Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(5):763-773
DOI: 10.1016/S1001-6058(16)60787-4
www.sciencedirect.com/
science/journal/l0016058

Flow-pipe-soil coupling mechanisms and predictions for submarine pipeline instability *

Fu-ping Gao (高福平)
Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China,
E-mail: fpgao@imech.ac.cn

(Received July 28, 2017, Revised August 3, 2017)

Abstract: The stability of a submarine pipeline on the seabed concerns the flow-pipe-soil coupling, with influential factors related to the ocean waves and/or currents, the pipeline and the surrounding soils. A flow-pipe-soil coupling system generally has various instability modes, including the vertical and lateral on-bottom instabilities, the tunnel-erosion of the underlying soil and the subsequent vortex-induced vibrations (VIVs) of free-spanning pipelines. This paper reviews the recent advances of the slip-line field solutions to the bearing capacity, the flow-pipe-soil coupling mechanism and the prediction for the lateral instability, the multi-physical coupling analysis of the tunnel-erosion, and the coupling mechanics between the VIVs and the local scour. It is revealed that the mechanism competition always exists among various instability modes, e.g., the competition between the lateral-instability and the tunnel-erosion. Finally, the prospects and scientific challenges for predicting the instability of a long-distance submarine pipeline are discussed in the context of the deep-water oil and gas exploitations.

Key words: Submarine pipeline, lateral stability, bearing capacity, vortex-induced vibration, local scour, fluid-structure-soil coupling

Introduction

Submarine pipelines for transporting offshore oil and gas are long-distance shallow foundations laid on the seabed. The pipeline instability induced by ocean waves and currents is one of the main causes of structural failures. Physical mechanisms and theoretical predictions of the pipeline seabed interaction have long been a research focus[1,2].

The pipeline on-bottom stability is complex and involves the fluid-structure-soil interaction, with quite a few influential factors of the hydrodynamics and the corresponding structural and soil responses. The on-bottom stability of a submarine pipeline is mainly characterized by two aspects in vertical and lateral directions, i.e., the (vertical) bearing capacity of the pipeline foundations and the lateral on-bottom stability. The soil should provide enough ultimate bearing capacity to avoid an excessive embedment into the seabed, especially in the pipeline laying process[3]. Moreover, during the in-service period, the lateral soil resistance should be large enough to balance the hydrodynamic forces from severe waves and/or currents to avoid the pipeline displacing from its original location[4]. In a more general sense, the pipeline instability should include not only the aforementioned on-bottom stability, but also the tunnel-erosion underneath the partially-embedded pipeline, the vortex-induced vibrations (VIVs) of the free spanning, and even the global buckling of a high-pressure/ high-temperature (HT/HP) pipeline under deepwater conditions.

In this paper, the advances of studies on the instability of a submarine pipeline are reviewed, focusing on the flow-pipe-soil coupling mechanisms and the theoretical predictions. The correlation analyses show that various instability modes are closely correlated and competitive with each other. The prospects and scientific challenges for predicting the instability of a long-distance submarine pipeline are discussed in the context of the deep-water oil and

* Project supported by the National Natural Science Foundation of China (Grant Nos. 11372319, 11232012), the Strategic Priority Research Program (Type-B) of CAS (Grant No. XDB22030000).
Biography: Fu-ping Gao (1973-), Male, Ph. D., Professor

gas exploitations.

1. Pipeline on-bottom stability: Ultimate bearing capacity and lateral instability

1.1 *Ultimate bearing capacity*

The prediction for the bearing capacity of shallow foundations is generally based on the slip-line stress field solutions and/or the limit analysis, combined with some empirical correlations[5]. The soil is essentially assumed to behave as an elastic Tresca material, if the undrained bearing capacity is considered, and as an elastic Mohr-Coulomb material, if the drained bearing capacity is under investigation[6].

In the on-bottom stability design[4], the bearing capacity of the pipeline foundations has ever been evaluated with conventional bearing capacity theories for the strip footings with flat bottoms[7]. The numerical modeling of the vertical pipe-soil interactions[8] indicated that the failure of the pipeline foundations is often in a general shear failure mode, especially for soft clayey soils or cohesionless sands, i.e., the plastic shear zone underneath the pipe extends gradually to the soil surface with the increase of the downward load.

Taking into account of the effects of the geometric curvature of the pipe, the adhesion/friction at the pipe-soil interface, and/or the internal friction of the soil, the slip-line field solutions under both undrained and fully drained conditions can be obtained, respectively[9,10]. A general slip-line field solution for the bearing capacity of a pipeline foundation obeying the Mohr-Coulomb yield criterion can be expressed as

$$\frac{P_u}{D\sin\theta} = cN_c + qN_q + (0.5D\gamma'\sin\theta)N_\gamma \qquad (1)$$

where P_u is the collapse load for a pipeline foundation in the general shear failure, D is the external diameter of the pipeline, $\theta = \arccos(1-2e/D)$ is the embedment angle (see Fig.1), e/D is the embedment-to-diameter ratio, "$D\sin\theta$" refers to the efficient width of the pipe-soil interface, which is related to the pipe penetration, c is the soil cohesion, q is the surcharge pressure (note: for $e/D \le 0.5$, q is set to zero. For $e/D > 0.5$, the pipeline embedment can be treated as $e/D \equiv 0.5$ with an equivalent uniform surcharge pressure $q = (e-0.5D)\gamma'$, where γ' is the buoyant unit weight of the soil), N_c, N_q and N_γ are the bearing capacity factors for the cohesion, the distributed load, and the buoyant weight of soils, respectively[10].

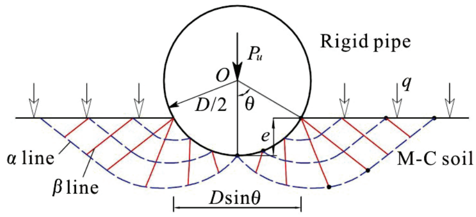

Fig.1 (Color online) The slip-line field of a pipeline (smooth) foundation on the soil obeying Mohr-Coulomb failure criterion[10]

The aforementioned slip-line field solutions for predicting the bearing capacity of the pipeline foundations are extensions from the conventional bearing capacity theories for the strip footings. Figure 1 illustrates the slip-line stress field underneath a partially-embedded smooth pipeline for the soil obeying Mohr-Coulomb yield criterion, indicating that α lines and β lines are not perpendicular to each other due to the effect of the internal friction of soils. Neglecting the effects of the geometric curvature of the pipe (i.e., the embedment-to-diameter ratio $e/D \to 0$), the adhesion of the pipe-soil interface (i.e., the interfacial friction/adhesion coefficient $\mu = 0$), and the internal friction of the soil (i.e., the angle of internal friction φ=0) for the clayey seabed under undrained conditions, the slip-line field solutions can thereby be degenerated into Prandtl solutions for conventional strip footings, i.e., $N_c = 2+\pi$. Parametric study showed that with the increase of the pipeline embedment, the value of N_c decreases from $N_c = 2+\pi$ $(e/D \to 0)$ finally to N_c=4.0 (at $e/D = 0.5$), indicating that the geometric curvature effect is not negligible. That is, for smooth pipelines on the undrained clayey seabed ($\mu = 0$ and φ=0), if the circular pipeline foundations are directly simplified as conventional strip footings, the bearing capacity factor N_c would be over evaluated, with an error up to 28.5%[9]. This geometric curvature effect on the bearing capacity factor[9] was recently adopted in the new version of the DNVGL Recommended Practice[11]. With a further consideration of the influence of the internal friction of the soil, such a geometric curvature effect can become more prominent[10].

1.2 *Lateral on-bottom stability*

1.2.1 Pipe-soil interaction

In the design practice for the on-bottom stability of submarine pipelines by Det Norske Veritas[4], the