THE HANGZHOU BAY PIPELINE CROSSING PROJECT - USE OF SPOILERS TO INITIATE PIPELINE SELF-BURIAL AND RE-INITIATE FUTURE RE-BURIAL

Authors: **Mr. Xia Yu Fei – Vice President, Sinopec Transportation and Storage**
Mr. Gu Jian Ning – Project Manager, Sinopec Project Management Team
Mr. Ng Eng Bin – Manager, Subsea and Pipelines, Worley Pte Ltd
Mr. Janardanan Kizhikkilod, Lead Pipeline Engineer, Worley Pte Ltd
Ms. Tan Sin Le, Pipeline Engineer, Worley Pte Ltd
Dr. Daniel Zhao, Area Representative, Submarine Pipeline Spoilers (Asia)

Abstract

In order to expand energy supply to fuel the industries in the Shanghai-Nanjing-Ningbo area, Sinopec decided to build 3 pipelines across this region. About 53km of the pipelines' route cross Hangzhou Bay, which is characterized by strong tidal variation and high tidal currents. Most importantly, Hangzhou Bay experiences alternating and recurring levels of siltation and erosion, which can result in seabed depth variation of up to 6m. Instead of burying the pipelines to a level to avoid future erosion, it was decided to install a mechanism that would initiate self burial and future self re-burial in the event of soil erosion. The chosen device was submarine pipeline spoiler manufactured by SPS (USA) Inc. This patented device has been successfully used in the North Sea where harsh conditions similar to Hangzhou Bay are encountered.

This paper explains the mechanism in which spoilers induce scouring around a pipeline, and the design methodology and approaches taken to apply this device for pipeline self-burial. Based on laboratory tests carried out by Delft Hydraulics on behalf of SPS, the effect of spoiler on the hydrodynamic coefficients for varying degree of pipe embedment is known and this is utilized in the on-bottom stability assessment. The paper demonstrates how the required concrete weight coating for on-bottom stability of pipeline with spoiler is determined for the Hangzhou Bay Pipeline Crossing Project. The paper also addresses the correct manner to mount the spoiler and the precautions necessary to ensure effectiveness of the spoiler after installation. Finally, the paper suggests that spoilers may be considered as a viable alternative for pipeline burial for similar projects under similar conditions.

Introduction

In recent years, there has been a dramatic increase in demand for energy in the Peoples Republic of China (PRC) due to rapid economic expansion. This is especially significant in vibrant cities, such as those within the Shanghai-Nanjing-Ningbo area, where extensive commercial and industrial activities take place. To meet the increasing energy demand, **China Petroleum and Chemical Corporation (SINOPEC)** and the division of **Sinopec Pipeline Storage and Transport Branch Co. Ltd** decided to build a pipeline system to transport imported crude oil from Ningbo, Cezi and Daxie area to Jinshan, Shanghai and Nanjing area. Part of pipeline system crosses the Hangzhou Bay, spanning from the south shore landing point at Shuiyu Pu to the north shore landing point at Baisha Wan in the Zha Pu area (see plan view below). This subsea pipeline section forms the basis of the **Hangzhou Bay Pipeline Project**.

Hangzhou pipelines consist of three pipelines (one 10" Naptha, one 28" crude oil and one 30" crude oil), approximately 53 km long each, crossing Hangzhou Bay of Changjiang (Yangtze River). During the preliminary design, supporting studies and over forty years of historical data conducted and compiled by **Zhejiang Institute of Coastal and Engineering Research** (ZICER) were reviewed and the phenomenon of the dynamic sea bottom profile was identified. The trends of silt deposit and scour were not consistent and the studies revealed a history of the process reversing indicating where silt fill, which had occurred earlier had scoured out, and vise-versa. The dynamic movement of the sea bottom during scouring and fill periods result in dynamic seabed profile changes of over six metres. The conclusion was that conventional pre-lay excavation or post lay burial would not be practical or cost effective, and that during the scouring periods, the pipelines could become exposed and be placed at risk by unstable free-spans and potentially damaged by third parties due to lack of cover. Hence, it was decided that a device, which can effective self bury and subsequently re-bury the pipelines be used. That chosen device was the spoiler, a patented device that has been successfully used in North Sea applications under similar harsh conditions since 1988. To date, the spoilers have been used on 27 projects, mainly in the North Sea and Gulf of Mexico.

Spoilers manufactured by **Submarine Pipeline Spoiler (SPS), USA,** are fastened to the top of pipeline utilizing corrosive resistant alloy straps for approximately 47 km of the offshore segment of both 10" and 30" pipeline and approximately 49 km of 28" pipeline to promote self-burial. This is the first pipeline project in the Asia where spoiler-fitted pipelines are engineered and installed. Hangzhou Bay is characterized by strong tidal variation coupled with high tidal currents. The soil in the area largely consists of loose sands / silty sand susceptible to liquefaction and soil erosion. The above site condition of erodible seabed with large water movement due to tidal effects is well suited for spoiler application. The application was a cost effective option. It enables not only of spoiler for pipeline burial is pipeline self-burial, but also re-initiate pipeline burial when it is exposed by the environment.

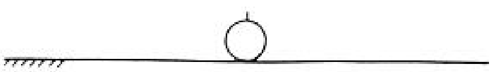
Spoiler Mechanics

The spoiler utilized in the Hangzhou Bay project was manufactured and supplied by SPS. Extensive research was carried out by Delft Hydraulics Laboratories in 1986 to establish the effect of spoilers on hydrodynamic forces and impact on pipe burial. Subsequently, the first test was carried out in the North Sea in 1988 and the spoiler began commercial application in 1989.

The effect of spoiler is based on scouring and fluid mechanical process. The spoiler, which is fitted on the top of pipeline, changes flow pattern around the pipeline compared with a plain pipeline. The spoiler causes an increased flow velocity underneath the pipeline. This results in tunnel erosion taking place at lower ambient velocities than with a plain pipe and more aggressively not only in the vertical direction but also along the pipeline length. The spoiler brings about significant changes in the flow pattern and results in:

- Smaller upward lift forces when the pipeline is in contact with the seabed;
- Increased downward (negative) lift forces when the pipeline lifts off from the seabed;
- Increased hydrodynamic drag and inertia coefficients;
- Suppressed vortex shedding;
- Increased stability of the hydrodynamic process - less scatter in drag and lift coefficients.

The schematic illustrating the phases and manner in which a spoiler-fitted pipeline achieves self-burial is presented in Figure 1.



touch down

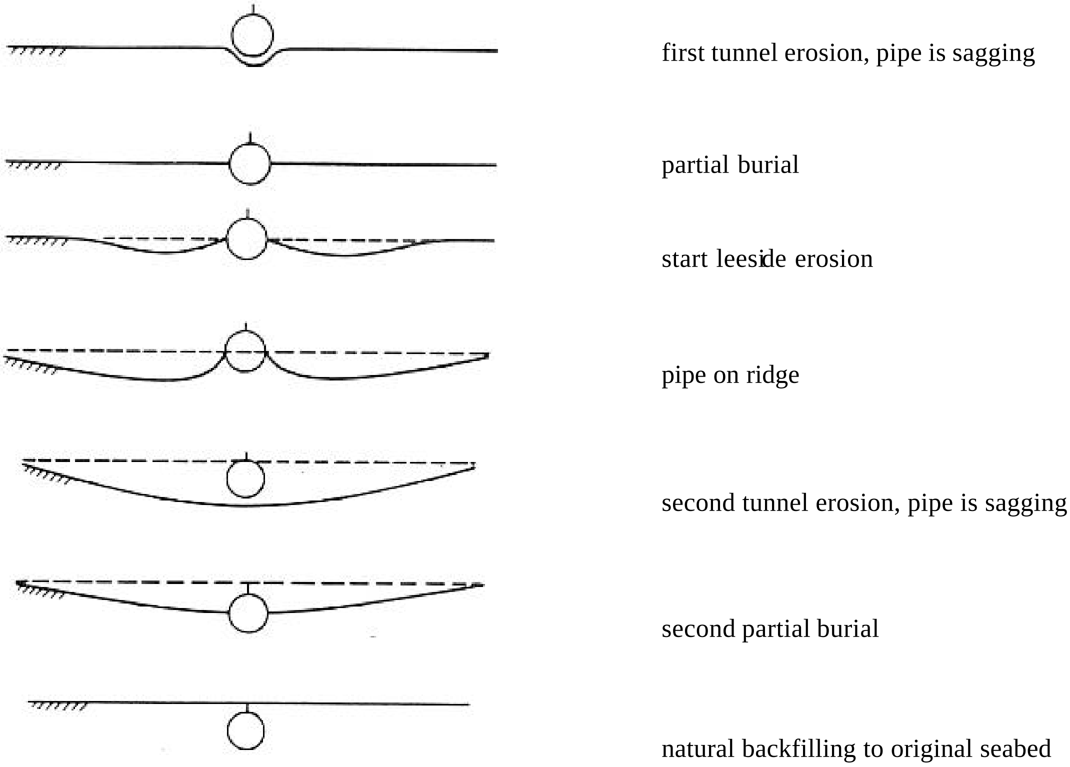


Figure 1 – Schematic of self-burial of a spoiler-fitted pipeline

Schematic of Self-Burial Process

First Stage -Touch Down

Second Stage – Tunneling

Final Stage - Burial

Environmental Conditions Favourable for Spoiler Application

Optimal performance of spoiler for pipeline self-burial is best achieved under certain environmental conditions as shown in Table 1 below. Based on the results of tests conducted by SPS at Delft Hydraulics Institute in Holland, sufficient tidal current velocity as well as a highly erodible seabed condition should be available to invoke the tunneling erosion effect, which is the mechanism of the self-burial process of pipeline.

Table 1 – Environmental Conditions for Optimal Spoiler Performance

	Complete Burial Expected	**Partial Burial Expected**
Seabed Material (Top Layer)	Sand + Maximum of 10 % Silt	Sand + Maximum of 20 % Silt
Current	Tidal current more than 0.8 m/s	Tidal current more than 0.4 m/s

Current Condition

The current condition in Hangzhou Bay poses serious challenges in the design and construction of the pipelines. The extraordinary surging tide of the Qiantang River caused by a combination of the gravitational effects of the moon and sun, the centrifugal force produced by the rotation of the Earth and the peculiar bottleneck shape of the Hangzhou Bay, brings about a tidal current velocity varying in the range of 2.2 to 9.5 knots (1.13m/s to 4.89m/s). With such tidal current velocity, SPS test data presents a high likelihood of spoiler-fitted pipeline achieving a complete burial in an erodible seabed. Comparison of peak currents at various places around the world are given below:

Current Comparison.

Gulf of Mexico:	0.9 to 1.1 Knots
Java Sea:	0.8 to 1.0 Knots
Singapore Straits:	2.0 to 6.0 Knots
North Sea:	3.0 to 6.0 Knots
Dahej, Gulf of Cambay:	4.0 to 8.0 Knots
Hangzhou Bay:	**2.2 to 9.5 Knots**

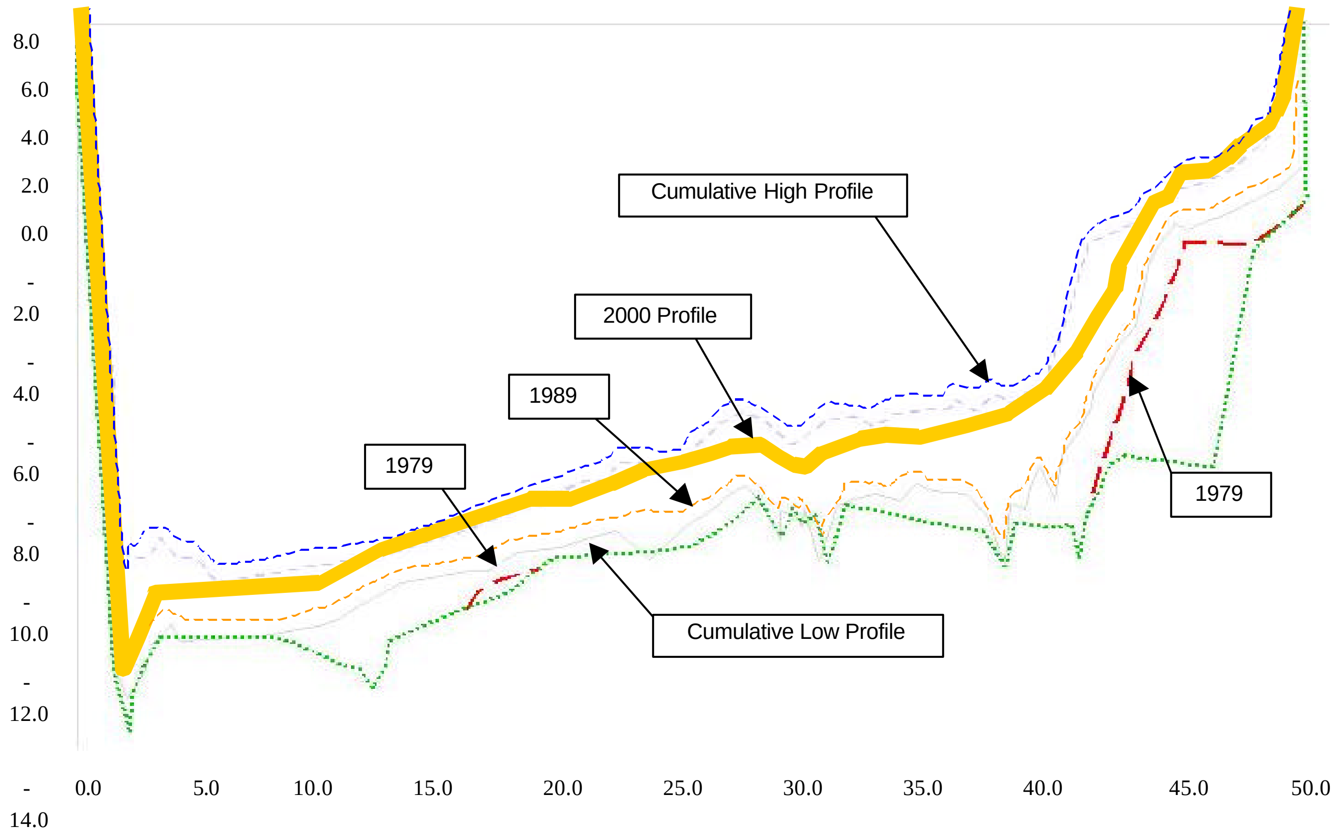
Soil Condition

The dynamic nature of the Hangzhou Bay seabed is evident from over forty of historical data collected and compiled by **Zhejiang Institute of Coastal and Engineering Research (ZICER)**. The recurring periods of siltation and scouring activities constantly modifies the seabed profile. The Figure 3 shows a history of changing seabed profile where the variation in seabed elevation could be as high as six meters.

Due to the dynamic movement of the seabed, the conventional pre-lay excavation or post-lay burial protection scheme could cause the pipeline to become exposed and be in peril of damage by third parties, or be subjected to the risk of buckling through Vortex-Induced Vibrations (VIV) or fatigue by the introduction of free spans during its design life. This is, unless, pipelines are buried to a depth greater than the maximum-recorded seabed elevation variation, which could be as deep as several metres. However, excavation to great depths reduces the cost effectiveness of the option.

A recent soil survey of the Hangzhou Bay seabed suggested a constitution of silky sand, which is sufficiently erodible for spoiler application. As illustrated earlier, pipeline self-burial is continual process given the presence of sufficiently strong current and erodible sea bottom soil. In the event of pipeline exposure or pipeline spanning, the negative (downward) lift force generated by the spoiler, more so when pipeline is lifted off the seabed, pushes the pipeline deep into the soil and the self-burial mechanism would act and re-bury the exposed pipeline.

Figure 2 – Historical Profile of Sea-bottom at Pipeline Route Centerline



Elevations are referenced to Low Astronomical Tide (LAT)

On-bottom Lateral Stability of Spoiler-fitted Pipeline

With pipeline burial as a result of spoiler intervention, an additional soil component is introduced in the lateral stability of the pipeline on the seabed. This force component acts to stabilize the pipeline against lateral movement and comes in the form of passive soil resistance. When a partially buried pipeline is subjected to lateral environmental forces, it pushes against the adjacent soil inducing the passive soil resistance. The passive soil resistance contributes to the lateral stability of the pipeline, resulting in the reduction of concrete weight coating required.

A simple static approach, based on DNV 1981 (Ref.[4]), is adopted for the analysis of the lateral stability of the pipelines. Although the latest DNV code for stability analysis is DNV RP 305 (1988), the guidelines given in this code could not be easily modified to account for effect of pipe self-burial and it's resultant passive resistance. Hence, DNV 1981, which could be easily modified to take into account the effect of passive resistance and change in hydrodynamic coefficients, remains adopted for the analysis. The full spectrum of the design aspect and the analysis result with reference to the Hangzhou Bay project is presented the following sections.

Analysis Methodology

The on-bottom lateral stability analysis is performed in according DNV 1981 (Ref.[4]) guideline utilizing the hydrodynamic coefficients for spoiler fitted pipes. The pipeline stability analysis has been performed for installation and operation design conditions. A minimum factor of safety of 1.1 set by DNV 1981 (Ref.[4]) has been used for the analysis. The forces action on spoiler fitted pipelines embedded in soil is schematically presented in Figure 3.

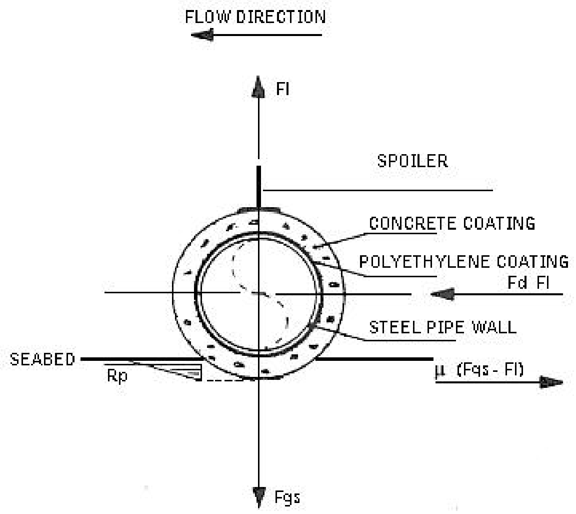


Figure 3 – Forces acting on the spoiler pipe embedded into soil

The stability criteria for the pipeline embedded into soil can be expressed as

$$\frac{\{\mu(F_{gs} - F_L) + R_P\}}{F_D + F_I} \geq 1.1$$

Where F_{gs} = Submerged weight of the pipeline, F_L = Hydrodynamic lift force per unit length
F_D = Hydrodynamic drag force per unit length, F_I = Hydrodynamic lift forces per unit length
μ = Coefficient of lateral friction between pipe and seabed, R_P = Passive soil resistance

Based on the Morrison equations, the drag force, lift force and inertia force per unit length of pipeline length can be calculated as follow:

$$F_D = \frac{1}{2}\gamma_w C_D D_t U_d |U_d| \; ; F_L = \frac{1}{2}\gamma_w C_L D_t U_d |U_d| \; ; \; F_I = \frac{\pi}{4}\gamma_w C_I a Sin\,\phi$$

where: γ_w = Mass density of seawater, C_D = Drag coefficient, C_L = Lift coefficient
C_I = Inertia coefficient, D_t = Total diameter of pipeline including coating
a = Horizontal water particle acceleration normal to the pipe axis, U_d = Horizontal water particle velocity normal to the pipe axis = $U_c + U_w Cos\phi$, U_c = Horizontal steady current velocity normal to pipe axis, U_c = Wave induced horizontal water particle velocity normal to pipe axis, ϕ = Phase angle

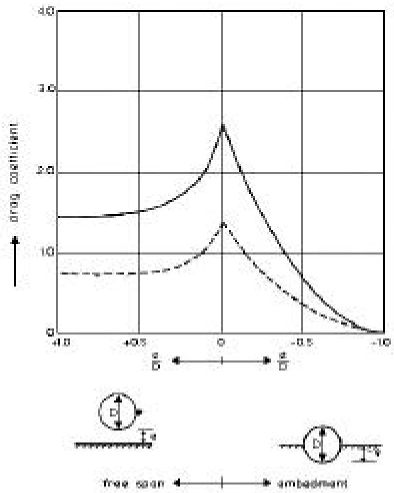
The lateral friction factor for a pipeline resting on the seabed for sandy soil condition is 0.7, corresponding to a soil internal friction angle of 35^o. Embedment of pipe increases the passive soil resistance. The soil resistance due to embedment can be calculated as follows:

$$R_P = \frac{1}{2}\lambda_P \gamma_s z^2$$

where: λ_P = Passive Earth Pressure Coefficient (-), γ_s = Soil Submerged Density, z = Depth of Embedment

Hydrodynamic Coefficients

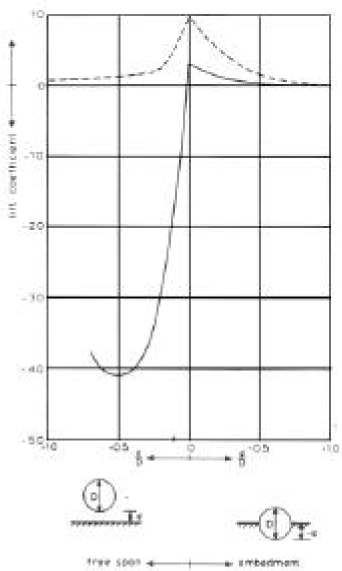
The Hydrodynamic coefficients for spoiler fitted pipes are taken from SPS report (Ref.[1]). The values of C_D, C_M and C_L for various pipe embedment extracted from above mentioned report is presented in Figures 4, 5 and 6, respectively.



------ pipeline without spoiler

—— pipeline with spoiler

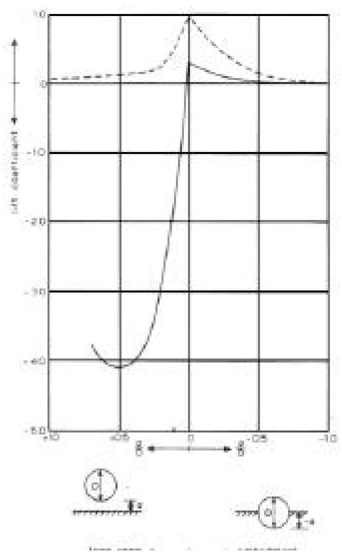
Figure 4 – Hydrodynamic Drag Coefficient (C_D)



------ pipeline without spoiler

—— pipeline with spoiler

Figure 5 – Hydrodynamic Inertia Coefficient (C_M)



------ pipeline without spoiler

—— pipeline with spoiler

Figure 6 – Hydrodynamic Lift Coefficient (C_L)

The values of C_D, C_M and C_L for various pipe embedment extracted from the above figures are summarized in Table 2.

Table 2 – Hydrodynamic Coefficients Versus Pipe Embedment

Hydrodynamic Coefficient	Pipe Embedment (e/D)						Hydrodynamic Coefficients based on DNV 1981
	0% e/D	10% e/D	20% e/D	30% e/D	40% e/D	50% e/D	0% e/D
Drag (C_D)	2.60	2.00	1.60	1.30	1.00	0.70	1.30
Inertia (C_I)	4.10	3.90	3.50	3.00	2.55	2.10	3.29
Lift (C_L)	0.31	0.20	0.16	0.10	0.07	0.05	1.0

Analysis Approach

The submarine pipelines pass through water depth ranges varying between zero at both shore landfall points and maximum of 16.7 m with respect to 1985 Chinese National Reference Level. As the pipelines are to be fitted with spoilers, which would induce self-burial, the lateral stability is carried out for the following cases in line with recommendations given by SPS, as reflected in Table 3.

Table 3 – Design Assumptions for On-bottom Lateral Stability Analysis

Case	Pipe Condition	Environment	Assumed level of embedment
During initial period (Installation)	Empty	3-month construction weather window (80 % of 1-year return wave)	30 % of outer diameter
After installation but prior to operation	Empty	1-year return wave and current	50 % of outer diameter
Initial period of operation	Product -filled	10-year return wave and current	50 % of outer diameter
Operating condition	Product -filled	100-year return wave and current	Fully buried

Concrete Coating Requirement

The data for the Hangzhou Bay pipeline system and the environmental data for Hangzhou Bay are shown in Table 3 and 4, respectively.

Table 3 – Pipe Data

Item No.	Item Description	Hang Zhou Bay Pipelines		
		30” P/L	28” P/L	10” P/L
1.	Approximate Pipeline Length (km)	53	53	53
2.	Pipeline OD (inch/mm)	30/ 762	28/ 711.2	10.75 / 273.1
10.	Pipeline Wall Thickness (mm)	14.3	14.3	8.7
13.	Product Density (kg/m ^{3})	856	856	730
14.	External Corrosion Coating	3-Layer PE		
15.	Concrete Density (kg/m^3)	3044	3044	3044 / 2244

Table 4 – Environmental Data

100-Year Return Period			10-Year Return Period			1-Year Return Period		
Hs (m)	Tp (sec)	Bottom Current (m/s)	Hs (m)	Tp (sec)	Bottom Current (m/s)	Hs (m)	Tp (sec)	Bottom Current (m/s)
3.3 -4.4	8.8 -8.9	1.1 – 2.0	2.9 -3.5	7.8 -7.9	0.9 – 1.8	2.0 - 2.3	6.2 - 6.4	0.8 – 1.6

The pipeline route is divided into various segments to account for variations in water depth ranges, pipeline orientation and environmental data. The lateral stability analysis is performed for both installation and initial phase of operating design conditions. As the pipelines are to be fitted with spoilers, it is assumed that pipelines are self-buried during operation phase. Appropriate environmental data with the directionality of both wave and current listed above are utilized for the lateral stability analysis.

The minimum water depth with respect to mean sea level in each segment is used in the calculations. The concrete coating thickness required to satisfy the lateral stability requirements for various design conditions, i.e. case (a) to case (c), are then determined. During operation phase, i.e. case (d), the pipelines will be self-buried and not subjected to any environmental loading; hence, analysis is not required. Results of the analysis show that case (a) is the critical case, as shown in Table 5.

The recommended distribution in concrete weight coating along the pipeline route is presented in Table 6. The concrete coating thicknesses are selected to meet both installation and operation conditions. A concrete density of 3044 kg/m^3 (190 pcf) is used for the lateral stability design. The concrete density has been adjusted to account for the effect of field joint coating on the average coating density. The proposed concrete weight coating thicknesses are governed by the requirement for case (a), i.e. during the initial installation phase with 30% pipe embedment. It is noted that concrete coating requirement is greater during installation phase than during operation because the pipelines are empty and pipe embedment is less. Finally, the required concrete coating thicknesses for the entire pipeline route are rationalised based on logistic and installation considerations

Table 6 – Recommended Concrete Coating Thickness for Lateral Stability

KP Range	Governing Concrete Coating Thickness (mm)			Selected Concrete Thickness (mm)		
	10” Pipeline	28” Pipeline	30” Pipeline	10” Pipeline	28” Pipeline	30” Pipeline
0+000 – 2+548	Pipeline laid in trench with no spoiler					
2+548 – 3+680	16	48	47	34	66	72
3+680 – 11+145	30	59	64	34	66	72
11+145 – 16+827	34	64	70	34	66	72
16+827 – 22+066	24	53	59	34	66	72
22+066 – 24+260	37	67	73	51	82	88
24+260 – 26+857	51	82	88	51	82	88
26+857 – 31+671	40	70	75	51	82	88
31+671 – 36+049	47	76	82	51	82	88
36+049 – 39+084	34	66	72	34	66	72
39+084 – 47+154	26	61	68	34	66	72
47+154 – 48+690	19	49	55	34	66	72
48+690 – End of Spoiler P/L	21	64	72	34	66	72

Installation of Spoiler-fitted Pipeline

Spoilers are typically manufactured in either 3.8m or 5.6m lengths. For the Hangzhou Bay Project, 5.6m length spoiler sections were used. Each section of spoiler consists of two parts, i.e. fin and template. The fin is inserted into slot of the template. The details of the spoiler are shown in Figure 7.

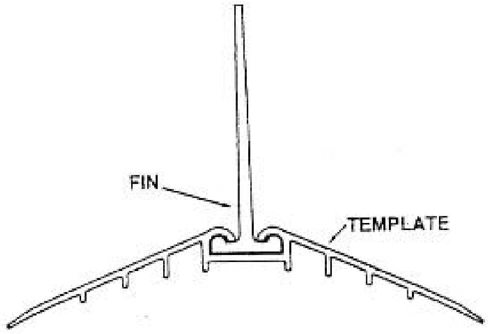


Figure 7 – Spoiler Details

Hyundai Heavy Industries' laybarge HD289 was utilized for the pipeline installation. The spoiler was strapped onto the pipeline at the laybarge between the field joint station and entrance to the stinger. The spoiler were shipped in containers and stored on deck the laybarge.

The spoilers were positioned at top dead center of the pipe (12 0'clock position). At this position, the spoiler is most efficient in its scouring effect. Pipelaying was carried out in a manner that would ensure that this position was maintained when the pipeline reached the seabed. To hold the spoiler rigidly in position, each section of the spoilers was attached to pipeline with 4 alloy 625 metallic straps and 2 sacrificial carbon steel straps that pass through the holes in the fin and over the template. A spacing of 100 mm was maintained between the spoiler sections. Post-stinger inspections were regularly performed to ensure that the spoiler did not rotate during pipelaying and that the straps were not damaged.

Risks and Challenges

The severe Hangzhou Bay environment proved difficult for operating the offshore pipelaying equipment. At the peak lunar tides, the current would approach 9.5 Knots. During such periods, control of the lay barge became very difficult as the forces on the laybarge caused by the strong current played havoc with the barge anchoring system. A push tug had to be used to help keep the laybarge in position. However, at locations where the direction of the current was nearly perpendicular to the pipeline axis, pipelaying and push tug operations became hazardous, and the pipeline was susceptible to damage while proceeding down the stinger. Several repairs of buckles had to be made as indicated in the photo below.

The main risk associated with utilizing the spoiler is the effect of additional hydrodynamic forces caused by the presence of the spoilers if self-burial did not occur immediately upon touchdown. In such an event, the concrete weight coating provided will not be sufficient to prevent pipeline movement. However, once initial tunneling occurs, pipeline stability is enhanced due to passive resistance provided by the soil surrounding the partially buried pipeline and the self-embedment process will progress further.

Field Verification of Spoiler Performances

Subsea survey was carried out regularly during pipelaying to determine the burial condition of the pipeline. Generally, it was found that the pipeline underwent burial almost upon touchdown and the tunneling effect continued until almost all the pipeline was below the natural seabed. In areas where there were greater concentration of fine particles, the burial rate proceeded at a slower rate and portions of the pipeline continued the tunneling at a slower rate until the top of pipeline was below the natural seabed.

As-built survey of the pipelines showed that prior to hydrotesting, the entire pipeline route achieved at least 50% burial and considerable portions achieved complete burial to over one meter of cover.

During the installation and preliminary survey inspection of the pipeline burial, it was observed that due to the soil characteristics, once the pipeline achieved the stage of second burial as illustrated in Figure 2, the tunnel erosion had restarted, placing the top of the pipeline a minimum of one pipe diameter below the natural seabed.

Conclusions

The outcome of spoiler application on the Hangzhou Pipeline Crossing Project demonstrates that spoilers can be effectively used to promote and accelerate the self burial of pipelines. Application of pipeline spoiler has the following advantages:

- It stimulates self-burial of pipeline;
- Inherent passive soil resistance resulting from self-burial generally helps reduce design concrete weight coating requirement;
- It allows pipeline to be buried in environmentally sensitive areas without stirring up the seabed;
- It reduces project cost as spoiler can be applied without affecting pipelaying rate, and the cost of conventional burial method, such as jetting, is eliminated;

Third party review of the detailed engineering design using the modified DNV 1981 method was carried out by DNV and verified for the project.

The spoiler is particularly suited for the Hangzhou bay, which experiences dynamic movements of sea bottom profile. When the pipeline is exposed to the environment due to scouring, the spoiler, which is highly effective in erodible Hangzhou Bay seabed, is expected to re-initiate burial.

Based on the successful use of spoilers in the Hangzhou Bay Pipeline Crossing project, as well as other applications in the North Sea, it is envisaged that the spoiler would find many more uses for similar projects under similar conditions worldwide. It is hoped that this paper highlights the availability of a simple and cost effective method for burying submarine pipelines in place of the more expensive conventional pre-trenching and post-trenching methods, and without the adverse environmental effects of these methods caused by mechanical disturbance of the seabed.

Acknowledgement

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Spoilers are strapped on pipeline at stern of laybarge, just before entrance to stinger

Pipeline with spoiler traveling down the stinger in "strong" current

View of pipeline at shore approach during low tide. Note that minor rotation had occurred during pulling operation, partially due to flooding and receding tides.
Note scour on both sides of pipeline due to spoiler effects.