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Dynamics of Seabed Pipelines and Study on Critical Free Span Length

Anu Mathew
Assistant Professor,
Department of Civil Engineering
Mangalam College of Engineering,
Kottayam, India

Dr. T. P. Somasundaran
Professor
Department of Civil Engineering
National Institute of Technology
Calicut, India

***Abstract*— Over the past few years there has been an enormous need for natural resources. The increase in demand of pipelines which are used to carry such natural resources in sea conditions have also been increased which creates a need for research in this area. Offshore pipelines should be stable under the combined action of hydrodynamic and hydrostatic forces. Thus a study is carried on the pipelines resting on sea bed for various hydrodynamic forces. An accurate prediction of response is crucial assessment of the safety of submarine pipelines. Accurate response requires a well -adapted structural formulation and realistic description of both the external loading and interaction between the response and the loading. A MATLAB coding is developed for the prediction of dynamic motion of ocean bed pipelines. An elastic spring system simulates transverse, axial and vertical resistance of the soil. The pressure differential across the pipeline wall modifies the tensile stress and influences the flexural stiffness of the finite element model through geometric stiffness. Hydrodynamic inertia and viscous drag forces are calculated using modified Morison's equation. The equation of motion during wave activity can be integrated using Newmark-Beta method. The primary features of the work are Modelling pipe as a series of 3D- beam elements , Modelling soil using Winkler's model , Modelling hydrodynamic forces and Prediction of responses under monochromatic and random wave. Currents are very important underwater, there can be positive or negative currents. For the present study a steady current with constant velocity is allowed to act along with wave and the response is studied. The most crucial part in the area of response due to uneven seabed is the determination of critical free-span length is also included in the present study. Thus all the possible sea conditions are studied in this work to assess the safety of pipelines.**

Key words: Pipelines, Stiffness, Morison's equation, Currents

I. INTRODUCTION

A pipeline system is defined as a pipeline section extending from an inlet point, typically an offshore platform or an onshore compressor station to an outlet point typically another offshore platform or an onshore compressor receiver station. Offshore pipelines are used to transport oil and gas between offshore platforms or to transport oil and gas directly from offshore to land. Offshore pipelines should be stable under the combined action of hydrodynamic and hydrostatic forces. The hydrodynamic forces on the pipeline and seabed are functions of wave and current climate. It is important to correctly predict the forces acting on pipelines since they have a direct bearing on the safety of pipelines. The excessive pipe movement and oscillatory motions may cause high stress and fatigue damage to pipe. An accurate prediction of response is crucial assessment of the safety of submarine pipelines. Accurate response requires a well-adapted structural formulation and realistic description of both the external loading and interaction between the response and the loading. The response of pipeline is highly nonlinear because of the nonlinear pipe-soil interaction and the hydrodynamic loading.

When a part of a subsea pipeline is suspended between two points on an uneven seabed, it is referred to as a free span pipeline which is an important factor for safe operation of offshore gas or oil pipelines during and after installation, the free span lengths should be maintained within allowable lengths, determined during the design stage. Determination of the critical length of spans under various environmental conditions along the pipeline is an important element in pipeline design.

II. LITERATURE REVIEW

Zimmerman and Robert Hudspeth (1986) studied on the nonlinear transient response of deep –ocean pipeline in random wave environment. A finite element program has been developed for the prediction of large displacements of pipeline subjected to hydrodynamic loads on irregularly contoured marine sediments.Vincent et al (2006) studied dynamic response interaction of vibrating offshore pipeline on moving seabed. Pipeline was idealized as a beam vibrating on an elastic foundation. The seabed acts either as a damper or as a spring. The external excitation will increase the response of these pipes for which an amplification factor was derived. Whitea and Cheuk (2010) studied on modeling the soil resistance on seabed pipelines during large cycles of lateral movement. Response of long seabed pipelines that operate under high temperature and pressure and lateral buckling the pipeline undergoes were studied.

III. FINITE ELEMENT FORMULATION

The non-linear environmental loads to which the pipeline is subjected include hydrodynamic viscous drag, inertia lift and nonlinear sediment stiffness. A finite element formulation is employed that permits the pipeline to be discretized for numerical computations. Fluid loading on each element is computed from relative velocity form of Morison equation. A consistent mass approach is adopted. The structural and soil stiffness are computed. The soil stiffness is calculated by modelling soil as linear springs by Winkler's foundation model. For a random wave environment a 2D spectrum is adopted depending upon the sea conditions. The solution technique used to solve the equation is Newmark Beta. The displacement, velocity and acceleration of pipeline are determined in frequency domain for the study of parameters.

IV. GOVERNING EQUATIONS

The wave particle kinematics is as below,

A. REGULAR WAVE

The surface elevation for regular wave is given by,

$$\eta = a.\sin(kx - \omega t)$$

Fluid velocity component in the horizontal direction and vertical direction are given below

$$u = \frac{\omega H \cosh(k(d+z))}{2\sinh(k(d+\eta))}\cos(kx - \omega t)$$

$$v = \frac{\omega H \sinh(k(d+z))}{2\sinh(k(d+\eta))}\sin(kx - \omega t)$$

where, a is the wave amplitude, T is the time period of wave, $k = 2\pi / l$, is the wave number, l is the wave length, d is the water depth, z is the point at which water particle kinematics is to be determined with SWL as origin, η is the wave elevation, ω is the frequency of wave.

B. RANDOM WAVE

The wave particle kinematics for random waves is as below, In the present study, a Pierson Moskowitz wave spectrum model was taken as the representative spectrum.

It is given by

$$S(f) = \frac{5{H_s}^2}{16 f_0}\frac{1}{(f/f_0)^5}\exp\left(-1.25\left[\frac{f}{f_0}\right]^{-4}\right)$$

Where f is the frequency in cycles per second, f_0 is the peak frequency, H_s is the significant wave height.

The horizontal and vertical water particle velocity u(x,t) and the vertical water particle velocity v(x,t) are given by

$$u(x,t) = \sum_{n=1}^{N} a_n\omega_n \frac{\cosh(k_n y)}{\sinh(k_n(d+\eta))}(\cos((k_n x) - \omega_n t + \phi_n))$$

$$\dot{v}(x,t) = \sum_{n=1}^{N} a_n{\omega_n}^2 \frac{\sinh(k_n y)}{\sinh(k_n(d+\eta))}(\cos((k_n x) - \omega_n t + \phi_n))$$

Where k_n is the nth component wave number, y is the vertical distance at which the wave kinematics is calculated, d is the water depth.

A relative-motion form of the Morison equation is used to define the hydrodynamic loadings in terms of lift, drag and inertial forces.

$$F_X(t) = 0.5C_D\rho D(u-u_1)|u-u_1| + 0.25\pi\rho D^2 C_M\left[u - \left(1 - \frac{1}{C_m}\right)u_1\right]$$

$$F_Z(t) = .5C_L\rho D(v - \dot{u})^2$$

Where F_X is the distributed fluid loadings corresponding to inertia and drag and F_Z corresponds to lift. C_D, C_M, C_L are the drag, lift and inertial coefficients respectively.

C. DYNAMIC EQUILBRIUM EQUATION

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F(t)$$

Where '[M]' is consistent mass matrix, '[C]' is the damping matrix calculated using Rayleigh damping, [K] is the stiffness matrix which includes pipe stiffness (Ke), soil stiffness (Ks) based on Winkler's model and geometrical stiffness (Kg) from axial force.

V. PROBLEM DEFINITION

A straight stretch of pipeline with 72.5m span is used for the analysis. Table 1 gives the various physical properties of pipeline and fluids and Table 2 gives the wave data.

Table 1 Physical properties of pipeline and fluids

Youngs modulus of steel pipe(N/m^2)	2.06*10^{11}
Poissons ratio(μ)	0.3
Inner radius of the pipeline(m)	0.2923
Outer radius of the pipeline(m)	0.3050
Radius of concrete section(m)	0.3650
Length of pipe considered(m)	72.5
Depth of water(m)	61
Denisity of sea water(kg/m^3)	1025
Denisity of oil(kg/m^3)	881
Density of steel (kg/m^3)	7850
Density of concrete(kg/m^3)	2500
Shear modulus of soil(N/m^2)	5.53*10^6
Poison ratio of soil	0.25
External fluid pressure(kPa)	997
Internal fluid pressure(kPa)	1219.6

Table 2 Wave data

Wave height(m)	9.15
Time period(s)	12
C_D	1
C_L	1
C_M	2

VI. RESULTS AND DISCUSSIONS

The response in lateral direction is less as compared to that of the axial and vertical direction because the pipeline is lying on the seabed and in contact with it. The in-plane and out of plane rotations are negligible as the moments are only present at the boundary, at nodal points the moments are cancelled.

A steady current of is also considered to act along with wave. Currents are very important underwater, there can be positive or negative currents. For the present study a positive current of 0.61m/s is allowed to act along with wave. As the component of velocity attains higher values, the force values are increased. Also due to steady current a constant velocity acts and there will be a shift in the response. Instead of a displacement oscillating about mean position it is observed to have an initial shift due to current and displacements are observed about the shifted mean position as shown Fig. 2

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whereas Fig.1 shows response due to wave alone. A constant displacement 0.3m is observed due to the current and wave.

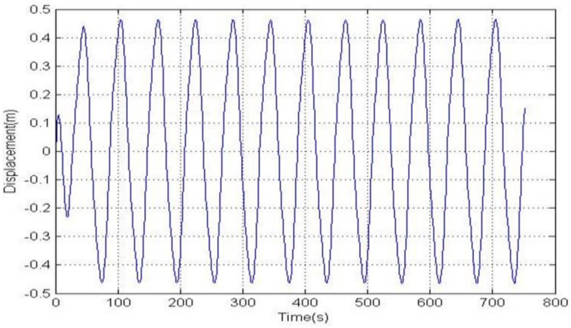

Fig.1: Midpoint displacement at wave incidence

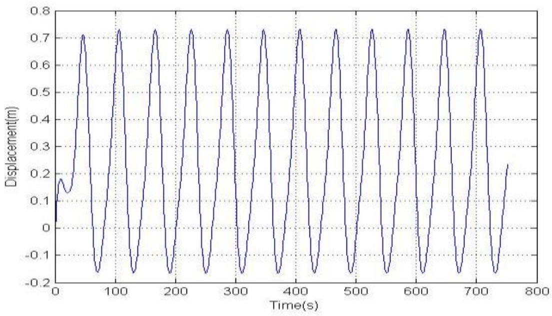

Fig.2: Midpoint displacement at wave and current incidence

In the present study, pipeline is now allowed to have a free-span at the center portion of pipe. The horizontal displacement observed in the pipeline due to free span at mid-point of the pipe is observed to have slightly larger amplitudes of 0.53m when compared with that of a pipeline completely resting on seabed. This is because of the decrease in the lateral stiffness of the pipeline due to uneven seabed Fig.3 shows the displacement at the centre node of the pipeline when there is a free span of 15m. The horizontal displacement observed in the pipeline due to wave and current at free-span of the pipe have larger amplitudes when compared with that of a pipeline completely resting on seabed or that having free-span and acted by wave. Comparison of midpoint displacement of pipelines with and without free-Span acted upon by wave alone, wave and current is tabulated in Table 3.

Table 3.Comparison of Displacement of Pipelines

Condition	Displacement(m)
Pipeline without free-span (Wave alone)	0.48
Pipeline with free span (Wave alone)	0.53
Pipeline without free-span (Wave+current)	0.74
Pipeline with free span (Wave +current)	0.86

The most crucial part in the area of response due to uneven seabed is the determination of critical free-span length. Table 4 shows the span lengths, stresses and the mid-point displacement when the pipeline is acted by wave and current. The critical free span length was obtained as 28.37m corresponding to a stress limit of 0.72fy=180N/mm^2.

Table 4 Variation of span lengths, stresses and the mid-point displacement when acted by wave and current

Free-span Length (m)	Stress (MPa) based on DNV-RP-F105	Horizontal Displacement (m)	Vertical Displacement (m)
15	50.310	0.8602	0.2968
15.75	55.466	0.8615	0.3173
16.5	60.875	0.8878	0.3398
17.25	66.534	0.9027	0.3634
18	72.446	0.9182	0.3881
18.75	78.609	0.9343	0.4138
19.5	85.024	0.9512	0.4405
20.25	91.689	0.9686	0.4683
21	98.607	0.9865	0.4972
21.75	105.776	1.0055	0.5271
22.5	113.197	1.0247	0.5613
23.25	120.869	1.0451	0.5900
24	128.793	1.0658	0.6231
24.75	136.968	1.0870	0.6572
25.5	145.396	1.1093	0.6923
26.25	154.074	1.1318	0.7285
27	163.004	1.1552	0.7657
27.75	172.185	1.1788	0.8040
28.5	181.619	1.2040	0.8432

$$\frac{L_{CR}}{D} = \sqrt[4]{\delta_{max} * \frac{384}{5} * E * \frac{\pi}{64} * (1-\lambda^4) * \frac{1}{w}}$$

$$\lambda = \frac{D_i}{D}$$

Where L_{CR} is the critical span length, D the outer diameter of the pipeline, D_i is the inner pipeline diameter, w is the weight per meter, E is the Young's modulus and δ_{max} is the displacement corresponding to L_{CR}. In the present study $\frac{L_{CR}}{D} = 48$

Simulation of unidirectional random waves PM spectrum is considered as a two parameter spectrum. In frequency spectrum the peak is observed at 0.414Hz as shown in Fig 3, which is the first natural frequency of pipeline and the frequency of the encountering waves is 0.08Hz.

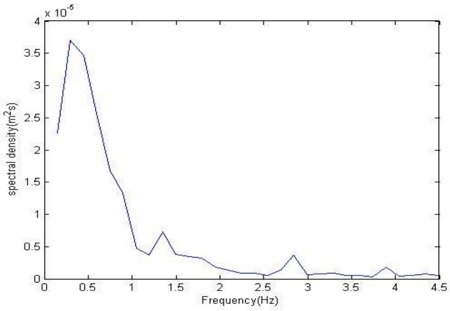

Fig 3: Power spectral density of vertical displacement

The significant value of vertical displacement is 0.0884m this is approximately one-eighth diameter of pipeline and the root mean square value, is calculated as 0.0631m.

VII. CONCLUSIONS

The pipeline is modeled as a 3-D beam element .Consistent mass approach is adopted for mass formulation and Rayleigh damping for calculation of damping matrix and Winkler's soil sprng model is adopted. The response of a seabed pipeline to wave forces in different wave environment is determined in frequency domain. Since the pipeline is in intermediate water depth, the effect of current and wave is predominant. A study on the critical free-span is conducted and an empirical relation derived.

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