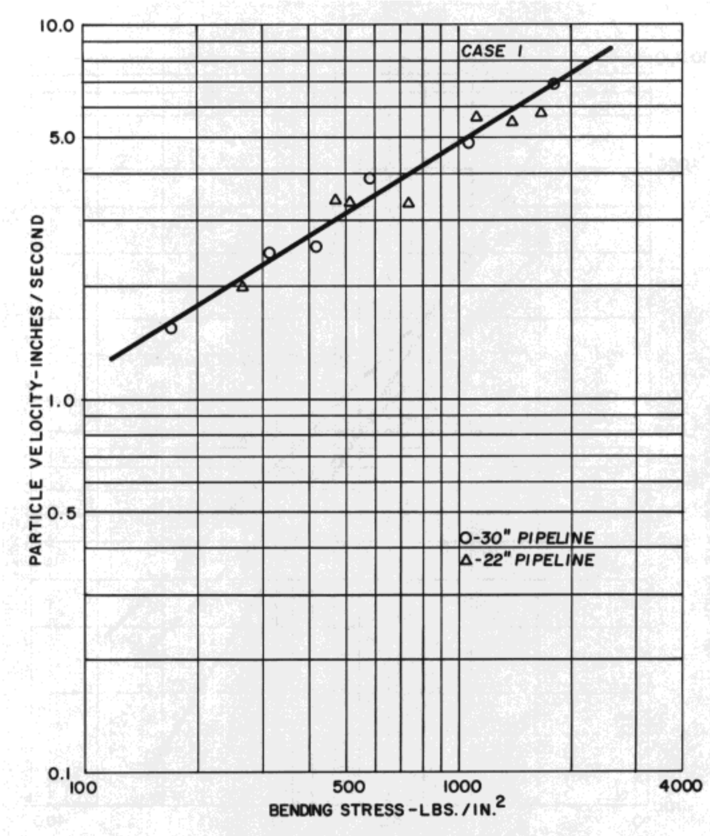

FIGURE- 3

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