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Upheaval buckling of pipelines due to internal pressure: A geometrically nonlinear finite element analysis

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ABSTRACT

This work presents an analysis of upheaval buckling of pipelines triggered by internal pressure. It discusses the existing relationship between internal pressure and equivalent compressive axial force in the buckling context. The main focus is on the relative influence of prop imperfections and soil friction coefficients in critical load prediction and post-buckling configuration. To perform the analyses, numerical models are developed using geometrically-exact finite element of beams, undergoing large displacements and finite rotations. Contact between the pipeline and the soil is also included in the models. As a result, the work shows the equivalence of applying the internal pressure as a distributed load dependent on pipe curvature and as a follower compressive axial force, both in terms of critical load and post-buckling configuration. Varying prop imperfections and soil friction coefficients, it is concluded that the first parameter has more influence in critical load prediction than the last one. The same occurs in terms of post-buckling configuration: for the same increase of internal pressure from critical load, the imperfections have more influence in the post-buckling displacements than the friction between the pipeline and the soil.

1. Introduction

An important activity in the productive chain of oil and gas is the transportation of the raw materials to the distribution and refining sites. Such transportation is made mainly by pipelines. The pipelines can experience high temperature and pressure, reaching levels above 150 °C and 70 MPa, respectively [1]. With such conditions, the pipeline tends to expand longitudinally. However, the pipeline expansion can be restricted, generating an axial compression. Depending on the level of compression, the pipeline can buckle. Buckling can occur either in the vertical plane (upheaval buckling) or in the horizontal plane (lateral buckling). It is important to have in mind, however, that the mere occurrence of buckling, regardless of its type, does not characterize the failure of the pipeline. The problem is in the uncontrolled buckling, which leads to failure phenomena such as local buckling, fracture and fatigue [2]. These phenomena can cause the oil leakage, damaging the environment. So, it is possible to infer that studies about buckling are important and necessary to minimize the probability of accidents involving pipelines.

First of all, it is important to understand the global effects of temperature and pressure in the pipeline. The temperature effect follows the idea previously exposed and can be considered as a compressive axial force providing from the integration of the stresses on the pipe cross section. The pressure effect, however, is not so intuitive as the temperature effect. For instance, for a pipeline without endcaps and only subjected to internal pressure, the integration of the stresses on the pipe cross section generates a tension axial force. But, depending on the magnitude of the internal pressure, buckling can occur. So, to analyze the pressure effects correctly, it is necessary to integrate the internal and external pressures on the internal and external wall areas of the pipeline. This procedure, however, can be very hard-working depending on pipe geometry, as discussed in [3]. This reference proposes, by the way, a formulation to apply the pressures as equivalent distributed loads dependent on pipe curvature, as it will be commented later in the present paper.

Another way to analyze the pressure effects is to use the effective axial force concept, as proposed by [4,5]. Fig. 1 shows a pipe segment with length ds, internal diameter D_i and external diameter D_e. It is subjected to the internal pressure p_i, the external pressure p_e, the self-weight $W_t$ds and the true axial force in the pipe wall T_{tw} (as a result of the integration of the stresses on the pipe cross section). As the system presented is not closed, for applying the Archimedes' Principle, it is necessary to separate the original system into three different contributions. The first and the second correspond to closed systems on which the external and internal pressures are applied, respectively. The third, in its turn, is a closed system on which act, besides the pipe self-

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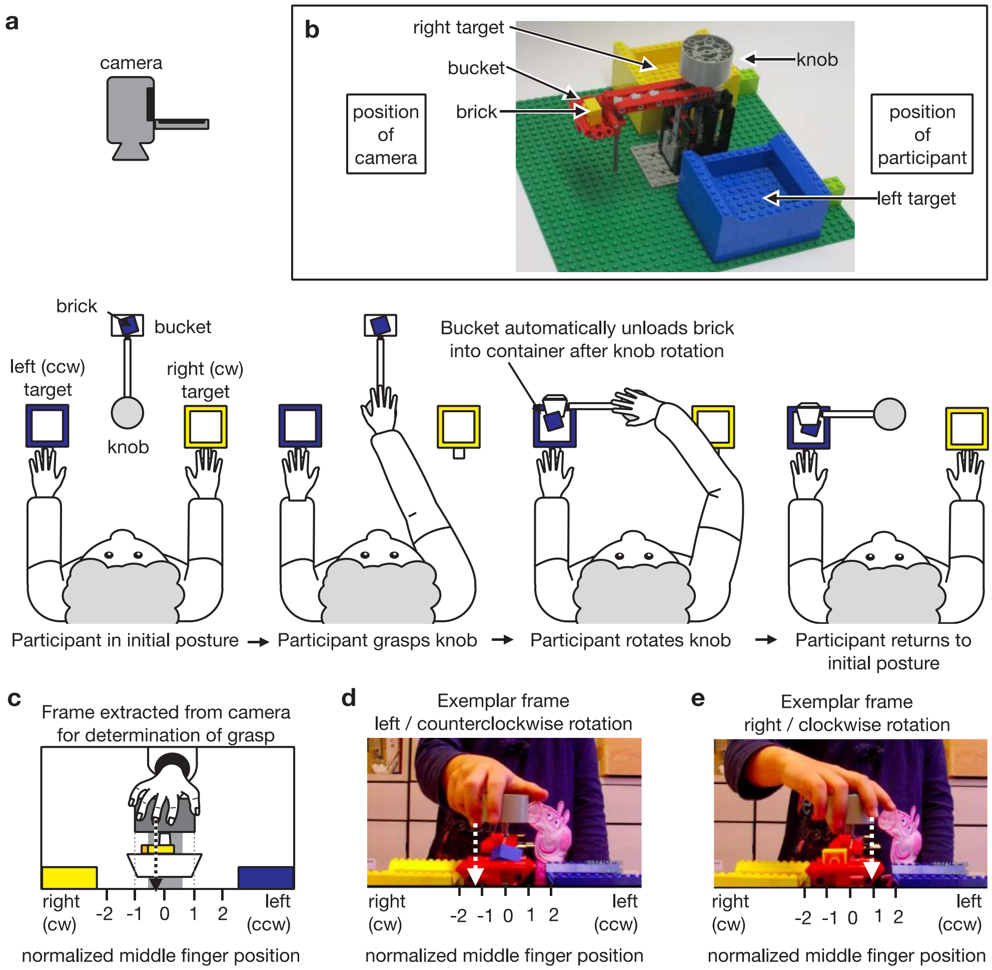

Fig. 1. Equivalent systems for pipelines subjected to external and internal pressures. Adapted from [6].

weight and the true axial force, terms of internal and external pressures at the pipe ends. These terms compensate the additional terms included in the previous systems. The effective axial force is given by

$$P_0 = T_{tw} + \frac{\pi}{4}D_e^2 p_e - \frac{\pi}{4}D_i^2 p_i, \quad (1)$$

which can be compressive due to internal pressure, making buckling possible. So, it is necessary to predict for which magnitude of such force buckling occurs.

Hobbs [7] studies analytically both upheaval and lateral buckling, without the consideration of imperfections in the pipeline. Assuming an elastic-linear approach with small slopes and varying the friction between the pipeline and the soil, the results are graphs that relate buckle lengths to temperature rises. The author concludes that lateral buckling occurs with smaller compressive forces than upheaval buckling and that the critical force increases when the coefficient of friction increases. With the same assumptions proposed by [7], Taylor and Gan [8] and Taylor and Tran [9] address pipelines with symmetrical imperfections. In the present paper, special attention will be given to the prop imperfection studied by [9]. It is characterized by not establishing a total contact with the pipeline (such as a pipeline on a rock). Having as result graphs that relate buckle lengths to temperature rises, [7,8] conclude that the cases with smaller imperfections have larger critical loads than the cases with larger imperfections. Concerning asymmetrical imperfections, Ballet and Hobbs [10] and Hunt and Blackmore [11] verify that they generate smaller critical loads than symmetrical imperfections.

The most recent studies about buckling of pipelines employ the finite element method (FEM) to perform numerical analyses. Liu, Wang and Yan [12], for example, analyze pipelines with the symmetrical imperfection proposed by [8]. They also verify that there is a dependence between the critical load and the imperfection amplitude. Zeng, Duan and Che [13] and Zhang and Duan [14] study various cases of imperfection, focusing on the determination of expressions for the critical load. The first research concludes that when the ratio between the amplitude and the length of the imperfection increases, buckling occurs with smaller critical temperature and less abruptly. The second research, in its turn, concludes that when the ratio between the curvature and the length of the imperfection increases, the critical load decreases.

All works exposed previously consider the pipeline as a beam. It is a simplification that brings significant reduction in the computational cost, when compared to shell/solid models. Besides this, depending on the level of detail required, this assumption provides suitable results for the global buckling of pipelines. In this context, Ref. [15] discusses results obtained from different FEM models. Still analyzing the works exposed, it is also possible to note that, although there are studies that address the influences of imperfections and of friction in the critical load, there is no study, by the authors' knowledge, that compares relatively such influences both in terms of critical load and post-buckling configuration.

Another notable aspect that can be highlighted from literature is that none of them uses the internal pressure as triggering load for buckling, but only temperature. It is clear that the objective of such works is to determine the magnitude of the critical load, generically. As both temperature and internal pressure affect the pipeline axial force distribution, critical loads can also be expressed in terms of internal pressure. And more relevant than that, the use of the internal pressure as the only triggering for buckling makes possible the application of the theoretical discussions raised by [4,5] in numerical and more realistic