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Modelling of upheaval buckling of offshore pipeline buried in clay soil using genetic programming

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ABSTRACT

Offshore pipeline is generally recognised to be the safest and most economical way to transport oil and gas. These pipelines are operated in elevated temperatures and pressures those are much higher than the ambient conditions. That will causes axial expansion in the pipeline, if such expansion is restrained by soil friction, the compressive force will be built up in the pipe, finally, induces the buried pipeline to buckle in the vertical plane. This paper investigates the effect of uncertainty in soil, operating condition and pipe properties on upheaval buckling behaviour of offshore pipeline buried in clayey soil. To simulate the upheaval buckling, a 2-D finite element model of 500 m long pipeline-seabed soil system was developed in OpenSEES using the thermal element. Using the finite element model prediction of upheaval buckling height, a total number of 12 upheaval buckling height prediction models were proposed by using genetic programming with varying levels of complexity and accuracy. To achieve the best performance model, a scoring table was proposed considering several factors including coefficient of determination, sum of errors, difference between training and testing errors, sum of residuals, deviation of predicted results from experimental one and complexity and generality of the models. Finally, the effect of each parameter on upheaval buckling displacement was studied by parametric analysis and the results were compared by simulated ones. On the basis of the results, most of the models developed using genetic programming show very good prediction with the numerical results. The developed model can be used to improve the design and upheaval bucking risk assessment of buried pipeline.

1. Introduction

In the last few decades, the operating temperatures and pressures for subsea oil and gas pipelines have dramatically increased due to the deep sea explorations. This causes axial thermal expansion in pipeline; however, the expansion is resisted by soil friction that will set up the axial compressive force in the pipe wall. The compressive forces are frequently large enough to induce either lateral buckling in as-laid pipe or upheaval buckling in buried pipe. Moreover, the new trend towards using small diameter pipes has potentially increased the risk of buckling in accordance with the greater axial loads. Although these two buckling modes (i.e., lateral or upheaval) are not essentially failure modes, they can precipitate failure through excessive bending. This may cause fracture, fatigue or propagative buckling [12,3].

Prediction of upheaval buckling resistance of buried pipelines has been a challenge as a result of uncertainty in the behaviour of seabed and cover soils, operating condition and pipe material [26]. The design and assessment of offshore pipeline against upheaval buckling are mostly based on the early analytical work reported in Randolph and Houlsby [23] and Maltby and Calladine [15]. Several experimental works were also reported in the past [27,5,4,8,16] to understand the uplift resistant provided by soil cover to pipe buried in granular soils. However, very limited number of studies was reported in the literature for pipe buried in clayey soils. Recently, Cheuk et al. [7] and Thusyanthan et al. [26] reported the experimental work to understand the uplift resistance of clay. However, the effect of variability in soil properties in uplift resistance has not been quantified, which requires significantly high number of experiments. One of the feasible ways to quantify the effect of variability in soil properties and other parameters is to model the pipeline system numerically and simulate the possible scenarios.

In this paper, upheaval buckling behaviour of offshore pipeline buried in clayey soils has been investigated numerically. Possible variability in soil uplift resistance, operating condition and pipe properties has been considered in the analysis. To simulate the

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Table 1
Soil, pipe and operational condition parameter uncertainty.

Parameter	Unit	Distribution	Mean	CoV (%)
Diameter	mm	Fixed	900	–
Thickness	mm	Lognormal	25.0	6.0
Elastic modulus	GPa	Lognormal	204.0	6.0
Clay stiffness	kPa	Lognormal	200	30
Temperature	°C	Truncated normal	75 [50–120]	15
Pressure	MPa	Normal	20.0	20
Product density	kg/m^3	Lognormal	200	10

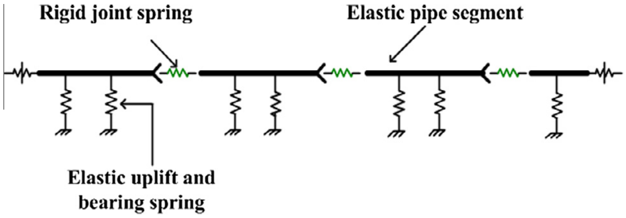

Fig. 1. Schematic diagram of buried offshore pipeline.

upheaval buckling behaviour, a 2-D finite element model of 500 m long pipeline-seabed system was developed in OpenSEES [17]. The uncertain variables were modelled using appropriate probability distributions discussed in Rajeev et al. [21], and also the optimised Latin Hyper Cube (LHC) sampling technique was utilised to draw the sample for numerical simulation. Finally, genetic programming was used to develop the upheaval buckling predictive equations with varying accuracy and complexity. The effect of uncertain in soil and pipe material properties and operating conditions in the upheaval buckling response of buried offshore pipeline was also quantified. The developed upheaval buckling height predictive equations can be used to improve the design and risk assessment of pipeline against upheaval buckling.

2. Definition of the problem

A 500 m of offshore pipeline was considered for the analysis with the pipe material properties given in Table 1. The OpenSEES (finite element software) was employed to model pipe-seabed soil system and to conduct the thermal analysis. In this study, the pipe was modelled with elastic beam element using displacement based beam–column element with steel thermal properties, while the seabed and cover soils were modelled with elastic zero-length spring element. The fibre section was used to model the pipe section and the joint in the pipeline was assumed behave as a rigid link. The ends of the pipe were restrained all directions. It was observed that the length of the pipeline considered is relatively high (i.e., 500 m), therefore the support condition at the ends have insignificant influence in the predicted buckling height. The temperature variation during the pumping operation has applied to the model as a thermal load and the pumping pressure was converted as an equivalent thermal load as explained in Liu et al. [24]. More details about the thermal modelling of structures using OpenSEES can be found elsewhere (e.g., [11]). It is worth noting that if the effect of elastic model parameters is considerable, then the effect will be much higher in the nonlinear system. Fig. 1 shows the schematic diagram of the finite element model of the pipeline.

3. Probabilistic modelling of uncertain variables

The soil cover, operating condition and pipe material and geometric properties are treated as uncertain variables that have significant influence in the performance of pipeline. Following variables are considered: elastic modulus of backfill soil (E_s), pipe wall thickness (t), pipe elastic modulus (E_p), operational temperature (T) and pressure (P), product density (γ_p). The assigned probability distribution and its statistical properties of considered variables are listed in Table 1 that gives the respective mean values and corresponding coefficient of variation (CoV) of the parameters together with assigned probability distribution as reported in Rajeev et al. [21]. Optimized Latin Hypercube Sampling (OLHS) technique is used to draw the samples to quantify the uncertainty in the pipe response [18]. OLHS provides a stratified sampling scheme rather than the purely random sampling, as it provides more efficient means of covering the probability space (e.g. [22].

4. Modelling procedure by genetic programming

Genetic programming (GP), which was proposed by Koza [14], is one of the newest paradigms of evolutionary computations and is capable to automatically learn the introduced problem through mimicking Darwinian evolution process [6]. An extension to GP is gene expression programming (GEP) that was used in this paper to develop the upheaval buckling predictive models. GEP is able to create computer programs, which can be written in MATLAB or C++, of different sizes and shapes encoded in linear chromosomes of fixed length, and to solve relatively complex problems by utilising small population sizes [25]. GEP encodes individuals of the created computer program as linear strings of fixed lengths (the genome or chromosomes). These are then expressed as genes (expression trees or ETs) with different sizes and shapes [25]. The final formulation is extracted from these ETs. Performance of a GEP model is evaluated by these equations that normally vary from very simple with lower accuracy to extremely complex with higher accuracy. The selection of the equation depends on the type of application and the required accuracy in the prediction (i.e., simple equation even with lower performances are preferred).

GEP has been successfully applied to many civil engineering problems including materials and structural branches

Table 2
Statistical parameters of input and target data.

Statistical parameter	t (mm)	E_P (GPa)	E_S (kPa)	T (C)	P (Pa)	ρ (kg/cm^3)	Displacement (mm)
Minimum	20.2	169	79.1	48.0	10.8	146	14.5
Maximum	29.7	242	460	106	28.9	267	30.9
Range	9.48	73.7	381	58.3	18.1	121	16.4
Average	25.0	204	201	73.4	19.9	200	21.8
Standard deviation	1.50	12.2	60.1	12.2	3.02	19.8	3.38
Sample variance	2.26	148	3608	150	9.10	392	11.4
Median	24.9	203	193	72.7	19.9	199	21.5
Skewness	0.144	0.163	0.866	0.224	0.04	0.316	0.465
Kurtosis	0.038	−0.053	1.092	−0.547	−0.051	0.134	−0.215