COMPUTATIONAL ANALYSIS OF HIGH PRESSURE WATER JETTING FOR NATURAL GAS PIPELINE

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ABSTRACT

Nowadays, pipeline system has become lifeblood of modern civilization, industrial society and residential community. Gas transmission and distribution lines transfer natural gas from a source to points of utilization. Typically, gas distribution pipeline is laid adjacent to water pipeline facility. This may pose a great danger through the release of high pressure water leakage that subsequently induced surrounding soil to form erosive slurry. If the hit is directed towards metal pipe, slurry could directly cause continuous wall thinning of pipe that may lead to its point of failure. Therefore, this research is aimed to observe and evaluate the erosion pattern on natural gas pipeline due to water jetting. The Computational Fluid Dynamics (CFD) technique was employed to estimate the hydrodynamic characteristics, erosion patterns and locating the ruptured locations on the pipe in more expanded version. The study also focused on the fluid velocity, sand wall shear, water wall shear and total pressure generated on surface of natural gas pipe. This work was validated by the incident of NPS8 carbon steel gas pipeline failure in April 2006. CFD simulation results showed that water jetting location at angle 45°, 60° and 75° on the NPS8 pipe surface had similar impact such as leakage point, surface roughness and smoothness. The enhanced CFD simulation results successfully showed similar hydrodynamic characteristics as the NPS8 rupture incident.

ABSTRAK

Pada masa kini, sistem perpaipan menjadi nadi kepada pengguna yang terdiri daripada kalangan penduduk perumahan serta masyarakat pengilangan. Penghantaran dan pengagihan gas dari punca ke titk penggunaan. Biasanya, paip pengagihan gas yang ditanam bersebelahan dengan fasiliti paip air. Sistem ini boleh menimbulkan kebocoran paip air dan mendatangkan bahaya yang besar menerusi "*slurry*" hakisan yang bertekanan tinggi terhadap sistem perpaipan gas asli. Jika "*slurry*" hakisan ini terkena secara terus pada permukaan paip, ia akan berterusan menghakis dinding paip dan akhirnya, mengakibatkan kegagalan sistem perpaipan tersebut. Penyelidikan ini bertujuan untuk memerhati dan menilai corak hakisan permukaan paip disebabkan hentaman jet air bertekanan tinggi melalui teknik "*Computaional Fluid Dynamic (CFD)".* Teknik CFD telah digunakan untuk menilai ciri-ciri hidrodinamik, corak hakisan dan lokasi kegagalan paip dengan lebih mendalam. Kajian terhadap halaju bendalir dan kesan ricihan pada pasir dan air dan tekanan keseluruhan yang terbina pada permukaan paip gas asli telah dijalankan. Kajian ini disahkan melalui perbandingan dengan kegagalan paip keluli karbon NPS8 yang berlaku pada tahun 2006. Keputusan simulasi CFD menunjukkan pancutan air dari sudut 45°, 60°, 75° kepada permukaan NPS8 paip mempunyai banyak persamaan seperti titik kegagalan paip, corak permukaan kasar dan licin. Keputusan simulasi CFD pada paip menunjukkan kejayaan keputusan yang diperohi dengan ciri hidrodinamik yang berlaku pada kejadian bocor paip, NPS8.

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$A, \varphi, a, b, w, x, y, z$	Empirical constant (A = 1.559)
A_{face}	Area of the cell face at the wall
A_t	Average area of the target
al	Aluminium
d	Diamond
B	Brinell hardness
B_F	Body force
B_W	Stiffness ratio
b,i	Function of material's properties (Huang took $b \approx 1.67$)
b	Brass
$b(v)$	Function of relative velocity
C_{soil}	Soil cohesion
C', K_1, K_2, K_3, k	Constants
C, D	Coefficients
c_F	Constant (Finnie took c_F = ½)
C_{PD}	Factor (≈ k/3, where k is a dimensionless adjustable constant, sometimes called the abrasive wear coefficient)
C_K	Cutting characteristic velocity
$C(d_p)$	Function of particle diameter
C_{μ}	Turbulent model constant
cal	Crushed alumina
c	Chalk

d_p	The ductility of eroded material
D	Diameter size of parallel pipe
D_p	Particle diameter
D_K	Deformation characteristic velocity
d	Maximum crater diameter
$\frac{dKE_{sPD}}{dt}$	Particle kinetic energy
E	Young's modulus
E_f	Empirical constant specifying the energy required to remove a unit volume of the target material by deformation wear
E_r	Reduced Young's modulus of elastically
E_t	Modulus elasticity of target material
E_p	Modulus elasticity of the particles
E_{PD}	Erosion rate for the power dissipation model
E_{sp}	Specific energy
ER	Erosion produced by M pounds of particles at angle of attack α
e	Rebounding coefficient
F_D	Drag force
F_s	Shape coefficient (F_s=1.0 for sharp (angular), $F_s = 0.53$ for semi-rounded, and $F_s = 0.2$ for fully rounded sand particles)
$f(\alpha)$	Function of impact angle
G_k	Generation of turbulent kinetic energy
g	Garnet
gb	Glass beads
H	Depth of bury parallel pipe
H_{v_s}	Vickers hardness
K_A	Shape factor

K_F	Ratio of vertical to horizontal (frictional) force (Finnie took K_F =2)
K_{NG}	Velocity component normal to the surface below which no erosion takes place in certain hard material
K_{W1} , K_{W2}	Material coefficients
k	Turbulence energy
k_c	Constant determined by the material properties of particle and target
M	Total mass of abrasive particles
M_p	Mass of impacting particle
n	Empirical coefficient
n_F	Velocity exponent ($\approx$ 2~3)
n_L	Velocity exponent ($\approx$1.7 ~ 2.7 for metallic materials)
n_{NG}	Empirical constant (n_{NG} = 4.85)
n_h	Shape factor of impingement particles and charges in a range of 0.5 (line cutting) - 1 (area cutting)
P	Constant pressure (analogous to the quasi-static indentation hardness)
P_A	Yield pressure during the impact
P_E	Eroding target material pressure
P_{PD}	Power dissipation
P_t	Tangential pressure during cutting process
P_n	Normal cutting pressures during cutting process
p	Eroding surface ‘flow stress’
Q_f	Particle mass flux
q	Quartz

q_p	Particles poisson’s ratio
q_t	Target material poisson’s ratio
R_f	Particle roundness factor
R_T	Tangential restitution ratio
r_s	Radius particle corresponding to the sphere
r_p	Radius of impacting particle
S_t	Stiffness of the target material
S_p	Stiffness of the particle
ss	Silica sand
sic	Silicon carbide
TRS	Transverse rupture stress
u	Fluctuating velocity due to turbulence
V	Velocity
V_c	Critical impact velocity
V_{el}	Threshold velocity (the velocity of collision at which the elastic limit of eroding surface is just reached)
V_f	Volume of fluid
V_n	Normal impact velocity
V_p	Particle velocity
W	Total volume of target material removed
W_c	Cutting wear
W_d	Deformation wear
X	Distance from the trench face to the parallel pipe
Z	Critical trench depth, which depends on the soil strength characteristics
α	Impingement angle
α_H	Fraction of the volume of indentation that depend on the indentation geometry, the impact

	velocity and the target material
β_0	Angle of maximum erosion
β_1	Relative angle between particle path and specimen surface
γ	Soil weight
φ	Soil friction angle of the trench wall
ψ	Ratio of the depth of contact to the depth of the cut (Finnie took ψ=1)
ε	Dissipation rate
ε_B	Hardness of the target material
ε_b	Deformation wear factor
$\varepsilon_0,\ \sigma_B$	Elongation of target material
ε_d	Energy needed to remove a unit volume of material from a body due to deformation wear
σ	Yield strength
σ_k	Turbulent Prandtl numbers for turbulent energy
σ_ε	Turbulent Prandtl numbers for dissipation rate
σ_y	Elastic load limit
ϕ_c	Energy needed to remove a unit volume of material from a body due to cutting wear
ρ	Fluid density
ρ_p	Particle density
ρ_t	Target material density
μ	Dynamic viscosity
μ_c	Friction coefficient
μ_T	Turbulent viscosity
ϵ_c	Critical strain
δ	Kronecker-Delta function

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CHAPTER 1

INTRODUCTION

1.0 Introduction

Pipelines have been used to transport many flow media. Pipelines neither aboveground nor underground (buried pipelines) can be categorized to different types. The most common pipelines are sewage, water distribution system, oil and gas transferring pipelines. Thus, pipelines are classified as lifelines since they are commonly used to carry important material to support human life activities. As pipelines are generally buried, it is necessary to consider every influencing factor and variables possibly encountered in the pipelines operation. Erosion pipelines may cause leakage which will disrupt service and hazardous chemical leakage may possibly contaminate the surrounding environmental vicinity.

In recent years, buried gas pipeline has been given a special attention and incur growing research of external surface pipe wear problems caused by subsurface hydraulic erosion, soil abrasion, poor ground conditions and seismic waves which energy travel through the Earth’s layer resulted by earthquake, explosion and volcano (Sun *et al.*, 2011; Lee *et al.*, 2009; Datta, 1999). Therefore, it is unsurprisingly the soil-pipe interaction (buried pipe) has been studied for a number of decades. Buried pipe wear is a usual phenomenon and has been a serious and continuing problem in many industrial operations. This work presented the prediction of the erosion pattern on the surface gas pipeline under the threat of 9 atm water jet release, represented by the leak from water pipe. Two major reasons resulted to this study were identified. Firstly, statistical data shows that accidents of service pipe leak accounting for 40% of gas leakage or so, in which about 50% of the underground service pipe leak are caused by the corrosion of pipes under erosion of abrasive particles (Wang *et al.*, 2012). It means underground service pipeline leaks were initially caused by erosion which thinning the pipeline coating in turn, pipe corrosion. Secondly, external erosion damage of surface buried pipe caused by the impaction (deformation and cutting action) has not been fully understood because of the complication of soil behaviour (Sun *et al.*, 2011).

In the earliest study, the main objectives of the study on buried pipe were to correlate predictions of pipe-soil interactions during installation, ground motion include seismic behaviour of buried gas pipe under earthquake, distribution of soil pressure and soil stress on buried pipe and earth loads effect (Lee *et al.*, 2009; McGrath, 1998; Ho, 2008; Choo *et al.*, 2007; Datta, 1999). But, recently, researchers are interested in the erosion caused by service pipe leakage under buried pipe condition (Majid *et al.*, 2010). Throughout the years there have been many studies of erosive wear and many type erosion patterns have been applied for erosive study. The first technical paper related on erosive wear is started at 1946 by Wahl and Harstein (1946), publishing the first systematic survey of erosion. American Society for Testing and Materials, ASTM G-73, G-76 and G-134 are ASTM wear testing standards (Peter *et al.*, 1999) which developed for used to solve practical erosion problem. ASTM G-73, G-76 and G-134 were used rotating apparatus, gas jet and cavitating liquid jet respectively for erosion tests. At the same time, there are still no practical solutions to real erosion mechanism under buried pipe for purposely improving qualitative understanding of buried pipe surface impact in idealized systems. Different engineering standard approved by a recognizes standard organization such as British Standard, Gas Malaysia Standard, etc. cause the confusedness of engineering practice in the field. Consequently, numbers of codes of practice which define as a set of guidelines and regulations to be followed to achieve the standards of health and safety. However, historical overview of the erosion problem study is beneficial in order to optimize future erosion testing or even approachable idealized simulation.

Erosion has been classified as a wear process in a classification scheme based on relative motion (Meng, 1994) and as wear mechanism. According to American Society for Testing and Materials (ASTM), erosion is 'progressive loss of original material from a solid surface due to the mechanical interaction between that surface and a fluid, a multi component fluid, or impingement liquid or solid particles' (Lindsley and Marder, 1999). In a strict sense, erosion is defined as cutting, fatiguing and melting by impingement particles of any of these wear mechanisms operating either singly or combination as shown in Figure 1.1 (Meng, 1994).

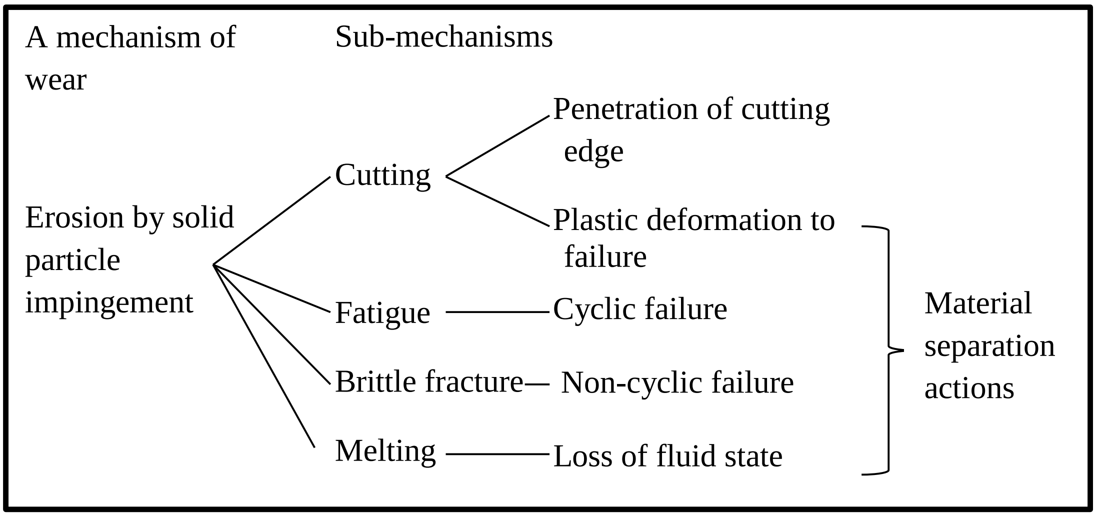

Figure 1.1 The Four Submechanisms by which Erosion Separates Materials From a Target and the Four Separate Modes of Material Behavior in the Loss Process (Meng, 1994).

Computational Fluid Dynamics (CFD) has been used in research of single phase or multiphase erosion for many years. CFD is a powerful tools and well known of predicting erosion pattern damage. Unlike many erosion models which shown from literatures, CFD modelling can be applied to any complex components or geometries. More importantly, CFD does allow investigators to target locations of high erosion and provide detailed patterns of erosion on surfaces. CFD can provide great help in developing either simple or complex geometries, short timely procedure to predict the amount of erosion.

1. 1 Problem Statements

In the ninth European Gas pipeline Incident data Group (EGIG) report, there are 1309 gas pipeline leakage incidents reported for the period 1970 to 2013. According to EGIG, over the 10 years, external interference (activities caused the incident e.g. digging, piling, anchor, ground work etc.), corrosion (internal and external), construction defects (material defect, field weld etc.) and ground movement (erosion, landslide, mining etc.) were represented 35%, 24%, 16% and 13% respectively of the gas pipeline incidents reported. However, according to U.S. Department of Transportation Pipeline and Hazardous Administration (PHMSA), there are 10,683 natural gas pipeline incidents was reported over the period 1968 to 2012. In Malaysia, natural gas pipeline failure was not rare incident. Within 2 years, 2006 to 2008, two natural gas pipe leak incidents were happened in Peninsular Malaysia. Both incidents were identified as erosion of slurry impact led to the rupture gas pipeline. For gas distribution pipeline system, gas pipeline was built nearby the utility pipeline. One of the gas pipeline incidents within 2006 to 2008 is happened as per similar environment whereas the gas pipeline was built crossing utility pipeline. For this work, the gas pipeline crossing utility pipeline was studied because it will take as comparative with CFD results. Frequent failure of natural gas pipeline, natural gas pipeline has been studied for number of decades.

There are many factors that may influence the erosion on external surface buried pipelines. These have been classified by Finnie (1972) into three main categories. First, the erosion is governed by particle flow such as angle of impingement, particle velocity and particle rotation. Secondly, properties of soil like hardness, angularity, shape and strength. Lastly, properties of target surface, such as surface topography, hardness, ductility and other mechanical properties. Generally, natural gas pipeline was in buried; the main causes and major governed the erosion of natural gas pipeline failure still remain doubt. Although Majid *et al.*, (2010) was identifying the main root cause of the buried pipeline leakage caused by continuous impaction of the erosive slurry (leaked water pipe mixed with surrounding soil), there was still lack of information on the impaction happened hidden beneath the ground.

A series of field research study to define the erosion impact of underground buried gas pipeline in order to assist the development of specific separation distance guide is therefore required. For instances, Mohsin *et al.*, (2014) suggested 1200 mm as safety distance for natural gas pipeline with water pipeline system. Moreover, it is believed that through this particular research could greatly enhance better understanding of erosion pattern and able to predict buried natural gas pipe impact due to environmental change on different backfill materials. At the same time, it is also believe that this research will improve and enhance for the safety and integrity of buried gas pipe safety.

Common dominating factors that typically enhance pipeline failures are wear, complication of soil and severity of other utility threats. The following sections provide below about the explanation on these three factors.

1.1.1 Wear

In engineering’s world, wear is defined as damage to a surface resulting from mechanical interaction with another surface, body or fluid which moves relative to it. Engineers and designers should have equations to predict wear rates. However, the available equations with different variables used are usually confused designers to promote its practical usage in predicting the product life. Critically, there is still no specific equation for prediction of buried pipeline wear due to complication of soil (Sun *et al*., 2011). For buried pipe wear analysis, researchers are only left in *word* form to description because of the reason hidden beneath the ground. Therefore, more information is highly required on the relevant wear tests and laboratory works. Corrosion is included one of wear phenomenon, but the damage is performed by chemical reaction rather than mechanical action. Thus, this research will focus upon the erosion of buried natural gas pipe to obtain the information underneath erosion natural gas pipe. The consequence of direct impact from direct exposure of high pressure water jetting will be studied accordingly.

1.1.2 Characteristic of Backfill Soil

The size and shape of particle are of fundamental importance in many areas of engineering. There is scientific research focus to study the backfill particle shapes; in particular abrasive and erosion wear processes known as tribology system. The determination of particles shape still remains one of the most difficult problems. Although much effort already been initiated by researchers to develop a universal definition of shape and angularity, there are still no precise definition exists to date because of the inability to quantify angularity.

1.1.3 Severity of Other Utility System Threats

As mentioned by Finnie, three main categories that are significant when addressing erosion on buried pipe are: angle impingement erosion, abrasivity or angularity of erodent impingement erosion and velocities. Therefore, safety distance used to place natural gas pipe away from water pipeline should be given special attention. However, only standard 300 mm safety distance between natural gas pipe and water pipe; such an encounter may arise when nearby water pipe leak from a wide variety angle and direction towards natural gas pipe which will eventually erode the natural gas pipe. Since buried gas pipe structure is located underground, main erosion causes of leaks such as impingement angle, angularity backfill etc. still remain doubtful and unidentified. In fact, buried gas pipe may evidently expose to other deterioration mechanisms than erosion, more specifically abrasivity, fatigue and other wear form. Due to doubtness on the main cause of gas pipeline leakage, specific study on severity of others utility system threat on buried gas pipeline need to be embarked.

1.2 Research Objectives

In line with the above mentioned problems encountered by buried gas pipeline system, the following objectives have been developed:

(a) To observed and evaluate the erosion pattern onto natural gas pipeline due to water jetting via computational fluid dynamic.

(b) To investigate the surface morphology onto the natural gas pipeline due to angle impingement slurry jetting via computational fluid dynamic.

(c) To verify the erosion pattern and surface morphology via expected data and field study.

1.3 Scope of Works

The scopes of work were directed towards assessing the effects of the severity erosion pattern on the gas pipeline. Incident of NPS 8 gas pipeline rupture was used to compare the extended physical impact towards testing case with CFD results. The scopes of work considered in the study are as follow:

i. Variation in leakage angle impact direction i.e. 30°, 45°, 60°, 75°, 85°, 90°, 100°, 105°, 115°, 130°, 145° to observed the water and sand velocities flow within buried condition.

ii. Variation in leakage angle impact direction i.e. 30°, 45°, 60°, 75°, 85°, 90°, 100°, 105°, 115°, 130°, 145° to observed the effect of wall shear pattern and total pressure impaction on the NPS 8 gas pipeline.

iii. Variation in sand compactness fraction (0.8 and 1.0) to observed the water and sand velocities flow within buried condition. The effect of wall shear pattern and total pressure impaction on the NPS 8 gas pipeline.

iv. Variation of sand particle size which acts as backfill to observed the impaction of the natural gas pipeline. The effect of wall shear pattern and total pressure impaction on the NPS 8 gas pipeline.

1.4 Assumptions

Four assumptions have been made for establishing the erosion behaviour of the buried pipe in this work. First, the live load over the ground surface is negligible.

Second, the internal pressure within the pipe is ignored. Finally, the condition is at pH 7, the degradation was non-corrosion dominated and that corrosion played only a little role in the several damage mechanisms. These three assumptions have been made on the basic sound engineering judgement for this work.

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