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Experimental study of the hydrodynamic force on a pipeline subjected to vertical seabed movement

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A R T I C L E I N F O

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A B S T R A C T

Using an underwater shaking table, model tests of a free-spanning flexible submarine pipe subjected to vertical seabed movement were carried out. The fluid field adjacent to the pipe and the hydrodynamic force exerted on the pipe were measured. Based on Morison's equation, the hydrodynamic force coefficients related to earthquake, such as the drag coefficient C_D and the added mass coefficient C_A, were obtained by the least squares method. The effects of the Reynolds number *Re*, the Keulegan–Carpenter number *Kc*, the water depth *d*, and the span height *e* on the hydrodynamic coefficients were analyzed. The experimental results illustrate that *Re* and K_c have a strong effect on the hydrodynamic forces imposed on the pipeline under vertical earthquakes. The variation of the hydrodynamic coefficients with *Re* and K_c is fitted by a regression analysis. The calculated results from the hydrodynamic force model suitable for vertical earthquakes are in good agreement with the measured data.

1. Introduction

Parts of offshore oil/gas fields in the United States, China, Malaysia, and Indonesia are located in seismically active areas. Thus, marine pipelines installed in these areas must be designed to resist earthquake motion. Regardless of whether a pipeline is buried in or laid on the seabed, free spanning would inevitably occur due to the scouring, erosion, or unevenness of the seabed. Therefore, earthquake ground motions affect spanning submarine pipeline through not only soil constraints but also the oscillatory fluid surrounding the pipeline.

For an exposed underwater pipe, the key problem is the structure–fluid interaction. When the waves and currents pass through free spans, periodic vortex shedding often occurs and results in hydrodynamic forces on free spans along the in-line or cross-flow directions. In the past few decades, many experimental studies and numerical simulations have been performed for submarine pipelines under steady currents, waves, or waves plus steady currents (Morison et al., 1950; Beckmann and Thibodeuax, 1962; Bearman and Zdravkovich, 1978; Wright and Yamamoto, 1979; Sarpkaya and Storm, 1985; Jacobsen et al., 1988, 1989).

Because earthquakes are of short duration and have an ample frequency content and high magnitude relative to waves and currents, the interaction between a pipeline and the surrounding fluid under earthquakes differs from that under waves and currents. The seismic response of submarine pipelines, however, has not been well addressed in the related design codes and recommended practices, such as DNV-OS-F101 (DNV, 2010) and ASME B31.8 (ASME, 2010). Li et al. (2002) employed an underwater shaking table and carried out model tests to study the response of submarine pipelines under dynamic inputs. Zhou et al. (2005) adopted added mass to perform numerical simulations of submarine pipelines under earthquakes. Zeinoddini et al. (2008) used ABAQUS and established a finite element model taking the interaction of the pipe body, seabed, and surrounding water into account. The results indicated that the added mass method was conservative. Datta and Mashaly (1990) presented a frequency domain spectral method for determining the transverse response of free spanning submarine pipelines subjected to random earthquake excitation. The effect of the drag coefficient C_D on the pipeline response was analyzed. Kalliontzis (1998) studied the dynamic response of submarine pipelines to earthquake-generated vertical seabed motions with the aid of a finite element model. However, the interaction between the fluid and the pipe is considered by added hydrodynamic mass and linearized fluid dampness. The application of the hydrodynamic force model to free spanning submarine pipelines under seismic action has received little attention in the literature. Vertical earthquake ground motions cause the fluid field to vibrate intensively within a short time. Therefore, to simulate and simplify the analysis of the interaction between the pipeline and the seawater under vertical

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Nomenclature

A	sectional area of the pipe, $A=(1/4)\pi D^2$ [m^2]
a	input acceleration [m/s^2]
a_m	amplitude of input acceleration [m/s^2]
C_A	added mass coefficient
C_A^{Re}	basic added mass coefficient related to Re
C_D	drag coefficient
C_D^{Re}	basic drag coefficient related to Re
C_M	inertial coefficient, $C_M=C_A+1$
C_{Vh}	horizontal hydrodynamic force coefficient
$C_{Vh\max}$	maximum horizontal hydrodynamic force coefficient
$C_{Vh\min}$	minimum horizontal hydrodynamic force coefficient
$C_{Vh\max}^{Re}$	basic maximum horizontal hydrodynamic force coefficient related to Re
$C_{Vh\min}^{Re}$	basic minimum horizontal hydrodynamic force coefficient related to Re
c	damping coefficient of a structure
D	pipe outer diameter [m]
D_m	outer diameter of the model pipe [m]
D_p	outer diameter of the prototype pipe [m]
d	water depth
E_m	dynamic elastic module of the model pipe [N/m^2]
E_p	dynamic elastic module of the prototype pipe [N/m^2]
e	span height
F_h	horizontal hydrodynamic force per unit length [N/m]
F_v	vertical hydrodynamic force per unit length [N/m]
F_{Vh}	calculated hydrodynamic force per unit length in the horizontal direction [N/m]
$F_{Vh\max}$	maximum calculated hydrodynamic forces per unit length in the horizontal direction [N/m]
$F_{Vh\min}$	minimum calculated hydrodynamic forces per unit length in the horizontal direction [N/m]
F_{Vv}	calculated hydrodynamic force per unit length in the vertical direction [N/m]
f	excitation frequency [Hz]
K_c	Keulegan–Carpenter number
k	stiffness coefficient of a structure
L_m	length of the model pipe [m]
m	mass of a structure
n	point number
p_n	measured hydrodynamic pressure for point n [N/m^2]
Re	Reynolds number
T	period of fluid oscillations [s]
t	time [s]
t_m	wall thickness of the model pipe [m]
t_p	wall thickness of the prototype pipe [m]
U_m	maximum (undisturbed) fluid particle velocity at the axis of the model pipe [m/s]
U_v	vertical velocity of water [m/s]
$U_{v\max}$	maximum vertical velocity of water [m/s]
U_{hh}	dimensionless horizontal flow velocity under horizontal ground excitation [m/s]
U_{vh}	dimensionless vertical flow velocity under horizontal ground excitation [m/s]
U_{hv}	dimensionless horizontal flow velocity under vertical ground excitation [m/s]
U_{vv}	dimensionless vertical flow velocity under vertical ground excitation [m/s]
u	excitation velocity [m/s]
u_{hh}	maximum horizontal velocity of water under horizontal ground excitation [m/s]
u_{hv}	maximum horizontal velocity of water under vertical ground excitation [m/s]
u_m	velocity amplitude of excitation [m/s]
u_{mh}	velocity amplitude of horizontal ground excitation [m/s]
u_{mv}	velocity amplitude of vertical ground excitation [m/s]
u_{vh}	maximum vertical velocity of water under horizontal ground excitation [m/s]
u_{vv}	maximum vertical velocity of water under vertical ground excitation [m/s]
v	vertical fluid velocity [m/s]
$\dot{v}$	vertical fluid acceleration [m/s^2]
v_{vp}	vertical pipe velocity [m/s]
$\dot{v}_{vp}$	vertical pipe acceleration [m/s^2]
$x(t)$	displacement histories of a structure
$\dot{x}(t)$	velocity histories of a structure
$\ddot{x}(t)$	acceleration histories of a structure
γ_p	prototype liquid density [kg/m^3]
γ_m	model liquid density [kg/m^3]
λ	scale ratio of geometry
λ_a	scale ratio of acceleration
λ_E	scale ratio of elastic module
λ_t	scale ratio of time
λ_V	scale ratio of liquid velocity
λ_ρ	scale ratio of density
μ_m	Poisson ratio of model pipe
ν	fluid kinematic viscosity [m^2/s]
ρ	fluid density [kg/m^3]
ρ_p	prototype pipe density [kg/m^3]
ρ_m	model pipe density [kg/m^3]
$\psi_{e/D}^{C_A}$	correction factor for C_A associated with e/D
$\psi_{e/D}^{C_D}$	correction factor for C_D associated with e/D
$\psi_{e/D}^{C_{Vh\max}}$	correction factor for $C_{Vh\max}$ associated with e/D
$\psi_{e/D}^{C_{Vh\min}}$	correction factor for $C_{Vh\min}$ associated with e/D
$\psi_{d/D}^{C_A}$	correction factor for C_A associated with d/D
$\psi_{d/D}^{C_D}$	correction factor for C_D associated with d/D
$\psi_{d/D}^{C_{Vh\max}}$	correction factor for $C_{Vh\max}$ associated with d/D
$\psi_{d/D}^{C_{Vh\min}}$	correction factor for $C_{Vh\min}$ associated with d/D
$\psi_{K_c}^{C_A}$	correction factor for C_A associated with K_c
$\psi_{K_c}^{C_D}$	correction factor for C_D associated with K_c
$\psi_{K_c}^{C_{Vh\max}}$	correction factor for $C_{Vh\max}$ associated with K_c
$\psi_{K_c}^{C_{Vh\min}}$	correction factor for $C_{Vh\min}$ associated with K_c
ω	angular frequency [rad/s]

earthquakes, it is important to study the hydrodynamic force models.

Using an underwater shaking table, a series of model tests studying hydrodynamic forces on pipe subjected to vertical earthquakes are carried out. The drag coefficient C_D and inertia coefficient C_M are obtained by the least squares method. The effects of the seismic ground motion amplitude, frequency, water depth and span height on C_D and C_M are investigated.

2. Experimental design

2.1. Similarity law

To perform a model test to study the interaction of water and pipeline, the dynamic similarity between model and prototype must be developed firstly. The forces acting on the model and the prototype should be in the same ratio throughout the entire flow