Literature review of research on scour propagation below the submarine pipeline

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Abstract: The scour process is closely related to the damage and failure of pipelines, so the study of the flow field around pipelines and the sediment transport below pipelines is especially important. Furthermore, the effects of scour propagation below submarine pipelines especially around span shoulders have significant meaning for the study of hydraulics and sediment transport in the ocean. In this paper, investigations in this area are considered and summarized with respect to the different methods of studying the mechanisms: experiment and numerical simulation. The main achievements are presented and compared. The majority of these achievements were derived from experiments because of the lack of a precise theory of sediment transport below pipelines and the difficulties of generating numerical simulations. The different devices used to monitor the scour process are discussed in this paper, and a new way of measuring the scour process is proposed which can be used in laboratory experiments.

Introduction

With the increasing use of pipelines, it is necessary to assess the long–term operation of pipelines in the ocean. Over the last decades, the stability of submarine pipelines has been a subject of significant concern for engineers and researchers. They found it is often the currents and the waves that lead to scouring below the pipelines and cause pipelines to become suspended, and finally broken. They also realized that in scouring it is always the s factor that induces failure of submarine pipelines. With the force of currents and waves, the sediment under the pipeline is first eroded, and then a hole is formed, and then, the hole becomes deeper and wider, at the same time, scouring propagates along the axis of the pipeline. That is briefly the scour process.

Due to the importance of scouring below pipelines, souring has been the focus of much research work. Specifically, attention has been focused, on the onset of scouring, and on the depth of the scour hole when scouring reaches the equilibrium state.

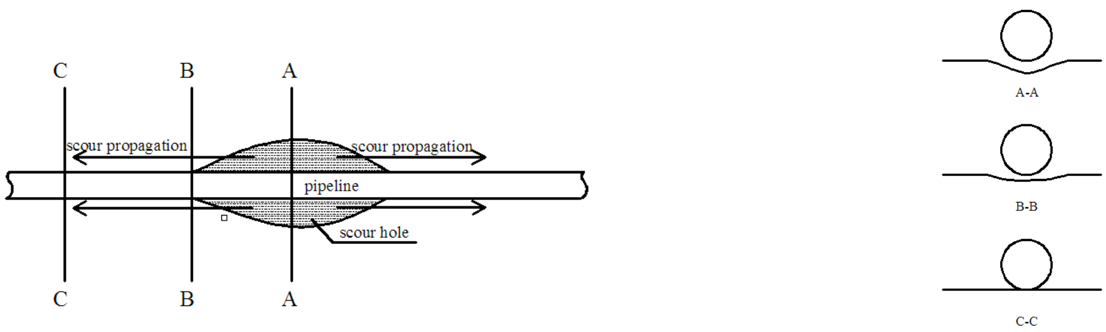
Y. Mao [1] and Y.M. Chiew [2] have studied the onset of scour below pipelines in steady currents while B. M. Sumer and J. Fredsoe [3] paid attention to the onset of scour in wave conditions. Mao described the potential factors that affect the onset of scour: i.e. the vortex at the rear of the pipe and the groundwater flow below the pipe. On the basis of Sumer's research, Chiew highlighted the pressure drop between upstream and downstream of the pipe and used experiments to test the critical conditions for the onset of scouring with a steady current and concluded that the scour will not happen if the pipeline is half-buried. In the situation of waves, Sumer and J. Fredsoe discussed factors which the onset of scour may depend on, and found the Keulegan-Carpenter number is the strongest factor. Based on former achievements, Z.P. Zang et al. [4] used a numerical model to discuss onset conditions of scour for steady currents and waves. A unified onset condition for steady currents and waves was proposed.

Another important contribution to the understanding of scour below pipelines is the investigation into the scour depth below pipelines where Y.M. Chiew [5] proposed an iterative method to predict the maximum scour depth. The critical condition of reaching equilibrium is that the applied shear stress is equal to the critical shear stresses for sediment entrainment. This method can be used when the pipeline is just lying on a plane bed and subjected to a pure unidirectional current. D.Z. Pan et al. [6] obtained the equilibrium scour depth versus KC number and the burial depth of the pipeline by a series of experiments. S. Dey [7] used a cubic polynomial to describe the equilibrium scour profiles in both uniform and non-uniform sediments in varying current conditions. The parameters of flow depth relative to pipe diameter, pipe diameter relative to sediment size, Froude number, non-uniform sediment gradation and cross section of pipes were taken into consideration and discussed elaborately. M. Najafzadeh et al. [8] applied the group method of handling data networks to these parameters, which was trained using a back-propagation algorithm to predict the scour depth in varying wave condition.

Though the topics of the onset of scour below pipelines and the scour depth have been fully discussed, some knowledge gaps remained. Scour propagation is one of them. This problem has a close relationship with former and further research. On the one hand, scour propagation is based on all the discoveries concerning scouring below pipelines, and on the other hand, it is the foundation for further study into the long-term protection of submarine pipelines.

Review

Most published researches in the past decades have focused on 2D scour, but it is obvious that scour below pipelines is a 3D problem, especially as the scour process is different in each dimension. The schematic scour propagation is shown in Fig.1



(a).The top view of scour below a pipeline (b) the profile of scour in different sections

Fig. 1 The schematic figure of scour below a pipeline in depth and along the axis of the pipeline

In profile A-A, scour hole has formed, and with time, the hole becomes deeper and wider until the equilibrium state is reached, and the scour hole has most characteristics of a two-dimensional scour. In B-B, the scouring is just starting, and the span shoulder has just reached this section. The flow blocked by the sand lying on the seabed and the pipeline, then changed direction. This complex situation supports the scour propagation along axis of the pipeline with constant depth and current direction. C-C shows the original pipeline and the stable seabed without scouring.

In the interest of pursuing further research in this area, substantial researches have been taken into consideration and are reviewed in this paper.

Research into the mechanism of scour propagation. J. Fredsoe et al. [9] studied the scour propagation with respect to depth and the span length using a physical model. R. Bernetti et al. [10] proposed a theoretical model of scouring along the axis of the pipeline by through the theory of conservation of sediment transport. E.A. Hansen et al [11] made an improvement to this model and proposed that the scour begins to propagate along the axis of the pipeline after the onset of scouring, this was consistent with J. Fredsoe. He also summarized the scour process with five steps. In another way, in 1988, M. Y. Mao [1] [1] deduced that it is the pressure difference between upstream and downstream sides of the pipe that cause seepage below the pipeline, and this theory has been used in 2D to explain the onset of scour in varying current and wave conditions. Similarly with Mao, Y.S. Wu and Y.M. Chiew[12] proposed using differential pressure between the upstream and the downstream sides of the pipe and local bed shear stress at the span shoulder to explain how scour propagation happens and the changing velocity with scour propagation. In their research, differential pressure and bed shear stress were deduced to be the two main reasons that induced scour propagation. When scour propagation had just started, sediment was extracted by the flow from the gap underneath the pipeline, and the differential pressure dropped rapidly. With time, when differential pressure drop had become small, the velocity of the scour propagation slowed down as well and scour propagation reached the second phase: the slack phase. The local bed shear stress was the only force present to extract the sediment in this phase. B.M. Sumer et al.[13] deduced using a submerged video camera that the onset of scouring always occurred at the weakest point in the seabed and then propagated spanwise. As the process continued, the suspend length became larger and more weight is loaded onto the soil where it has not scoured. When the weight exceeds the maximum weight that the soil can bear, the soil will fall into the scour hole. Besides, B.M. Sumer and J. Fredsøe [14] surmised that the elongation of the free span is driven by a spiral vortex at the upstream side of the span shoulders caused by the three dimensional separation of the boundary layer. Recently, Y.S. Wu and Y.M. Chiew[15] emphasized the pipe and the onset of scouring induce a stronger force at the span shoulder, which made it easier for the soil to be entrained.

Research into scour propagation with experiments. Experiment is a visualized way to find out the effect of changing a parameter, and developing the principles of a phenomenon. Researchers have made more progress using this method.

L. Cheng et al. [16] systematically studied the effect of different parameters on the propagation velocity of scouring. Formulas for scour propagation along the axis of the pipeline in current, wave and combined wave and current were established through experimental data. In current conditions, scour propagation has a constant propagation rate or can be divided into two stages, depending on the embedment of the pipeline, the velocity of the approaching flow and the initial angle of the flow. The formula for the propagation rate is shown as follow:-

$$V_h = K(25\frac{\sqrt{g(s-1)d_{50}^3}}{D\tan b}q^{\frac{5}{3}}(1-\frac{e}{D}(1+\sin a))) \tag{1}$$

Where α is the angle of attack, β is the average slope at the span shoulder, θ is Shields parameter, $d_{50}$is the grain size, D is the diameter of pipe, e is the embedment depth, g is the acceleration due to gravity, s is the specific gravity of the sediment grains and K is an empirical value due to experiment.

In case of scour propagation in wave and combined wave and current conditions, the phenomenon varied with current. Spanwise scour propagation kept at a constant speed in the wave only condition. Initial angle of the pipe influences the scour propagation velocity in an inverse relationship while propagation is identical along the two opposite directions of the pipe. A formula used to calculate velocity of propagation was established as follows:-.

$$V_h = K_{wc}((1-\frac{e}{D}(1+\sin a))\frac{\sqrt{g(s-1)d_{50}^3}}{D\tan f}(1-m)q_w + mq_c)^{\frac{5}{3}}F \qquad (2)$$

Where K_{wc} is a constant calibration parameter for scour propagation rate for combined wave and current, F is given by a series of empirical equations, m is the ratio of velocity induced by the current component to the total velocity, φ is the angle of repose of the sediment, w is the wave Shields parameter and θ_c is the Shields parameter due to a steady current.

Y.S. Wu and Y.M. Chiew [18] [19] , [15] [14] did a series of investigations in this field. They proposed propagation velocity was fast and nearly a constant in a rapid phase whilst it was slower and reducing in a slack phase. As to parameters which have the potential to have an influence on scour propagation, four parameters (ratio of embedment to pipeline diameter, ratio of water depth to pipeline diameter, Shields parameter, Froude number) were identified by dimensional analysis and then tested in a series of experiments. The former two parameters represented stabilisation forces whilst the latter two represented the environmental forces. They together determine the propagation velocity and duration of the two scour propagation phases. In study of the flow field span shoulder, Wu fixed the scour below the pipeline to represent the partially developed scour hole, and measured the flow field around the fixed boundary by a three-dimensional down-looking acoustic Doppler velocimeter. The experimental results showed that, flow around the span shoulder was a complex three-dimensional problem while the position where the scour initially happened was more like a two-dimensional development stage which developed with time because of the block of the pipeline and the gap under the pipeline.

In Wu’s latest research on scour propagation, wet-wet differential low-pressure sensors were used to monitor the differential pressure between the upstream and downstream sides of pipelines and helped to find the correlation between the pressure gradient drop and the non-dimensional propagation velocity, which also helped to understand the mechanics of scour propagation.

Research on the numerical simulation of scour propagation. Limitations of computer science and lacking a systematic theory of 3D scouring results in few published papers in this field.

K.A. Hatton et al. [20] simulated the flow field of a short cylindrical object assuming a 10% initial burial on a flat, fixed bed with the axis of this cylinder perpendicular to the direction of wave propagation and parallel to approaching flow in a three-dimensional model using Flow-3D. They deduced that the local scour and deposition around the pipeline is dependent on the bed load and level of suspended sediment in the flowing water.

B. Chen et al.[21] [22] simulated the flow field around a free-spanned pipeline using a fractional step finite element method. The simulation results showed the vortex in the free-spanned area interacted with vertex which was induced by bed shear stress and formed a complicated flow field.

In scour propagation prediction, L. Cheng and M. Zhao [23] used an FEM numerical model which is based on the Navier-Stokes equations and the κ-ε turbulent flow equations to simulate three-dimensional scouring spanwise but the numerical simulation produced results 50% less than the laboratory model.

Also, a three-dimensional Lattice Boltzman flow and scour model was established by M.S. Alam and L. Cheng [24] to simulate scour propagation streamwise and spanwise. In this research, the flow field around the pipeline was developed, and a spiral vortex around the span shoulder is confirmed.

A new method of measuring the scour process. When studying scouring below the pipeline, the instrument which can be used to measure scour with time is the short board of the bucket.

In recent years, researchers tried to understand the process of scour below pipelines by using different devices. F.P. Gao et al.[25] used a camera to record the scour process from one side of the trough. They simplified the scour in a 2D process, that is to say they considered the scour everywhere below the pipeline to have the same scour depth and the same propagation velocity, that is not accurate enough nowadays. Likewise, a camera was also used to record scour propagation along the axis of pipelines in Yushi Wu and Yee-Meng Chiew's paper [19] [15]. Liang Cheng [16] used scour probes to measure the scour process under pipelines. Scour probes had an influence around the probes and this error can be allowed for only in the circumstances that the pipeline is long enough and the probe is thin enough. Furthermore, a BP neural network recognition algorithm was introduced by X.F. Zhao [26] which was used to monitor scour which is based on the heating transfer properties between the sand bed and the sediment. It can be used in detecting free span movement under pipelines.

However, if the model pipe can be made of a transparent material like acrylic glass, maybe a laser can be used in this situation. A laser displacement sensor has been widely used in the measurement of size of particles, distance, and displacement. Based on the research of Z.J. Ding et al.[27], a linear relationship can be used between the value of laser displacement measurements which are based on triangulation. So, the laser displacement sensor could be used to realize the real-time measurement of scouring below pipelines.

The use of a laser displacement sensor is discussed by other researchers which have not published yet and the practicality has been proved by a series of experiments which shows that it is a rapidly developing field (personal communications).

Conclusion

In this paper, scour propagation especially spanwise was reviewed in three aspects: mechanics, experiments and numerical simulation. Among them, experiment is the most widely used method to analyze the scour propagation phenomenon and the relationship between the velocity of scour propagation and potentially important parameters, like embedment, Shields parameters, and pipeline diameter. Some experimental formulas were established to estimate the velocity of scour propagation. Furthermore, the mechanics of the onset of 3D scouring around a free span shoulder were discussed in relation to differential pressure, bed shear stress and vertex. The achievements of numerical simulation were less. Researchers have been focused on simulating flow field changing around pipelines using 3D models, and 3D scour propagations have been roughly simulated in recent years. Besides, monitoring devices and real-time measurements of scouring have been discussed in this paper. A new method of using a laser displacement sensor has also been proposed.

References

[1] Y. Mao, Seabed scour under pipelines. Proc. 7th International conference on offshore and Arctic engineering. Houston, Tex., (1988) 33-38

[2] Y.M Chiew, Mechanics of local scour around submarine pipelines, Journal of Engineering. 116

(1990)515-529
[3] B.M. Sumer, J. Fredsoe, Onset of scour below a pipeline exposed to waves, International journal of offshore and polar engineering. 1 (1991) 189-194
[4] Z.P. Zang, L. Cheng, M. Zhao, D. Liang, B. Teng, A numerical model for onset of scour below offshore pipelines. Coastal Engineering. 56 (2009) 458-466
[5] Y.M. Chiew, Prediction of maximum depth at submarine pipelines. Journal of Engineering. 117(1991) 452-466
[6] D.Z. Pan, L.Z. Wang, C.H. Pan, J.C. Hu, Local scour around pipeline due to progressive waves. The ocean engineering, 27 (2007) 27-32 (in Chinese)
[7] S. Dey, N.P. Singh, Clear-Water scour below underwater pipelines under steady flow. Journal of hydraulic engineering. 134 (2008) 588-600
[8] M. Najafzadeh, G.A. Barani, M.R.H. Kermani, Estimation of pipeline scour due to waves by GMDH. Journal of pipeline system engineering practice., 5 (2014) 0614002
[9] J. Fredsoe, E.A. Hansen, Y. Mao, B.M. Sumer, Three-dimensional scour below pipelines. Journal of offshore mechanics and arctic engineering. 110 (1998) 373-379
[10] R Bernetti, R Bruschi and V Valentini, Pipelines placed on erodible seabeds: Proc.9th International Conference on Offshore Mechanics and Artic Engineering, Houston, 1990
[11] E.A. Hansen, C. Staub, J Fredsoe, B.M. Sumer, Time-development of scour induced free spans of pipelines. Proc. 10th offshore mechanics and Arctic engineering conference, ASME, Stavanger, Norway. Pipeline technology, 5 (1991) 25-31
[12] Y.S Wu, Y.M. Chiew, Journal of waterway, port, coastal and ocean engineering. 141 (2015) 04014045
[13] B.M. Sumer, C. Truelsen, T. Sichmann, J Fredsoe, Onset of scour below pipelines and self-burial. Coastal engineering. 42 (2001) 313-315
[14] B.M. Sumer, J. Fredsoe, The mechanics of scour in the marine environment. Advanced Series on ocean engineering. Vol.17, World Scientific, Singapore (2002)
[15] Y.S. Wu, Y.M. Chiew, Mechanics of three-dimensional pipeline scour in unidirectional steady current. Journal of pipeline system engineering practice. 4 (2013) 3-10
[16] L. Cheng K. Yeow, Z.P. Zhang, B. Teng, Three-dimensional scour below offshore pipelines in steady currents. Costal Engineering. 56 (2009) 557-590
[17] C. Liang, K. Yeow, Z.P. Zang, F.J. Li, 3D scour below pipelines under waves and combined waves and currents. Coastal Engineering.83 (2014) 137-149
[18] Y.S. Wu, Y.M. Chiew, Three-dimensional scour at submarine pipelines in unidirectional steady current. International Conference on Scour and Erosion.(2010)
[19] Y.S. Wu, Y.M. Chiew, Three-dimensional scour at submarine pipelines. Journal of Hydraulic engineering. 138 (2012) 788-795
[20] K.A. Hatton, D.L. Foster, P. Traykovski, H.D Smith, Numerical simulations of the flow and sediment transport regimes surrounding a short cylinder. Journal of ocean engineering.32 (2007) 249-259
[21] B. Chen, Y.C. Li, L. Cheng, Numerical study of three dimensional turbulent flow structure around free span shoulder of a pipeline. Shipbuilding of China.43 (2002) 330-335(In Chinese)
[22] B. Chen. Numerical investigation of three-dimensional flow and bed shear stress distribution around the span shoulder of pipeline. Journal of Hydrodynamics, Ser. B.16 (2004) 687-694
[23] C. Liang, M. Zhao, Numerical model for three-dimensional scour below a pipeline in

steady currents International Conference on Scour and Erosion (2010)
[24] M.S. Alam, L. Cheng, A parallel three-dimensional scour model to predict flow and scour below a submarine pipeline. Central European Journal of Physics. 8 (2010) 604-619
[25] Gao F.P, Yang B, Y. X. Wu, Steady current induced seabed scour around a vibrating pipeline. Applied ocean research. 28 (2006) 291-298
[26] X.F. Zhao, Q. Bai, L. Zhou, W.J. Li, J.P. Qu, BP neural network recognition algorithm for scour monitoring of subsea pipelines based on active thermometry. 125 (2014) 52426-52431
[27] Z.J. Ding, Y.W. Li, S.L. Xu, S.S. Li, Development of three-dimensional terrain apparatus based on laser testing for under water microrelief. The ocean engineering. 31 (2013) 84-89 (In Chinese)