Journal of Civil Engineering and Construction 2018;7(4):171-177
https://doi.org/10.32732/jcec.2018.7.4.171

Scour Protection of Underwater Pipelines

Liquan Xie, Yehui Zhu*
College of Civil Engineering, Tongji University, Shanghai 200092, China
E-mail: yehui_zhu@tongji.edu.cn (Y. Zhu)

Received: 21 October 2018; Accepted: 2 November 2018; Available online: 25 November 2018

Abstract: A detailed literature review on the protection of local scour beneath a submarine pipeline is presented. The review covers two basic parts of countermeasures against the pipeline scour, namely preventing the onset of scour and stimulating the self-burial of a pipeline. The research progress on the methods of the two sections is discussed in detail separately. The methods preventing the onset of scour have been extensively studied, but the understanding on their mechanisms is yet to be improved. The progress in stimulating the self-burial of a pipeline mainly focuses on a spoiler attached to a pipeline, which is investigated comprehensively with both experiments and numerical simulations. Both parts of countermeasures have been applied in some practical engineering projects and the protection effects are generally satisfying.
Keywords: pipeline scour; scour protection; impermeable plate; geotextile mattress with sloping curtain (GMSC); spoiler.

1. Introduction

Submarine pipelines are vital to oil and gas transportation from offshore platforms. Oil leakage due to pipeline failure can trigger both economic and ecological catastrophe. One of the most common causes of the pipeline failure is the metal fatigue due to vortex induced vibration (VIV). When submarine pipelines are faced with fierce ocean currents or waves, local scour may appear underneath them. As the scour hole extends along the pipeline, the span length of the pipeline increases, leading to pipeline spanning. When the free span is long enough, the pipeline may experience VIV. So the protection of pipelines from scour bears significant importance.

The local scour under the pipelines starts from the onset of scour. The basic mechanism of the onset of scour below the pipelines was revealed by Chiew[1]. Chiew [1] performed a series of laboratory tests and pointed out that piping powered by excessive seepage flow is the dominant cause of the scour onset under pipelines in steady currents. The experimental results showed that the onset of scour starts from the downstream side of the pipeline and sand particles eject from the bottom of the pipeline. Thus an initial scour hole appears. After the onset of scour, the scour hole quickly extends along the pipeline powered by the shear stress in the tunnel flow and the pressure difference on two sides of the pipeline[2]. Sumer et al. [3] conducted a series of flume experiments on the onset of scour process with an underwater camera and pressure transducers. The results agreed well with that of Chiew[1]. A criterion formula for the onset of scour in steady current was also proposed. Zang et al. [4] simulated the onset of scour process numerically. The effects of flow parameters on the pressure difference coefficient were studied comprehensively, including the Reynolds number, the flow depth, the pipeline embedment and the thickness of boundary layer. An amplification coefficient was proposed to calculate the pressure gradient at the downstream side of the pipeline with the averaged pressure gradient along the buried part of the pipeline.

In general, the countermeasures against pipeline scour can be classified into two parts according to their principles: (1) preventing the appearance of onset of scour, and (2) accelerating the self-burial of pipelines. In the following sections, scour preventing measures of these two kinds will be described in detail.

2. Preventing the onset of scour

This part of pipeline scour protection methods mainly aim at reducing the intensity of seepage flow beneath the pipeline, thus decreasing the possibility of onset of scour. These methods include impermeable plates under the pipeline, the fiber reinforced mats, concrete mattresses covering the pipeline, the geotextile mattress with sloping curtain (GMSC), and conventional methods like graded engineering rocks.

2.1. Impermeable plate under a pipeline

Chiew [1] pointed out that the scour onset can be eradicated by placing an impermeable plate on the upstream side of a pipeline in steady currents. In this occasion, the interaction between the seepage flow and mainstream flow is terminated in the area covered by the plate. The length of seepage path below the pipeline is extended to that of the plate, and the hydraulic gradient can be greatly decreased. The critical lengths of the plate in two different flow depth conditions were also proposed. Zhang et al. [5] further investigated the protection effects of a rigid impermeable plate on a pipeline in currents with numerical simulation. The calculated results coincide well with the experiment results of Chiew [1]. The results showed that the unidirectional plate (see Fig. 1(a)) and the bidirectional plate (see Fig. 1(b)) with the same length have similar protection effects. The effects of flow depth and non-dimensional flow velocity on the critical length of the protection plate were also analyzed in detail. When the flow depth is over 4 times of the pipe diameter, the critical length of the plate is almost independent from the flow depth.

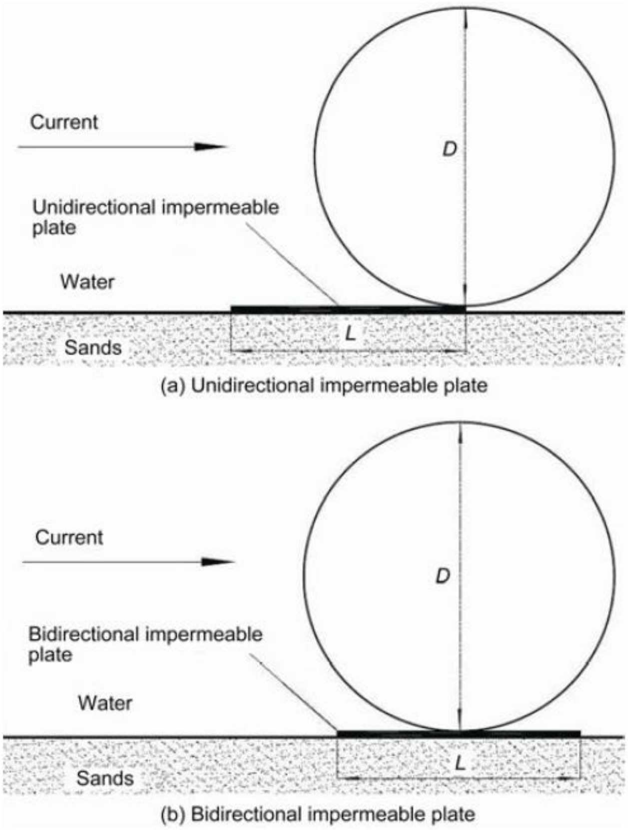

Fig. 1 Impermeable plates beneath the pipeline[5].

Yang et al. [6] conducted a series of experiments on a flexible plate protecting a pipeline in currents. The results demonstrated a critical pressure difference on two sides of a pipeline for the onset of scour. A critical length of the rubber plate was identified. The scour does not occur when the length of the protecting plate is over this critical value. An empirical formula for the critical plate length was proposed based on the results of critical pressure difference. The calculated critical plate length meets well with the experiment results.

2.2 Fiber reinforced mat

Fiber reinforced mats are also termed as artificial grass or bionic grass. A fiber reinforced mat is composed of a polymer textile mat, a bunch of vertical polymer “grass” and short piles under the mat for installation on the seabed (see Fig. 2). Fiber reinforced mats can reduce the flow velocity near the bed and stimulate the deposition of sediment. When fiber reinforced mats are installed on two sides of a pipeline, the impact of flow and waves on the pipeline can be reduced. The flow velocity over the pipeline can be decreased and the seepage flow under the pipeline is less intense, thus descending the hydraulic gradient in the sediment. So the pipeline can be protected. Furthermore, the fiber reinforced mats can stimulate sediment deposition by slowing down the near bottom flow carrying a high concentration of bed load, which is also helpful to protect the pipeline from scour onset. The fiber reinforced mats can be applied in various flow conditions, and they need little maintenance work after deployment.

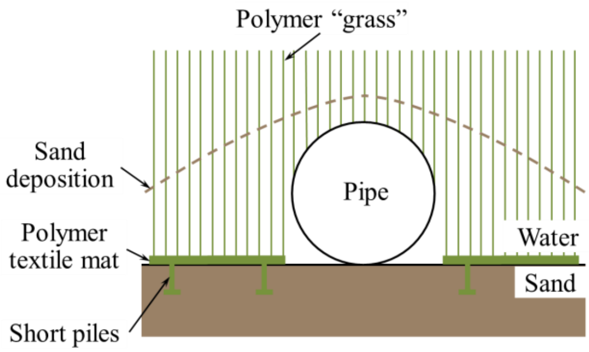

Fig. 2. Fiber reinforced mat.

Yang et al. [7] designed a series of experiments in a slope flume, and the protection effects of two different fiber reinforced mats were compared with bare slope flow. When the slope is equipped with artificial grass, the sediment erosion volume is significantly decreased to 2% - 5% of that on the bare slope, and the flow rate on the slope and the time used to reach a balanced profile drop remarkably as well.

Zhao et al. [8] studied the protection effects of fiber reinforced mats on a pipeline in waves. The experimental results showed that the fiber reinforced mats successfully eliminates the scour under the pipeline on a sandy bed. Sand dunes appear on both sides of the pipeline. The results also showed that when the fiber reinforced mat is installed on the top of the pipeline only, the scour is not prevented.

Fiber reinforced mats have been applied in practical scour control projects during the past decade [9]. Jiang and Chen [10] carried out a field survey on the protected pipeline sections which were threatened by pipeline spanning. They found that the length of the free span and the scour depth reduce remarkably after the fiber reinforced mats are installed for all 11 protection pipe sections. However, they also reported that about 50% of the mats installed 5 to 6 years before were missing.

2.3 Concrete mattress covering a pipeline

Concrete mattresses covering a pipeline are originally designed to protect the pipeline from the damage of falling objects, like anchors [11]. In some occasions, they are also used to improve the stability of the pipeline.

Zhang et al. [12] investigated the flow pattern adjacent to the surface of a concrete mattress, revealing a low velocity zone in the lateral margin between two blocks and a high velocity zone near the surface of the upstream concrete block. They designed a series of flume experiments on the protection effects of concrete mattress. The result showed that the concrete mattress can protect the pipeline under it from local scour. They also found that scour holes appear near the edge of the concrete mattress.

2.4 Geotextile mattress with sloping curtain (GMSC)

A geotextile mattress with sloping curtain (GMSC, see Fig. 3) is a novel countermeasure against scour and erosion on seabed, river bed and river banks [13]. A GMSC is constituted of a geotextile mattress and a sloping curtain sewn together. The geotextile mattress is composed of a string of geotextile tubes, which are filled with local sediments like sand or gravel, or artificial materials like cement or concrete. The bottom edge of the sloping curtain is sewn on the middle of the mattress, and the top edge of the curtain is attached to a floating tube, which is filled with light materials. When the GMSC is placed in still water, the buoyancy of the floating tube pulls the curtain straight up. When the GMSC is affected by steady currents, the flow will push the curtain forward, and the curtain leans to the downstream side. The curtain is thus termed as sloping curtain. Some sand-pass openings are set close to the bottom of sloping curtain, providing a pass for bed load. Belts on the mattress and the curtain are designed to improve the stability of the device.

Xie et al. [14] researched the protection effects of a GMSC in currents in a live-bed flume. They found that the GMSC can successfully prevent the bed nearby from scour and a sand dune formed immediately downstream to the GMSC (see Fig. 4). They proposed the basic protection mechanism of a GMSC (see Fig. 5). When a GMSC is deployed in steady currents, the approaching flow is separated into two sections: an upward flow and a downward flow. These two parts collide on the leeside of the GMSC and creates two vortex systems: the top vortex system and the bottom vortex system. The top vortex system stays close to the top edge of the curtain and can hardly affect the bed. The bottom vortex system provides a long low velocity area on the leeside of the GMSC. The bed in the low velocity area can be effectively protected from erosion.

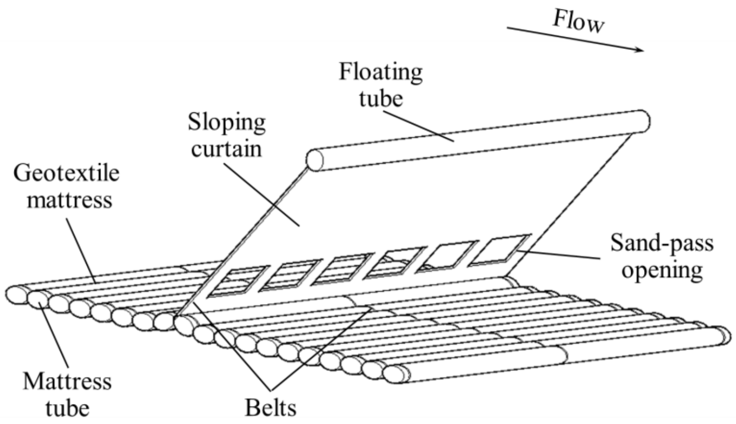

Fig. 3. Geotextile mattress with sloping curtain.

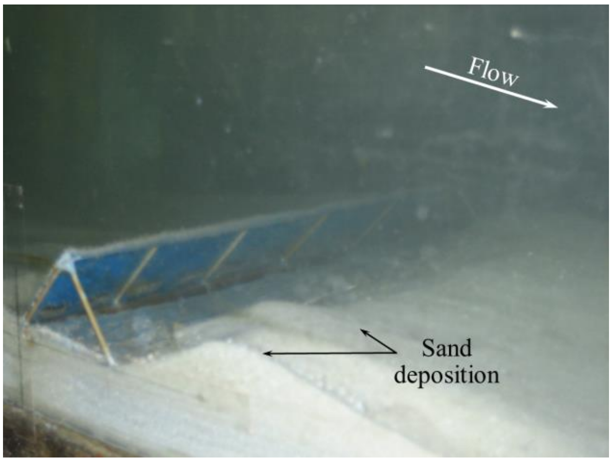

Fig. 4. Bed profile variation near a GMSC in currents.

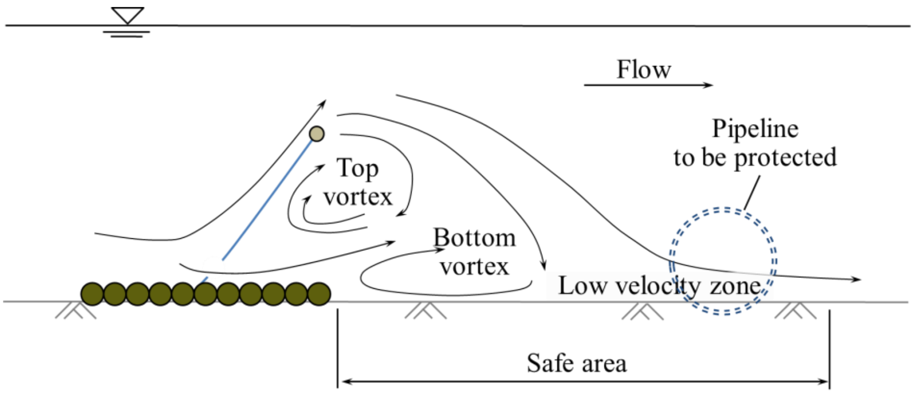

Fig. 5. Sketch of flow structure around GMSC.

Xie et al. [15] verified the protection effects of a GMSC on a partially buried pipeline with a visualization experiment in steady currents. An optimal distance between the GMSC and the pipeline was proposed, where the flow velocity approaching the pipeline approximately reduces to zero and the seepage beneath the pipeline generally stops. They pointed out that the seepage hydraulic gradient decreases remarkably as the GMSC gets closer to the pipeline and the seepage flow reverses when the GMSC is close enough to the pipeline.

3. Accelerating the pipeline self-burial

Burying the pipeline under the seabed is an effective way of protecting the pipeline. When a pipeline is below the surface of seabed, it is protected from the threat of local scour due to currents, waves and accidental damage from anchors. The conventional method of burying a pipeline beneath the seabed surface is digging a trench for the pipeline before or after installation. After that, the trench is artificially refilled. Sometimes, the trench for the pipeline can be also refilled automatically by sediment deposition. However, digging a trench on the seabed requires specially designed machines and the cost may sometimes be very considerable. Hulsbergen [16] found that a pipeline can bury itself under the surface of the seabed in specific flow conditions and the burial depth can reach up to 3 times of the pipeline diameter. This process is termed as self-burial. To accelerate this process, some attachments are installed on the surface of the pipeline to change its cross section profile. Two of the most widely studied attachments are the spoiler (see Fig. 6) and the flexible plate in waves. In practical application, spoilers have already been used on the pipeline across Hangzhou Bay in China where tidal currents are fierce [17].

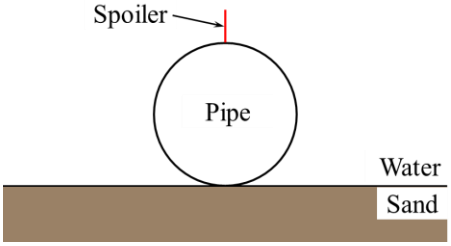

Fig. 6. Spoiler installed on the top of a pipeline.

3.1 Spoiler

A spoiler is a thin plate attached to the surface of a pipeline, usually on the top. The height of the spoiler usually ranges from 15% to 25% of the pipeline diameter. When waves and currents affect a pipeline with a spoiler, the flow is blocked by the spoiler. The flow rate and velocity through the scour hole can increase due to the enhanced blockage effect, thus increasing the scour rate under the pipeline. When the scour hole extends long enough, the pipeline may sag into and touch the bottom of the scour hole. After that the scour hole can be refilled due to sediment deposition. The blockage effect of the spoiler may trigger secondary scour holes on both sides of a pipeline thereafter, and pipeline can sag into the scour hole again. When the scour hole is refilled again, the self-burial process is completed.

Chiew [18] investigated the scour depth under a pipeline with and without a spoiler. Detailed flume experiments were designed to reveal the effect of the spoiler height and the location of the spoiler on the scour depth. The results showed that the scour rate and the scour depth under the pipeline rise remarkably after a spoiler is installed. The results also indicated that the scour depth reaches a maximum value when the tip of the spoiler touches the bed on the upstream side. This was attributed to the flow separation at the tip of the spoiler. Chiew [19] further analyzed the effects of a spoiler on a pipeline in waves. The width and the depth of the scour hole increases remarkably when a spoiler is installed. The rise in the width of the scour hole was attributed to the intensified lee wake vortex due to the increase of blockage area of the pipeline. The rise in the scour depth was reckoned to be associated to the strengthened tunnel flow through the scour hole. A secondary scour hole was observed adjacent to the tip of the spoiler in some occasions. Cheng and Chew [20] established a finite difference model solving the Navier-Stocks equations and analyzed the influence of spoiler on the hydrodynamic forces on the pipeline, the vortex shedding frequency and the velocity profile in the scour hole. The results showed that the spoiler on the pipeline can increase pipeline drag force and the bed shear stress.

Alam and Cheng [21] conducted a series of numerical simulation with a Lattice Boltzmann model. The model was proved to be capable of revealing the development of the scour hole. The scour process under a pipeline with a spoiler was studied. The effects of the location and the length of the spoiler on the scour process were analyzed. Yang et al. [22] proposed two formulae with theoretical analysis for the scour depth under a pipeline with and without a spoiler, respectively. The formulae were validated with a series of flume experiments and can reflect the scour process correctly. The approaching flow Reynolds number and the height of the spoiler was found to affect the scour depth remarkably.

Oner [23] studied the flow field around a pipeline with a spoiler in steady currents with PIV (Particle Image Velocimetry) method. The effects of the spoiler were compared in different Reynolds numbers. The results showed that the length of flow separation zone is extended after a spoiler is installed, but there were no significant changes in the flow rate through the scour hole and the bed shear stress.

Han [24] studied a flexible spoiler attached on a pipeline at two different locations: on the top of a pipeline and on the bottom. The pressure distribution around the pipeline and the scour process were observed and measured. The flexible spoiler installed on the top of a pipeline behaves like common rigid spoilers, and can increase the scour depth and the drag force on the pipeline. On the contrary, the flexible spoiler attached on the bottom of a pipeline can reduce the scour depth remarkably and seize the scour process in some occasions.

Zhu et al. [25] simulated the scour process adjacent to a pipeline with a spoiler. The flow field was modeled with SST $k-\omega$ turbulence model and the variation of the bed surface profile is described by an Euler-Euler two-phase model. The simulation showed that the bed surface and the flow field are very sensitive to the height of the spoiler and the gap between the pipeline and the bed.

Oner [26] simulated the flow pattern around a pipeline with or without a spoiler in steady currents. The results of three different turbulence models and five different meshes of various densities were compared and validated with previous experimental results. It was reckoned that the standard $k-\omega$ model with the finest mesh reflects the flow field most reasonably. The results showed that the installation of a spoiler on the top of the pipeline can trigger a rise in the drag force on the pipeline and a drop in the lift force.

3.2 Flexible plate under a pipeline in waves

In the previous section, a flexible plate underneath a pipeline was utilized to prevent the onset of scour in unidirectional currents [6]. However, a similar device can greatly accelerate the scour rate under the pipeline in waves. Yang et al. [27] analyzed the scour process around a pipeline with a flexible plate or a spoiler in regular and irregular waves. They reckoned that the spoiler and the flexible plate under a pipeline can intensify the scour rate below a pipeline, and proposed an optimal length of the flexible plate for accelerating the scour process, which is 1.5 times of the pipeline diameter. They pointed out that the spoiler may trigger remarkable variation on the bed profile on two sides of the pipeline.

4. Conclusions

Researches on pipeline scour protection have made significant progress in the past few decades. In this paper, the progress on the pipeline scour protection is reviewed in two sections: preventing the onset of scour and stimulating the pipeline self-burial. The former section includes several different novel methods. These methods have been extensively studied, but the understanding on their mechanisms is yet to be improved. Some of these methods have not been applied into practical engineering, due to the cost or difficulties in the installation process, e.g. the impermeable plate under a pipeline. The progress in the latter section mainly focuses on a spoiler attached to a pipeline, which is investigated comprehensively with both experiments and numerical simulations. Spoilers have been applied in many pipeline projects worldwide, and have been widely accepted as an effective way to protect the pipeline by stimulating the self-burial process. However, some drawbacks of spoilers have been noticed and are attracting the attention of researchers.

Acknowledgements

This paper was supported by Chinese National Natural Science Foundation Council under Grants 11172213 and 51479137. The corresponding author would like to acknowledge the support from the China Scholarship Council (Grant No. 201806260166).

5. References

[1] Chiew Y. Mechanics of local scour around submarine pipelines. Journal of Hydraulic Engineering, 1990: 515–529. 10.1061/ (ASCE)0733-9429(1990)116:4(515).
[2] Wu Y, Chiew Y. Mechanics of pipeline scour propagation in the spanwise direction. Journal of Waterway, Port, Costal and Ocean Engineering, 2014: 4014045. 10.1061/(ASCE)WW.1943-5460.0000288.
[3] Sumer B M, Truelsen C, Sichmann T, Fredsøe J. Onset of scour below pipelines and self-burial. Costal Engineering, 2001, 42(4): 313–335.
[4] Zang Z, Cheng L, Zhao M, Liang D, Teng B. A numerical model for onset of scour below offshore pipelines. Costal Engineering, 2009, 56(4): 458–466.
[5] Zhang Z, Shi B, Guo Y, Yang L. Numerical investigation on critical length of impermeable plate below underwater pipeline under steady current. Science China: Technological Science, 2013, 56(5): 1232-1240.

[6] Yang L, Shi B, Guo Y, Zhang L, Zhang J, Han Y. Scour protection of submarine pipelines using rubber plates underneath the pipes. Ocean Engineering, 2014, 84: 176–182.
[7] Yang C, Xiao P, Zhen B, Shen Z, Li L. Effects of vegetation cover on runoff and sediment in field prototype slope by experimental. Advances in Environmental Science and Engineering. Stafa-Zurich: Trans Tech Publications Ltd. 2012, 518-523: 4707-4711.
[8] Zhao D, Yu J, Li G, Wang C. An experimental scour-prevention technique for subsea pipeline. Journal of Harbin Engineering University, 2009, 30(6): 597-601. (in Chinese)
[9] Liu J, Zhang Z. Application of bionic aquatic weed for scour prevention of subsea pipeline. Petroleum Engineering Construction, 2009, 35(3): 20-22. (in Chinese)
[10] Jiang X, Chen T. Investigation on application of bionic aquatic grass for treating subsea pipeline suspension and improvement measure. Petroleum Engineering Construction, 2013, 39(5): 15-18. (in Chinese)
[11] Crowhurst A D. Marine pipeline protection with flexible mattress. Costal Engineering, 1982: 2403-2417.
[12] Zhang Z, Ding H, Liu J. Model test on concrete slab interlocking mattress applied in anti-scour protection of subsea pipeline. The Ocean Engineering, 2015, 33(2): 77-83. (in Chinese)
[13] Xie L, Liu S. Stability of Sand Beds Around Mattress-Curtain Sets. 29th International Conference on Ocean, Offshore and Arctic Engineering, ASME 2010. American Society of Mechanical Engineers. 2010: 839-844.
[14] Xie L, Huang W, Yu Y. Experimental study of sediment trapping by geotextile mattress installed with sloping curtain. Geosynthetics International, 2013, 20(6): 389-395.
[15] Xie L, Zhu Y, Su T C. Scour protection of partially embedded pipelines using sloping curtains. Journal of Hydraulic Engineering, 2018, in Press. 10.1061/(ASCE)HY.1943-7900.0001571.
[16] Hulsbergen C H. Spoilers for stimulated burial of submarine pipelines. 18th Offshore Technology Conference. OTC 5339: 441–444.
[17] Zhao J, Wang X. CFD Numerical Simulation of the Submarine Pipeline with a Spoiler. Journal of Offshore Mechanics and Arctic Engineering ASME, 2009, 131(3): 031601.
[18] Chiew Y. Effect of spoilers on scour at submarine pipelines. Journal of Hydraulic Engineering, 1990: 1311-1317. 10.1061/ (ASCE)0733-9429(1992)118:9(1311).
[19] Chiew Y. Effect of spoilers on wave-induced scour at submarine pipelines. Journal of Waterway, Port, Costal and Ocean Engineering, 1993: 417–428. 10.1061/(ASCE)0733-950X(1993)119:4(417).
[20] Cheng L, Chew L W. Modelling of flow around a near-bed pipeline with a spoiler. Ocean Engineering, 2003, 30(13): 1595-1611.
[21] Alam M S, Cheng L. A 2-D Model to Predict Time Development of Scour below Pipelines with Spoiler. 2nd International Symposium on Computational Mechanics and 12th International Conference on the Enhancement and Promotion of Computational Methods in Engineering and Science. American Institution of Physics. 2010: 993-998.
[22] Yang L, Shi B, Guo Y, Wen X. Calculation and experiment on scour depth for submarine pipeline with a spoiler. Ocean Engineering, 2012, 55: 191-198.
[23] Oner A A. The flow around a pipeline with a spoiler. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2010, 224(1): 109-121.
[24] Han Y. Study on the Submarine Pipeline with Flexible Spoilers. Progress in Polymer Processing, Asian Workshop on Polymer Processing (AWPP2011). Trans Tech Publications Ltd. 2011, 501: 431-435.
[25] Zhu H, Qi X, Lin P, Yang Y. Numerical simulation of flow around a submarine pipe with a spoiler and current-induced scour beneath the pipe . Applied Ocean Research, 2013, 41(3): 87-100.
[26] Oner A A. Numerical investigation of flow around a pipeline with a spoiler near a rigid bed. Advances in Mechanical Engineering. 2016, 8(6): 1-13. 10.1177/1687814016651794.
[27] Yang L, Guo Y, Shi B, Kuang C, Xu W, Cao S. Study of Scour around Submarine Pipeline with a Rubber Plate or Rigid Spoiler in Wave Conditions. Journal of Waterway, Port, Coastal and Ocean Engineering, 2012: 484-490. 10.1061/(ASCE)WW.1943-5460.0000150.

© 2018 by the author(s). This work is licensed under a Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/). Authors retain copyright of their work, with first publication rights granted to Tech Reviews Ltd.