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Letter

Assessment of pipeline stability in the Gulf of Mexico during hurricanes using dynamic analysis

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ABSTRACT

Pipelines are the critical link between major offshore oil and gas developments and the mainland. Any inadequate on-bottom stability design could result in disruption and failure, having a devastating impact on the economy and environment. Predicting the stability behavior of offshore pipelines in hurricanes is therefore vital to the assessment of both new design and existing assets. The Gulf of Mexico has a very dense network of pipeline systems constructed on the seabed. During the last two decades, the Gulf of Mexico has experienced a series of strong hurricanes, which have destroyed, disrupted and destabilized many pipelines. This paper first reviews some of these engineering cases. Following that, three case studies are retrospectively simulated using an in-house developed program. The study utilizes the offshore pipeline and hurricane details to conduct a Dynamic Lateral Stability analysis, with the results providing evidence as to the accuracy of the modeling techniques developed.

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Introduction The Gulf of Mexico is a small oceanic basin surrounded by continental land masses and a relatively simple and roughly circular structure approximately 1500 km in diameter [1]. As shown in Fig. 1, the Gulf of Mexico basin resembles a large pit with a broad shallow rim. Approximately 38% of the Gulf comprises shallow and intertidal areas (<20 m deep). The area of the continental shelf (<180 m) and continental slope (180–3000 m) are 22% and 20% of the total area, respectively. Abyssal areas deeper than 3000 m make up the final 20% [2]. The northeast Gulf of Mexico is the region with the most reported damaged pipelines. This region extends from east of the Mississippi Delta near Biloxi to the eastern side of Apalachee Bay. The majority of this region is characterized by soft sediments [3].

Five hurricanes hit the Gulf of Mexico between 1992 and 2005: Andrew in 1992, Lili in 2002, Ivan in 2004, Katrina and Rita in 2005 and their paths are shown in Fig. 1. These hurricanes caused severe destruction and the economic loss is estimated to be worth 75 billion US dollars due to Katrina alone [4]. Table 1 summarizes destruction of the 5 hurricanes. The majority of the pipeline failures are in areas perpendicular to the maximum current and in water depths less than 60 m. Large displacements of pipelines have been highlighted by Gagliano [5] and this agrees with the reported data in Table 1. For example, an 18 inch (0.457 m) unburied oil pipeline with a specific gravity of 1.6 drifted southward 910 m from its original location during Hurricane Ivan. During Hurricane Katrina, a 26 inch (0.66 m) buried gas pipeline with a specific gravity of 1.4 in a water depth of 15 m was displaced about 1219 m to the north over 14.5 km of its length. A sonar survey after Hurricane Ivan presented in Thomson et al. [6] revealed that an 18 inch (0.457 m) pipeline, approximately 44.25 km long, that ran from an oil gathering platform westward to near the Mississippi River Delta was found displaced by 580 m. In addition, approximately 100 pipeline failures due to hurricanes were reported from 1971 to 1988, whereas about 600 cases of pipeline damage were reported after Hurricanes Katrina and Rita in 2005 [7].

Pipeline on-bottom stability assessment post Hurricane Ivan After the enormous destruction to the offshore oil and gas facilities by Hurricane Ivan, many research publications assessed and reviewed the design of the damaged pipelines [4,7–12]. As reported by Det Norske Veritas (DNV) [7], three on-bottom pipeline stability studies were conducted to model pipelines under Hurricane Ivan using the PONDUS software [13]. In the analysis, the pipelines were assumed to be oriented perpendicular to the path of Hurricane Ivan. Table 2 summarizes the input parameter values

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Table 1
Summary of the 5 hurricanes in the Gulf of Mexico.

Hurricane	Hurricane scale*	Sea state	Total damage	Damages due to excessive disp.
Andrew	4	$H_s \approx 10.7–12.2$ m	485 pipelines and flow lines were damaged. Eight seven percent (87%) of the pipeline damages occurred in small diameter pipes and most in water depths < 30.5 m.	44
Lili	4		120 pipelines were damaged. Eight five percent (85%) of the pipeline failures occurred in small diameter pipelines and there was no apparent correlation with pipeline age.	
Ivan	4–5	$H_s >$ 2500 year return period	168 pipeline damages report with an estimated 16093 km out of the 53108 km of the Outer Continental Shelf pipelines in the direct path of the hurricane.	38
Katrina	5	$H_s \approx 16.8$ m	299 pipelines and flow lines were damaged. Approximate 35405 km out of the 53108 km of pipelines were in the path of Katrina and Rita.	61
Rita	4	$H_s \approx 11.6$ m	243 pipelines and flow lines were damaged	31

* See DNV [4] for details about the hurricane scale based on Saffir–Simpson scale standard.

Table 2
Three pipeline analysis cases in DNV [7].

Parameters	Pipeline case 1	Pipeline case 2	Pipeline case 3
Significant wave height/m	11.7	11.7	11.7
Peak period/s	15	15	15
Water depth/m	63.7	95	100
Outer diameter/mm	465.4	406.4	355.6
Outer diameter of steel/mm	457.2	355.6	304.8
Wall thickness/mm	9.53	12.7	9.53
Current velocity at sea-bed/$\text{m} \cdot \text{s}^{-1}$	0.758	0.703	0.684
Submerged weight/$\text{N} \cdot \text{m}^{-1}$	892 (water-filled)	372 (empty)	871 (water-filled)
Soil undrained shear strength/kPa	50	1.47	50
Reported movement in field/m	914.4	518.2	0
Reported displaced length/km	43.5	3.4	0
PONDUS predicted displacement (under 3 h storm)/m	1446	628	254

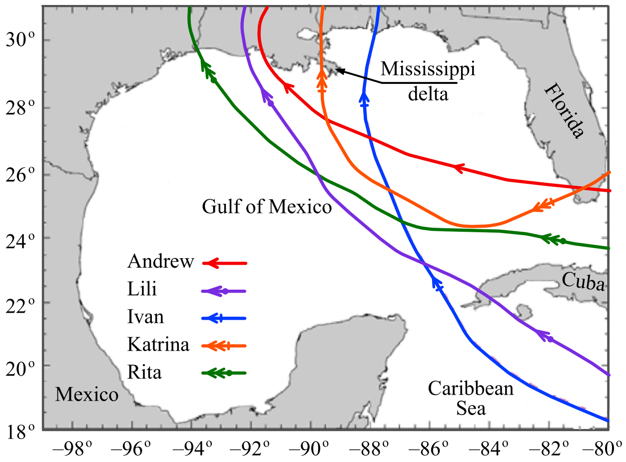

Fig. 1. Gulf of Mexico location and the path of the main hurricanes.

used in the PONDUS simulations and the pipeline displacements measured in the field. In the first two cases, pipelines experienced massive lateral displacements of 914 m and 518 m, respectively, and the third pipeline case did not experience any displacement under Hurricane Ivan. The numerical simulation predicted that all three pipeline cases would experience lateral movement, 1446 m, 628 m, and 254 m, respectively. It is clear that PONDUS overestimated the pipeline displacement of the three pipeline cases.

In-house developed dynamic finite element program Tian and Cassidy [14–16] and Tian et al. [17] developed an integrated fluid–pipe–soil modeling Dynamic Lateral Stability package. Dynamic Lateral Stability analysis is considered to be the most comprehensive method because a complete three-dimensional pipeline simulation can be performed for any given combination of waves and currents in time domain analysis (see DNV [18] for details). This in-house package adopted advanced plasticity pipe–soil force-resultant models [19–22] and Fourier hydrodynamic load models [23] to evaluate soil resistance and hydrodynamic loading, respectively. The commercially available finite element package ABAQUS/Standard was used (implicit analysis), with modules for pipe–soil interactions and hydrodynamic loading implemented as user subroutines UEL and DLOAD, respectively (see Dassault System for technical details [24]).

The pipe–soil interaction module implements available force-resultant models on calcareous sand [19–21] and clay soil [22] as ABAQUS user-defined elements through the user subroutine UEL. Figure 2 illustrates the symbolic convention for loading acting on a segment of a pipeline. The vertical component of the resultant force is $V = W_s - F_V$, where W_s is the pipeline submerged weight and F_V is the vertical hydrodynamic loading. The horizontal component is $H = F_H$, where F_H is the horizontal hydrodynamic loading. Most available pipe–soil interaction models are based on the simplistic Coulomb friction concept [25–27] and link H directly to V through only one simplistic friction factor. More advanced force-resultant models have been presented in the last decade, allowing a more fundamental understanding of pipe–soil behavior by relating the resultant forces (V, H) directly to the corresponding displacement (w, u) within a plasticity framework. Schotman and Stork [28] initially proposed the force-resultant concept to pipe–soil modeling. Subsequently, other fully developed force-resultant pipe–soil models have been presented by Zhang [19], Zhang et al. [20], Calvetti et al. [29], Di Prisco et al. [30], Hodder and Cassidy [22], Tian et al. [21], and Tian and Cassidy [16] through experimental and numerical studies. Among these, Hodder and Cassidy [22] conducted centrifuge testing at 50g with a pipeline model 0.5 m in diameter and 2.5 m in length in prototype. The tested soil samples of kaolin clay were commercially available but can well represent the undrained behavior of clayey soil. These

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