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Research Paper

Uplift Resistance of Buried Pipelines in Partially Saturated Sands

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ABSTRACT

High Pressure and High Temperature (HPHT) oil and gas pipelines are commonly buried subsurface and the depth of burial is determined by upheaval buckling mitigation requirement or legislation requirement. The upheaval buckling mitigation design requires evaluation of uplift resistance of soil in which pipeline is buried. Conventional design guidelines and current analytical models for predicting the soil uplift resistance are based on either dry soil or fully saturated soil. However, onshore pipeline are buried in soils which are often partially saturated. Therefore, current analytical models do not capture the effects of soil saturation on the uplift resistance of buried pipeline. In partially saturated soils, the uplift resistance is greater than that under fully saturated conditions. This is because the water meniscus between soil particles creates an additional normal force due to suction, which in turn makes the soil behaviour stiffer and stronger. This paper presents full scale pipe-soil tests results and finite-element parametric studies conducted to investigate the effects of soil moisture content, dimensionless cover heights (soil cover height to diameter ratio) and soil relative density on the peak uplift resistance of pipes. The results demonstrate that the current available analytical models under-predict the soil peak uplift resistance in partially saturated conditions. Further, the analyzed results are presented as dimensionless design charts and non-linear regression models which can be used to quantify the partial saturation effect on uplift resistance of buried pipes.

1. Introduction

Onshore pipelines are commonly buried at shallow depths typically ranging from 0.5 m to 2 m in which the soil condition is most often partially saturated. However, the conventional design guidelines and analytical models for predicting the uplift pipeline resistance are based on either dry or fully saturated soil condition. In partially saturated soils, a meniscus forms between soil particles, creating an additional normal force binding the particles by suction. This in turn forms temporary bonds so that the unsaturated soil behaves stiffer and stronger than the dry or fully saturated soils (having the same dry density).

High pressure and high temperature (HPHT) pipelines, which are susceptible to upheaval buckling, requires a minimum depth of soil cover to provide the sufficient uplift resistance against upheaval buckling. The depth of soil cover, either within a trench or in a soil berm, is determined based on pipeline operating conditions and soil uplift resistance. The cost associated with burial depth is a significant portion of the total construction cost of the pipeline. Therefore, the depth of soil cover height in HPHT pipelines requires a compromising decision of choosing sufficient soil cover height while minimizing the construction costs & making the design economically viable. Thus, an in-depth understanding of peak uplift resistance in realistic non-dry soil (i.e. partially saturated soils) condition is beneficial in the design of onshore HPHT pipelines.

The paper presents full-scale results and finite-element (FE) parametric studies conducted to investigate the effects of soil moisture content, dimensionless cover heights (soil cover height to diameter ratio) and soil relative density on the peak uplift resistance of pipes. Two-dimensional FE analyses were conducted on the basis of steel pipeline buried in unsaturated finer sand, behaviour of which was modelled using unsaturated Nor-Sand model [24]. Firstly, the finite element models are validated against the data from large scale physical model tests at different soil conditions. Then, a series of FE analysis was conducted to investigate the effect of soil saturation on uplift pipe resistance. The analyzed results are presented using dimensionless design charts and an analytical tool which can be used to quantify the partial saturation effect on uplift resistance of buried pipes.

2. Literature review on soil uplift resistance

Substantial analytical and numerical works have been conducted by previous researchers to investigate the uplift resistance and failure

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Nomenclature

a	void ratio constant
A_d	dilatancy enhancement shape function constant
A_s	cohesion enhancement shape function constant
A	shear modulus constant
b	water saturation constant
CPE4R	4-node bilinear, plane strain, reduced integration with hourglass control elements
D	pipeline diameter
$d\varepsilon^{vol}$	change in volumetric strain during load increment
FE	Finite Element
$F_{\max}$	maximum soil uplift resistance on the pipe
f_p	uplift factor based on [11]
G_{sat}	saturated shear modulus
G_{unsat}	unsaturated shear modulus
G	shear modulus constant
H	cover height to the middle of the pipeline
H_t	cover height to the top of the pipeline
HPHT	high pressure and high temperature
I_D	relative density
I_R	relative dilatancy index
K	co-efficient of earth pressure
k_1	dilatancy enhancement shape function constant
k_2	cohesion enhancement shape function constant
L	length of the pipe
n_1	initial porosity of the element
N	flow rule constant
N_q	uplift factor based on [2]
NCL	normal consolidation loci
NLGEOM	non-linear geometry option in ABAQUS
N_q^{sat}	peak dimensionless uplift resistance in saturated soil
N_q^{unsat}	peak dimensionless uplift resistance in unsaturated soil
P'	effective mean stress
p_d	dilation enhancement
p_s	cohesion enhancement
R	uplift soil resistance per unit length of the pipeline
S_r	residual degree of soil water saturation
S_w	soil degree of water saturation
S_{w1}	initial degree of saturation (before loading)
s	matric suction (negative pore water pressure)
S_1	dilatancy enhancement shape function constant
S_2	cohesion enhancement shape function constant
$S_{d\max}$	dilatancy enhancement shape function constant
$S_{s\max}$	cohesion enhancement shape function constant
u_a	pore air pressure
u_w	positive pore water pressure
γ'	effective unit weight of soil
γ_{dry}	dry unit weight of soil
δ_{ij}	Kronecker's Delta
ϕ'	soil effective friction angle
ϕ_μ	interface friction angle between pipe and soil
ψ	soil dilation angle
τ	frictional shear stress between pipe and soil
τ_{crit}	maximum allowable frictional shear stress
σ_n'	contact pressure
μ	interface friction coefficient
σ	total normal stress
σ'	soil effective stress

mechanisms of soil during upward displacement of pipes in dry/saturated soil medium [33,6,37,35,10,29,7,30,31,32,27].

The vertical slip failure mechanisms as shown in Fig. 1a is the most commonly used uplift model in the industry. Previous observations from model tests suggest that the uplift failure mechanism (i.e. inclination of the shear zone) depends on the initial state of the sands and the cover depth. For medium to dense backfill soils with shallow pipeline burial, inclined slip surface model (Fig. 1b) was experimentally proven to be a closer approximation for the real deformation mechanisms [30]. For deeper pipeline burials, a localized shear with a flow-around mechanism was observed in model tests conducted by [6] for very loose sands (Fig. 1c). A similar mechanism was also observed by [37] for initially dense sand after the peak resistance is achieved. Such mechanism has also been numerically predicted by [35] for very loose sand. [7] showed that the average inclination of the shear zones is influenced by the soil density, with denser soil being more dilatant.

Several prediction models have been reported in literature to assess the peak uplift resistance of pipes buried in granular soils. [28] have proposed a limit equilibrium solution (known as vertical slip model; Fig. 1a) to estimate the uplift resistance (Eq. (1)) due to shear resistance along the vertical slip surface and weight of the soil block.

$$R = \gamma' H_t D + \gamma' H_t^2 K \tan\varphi \tag{1}$$

where R is the uplift soil resistance per unit length of the pipeline, D is the pipeline diameter, H_t is the cover height to top of pipeline, K is coefficient of earth pressure and φ is the soil friction angle.

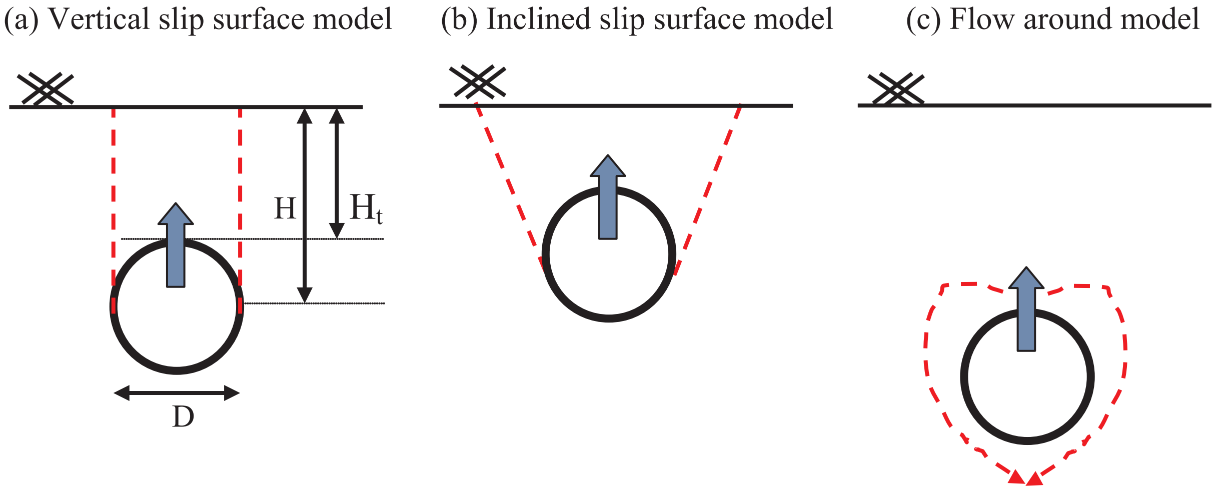

Fig. 1. Different uplift failure mechanisms in granular soils; (a) Vertical slip surface model, (b) Inclined slip surface model and (c) Flow around model.