INTEGRITY ASSESSMENT OF BURIED PIPE IN EROSIVE ENVIRONMENT

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Specially dedicated to my beloved late mother and father,
wife, my dear sons and daughters
those who had taught me useful lessons, provided continuous guide
and relentless love and support to me in my life.

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ABSTRACT

The integrity assessment of API 5L X42 carbon steel pipe in terms of erosion effect due to impaction of high pressure erosive slurry was studied. A water jet structure was analysed using a transparent perspex water filled tank. This was followed by buried pipe erosion study in a sieved sand as a backfilling material in a specially designed submerged experimental rig. Computational fluid dynamics (CFD) technique was applied to simulate numerically the pipeline erosion characteristics in comparison to the experimental findings. The sieved results indicated that majority of the backfilling materials; made up by quartz mineral having a size of 0.2 to 2.0 mm, was in angular shape. The impaction of sand-water slurry on the pipe wall produced two peculiar regions; smooth surface in the middle and surrounded by rough wavy surface. The smooth surface was formed due to the high-pressure water jet (potential core) perpendicular to the centre of the pipe surface. On contrary, the rough surface was formed due to the impact of sand-water in cutting action mode at the upper and bottom part of the pipe, as the water stream was being deflected radially. In comparison, the bottom part of the pipe experienced higher thickness reduction than the upper area. The average thickness reduction of the pipe wall due to the impaction of orifice jetting was 5.68% higher than that of the nozzle jet. The locations of ring type contours of water and sand wall shear from CFD simulation were found to be similar as the experimental findings. The contours of sand and water wall shear were found to be 68.67 kPa and 0.1054 kPa, respectively, at the upper and bottom sections of the pipe wall that corresponded to the higher thinning rate areas as in the experimental study. At the point of impaction that was perpendicular to the pipe surface, the sand and water wall shear stresses were found to be 13.73 kPa and 0.2208 kPa, respectively, this concurred by the smooth convex region on the pipe surface from the experimental results. Percentage of wall thinning rate from the experimental study (10.74%) was found to be comparable to CFD simulation results with the percentage difference of sand and water were 11.12% and 11.02%, respectively. It is therefore concluded that at 400 mm separation distance, the pipeline was found to be safe from any erosion effect of 1000 kPa water jetting, this could be considered for gas industry application.

ABSTRAK

Penaksiran integriti paip keluli karbon API 5L X42 dari aspek kesan hakisan akibat hentaman buburan hakis bertekanan tinggi telah dikaji. Struktur jet air telah dianalisis menggunakan tangki perspeks lutsinar yang dipenuhi air. Ini diikuti dengan kajian hakisan paip tertimbus dalam pasir bertapis sebagai bahan kambusan dalam rig uji kaji terbenam yang direka khas. Teknik dinamik aliran pengiraan (CFD) telah digunakan untuk mensimulasi secara berangka sifat hakisan talian paip berbanding dengan hasil uji kaji. Keputusan tapisan menunjukkan majoriti bahan kambusan tersebut; yang terdiri daripada mineral kuartza yang bersaiz antara 0.2 hingga 2.0 mm, adalah rupa bentuk bersegi. Hentaman buburan pasir-air terhadap dinding paip menghasilkan dua rantau yang khusus iaitu; permukaan licin di bahagian tengah dan permukaan kasar beralun di sekeliling. Permukaan licin dihasilkan oleh jet air bertekanan tinggi (potensi teras) yang bersudut tepat di bahagian tengah permukaan paip. Permukaan kasar pula dibentuk oleh hentaman pasir-air secara mod tindakan memotong di bahagian atas dan bawah paip apabila arus air dipesongkan secara kejejarian. Jika dibandingkan, bahagian bawah permukaan paip mengalami pengurangan ketebalan paip yang lebih tinggi daripada bahagian atas. Purata pengurangan ketebalan dinding paip disebabkan oleh jet orifis adalah 5.68% lebih tinggi berbanding jet muncung. Lokasi kontur jenis gelang bagi dinding ricih air dan pasir daripada hasil simulasi CFD didapati adalah serupa dengan keputusan eksperimen. Kontur bagi dinding ricih pasir dan air adalah masing-masing 68.76 kPa dan 0.1054 kPa di bahagian atas dan bawah dinding paip yang mana bertepatan dengan kawasan yang mengalami kadar pengurangan ketebalan yang lebih tinggi dalam eksperimen. Pada titik hentaman yang bersudut tepat dengan permukaan paip, tegasan ricih dinding pasir dan air adalah masing-masing 13.73 kPa and 0.2208 kPa, dan ini disokong oleh kawasan cembung yang licin pada permukaan paip oleh keputusan eksperimen. Peratus kadar penipisan dinding daripada eksperimen (10.74%) didapati setanding dengan keputusan simulasi CFD yang mana peratus perbezaan pasir dan air adalah masing-masing 11.12% dan 11.02%. Adalah disimpulkan bahawa pada kedudukan 400 mm jarak pemisahan, talian paip didapati selamat daripada sebarang kesan hakisan akibat hentaman jet air bertekanan 1000 kPa dan sesuai dipertimbangkan bagi aplikasi industri gas.

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LIST OF ABBREVIATIONS

SCADA	-	Supervisory Control and Data Acquisition System
CFD	-	Computational Fluid Dynamics
NPS	-	Nominal Pipe Size
SEM	-	Scanning Electron Microscopy
ASTM	-	American Standard Technical Material
ISO	-	International Organisation for Standardisation
API	-	American Petroleum Institute
PGU	-	Peninsula Gas Utilisation Project
BSCFD	-	Billion Standard Cubic Feet Day
GMB	-	Gas Malaysia Berhad
AISI	-	American Iron and Steel Institute
JIS	-	Japanese Industrial Standard
ASME	-	American Society of Mechanical Engineers
AASTHO	-	American Association of State Highway Transportation Officials
PSD	-	Particle Size Distribution
MS	-	Malaysian Standard
LNG	-	Liquified Natural Gas
RGT	-	Regasification Terminal
NG	-	Natural Gas
LPG	-	Liquified Petroleum Gas
MDPE	-	Medium Density Polyethylene
NPS	-	National Pipe Standard
UPVC	-	Unplasticised Polyvinyl Chloride
SPQ	-	Spike Parameter Quadratic
SP	-	Spike Parameter
EN	-	European Standard

PSD	-	Particle Size Distribution
NSE	-	Navier-Stokes Equation
RSN	-	Reynold Stress Model
SST	-	Shear Stress Transport
CRC	-	Corrosion Research Centre
DEM	-	Discrete Element Method

LIST OF SYMBOLS

α	-	Impaction angle
r	-	Radius
θ	-	Angle of particle rotation
C_D	-	Drag coefficient
d_p	-	Particle diameter
g	-	Gravitational acceleration
k	-	Fluid turbulent kinetic energy
k_1	-	Erosion model constant
L_s	-	Characteristic length
m	-	Particle mass
n	-	Erosion model constant
p	-	Fluid pressure
r_f	-	Fluid phase volume fraction
r_p	-	Particulate phase volume fraction
S_t	-	Stokes number
u_f	-	Fluid velocity
up	-	Particle velocity
V_R	-	particle relative velocity
V_I	-	Particle impact velocity
V_s	-	Characteristic velocity
β	-	Particle mass loading
ε	-	Fluid turbulence dissipation rate
γ_I	-	Particle impact angle
μ_{eff}	-	Effective viscosity for fluid phase
μ_f	-	Fluid dynamic viscosity
ρ_f	-	Fluid density
ρ_p	-	Particle density

d_P	-	Particle size
ER	-	Erosion ratio
F_D	-	Drag force per unit particle mass
F_s	-	Sharpness factor
L	-	Flow characteristic length
n	-	Velocity exponent constant
R_e	-	Reynolds number
St	-	Stokes number
U	-	Fluid velocity
V_{Jet}	-	Averaged jet exit velocity
V_P	-	Particle impact velocity
Δh	-	Erosion depth
θ	-	Jet impingement angle
μ	-	Fluid viscosity
ρ_P	-	Particle density
ρ_w	-	Target wall density
τ	-	Relaxation time of the particle
d_m	-	Mean particle diameter
E_L	-	Linear material removal rate
h	-	Step height
k	-	Kinetic energy of turbulence
p	-	pressure
$\overline{U}$	-	Free-stream velocity
v	-	Impact velocity
ρ_P	-	Particle density
a, b	-	Exponent constants
A_i	-	Impact angle empirical constant
C_μ	-	Turbulence model constant
d_p	-	Particle diameter
D	-	Pipe diameter
d_0	-	Threshold particle diameter below which no erosion occurs
d'	-	Standard particle diameter
e	-	Coefficient of restitution
e_n	-	Restitution coefficients in normal direction

e_t	-	Restitution coefficients in tangential direction
E_p	-	Elastic modulus of particle
E_t	-	Elastic modulus of target
E_e	-	Effective elastic modulus
F_S	-	Particle shape factor
F_P	-	Pressure gradient force
F_e	-	Specific erosion factor
F_P	-	Penetration factor
F_M	-	Empirical constant accounting for material hardness
g	-	Gravity acceleration
H_p	-	Hardness of particle
H_t	-	Hardness of target
H_V	-	Vickers hardness of target
K_c	-	Fracture toughness
K_p	-	Physical characteristics constant
K_s	-	Fitting erosion constant
K_T	-	Kinetic energy transferred from impacting particle to target per unit mass of particles
l_e	-	Eddy length scale
L	-	Depth of deformation
L_V	-	Plastic zone volume
L_{stag}	-	Stagnation region length
L_{ref}	-	Reference length
L_S	-	Slug body length
L_F	-	Liquid film length
m_p	-	Mass of single particle
$\dot{m}$	-	Sand mass ratio in slug body
n_h	-	Strain hardening exponent
n_p	-	Physical characteristics constant
n_s	-	Shape constant
$\bar{p}$	-	Mean stress
p_n	-	Normal pressure component
p_t	-	Tangential pressure component
P	-	Constant plastic flow stress

r	-	Radius of particle
R	-	Roundness of particle
r_c	-	Bend radius of curvature
Re_p	-	Particle Reynolds number
Re_L	-	Liquid Reynolds numbers
t_e	-	Eddy time scale
T_{int}	-	Particle eddy interaction time
t_{life}	-	Eddy life time
t_{cross}	-	Particle eddy cross time
V_{char}	-	Flow characteristic velocity
V_e	-	Erosional velocity
V_m	-	Mixture velocity
V_p	-	Particle velocity
V_{pn}	-	Normal velocity component of particle
V_{pt}	-	Tangential velocity component of particle
V_r	-	Residual parallel component of particle velocity at small angles of attack
V_0	-	Threshold velocity below which distortion is entirely elastic and no damage occurs
$\dot{W}_p$	-	Sand flow rate
x_t	-	Horizontal coordinate
δ	-	Deformation wear factor, the amount of energy needed to remove unit volume of material
σ^*	-	Pressure-stress ratio
ψ	-	Ratio of depth of contact to depth of cut
ε	-	Turbulent dissipation rate
τ	-	Particle relaxation time
B	-	Brinell hardness
B_F	-	Body force
B_w	-	Stiffness ratio
b, I	-	Function of material's properties
C_k	-	Cutting characteristic velocity
$C(d_P)$	-	Function of particle diameter
$C\mu$	-	Turbulent model constant
D_p	-	Particle diameter

D_K	-	Deformation characteristic velocity
d	-	Maximum crater diameter
$\frac{dKEsPD}{dt}$	-	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
e	-	Rebounding coefficient
$f(\alpha)$	-	Function of impact angle
G_k	-	Generation of turbulent kinetic energy
H	-	Depth of bury parallel pipe
H_{vs}	-	Vickers hardness
K_A	-	Shape factor
K_F	-	Ratio of vertical to horizontal (frictional) force
K_{NG}	-	Velocity component normal to the surface below which no erosion takes place in certain hard material
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
n_L	-	Velocity exponent for metallic materials
n_{NG}	-	Empirical constant
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
Q_f	-	Particle mass flux
q	-	Quartz
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
ε	-	Dissipation rate
ε_B	-	Hardness of the target material
ε_b	-	Deformation wear factor
ε_0, σ_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 Energy needed to remove a unit volume of material from a body due to cutting wear
ρ_t	-	Target material density
μ	-	Dynamic viscosity
μ_C	-	Friction coefficient
μ_T	-	Turbulent viscosity
ε_C	-	Critical strain
δ	-	Kronecker-Delta function
q_p	-	Particles Poisson's ratio
q_t	-	Target material Poisson's ratio
R_f	-	Particle roundness factor 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
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

Subscript

c	-	Centre line
p	-	Pipe
r	-	Radial
z	-	Vertical
Amb	-	Ambient
Avg	-	Average
Min	-	Minimum
Max	-	Maximum
t	-	Turbulence

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Natural gas is well known as the cleanest of all fossil fuels and highly efficient form of energy. Plentiful of supply and competitive cost of natural gas offers great advantage to become a prominent fuel used in either commercial or industrial. Pipeline systems covers a wide range of span from the production fields to the gas processing plants and finally to the end users. Natural gas is transported from gas processing plant to its users through a stretch of pipeline system. Natural gas is delivered directly to homes and business communities through local distribution lines via distribution gas utility companies. Therefore, gas transportation and distribution play significant role for the development of energy resource. In ensuring continuous supply of natural gas to residential, commercial and industrial area, natural gas pipeline is built with high integrity in ensuring the security of supply [1].

Natural gas is typically transported through buried pipeline. Natural gas distribution pipeline is commonly laid side-by-side with other utilities such as; water pipeline, electrical and telecommunication cables. Most utility system commonly found to be laid within a similar vicinity of natural gas pipe system is water pipeline. Failure of high pressurised water pipeline normally produced erosive slurry jetting towards adjacent utilities. It might due to material failure and poor jointing installation.

Water jet impact can exert enough forces upon any surface resulting to its subsequent physical penetration. Currently, mechanical cutting of materials using blades is being replaced with water cutting, using the principle of water jet. Water jet alone might not be able to contribute major degradation upon any surface, but with the presence of solid particle in the jet stream would result to a significant physical damage and might pose bigger threat to the gas pipeline. Failures due to the degradation of pipeline material could seriously disrupt supply continuity and pose threat to life and surrounding environment. Cases of natural gas pipeline failures have proven to be catastrophic as reported by National Transportation Safety Board. The most common reasons for such failures are from external interferences, corrosion, poor construction activities and erosion by erosivity slurries [2-5].

Erosive wear is a phenomenon of metal degradation due to the repetitive impaction of solid particles entrained in a moving fluid onto any surfaces that directly causes material losses [6]. Slurry erosion which is formed by the interaction of solid particles suspended in liquid media with metal surface could easily trigger losses of mass through repeated impacts of particles [7]. This type of erosion has been reported as one of the main sources of failure of many engineering equipment such as slurry pumps, control valves, actuators, accumulator, pipes, tubes and hoses [8-12]. This erosive slurry impact may cause serious metal thinning and finally lead to operational failures of pressurised natural gas pipes. This event could initiate much disastrous incidence especially to those involving escape of flammable gases [2-5]. Pipe was manufactured, hydrostatically tested and coated according to international standards such as API 5L Grade B, ASTM A106 and ISO 3183 to diminish possibility of material and manufacturing defects.

With the advancement in the pipe manufacturing technology, manufacturing defects could drastically reduce. Pipeline protections using appropriate pipe coating and cathodic protection system, coupled with good constructions practices, may boost the integrity of pipeline with longer operational services, whose life-span is estimated within

20 to 30 years [13]. Despite the advances in natural gas pipe manufacturing, effective construction management strategy, stringent testing procedures and thorough quality inspection, failure does occasionally occur. Over half of all in-service pipelines failures have been resulted from some externally applied mechanical force towards the pipes [14]. Mechanical damages such as gouge and dent, fatigue cracking, corrosion, and stress-corrosion cracking are among popular root cause for pipes failures [14]. Materials defects are non-common causes of service failures because they often revealed their quantities prior to placing in service, either during physical inspection of the pipe or during high pressure hydrostatic testing.

Pipeline failures were progressively reported mainly due to explosion, sandblasting and cracks [15-22]. Material degradation caused by corrosion was identified as the main contributing factor to the failure of the pipe. They were apparent based on published reports by Hernandez [23], Rodriguez [24], Shi [25] and Al-Owaisi [26]. Another common caused in pipeline failure is ductile fracture as was reported by Zhang [27]. Whereas Majid et al. [28] reported that the root cause of the buried pipeline leak was due to continuous impact mode by the erosive slurries (a mixture of an insoluble substance in a liquid) from leaked water pipe mixed with the surrounding erosive soil.

Historical data have shown that serious accidents involving natural gas pipeline are considerably rare in nature compared to road accidents, yet they often cause more severe implication to the society [29-32]. The impact of this mishap always relates to the loss of life and structures [2-5]. These scales of event have driven intensive research efforts to formulate preventive measures towards predicting, overcoming and quantify these incidents. Diverse disciplines of research have been enlisted to tackle these issues. Many efforts and methods have been applied in order to identify the impacts [33-37], estimate the risks [38-42], analyse the system reliability [43-45], establish the safety distances from pipeline facilities [30 & 46] as well as other relevant studies that have been conducted with regards to pipeline accident [47].

Since corrosion has been recorded as the major cause of pipeline failure [2-5], less attention was given on the aspect of possible danger that could be created by water pipeline leakage positioned adjacent to the operational gas pipe system. In the presence of water, sands granules (typically employed as part of backfilling material) can easily form slurries. Continuous impaction has proven to cause severe metal loses and metal thinning which eventually leads to pipeline failure [11, 12, 28].

Haklar and Dresnack [47] studied and proposed standardised safe separation distance (above ground) at which pipelines can be safely assigned from the community arrangement by determining the heat flux, mass release rate from the ruptured pipe and the flame height of the ignited gas. Study carried out by Sklavounos and Rigas [30] focused on estimating the safety distances for liquefied petroleum gas and natural gas pipelines, based on possible outcomes of an accident associated with fuel gas released from pressurised distribution piping system. To date, the study on safety distance is only limited to the explosion of above ground pressurised transmission system. Although this is a common concern among industrial players and government agencies, it should be noted that similar phenomenon can also trigger serious threats to underground pipes by silent yet destructive trail. ASME B31.8 stipulated 152 mm for gas pipeline to any structures whereas Institution of Gas Engineers under their technical directive applied 250 mm safety distance. Experimental study is the best method to understand and establish the relationship between various parameters on the subject being studied. With the established experimental data and appropriate validation, computer simulation can be employed to reduce the cost and time taken for full scale experimental investigations.

Computer simulation is an effective method that complements the experimental techniques. It is in a form of controlled computational experiments which allow various parameters to be studied separately under various conditions within stipulated boundary. Additionally, model generated by simulation process could provide details insight in understanding the dynamic behaviour of various engineering problems, thus drawing appropriate preventive design measures. The use of this method by many researchers proven to shows good agreement with what was presented by analytical techniques [48-50]. A prediction of pipeline failure through computer simulation is proven to be an effective method to optimise the design of pipes and their operating conditions. Study by Yang [51] on the failure analyses of a piping system in hydro processing reactor effluent air cooler showed that the analytical results are having similar trends with the actual failure instances, whereas study by Moustabchir and Alhussein [52-53], proved that numerical calculations are a reliable technique by showing acceptable coincidence with the actual failed specimen.

In the present study, the experimental study was conducted with the aims of shedding some light on the effect of erosive jetting upon an impacted surface thus allowing a better understanding on the prevention technique to be deployed for the existing natural gas pipeline sharing the similar trench with water utility pipeline. At present, the typical construction approach of similar sort employs a separation distance at the minimum of 300 mm horizontally away from surface curvature tip [56]. It is imperative that this distance be scrutinised in ensuring sufficient distance to minimise or curbing the effect of erosive jetting by performing this experiment.

In this particular work, a newly designed experimental rig was developed to facilitate the experimental exercise that may represent the actual condition of erosion study of the failed natural gas piping system at site. The study is considered as a unique attempt to study erosion of buries pipe in slurry environment. This rig can also be employed for the extended study in different mixing environment of water-sand proportion and at elevated jetting pressure. The water jetting characteristics and pressure decay curve in water-water, water-air and water-sand environment were established and can be used as an initial guide for further study in determining the separation distance for other pipeline configurations.

1.2 Problem Statement

In late September of 2004, a natural gas pipeline leak was identified. This gas pipe failure was categorized as a gas distribution system which was located within industrial community customers. The continuous bubbling gas through water-logged soil was just like a sounding alarm of gas pipc leak. Ruptured pipe at incident location was evident after excavation as shown in Figure 1.1a. Figure 1.1b shows the ruptured natural gas pipe. It was discovered that there were three pipes; DN200 API 5L X42 carbon steel and a 125 mm medium density polyethylene (MDPE) natural gas pipes, and 152 mm asbestos water pipe lying parallel to each other were directly affected, with all three indicating signs of serious damage or leakage. An electrical cable lying parallel to the pipes slightly at a high elevation indicates no apparent sign of damage. Figure 1.2 shows the pipeline layout at the location of incident.

(a) Ruptured pipes at incident site (b) Closed-up view of natural gas pipe

Figure 1.1 Arrangement of failed pipes

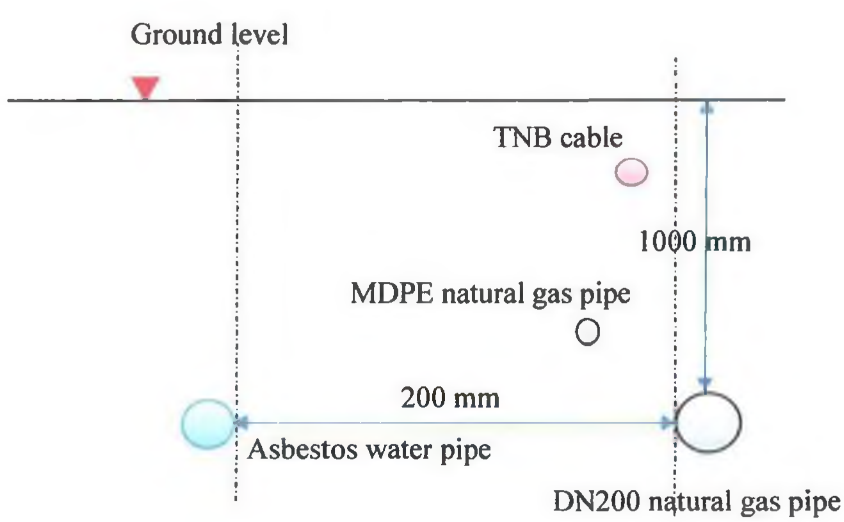

Figure 1.2 Pipeline layouts

The API 5L X42 carbon steel with a nominal pipe size of 203 mm and MDPE pipe was carrying 1,800 kPa and 345 kPa natural gas, respectively, prior to shut down. The 152 mm, asbestos pipe was transporting water with an estimating flowing pressure of 1,000 kPa. The DN200 natural gas pipe is made of carbon steel manufactured with stringent specification of API 5L X42. It was buried around 1000 mm below the ground level at about 200 mm laterally from the underground water pipe (surface to surface distance). Roughly with a shorter distance between the gas and the water pipes is the location of MDPE gas pipe. The established thicknesses of the DN200 pipe, MDPE and asbestos pipe were 5.6 mm, 11.4 mm and 10 mm, respectively.

Water pipelines are normally designed and work at high pressure level for more than 500 kPa. These sorts of facilities are in fact a common typical feature laid in the vicinity of natural gas pipes that may pose severe threat due their probabilities of failures. Water might be considered as non-hazardous material to our environment and usually any leakages was not entertained at once. Failure of water pipeline will normally start with small slit and the size will enlarge until it reaches the bursting stage. The initial leak will form high pressure water jetting. A leak of high pressure water pipe in a mixture of soil and sand could create erosive slurry impaction on nearby pipes. Slurry erosion is usually formed by the interaction of solid particles suspended in liquid with a surface that experiences losses of mass by repeated impacts of particles entrained in moving liquid.

They are many factors that influence the erosion effect on the external surface of buries pipelines. Finnie [54] has identified and classified it into three categories; first, particle flow conditions such as particle velocity, particle rotation and angle of impingement. Secondly, properties of the slurries which is soil hardness, angularity, shape, and strength. Lastly the properties of target material, such as surface hardness, topography, ductility and other mechanical properties. The actual effect of these factors is still dubious due to its physical arrangement complexity and unpredictable nature at buried pipelines conditions. Thus, it is imperative for this study to be carried out in order to understand the hydrodynamic characteristics of water jetting to understand the effect of water jet diameters, sand particle size and separation distance upon the erosion of natural gas pipe. This study is the first ever conducted to understand the erosion effect on external surface of buried natural gas pipeline. Previous erosion study by other researches are mainly focusing on internal surface of pipeline [15, 29, 54].

1.3 Research Hypothesis

Erosion of external surface of buried pipelines in slurry environment is very much influenced by the slurry properties as well as the pressure of the carrier medium. Since the backfilling materials are mainly soil with sand the presence of various sand size with irregular edges will significantly affect erosion rate. Furthermore, the higher the pressure of the carrier medium the higher the impaction pressure thus causes high velocity region around the stagnation point. It is expected that the formation of the impact area will be in form of less eroded smooth surface zone at the centre of impaction will be surrounded by highly eroded rough surface region. It is also expected that the thinning rate and stand-off or zero effect distance will be lesser as the source of impact is located furthers from the jetting source. The thinning rate of specimen will also be expected to vary with an increase of time scale.

1.4 Objectives

The aim of this study is to assess the buried natural gas distribution pipeline integrity in close vicinity with the adjacent water piping utilities. Specific objectives include the following:

(a) To characterize the backfilling materials used in underground natural gas pipeline installation.

(b) To experimentally evaluate the effect of water leakage in a slurry environment on the erosion characteristics of natural gas pipeline.

(c) To computationally evaluate the erosion characteristics of natural gas pipeline.

1.5 Scope of Study

The research was conducted experimentally using DN200 API 5L X42 carbon steel natural gas pipe environment and computationally by conducting Computational Fluid Dynamic (CFD) simulation using Reynold Average Navier-Stokes flow model. The Eularian-Lagrangian particle tracking technique was used to validate the experimental results. In order to accomplish all the objectives, several scopes are outlines, which are:

i. Identifying the particle size distribution, mineral types and angularity of the backfilling material.
ii. Variating of jetting sizes at 1, 3, 5, and 7 mm.
iii. Variating of sand sizes between 0.2 mm to 2 mm.
iv. Fixing the jetting distance at 200, 300, and 400 mm.
v. Variation of soil compactness of 90%, 70% and 50% was used to imitate typical condition of buried pipe.

1.6 Limitation of Study

This research involves experimental and numerical studies on the erosion of natural gas pipe due to the impaction of erosive slurry formed by the induction of high pressure water jet onto the surface of high pressure natural gas pipe. The best suited condition of preparing a similar buried pipe environment used in the experimental study is limited to the following constraints:

i. Pipe material of only type DN200 API 5L X42 to simulate the actual specimen in the case study.
ii. Test pipe contains no pressurised gas.
iii. Coating condition is as received and supplied from the mill (organic paint of 3.76 x 10^{-6} m thickness).
iv. Water jet supply pressure was fixed at 1000 kPa.
v. Jetting angle was positioned at 90° (horizontal position).
vi. Jetting source is from nozzle and orifice type of outlet induced leakage.
vii. The pipe is use for class location 4 (pipe thickness: 5.6 mm).
viii. No corrosion effect will be considered.
ix. Computational domain of 2815 mm, 1220 mm and 810 mm for long, height and wide respectively.
x. Inlet and outlet pressure were at 1013 atm and 103 atm.
xi. Standards k-$\mathcal{E}$ turbulence model.
xii. Eularian-Lagrangian model for the particle tracking.
xiii. Discrete phase model for velocity tracking.

1.7 Significance of the Study

A common practice in the natural gas distribution pipeline system is that the designated trench is usually located side-by-side with other utility system such as water utility pipeline and electricity utility cabling due to limited spacing availability or congested nature of the area. To lay a natural gas pipeline next to an electricity utility could pose higher threats of explosion should there be cases of gas leakage. Therefore, laying the gas pipeline next to the water utility pipeline would be the solution as water is considered as non-ignited source to initiate ignition. However, as the water pipe leaks, high pressure water is typically triggered, coupled with surrounding sand and soil, highly erosive slurries usually be formed. The impaction of this slurries may cause severe metal loses and metal thinning of the impacted pipes which eventually lead to its failure.

1.8 Thesis Organisation

This thesis describes the erosion of carbon steel gas pipe due to high pressure water jetting in erosive slurry environment. Although much knowledge has already been acquired in solid particle impaction on flat surface material. Considerable amount of understanding is very much limited to emulate actual surrounding environment using experimental and numerical studies. In view of its significance, this thesis outlined the documented structure of experimental and numerical approach on the erosion of DN200 API 5L X42 carbon steel natural gas pipeline due to high pressure water jetting in erosive slurry environment.

Chapter 1 provides a general preface of pipeline erosion and its effect on safety of the gas distribution system. Series of reported pipeline failures urged the need to study to the erosion behaviour with respect to the effect of backfilling soil properties and jetting pressure. The chapter also presents the background, problem statement, objectives, scopes, limitations of the study, significant of the study and thesis organisation. The thesis has been divided into five chapters with seven appendices.

Chapter 2 provides the overall review on previous works related to similar issues of research findings on erosive wear due to slurry erosion. Literature review was designed to provide a summary of the available knowledge involving the issues of interest. It presents the research works on erosive wear and its major influencing factors, effect of slurry erosion on ductile materials and CFD simulation study in erosive wear of pipeline surface by various investigators.

Chapter 3 explains the research methodology in two different sections. It includes a detailed description of the experimental activities and simulation sequences. This chapter details out the experimental activities that will include the study of backfilling soil, jet dispersion and water jetting erosion experiments. Finally, this chapter will highlight the employed CFD simulation study to establish erosion morphology on the surface of pipeline.

Chapter 4 presents the detailed discussion of the results obtained on the jet dispersion study and erosion morphology analyses for both experimental and numerical simulation on pipeline due to high pressure jet using selected sand particle sizes that was pre-determined from the incident site.

Chapter 5 provides overall conclusion of research conducted and accommodate recommendations for future undertakings.

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