SCOUR BELOW SUBMERGED SKEWED PIPELINE

By

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TABLE OF CONTENTS

CHAPTER 4 – RESULTS AND DISCUSSIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVATIONS

ADV	Acoustic Doppler Velocimeter
AI	Artificial Intelligence
ANFIS	Adaptive Neural Fuzzy Inference System
ANN	Artificial Neural Network
BMP	Best Management Practice
ET	Expression Tree
FDM	Finite Difference Method
FEM	Finite Element Method
FISRWG	Federal Integency Stream Restoration Working Group
GA	Genetic Algorith
GEP	Gene Expression Programming
GP	Genetic Programming
LGP	Linear Genetic Programming
MDNR	Michigan Department of Natural Resources
MLR	Multi Linear Regression

PVC	Plyvinyl Chloride
REDAC	River Engineering and Urban Drainage Research Centre
USM	Universiti Sains Malaysia
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional

LIST OF SYMBOLS

b	width of channel/flume
C_d	discharge coefficient
d_{50}	median of sediment size
d_e	equilibrium sediment size
d_s	scour depth
D	diameter of pipe
Fr	Froude number
g	gravitational accelaration
h	head over the weir
k_s	surface roughness
K_T	coefficient for time scale depending on sediment gradation
n	Manning`s roughness coefficient
Q	discharge (m^3/s)
R	hydraulic radius
Re	Reynolds number

S	bed slope
s	relative density of sediment
T	time scale of scour depth
T_*	nondimensional time scale of scour depth
t	time of scour
U	approach flow velocity
U_c	critical velocity for sediment
U_*	shear velocity
U_{*c}	critical shear velocity
y	approach flow depth
Δ	$s - 1$
θ_c	critical Shields parameter
θ	skew angle
υ	kinematic viscosity
μ	dynamic viscosity
ρ	mass density of water
ρ_s	mass density of sediment

σ_g	geometric standard deviation
τ	shear stress
τ_c	critical shear stress

HAKISAN DI BAWAH PESONGAN SALURAN PAIP YANG TENGGELAM

ABSTRAK

Hakisan dibawah saluran paip terjadi disebabkan oleh tindakan arus sungai yang menyebabkan saluran paip terdedah kegagalan. Saluran paip merentasi sungai menganggu aliran sungai dan seterusnya menyebabkan kesan aluran yang bertindak balas dengan pusaran air di sekitar saluran paip. Dalam penyelidikan ini, beberapa ekspresimen dijalankan untuk mengkaji dari segi fizikal kesan pemasangan saluran yang dipesongkan mengikut darjah (30º, 45º, 60º dan 90º) merentasi sungai. Penyelidikan ini juga bertujuan untuk menilai GEP dan model-model regrasi sebagai salah satu medium dalam menentukan hakisan di bawah saluran paip yang dipesongkan merentasi sungai. Permulaan proses hakisan bagi kedalaman air (y/D =3) meningkat dengan mendadak. Walau bagaimanapun, bagi y/D = 4, permulaan proses hakisan adalah lebih perlahan. Bukaan kecil antara saluran paip dan dasar menyebabkan terjadinya aliran jet yang melalui bukaan tersebut. Lokasi pembentukan hakisan maksimum dibawah saluran paip yang dipesongkan berada hampir disebelah kiri saluran air disebabkan oleh tindak balas daya-daya hidrodinamik. Pembentukan model regrasi untuk kombinasi sumber data menghasilkan penilaian yang agak baik. Model regrasi (Persamaan 4.4) dengan pekali ketentuan, R^2=0.55 dan RMSE=0.47 telah disahkan dengan data-data daripada kerja-kerja penyelidikan sebelum ini. Pengesahan tersebut menunjukkan korelasi yang baik dengan nilai R = 0.71. Penilaian kedalaman hakisan menggunakan peranti GEP adalah baik dengan nilai pekali ketentuan yang tinggi (R^2). Model GEP yang dicadangkan (Persamaan 4.7) menunjukkan kemampuan yang baik dengan nilai R = 0.94 untuk latihan dan R = 0.9 untuk ujian. Daripada sensitif analisis, kedalaman aliran air, y dan masa yang diambil untuk hakisan terbentuk merupakan faktor-faktor yang dominan dalam penilaian hakisan.

SCOUR BELOW SUBMERGED SKEWED PIPELINE

ABTSRACT

Local scour below submerged pipelines occurs due to the erosive and action of currents which cause pipeline failure. The presence of pipe across river initiates the piping effect combined with the stagnation eddy and vortex system undermine the pipeline and mark the onset of scour. The main objective of the research is to investigate the physics of scour below pipeline in river crossing as well as its factor associated. In this study, experiments were conducted to investigate the effect of four different pipeline angles (30º, 45º, 60º and 90º) across a channel. Gene Expression Programming (GEP) have been widely applied in engineering practice in recent years. Thus, the study aims to apply GEP and regression models as the predictive tools on the scour depth below skew pipeline across river. The initial scour process for flow shallowness y/D= 3 increases rapidly due to the piping effect which leads to the tunnel erosion, lee erosion and luff erosion. Whilst, for flow shallowness, y/D = 4 the scour process at initial stage is slower than the case of flow shallowness, y/D = 3. A small gap between the pipeline and undisturbed sediment bed allowing a jet like of high velocity flow through the gap. The maximum scour location for skew pipe occurs near to the left sidewall as the reaction of hydrodynamic forces towards the channel wall at the left side. The regression model (Equation 4.4) with R^2 = 0.55, and a low root mean square error (RMSE = 0.47) was validated with the external data sets from previous research works. The validation shows a good correlation with R = 0.71. The GEP prediction on the scour depth also is significant with high R^2 and low root mean square error. The proposed GEP model (Equation 4.7) showed a good agreement with R = 0.94 for training and R = 0.9 for testing. From the sensitivity analysis, the flow depth and time variation of scour depth are the most dominant factors for the scour predictions.

CHAPTER 1

INTRODUCTION

1.0 General

Naturally, scour process is a part of morphologic changes occurs in the rivers. Natural events and human activities or any disturbances within the river can bring changes to the river morphology. Any disturbances on the hydrodynamic forces and the sediment transport capacity contributed to the instability of the natural condition of the river system. In recent times, the appearance of various hydraulic structures has greatly altered river regimes, with significant impact on the sediment transport capacity and sediment deposition. Natural free flowing river seeks a state of the dynamic equilibrium where there is a balance between the flow conditions and the sediment transport capacity. The dynamic equilibrium phase allowed the sediment transport capacity of the natural flowing water is at the rate where it is supplied (Vanoni, 1975; Graf, 1984; Chang, 1988; Alekseevskiy et. al., 2008). Generally, understanding the river morphology and its natural characteristics are among the most complex and phenomena. Numerous researchers, scientists and engineers around the globe have been looking for the best solutions to overcome the river environment and engineering problem that associated with the human daily life (Garcia, 2008).

The presence of the pipeline in the river or stream obstructed the flow pattern within the structure may cause erosion or scour that can be divided into general scour and local scour. The changes in flow characteristics lead to a change of sediment transport capacity, hence affecting the equilibrium and the stability of the actual sediment transport capacity. The hydraulic conditions eventually are adjusted to a new state of equilibrium through scour process (Hoffmans and Verheij, 1997). The impact of the structure on the flow in the river directly creates the local scour that is relatively has a shorter time scale than the general scour. There are several approaches in studying the river hydraulics and the local scour process that permitted the development of methods to predict and prevent the scour at different types of structures. Physical model testing and prototype, mathematical model, soft computing technique and field measurements provide the information with respect to the scour may particularly appropriate to overcome the problem. Nevertheless, there is still lack of research on the local scour especially scour below the pipeline in river crossing. One of the main reasons is the complexity to determine the flow and the scour patterns around the pipe. The combination of the techniques can provide the best solutions of the complex process with respect to the local scour problems.

1.1 Background

Local scour below the pipelines commonly occurs due to the erosive action of currents and waves. The underlying erosion process is complicated and depends on the interaction of hydraulic, geotechnical, and hydrologic (discharges varying with time) conditions. Structure failures induced by scour in pipelines occur in extreme cases of unsteady flows interacting with changing channel conditions (Breusers and Raudkivi, 1991). Although there are several physical and numerical studies on offshore pipelines on movable beds, few investigations have focused on local scouring across rivers, which is an important issue for river engineering. The free span of the pipeline is susceptible to damage due to the natural process and the environmental forces of human activities which may cause severe environmental and economy problems. Generally, local scour occurs due to several conditions i.e. (a) flow condition, (b) structure, and (c) riverbed materials which are very severe in hydraulic problems especially for structure failures in rivers or oceans. Many difficulties were encountered in past research studies in terms of considering the riverbed materials and scour changes on time which vary according to the equivalent scour development stage. Chen and Zhang (2009) reviewed pipeline scour in three perspectives, i.e., two-dimensional physical scour modeling, three-dimensional physical scour modeling, and numerical scour modeling. The onset scour phenomenon is attributed to the seepage flow underneath the pipeline, which is caused by a large jump in the pressure or a different relative pressure coefficient (C_p) between the upstream and downstream sides (Mao, 1988). Dey and Singh (2008) concluded that the maximum scour depth below the pipelines with upward seepage through the bed was smaller than that without seepage. They also concluded that the existing of critical seepage-main flow velocity ratio for which the scour depth is minimum.

The three-dimensional flow field around the pipeline is extremely complicated due to the separation and multiple vortices that occur around the pipes. The complexity of the flow is further exaggerated due to the dynamic interaction between the flow and the movable boundary in the process of obtaining the maximum scour hole. Many previous studies in pipeline scouring focused on the sea bed condition whereas not many studies have been done on river (Moncada and Aguirre, 1999). Therefore, the main objective of this research is to conduct experimental simulations of scour caused by submerged skew pipelines across rivers. Previous research confirmed that the scour hole under pipelines could be regarded as a function of the Froude number and of a dimensionless clearance between the pipe and the undisturbed bed (Maza, 1987). The initiation of local scour underneath submerged pipelines is predominantly caused by the presence of the pipe that creates a pressure gradient across the cylinder. The difference of the pressure causes tunnel erosion which is affected by the seepage process. The increasing length of the seepage flow along the streamlines can reduce the pressure gradient as well as the seepage effect. The piping effect occurs when the pressure gradient exceeds the flotation gradient of the bed sediment and the associated upward flow. Tunnel erosion does not occur when the ratio of the low depth to the pipe diameter exceeds 3.5 and when the embedded ratio is too high (Chiew, 1990).

Interactions between the pipeline and its erodible bed under strong current and wave conditions may cause scour around the pipeline. This process involves the complexities of both the three-dimensional flow pattern and sediment movement. Scour below submerged pipeline may expose a section of the pipe, causing it to become unsupported. If the free span of the pipe is long enough, the pipe may experience resonant flow-induced oscillations, leading to settlement and potentially structural failure. An accurate estimate of the scour depth is important in the design of submarine pipelines (Chiew, 1991a) and the estimation of the scour characteristics of underwater pipeline continues to be a concern for hydraulic engineers.

A number of empirical formulas were developed in the past to estimate the maximum scour depth below pipelines (Chao and Hennessy, 1972; Kjeldsen et al., 1973; Ibrahim and Nalluri, 1986; Bijker and Leeuwestein, 1984; Moncada and Aguirre 1999, Chiew 1991a). Although numerous techniques and methodologies for the prediction of the maximum scour depth below the pipelines were proposed by various investigators, a few of these techniques and methodologies have been found to be suitable and easily applicable (Dey and Singh, 2008). Deng et al. (2013) analyzed and presented some pertinent protective measures based on the principle of hazard mitigation. They also presented the relation between pipe axis and river flow direction. The cross-river pipeline construction projects are the key projects in long-distance pipeline construction. Based on years of geological hazard investigation and washout protection in Zhongxian-Wuhan Pipeline and Lanzhou-Zhengzhou-Changsha Oil Pipeline, scouring and erosion as well as change in the river`s course are the main dynamic factors in river washout (Deng et al., 2013). Statistical results of river washout hazards in Zhongxian-Wuhan Gas Pipeline and Lanzhou-Zhengzhou-Changsha Oil Pipeline can be seen in Table 1.1.

Table 1.1 Statistical results of river washout hazards in Zhongxian-Wuhan Gas Pipeline and Lanzhou-Zhengzhou-Changsha Oil Pipeline (Deng et al., 2013)

Date	Zhongxian-Wuhan Gas Pipeline			Lanzhou-Zhengzhou-Changsha Oil Pipeline		
	High-risk Hazards	Total Hazards	Scale	High-risk Hazards	Total Hazards	Scale
2008	334	1239	27.0%	/	/	/
2009	/	/	/	117	1022	11.4%
2010	441	2418	18.2%	/	/	/

The pipeline cross-river modes can be divided into three kinds: transverse crossing, oblique crossing and straight crossing (Qin and Zhao, 2009) as shown in Figure 1.1. The river washout hazards occur depends on the stability of the riverbed which can be divided into two kinds: longitudinal stability and lateral stability. Longitudinal stability is the stability of the riverbed alone the river direction of flow manifested mainly as changes in the longitudinal profile and cross-section of the riverbed. Lateral stability is the stability of riverbed alone the river`s vertical flow direction, manifested mainly as the watercourse swing of the riverbed. There are lots of river washout hazards in rainy season due to the excessive rainfall which leads to the constant increase in water level and flow velocity, lots of erosion activities results in large impacting kinetic energy and eroding force and poor river stability either longitudinal or lateral of the river (Li, 1994). The main causes of river washout include riverbed and lateral erosion, while human engineering activities generally cause or aggravate those harmful effects. Floating, suspending, shoving and impacting are the main four types of threat in river washout hazards.

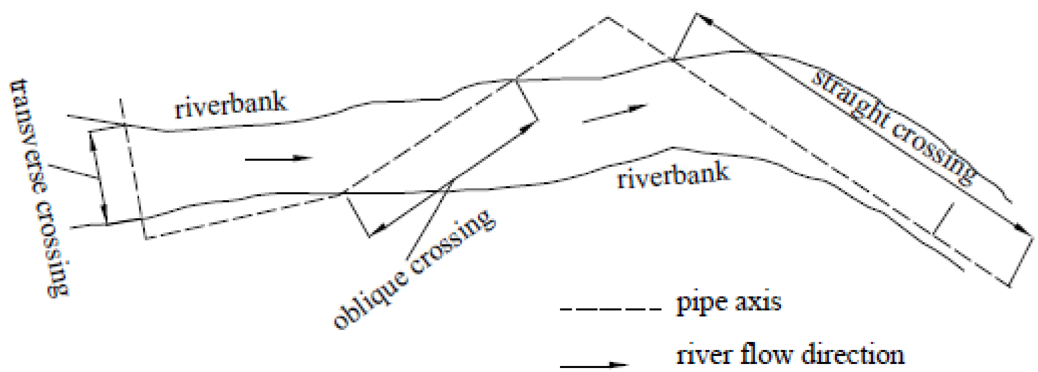

Figure 1.1 Relation between the pipeline axis and river flow direction (Qin and Zhao, 2009).

MDNR (1992) suggested that all watercourse crossings should be designed by registered professional engineers and few of general items need to consider during the planning of any watercourse crossing. Purposely, Best Management Practice (BMP) in Lansing, Michigan produced a manual on watercourse crossings where any watercourse crossings need to confine and consolidate to less sensitive areas which eliminates random crossing and allows greater protection of the water course. Watercourse crossings can be either above or below the water surface and may vary with respect to length, width, height, and construction design depending on the purpose of the crossing and the environmental and physical characteristics of the watercourse. Watercourse crossings are used when there is a dependency for their use at a given location and when there are no other feasible and prudent alternatives to access the desired location without the use of a crossing. Constructions of watercourse crossings restricted to periods of low water levels when impacts to aquatic resources within the watercourse can be minimized. The utility, cables and pipelines are all possible methods of below-ground crossings. The specifications and designed of the below-ground crossings should be done in one operation to minimize the impacts on the environment (Figure 1.2 to Figure 1.4).

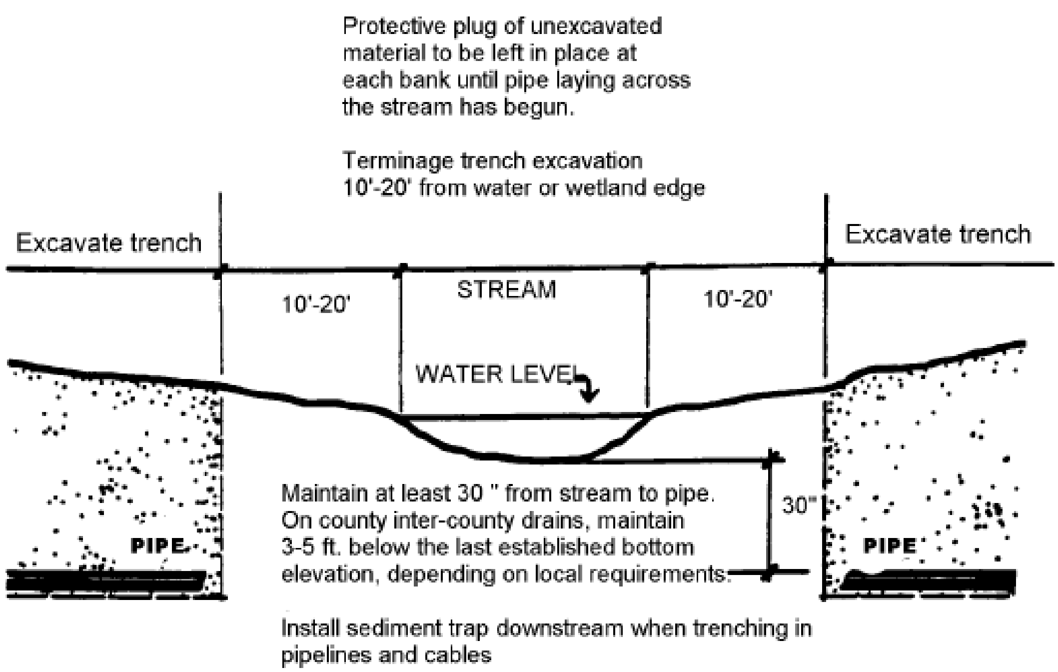

Figure 1.2 Stream crossing for pipelines (MDNR, 1992)

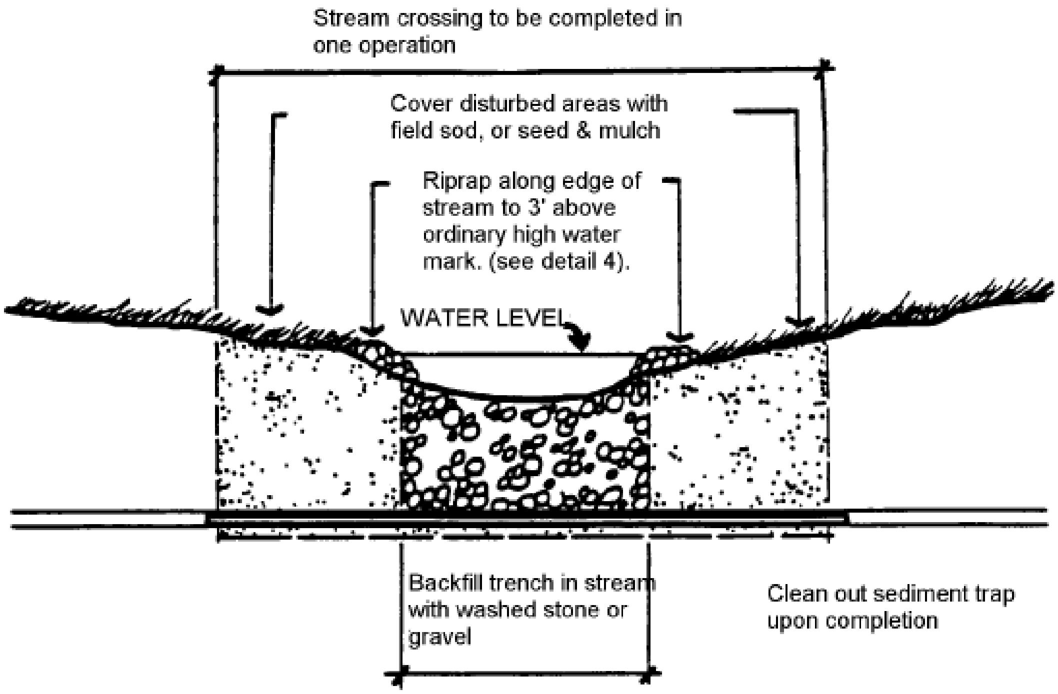

Figure 1.3 Detail of stream crossing for pipelines (MDNR, 1992)

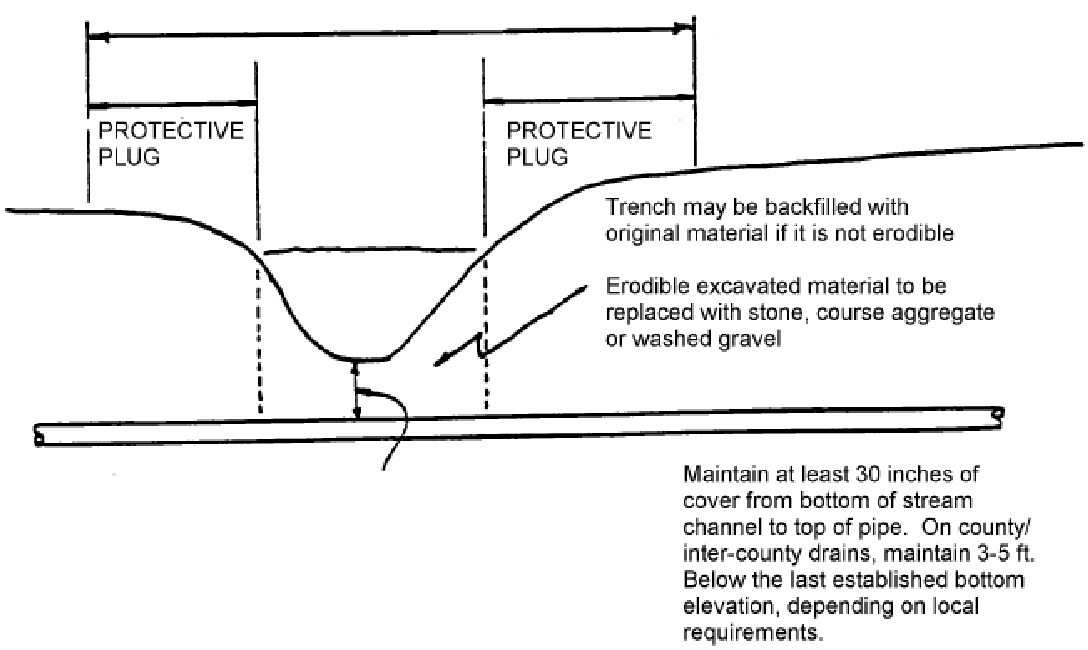

Figure 1.4 Detail section of stream crossing for pipelines (MDNR, 1992)

Boyd et al., (2013) observed the on-site irrigation pipeline crossings at Musselshell River. They have applied the Best Management Practice (BMP) that focuses primarily on irrigation water pipelines and also does include some criteria on permitting oil/gas pipeline crossings. The irrigation pipeline crossings on the Musselshell River are primarily inverted siphons that are from steel, pre-cast concretes, or PVC pipelines which carry water under the bed of the river. The pipelines are usually buried less than 5 feet below the river bed, trenched into the river bed with heavy equipment. If the irrigation pipeline is not buried deep enough and located in a channel section subject to scouring, it may become exposed during a high water. Once exposed, the likelihood of the pipeline becoming severely damaged by debris is high (Figure 1.5). There are some oil/gas pipelines that cross the Musselshell River. Many are buried beneath the river bed although some smaller pipelines attached to bridges. Some oil pipelines are exposed due to the high water and increased the hydrodynamic forces that could lead to scour process and lowering the river bed (Figure 1.6). Boyd et al., (2013) suggested that the inverted siphons locate on a straight section of river that is table and has not moved laterally or vertically over the last 30 years. The designed also need to avoid meander bends and braided channels. The general design considerations also include that bury the pipeline as deep as possible under the river bed. If the river bed does not have sufficient natural armoring, carefully construct a graded rock apron that extends far enough upstream and downstream from the buried siphon to assure the channel bed over the siphon fits the overall river channel gradients. The inverted siphons and cross channel flumes for irrigation pipeline crossings are expensive and require continual maintenance. Thus, the new approach of pipeline crossings need to be built and the design criteria need to minimized the impact on the environment and the natural free flowing river.

Figure 1.5 2011 flood scoured the river bed, exposing the irrigation inverted siphon on the Musselshell River (Boyd et al., 2013).


Figure 1.6 Exposed oil pipeline on Beaver Creek near Helena (Boyd et al., 2013).

Although numerous researches have been conducted to study the scour process, not many of the research discussed the impact and influence of skew angle, θ, on the scour profiles. This study investigates the influence of skew angle, θ, on scour depth. The main deficiency of these formulas is that the empirical equations do not model actual scour process. Predictive approaches such as artificial neural networks (ANN) and adaptive neuro-fuzzy inference systems (ANFIS) (Bateni et al., 2007) have recently shown to yield effective estimates of scour around hydraulic structures. ANNs have been reported to provide reasonably good solutions for hydraulic-engineering problems, particularly in cases of highly nonlinear and complex relationship among the input-output pairs.

1.2 Problem Statement

The prediction of local scour below submerged pipelines that lay across the river on a moveable bed constitutes a problem in pipeline engineering practice (Moncada-M and Aguirre-Pe, 1999). The accelerations and higher water velocities of the river increase shear velocity, thus generating a scour hole. Previous research has stated that the scour hole below submerged pipelines could be regarded as a function of the Froude number and of a dimensionless clearance between the pipe and the undisturbed bed (Maza, 1987). Riverbed removal and sediment below underwater pipelines take places by the scouring action of the stream flow. Flow-induced oscillation that was affected by the wake-vortex causes fatigue failure and exposes the pipeline unsupported over a considerable distance (Dey and Singh, 2008).

Previous studies in pipeline scouring focused on the sea bed condition whereas few studies have been done on rivers (Moncada and Aguirre, 1999). Previous research confirmed that the scour hole below submerged pipelines could be regarded as a function of the Froude number and of a dimensionless clearance between the pipe and the undisturbed bed (Maza, 1987). Kjeldsen et al. (1973) found that scour depth, d_s is affected by the approach flow velocity, *U* and pipe diameter, *D* but the effect of flow depth, *y* and the sediment size, d_{50} is not included. Mao (1986) identified that there are two cases of scour process, (a) jet period, which decides the maximum scour depth, and (b) wake period, which decides the location of scour depth. He also observed that for $d_s/D<1$, the scour depth, d_s is a weak function of the flow Shields parameter. Sumer et al. (1988) compared the effective Shields parameter with the time-averaged value to assess the influence of lee wake on the scour profile downstream of the pipelines. The onset of scour below pipelines occur due to the piping effect and no scour takes place if the ratio of the approach flow depth to the pipe diameter exceed 3.5, and flow shallowness, $y/D<3.5$ for the pipelines that laid on the sediment bed. Chiew (1991) investigated the influence of the gap discharge, q_g in estimation of the scour depth and proposed an iterative method with an empirical function that relate, y/D with the gap discharge, q_g.

Many equations and methodologies for the prediction of the scour hole below submerged pipelines have been proposed by various researchers. Predictive approaches such as GEP (Guven et al., 2009) have recently shown to yield effective estimates of scour around hydraulic structures. The pipeline and its erodible bed under strong currents conditions may cause scour around the pipelines. This process involves the complexities of both the three-dimensional flow pattern and sediment movement. The investigation of the scour characteristics of submerged pipelines continues to be a concern for hydraulic engineers. Most of the common practices for pipeline cross-river in Malaysia are transverse crossing modes (Figure 1.1). None of the aforementioned studies examined the influence of skew pipelines cross-river under clear-water scour condition. Therefore, the main objective of this research is to conduct experimental and simulations of scour caused by submerged skew pipelines across the river.

1.3 Objectives

There is a need to understand the scour problem below submerged pipelines. Thus, an in-depth study has been undertaken with the following objectives:

1. To investigate the impact of skewed pipeline on the scour depth.
2. To compare the performance of GEP for the prediction of the scour depth and scour location.
3. To develop and verify the selected predictive equation using physical hydraulic model data and the comparison of the scour process.

1.4 Scope of Study

Many difficulties were encountered in past research studies in terms of considering the riverbed material and scour change over time and the equilibrium scour development stage. Scope of the research focused on the mechanism of the scour especially the physics of the scour process that can provide a better understanding of the scour process. The influence of the shear-stress that is applied on the boundary between the riverbed and the structure needs to be investigated so that we can understand the scour phenomenon and the effect of time on scour depth, the shear-stress around hydraulic structures and the particles critical shear-stress. Generally, the main concentration of the research can be divided into two stages; first, the setting up and testing of the physical model to replicate pipeline scour under a controlled environment.

The aim is to obtain reliable results on each scouring phenomenon and its corresponding hydraulic and geomorphologic conditions. The experiments will be conducted in a 12m long man-made concrete rectangular flume with 1.5m width and 0.9m depth. Pipes model will be placed across the flume at 30˚, 45˚, 60˚ and 90˚. There are two different approach flow depth, y for the each experiment which are 150 mm and 200mm. The laboratory experiments will focus on the clear water scour condition whereas the sediment motion is localized. The mean sediment size, d_{50} for the laboratory is 0.58mm and the sediments can be classified as coarse sand and non-cohesive sediment (BS1377, 1975). The dominant parameters for the non-cohesive sediment are the particle size and particle weight which it may influence the buoyancy of the sediment particle. The laboratory experiment will also investigate the significant impact of different flow depths on the scour process because of the limitations mentioned by several researchers. Practically, the flow depth effect need to be considered and may influence the scour development below submerged pipelines for river conditions and pipelines crossing the intertidal zone. As for offshore pipelines, the flow depth effects can be neglected. The collected laboratory data sets will be analyzed using two methods, which are multi-linear regression analysis and the GEP model. The predictive performance is compared to determine the best predictive result on pipeline scour. To further test the applicability and robustness, the models will be tested with external data sets obtained from the literature or contributed by other researchers.

1.5 Relevancy of Research.

Generally, local scour occurs due to several conditions i.e. (a) flow condition, (b) hydraulic structure, and (c) riverbed material, which is a very severe hydraulic problem especially when it causes pipeline failures. Malaysia has experienced substantial economic growth since 1980s, resulting in increasing of water demands in the commercial and substantial development centres. The Klang Valley region which is the political, commercial and industrial centre of the nation is the most important focus for these high demands which are expected to continue their rapid growth into the 21st century. However, the water resources available within the Selangor and Kuala Lumpur region will not be able to meet the demands in the near future. A scheme to transfer water from Pahang to Selangor has been proposed to cope with future water demand shortfalls in Selangor, Kuala Lumpur region and at a later stage, the western part of Negeri Sembilan. Pahang State which lies to the east of Selangor State, possess ample water resources compared with their local demand and has sufficient reserve for interstate transfer. Two lanes of pipeline each with a diameter of 3.0 m are designed to convey raw water from the pumping station to the tunnel in Karak. The pipeline is approximately 11.8 km long. The pipe is designed largely to be below ground to minimize environmental and social impacts. The route traverses the northern, left bank of the Sungai Bentong, passing through a disused rubber estate on the left bank where the terrain is undulating, and crosses the Sungai Bentong, the main highway, and Sungai Telemong. There are lacks of guidelines of river crossing construction in Malaysia. Resources alteration activities including temporary or permanent structure of bridges, water pipeline, gases pipes, sewerage pipes and cables of utility services that crosses rivers in Selangor State (Plate 1.1). The guidelines for crossing of rivers need to have consideration of applicability, design and sitting, maintenance, effectiveness, costs and environmental impact.

The objectives of the study are to conduct experiments in the laboratory and to collect additional data of the depth, the length and the width of the scour holes and to incorporate the factors that affect the scour phenomena. The outcome of this study is to collect and interpret information from both the laboratory and the field which would help engineers to produce safe and economical pipeline in streams with erodible beds. This study is also expected to contribute to the understanding of new approaches in the prediction of the scour holes around submerged pipeline. The research emphasizes the comparison of the physical hydraulic modeling and soft computing techniques on the scour profiles. Such structures often induce serious erosion problems due to the interference with the flow pattern that leads to an increase in the erosion process.

Plate 1.1 Temporary bridge at Sungai Damansara, Selangor

1.6 Structure of Thesis

This thesis is divided into six chapters. Chapter 1 briefs an introduction of the research including the research background, the problem statement, objectives, scope of research and relevancy of the research. Chapter 2 briefs the past study related to the research with respect to the influence of various parameters on the scour depth as well as the application of various soft computing techniques to estimate the scour depth. Chapter 3 explains the detail research methods of the physical hydraulic modeling and the details of the mathematical model setup (MLR and GEP) including the data range for the model inputs and data filtering of the approach flow using the WinADV. Chapter 4 discusses the mechanism and analysis of the scour depth below submerged pipeline and also the prediction model for the scour depth using MLR and GEP. Chapter 5 presents the conclusions and recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The basic principles of open channel hydraulics are used to describe the sediment transport phenomenon as well as the scouring process due to the natural process or human activities. The presence of submerged pipelines cross-river is part of the problem from a practical engineering point of view and approach, and has created obstacles and interrupted the natural flowing water of the waterways and streams (Sturm, 2010). Geotechnical aspects and engineering characteristics such as social conditions, economics, environmental impact and safety requirements also influence the design process (Hoffmans and Verheij, 1997). In recent years, mathematical modeling and understanding the physical process of water and sediment movement in rivers, estuaries and coastal waters have made much progress and this has led to various mathematical model systems for new research. Changes in flow characteristics affected the sediment transport capacity in the river. Hence, the unnatural flow conditions cause disequilibrium between the natural sediment transport and flow transportation capacity. Thus, scour process begin to develop eventually as hydraulic conditions are adjusted to reach the natural equilibrium state (Hoffmans and Verheij, 1997). Naturally, scouring is part of the morphologic changes of rivers and is also affected by man-made structures which greatly alter the river regimes. The presence of the structures may lead to the scouring process and may cause dramatic changes to the river morphology. The tendency of the natural river to wander and the presence of structures in the rivers usually increase the scouring process locally, thus protection to the pipeline failures is undermined and this attracts the interest of designers and engineers. A good comprehensive assessment and an understanding of two phenomena that are closely associated with scouring would lead to accurate solutions and reduce the impact of scour significantly. The two phenomena are turbulence flow, with its great complexity and variability, and sediment transport, with its strong dependence and interaction with the turbulent flows (Breusers and Raudkivi, 1991).

2.1 Mechanics of Local Scour at Submerged Pipeline

In the analysis of local scour, one must differentiate between clear-water scour and live-bed scour because both the development of the scour hole with time and the relationship between scour depth and approach flow velocity depend upon which type of scour that occurs (Breusers and Raudkivi, 1991). Pipeline that is laid on an erodible bed are assume to be the same in the sediment soil and the flow conditions along the length of the pipe. Therefore, the pipe can be analyzed for onset of scour. Mao (1988) attributed the scour onset to the seepage flow underneath the pipeline, which is caused by a large jump of pressure or the difference of relative pressure coefficient, C_p between the upstream and downstream sides. The scour-digging effect of vortices A and C lead to scour development but Chiew (1990) found that the action of vortex C was completely overshadowed by vortex B, which is against Mao`s deduction and linked the onset of scour to the phenomenon of seepage (Figure 2.1). Scour around submerged pipelines may be caused by currents and waves for pipelines that are buried under the seabed while pipelines in river crossings are affected by the action of a current generated by the flood problems. The pipes may become partially exposed due to the current force generated by the flood that causes general scour in the bed of the river. The prediction of the scour below pipelines that are laid across the river is affected by the current on a moveable bed that constitutes an important problem in pipeline engineering practice (Moncada-M and Aguirre-Pe, 1999). The developed down flow, due to the stagnation of the pressure gradient of the non-uniform approach flow adjacent to the upstream surface of the pipe laid on the seabed creates the downward flow and the flow separation close to the bed which causes the vortex to occur. The vortex system is swept downstream by the flow and wraps the pipe in the shape of a horseshoe and this significantly affects the scouring process (Chen and Zhang, 2009). The flow separates at the top and the bottom of the pipeline and the flow separation surfaces enclose the wake downstream of the pipe. The separation creates a surface with a discontinuity in the velocity profile and this leads to the development of the concentrated “cast off” vortices in the interface between the flow and the wake. The wake vortex system has vertical axes, which are commonly seen as eddies. At the water surface, the flow and structure interaction form a bow wave known as the surface roller. The developed scour prediction based on the laboratory data did not produce reasonable results for field conditions and sometimes even for other laboratory conditions (Dargahi, 1987). The lack of understanding of the physics and the structure of the flow as well as the erosion mechanism seems to be the main contribution for the failure.

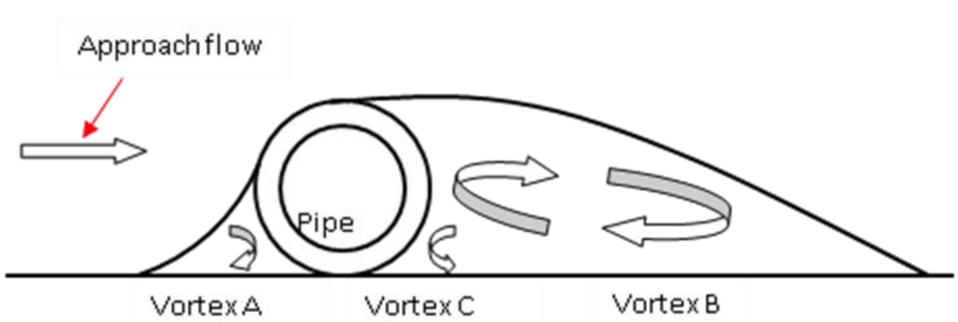

Figure 2.1 The three- vortex system around pipelines (Chen and Zhang 2009)

Scour occurs when sediment is eroded from an area of the bed in response to the force that is generated by the approaching flow, wave and current. Generally, there are three types of scour which are typically occur in the river environment, namely, general scour, constriction scour and local scour. There is also scour in different conditions of transport (Raudkivi, 1993).

- General scour occurs in a river or stream as the result of natural processes irrespective of whether a structure is there.
- Constriction scour occurs if a structure causes the narrowing of a water course or the rechanneling of the river bank or the flood plain flow
- Local scour results directly from the impact of the flow structure
- Clear-water scour occurs if the bed material in the natural flow upstream of the scour area is at rest. The shear stresses on the bed some distance away from the structure are thus not greater than the critical or threshold shear stress for the initiation of particle movement
- Live bed scour referred to as scour with bed material sediment transport, occurs when the flow induces a general movement of the bed material. The shear stress on the bed generally greater than the critical one

Pipelines that are laid on the sediment bed obstruct the natural river flowing which creates the local scour below the pipeline. In order to reach a new equilibrium state, the scour developed around the pipelines due to the flow field change (Figure 2.2).

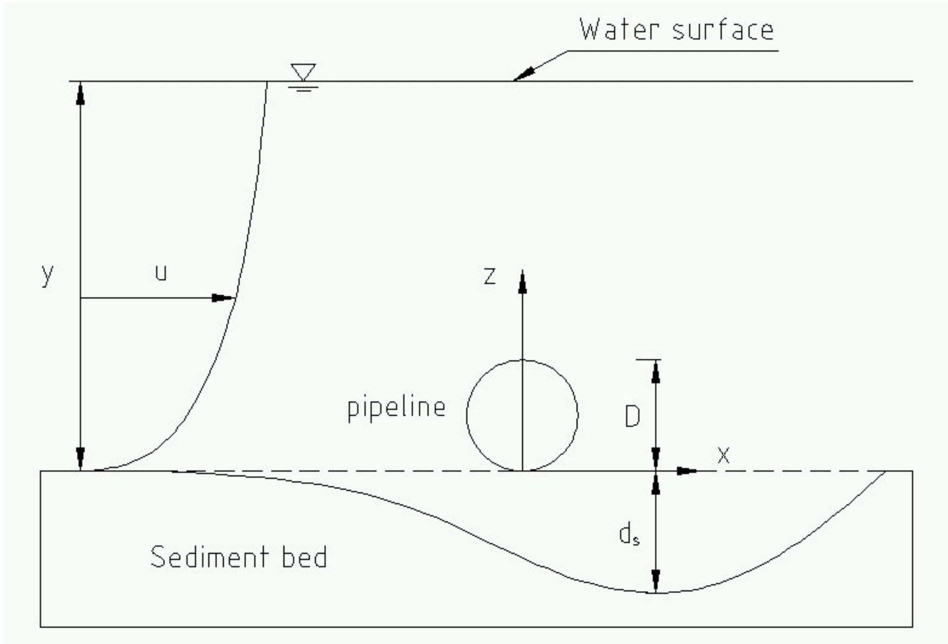

Figure 2.2 Schematic drawing of scour hole below a pipeline (Dey and Singh, 2007).

2.2 Pipeline Scour Prediction

Scouring is a natural phenomenon caused by the flow of water in rivers and streams. Under certain circumstances, the alluvial material and the deeply weathered rock are vulnerable. Naturally, scour occurs as part of the morphologic changes of rivers and as the result of man-made structures. The development of river valleys reveals such activity throughout the millennia, long before man`s efforts had any appreciable impact on them. In recent times, the appearance of various hydraulic structures has greatly altered river regimes, and ha a significant impacts on the transport and deposition of sediments. Natural scouring can cause dramatic changes in the plan, cross section and even location of rivers. Structure failures induced by scour such as in pipelines occur in extreme cases of unsteady flows interacting with changing channel conditions (Breusers and Raudkivi, 1991). Interactions between the pipeline and its erodible bed under strong currents conditions may cause scour below the pipelines. This process involves the complexities of both the three-dimensional flow pattern and the sediment movement. Scour underneath the pipeline may expose a section of the pipe, causing it to become unsupported. If the free span of the pipe is long enough, the pipe may experience resonant flow-induced oscillations, leading to settlement and potentially structural failure. An accurate estimate of the scour depth is important in the design of submarine pipelines (Chiew, 1991b). Thus, the estimation of the scour characteristics of underwater pipelines continues to be a concern for hydraulic engineers.

Pipeline scour problems have been studied using physical modeling due to the complexity of the problem, i.e. three-dimensional turbulent flow with sediment transport. Scour problems have been evaluated from the numerical point of view where the development of numerical models for pipeline scour is an alternative way for design engineers to predict and understand the local scour around pipelines. However, there are still some constraints on that particular effort. Chen and Zhang (2009) have reviewed the pipeline scour based on three perspectives, i.e., two-dimensional (2D) physical scour modeling, three-dimensional (3D) physical scour modeling, and numerical scour modeling. By assuming that a pipeline is laid on an erodible bed in the currents, and the sediment soil and flow conditions are the same along the pipeline length, a two-dimensional (2D) analysis was conducted. The onset of the scour phenomenon was attributed to the seepage flow underneath the pipeline that was caused by a large jump in the pressure or the difference relative pressure coefficient (C_p) between the upstream and downstream sides (Mao, 1988). The presence of the vortices system at the river pipeline on the river bed also contributed to the scour development at the laid pipeline on the riverbed. Dey and Singh (2008) conducted laboratory experiments on clear-water scour below underwater pipelines in uniform and non-uniform sediments under steady flow. The experiments also investigated the influence of various pipeline shapes on the scour depth where circular pipes, 45° (diagonal facing) and 90° (side facing) square pipes were tested. There were three similarities in the scour profiles. The equilibrium scour depth increased in conjunction with the approach flow depth for shallow flow depths and was not influenced by the higher flow depth. Furthermore, the researchers investigated the impact of the armor layer on the sediment bed. The scour depth of the pipeline with an armor layer was greater than that without an armor layer for the same sand bed. If the secondary armoring formed within the scour holes was scattered. In addition, the scour depth with an armor layer was less than that without an armor layer for the same bed when the scour hole was shielded by the secondary armor layer (Dey and Singh, 2008). The onset scour that was closely related to the embedment of pipelines in currents was studied by Sumer et al., (2001).

Scour also propagates along the length of the pipeline after the onset scour. As the time of scour elapses, the scour hole is sufficiently long and the pipeline starts to sag in the scour hole. Thus, the introduction of 3D physical modeling has to be considered. The pipeline will block the flow and this will lead to the self-burial process after reaching the bottom of the scour hole. A spiral type of vortex which forms in front of the pipe near the span shoulder is also one of the factors that cause the longitudinal pipeline scour development. Scour development under the pipeline is not significant when the upstream water depth exceeds 4 times the pipe diameter and that affected the flow around the pipe (Chiew, 1991a). The characteristic of the pipeline scour in deep water conditions is approximated when the flow depth is greater than 3 times the pipe diameter. The 1D scour can occur under the pipeline when the initial gap is as large as 2D, increasing the total gap for a fixed pipe to 3D (Sumer and FredsØe, 1990).

Predictive approaches using soft computing techniques have been applied widely in many branches of engineering science and technology but some approaches have been limited to a range of experimental data and empirical formulae. Bateni et al. (2007) concluded that the application of the Bayesian network to predict the equilibrium and time-dependent scour depth gave more accurate predictions and improved the reliability of the model predictions. It was found that several critical parameters influenced the pipeline scour process. It was also found that the physical models were simple and easy to use but were often inadequate for the study of complex currents as well as pipeline support conditions (Chen and Zhang, 2009). Furthermore, the application of the finite-difference method to solve the Laplace equation to predict the velocity potential and a boundary adjustment technique to calculate the scour profiles below pipelines were implemented by Li and Cheng (1999). BrØrs (1999) implemented the finite element method for scour below pipelines simulation.

2.3 Sediment Transport

The sedimentation process in a river is a non-equilibrium state caused by an imbalance between sediment transport rates and sediment supply rates (Molinas, 1996). The function of a river is to carry to the sea the quantity of sediment delivered at the rate it is supplied. The way a river does this is to adjust its own slope and form by eroding or depositing sediment that follows the equilibrium state. Biedenharn et al. (2008) stated that the river responds to changes in the controlling variables of water discharge (Q), slope (S), bed material load (Qs) and median size of bed material (d_{50}). Figure 2.3 shows the principle of river equilibrium. When a river is in a dynamic equilibrium, it has adjusted these four variables so that the sediments transported into the reach are also transported out, without aggradations or degradation (FISRWG, 1998; Biedenharn et al 2008).

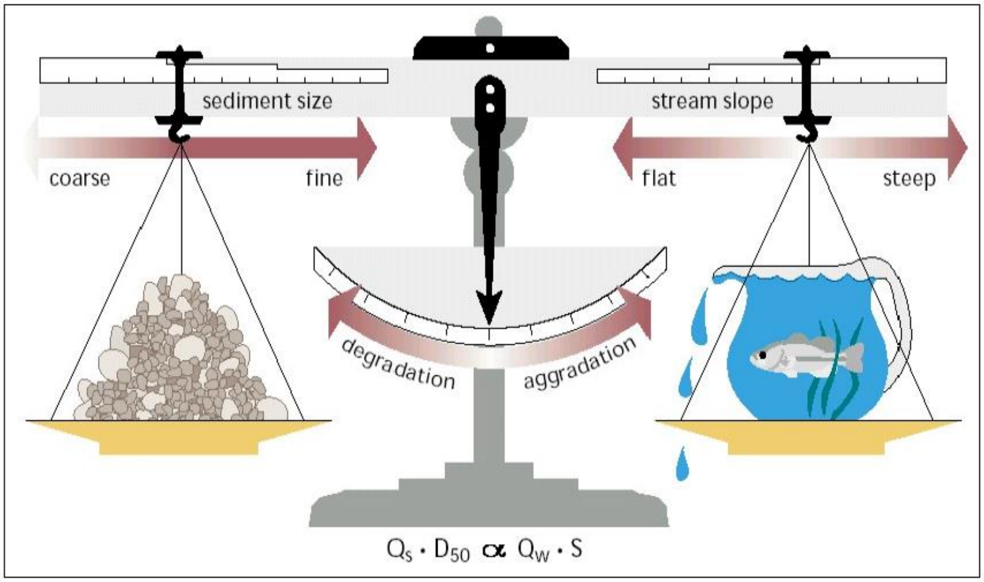

Figure 2.3 Lane's balance of sediment supply and sediment size with slope (energy grade) and discharge (FISRWG, 1998).

The sedimentation taking place in a river system is classified under three categories, i.e. (a) aggradations or degradation; (b) general scour or deposition; and (c) local scour or deposition (Molinas, 1996). Aggradations or degradation of a river takes place over long reaches and were relatively long periods of time and are due to changes in river controls, changes in sediment supply and changes in river morphology (Vanoni 1975; Molinas, 1996; Garcia 2008). General scour/deposition is a phenomenon caused by expansions and contractions of spur dikes, bridge piers, abutments and other hydraulics structures that change the flow area and flow velocities (Vanoni 1975; Molinas, 1996; Garcia 2008). Local scour or deposition is a localized problem associated with intake structures, piers, dikes, etc. This is caused by flow separation where the