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Nonlinear Coupled Responses to Impact Loads on Free-Span Pipeline: Torsional Coupling, Load Steps and Boundary Conditions

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ABSTRACT

For a heavy object falling on a free-span pipeline, this study assesses three-dimensional (3-D) pipe-span responses with the torsional (qx-) coupling of a pipeline through the biaxial (y) bending responses. The static pipe-span equilibrium is achieved with its self-weight and buoyancy and the external torsional moment induced by the cross-flow (y-directional) current on the sagged pipe span. Load steps taken in two different sequences of applying static loads induce different pipe deformations, and the pipe twists in entirely different patterns. The two types of impact loads are applied in the vertical (z-) direction to excite the pipe span in its static equilibrium: (1) triangular impulse loading and (2) ramp loading. Two boundary conditions of the span supports are fixed-fixed and fixed-pinned. 3-D coupled axial (x-), bending (y- and z-) and torsional (qx-) responses, both static and dynamic, to the z-directional impact loadings, are modeled and analyzed by a nonlinear FEM method for a 16-in pipeline. Significant torsional vibrations occur by the cross-flow current, especially for longer spans. The torsional (qx-) coupling is very sensitive to the time-step size in achieving numerical stability and accuracy, particularly for the ramp loading and for a shorter span. Two boundary conditions give different torsional responses. For very large impact loads, the response frequencies differ from the fundamental frequencies of the span, exhibiting beatings and strong bending-to-axial and to-twist couplings. Also, the torsional eigenvalues for the linear system differ greatly between straight and sagged pipes.

INTRODUCTION

A free span of a pipeline on the seafloor can experience excessive stresses due to hydrodynamic forces in the x-, y-, and z-directions and impact loads in the z-direction in addition to its wet weight (self-weight and buoyancy) in the z-direction and the steady drag by the cross-flow current in the y-direction.

3-D pipeline responses coupled with torsion were first analyzed by Chung, Cheng and Huttelmaier (1995). A ship anchor impact on a pipeline was investigated previously for the 2-D cases by Al-Warthan et al. (1993), using a discrete element method (DEM) with the conditions of both ends being fixed: fixed-fixed. Further work on this 2-D DEM encountered a numerical instability problem.

For the present investigation of nonlinear free-span pipeline responses, the nonlinear 3-D FEM code developed for deep-ocean mining (vertical) pipe (Chung, Cheng, Huttelmaier, 1994) is extended to analyze a horizontal pipeline. The present analysis of the 16-in-diameter pipeline, which was used by Al-Warthan et al. (1993), places its emphasis on the 3-D effect with torsional coupling. It includes effects of: (a) the sequence of the load steps of the wet self-weight of the pipe and the cross-flow drag; (b) boundary conditions; (c) pipe-span length; and (d) types of impact loading for the pipe excitation. Two types of loadings are applied: (1) impulse impact and (2) ramp impact.

The nonlinear static equilibrium state and the eigenvalues of a linear system are first presented and are followed by dynamic excitations of the free pipe span by the impact of a falling object. The dynamic response is studied, assuming that the pipe behaves elastically. Responses of continuous pipe spans will be published in a separate paper.

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FINITE ELEMENT MODELING (FEM)

A pipe finite element code was previously developed to model the nonlinear 3-D dynamic behavior of a deep-ocean mining pipe. Other special features of the analysis procedure are: an updated Lagrangian formulation is used to account for geometric nonlinearities; also, elastic behavior and small strain theory are applied. For the present "large deflection," the small strain theory is considered to be adequate. For the present pipeline study the FEM code is modified to include the horizontal orientation of the pipeline. The mathematical basis of the 3-D nonlinear FEM code used is briefly presented, and further detail is referred to in Chung, Cheng, and Huttelmaier (1994).

The Large-Displacement Pipe Element

A two-noded pipe element using linear displacement functions for axial and torsional effects and cubic functions for bending is used. A 3-D continuum mechanics approach is applied to derive the 12 degrees-of-freedom pipe element (3 translations and 3 rotations per node). This formulation excludes shear effects due to the highly flexible nature of ocean pipe. The usual linear and nonlinear strain-displacement matrices are derived to obtain the linear and nonlinear incremental element stiffness matrices. Mass properties are represented through lumped masses on the element level.

Linear and nonlinear stiffness matrices. The linear and nonlinear strain-displacement matrices are expressed in terms of the