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Analysis of buried pipelines subjected to reverse fault motion using the vector form intrinsic finite element method

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ABSTRACT

Buried pipelines crossing reverse faults is a common case in practice, while their mechanical responses are not very clear. To analyze buried pipelines subjected to reverse faults, a beam-shell coupling scheme is proposed based on the Vector Form Intrinsic Finite Element (VFIFE or V-5) method. Particular emphasis is given to identifying pipeline failure with three performance based limit states: the local buckling, the tensile strain limit and the flattening parameter limit. The critical fault displacements, at which the specified performance criteria are reached, are presented in diagram form. Effects of fault displacement, crossing angle, as well as fault dip angle on critical fault displacements are examined. This study shows that when the fault dip angle is 40°, the critical fault displacements of local buckling and pipe-wall rupture are the largest when a pipeline is oriented approximately parallel to a reverse fault plane. And for a perpendicularly crossing pipeline, the smaller the dip angle is, the more severe the cross-section distortion will be. Moreover, the critical strain of local buckling are obtained and compared with the recommendation of CSA Z662.

1. Introduction

Long distance buried pipelines are among the most important transportation means of natural gas and oil. When a buried pipeline crosses an active reverse fault, it is expected to develop severe stresses and strains and sometimes even rupture of the pipeline wall. This could result in leakage of the hydrocarbon contents and further cause irrecoverable ecological disaster. Investigation shows that a large number of active faults that threaten the safety of many long-distance buried pipelines in western China are reverse fault [1]. Given this fact, an in-depth understanding of the behavior of the pipelines subjected to reverse faults has become one of the top priorities in design of pipeline systems.

A large amount of literature is available on the performance of pipelines subjected to active faults. Many researchers conducted studies on pipelines subjected to active faults by means of field experiments [2,3], small-scale experiments [4], large-scale (full-scale) experiments [5–9], centrifuge tests [10] and shaking table tests [11,12]. In these studies, effect of the angle of a pipeline crossing an active fault is proved significant [3,10] and considering the nature of soil behavior is proved essential. Ignoring there factors may lead to either unsafe or uneconomical design of pipeline systems. Results of experimental studies are reliable and enlightening, while it may be very time-consuming and expensive to conduct an experiment. Therefore, analytical and numerical methods are also preferred by researchers and engineers.

Analytical researches in this field were firstly conducted by Newmark and Hall [13], Kennedy et al. [14] and Wang and Yeh [15] and were extended recently [16–20]. Effects of the geometric and material nonlinearities [16,17], the internal pressure and temperature variation [19], as well as formation of the plastic hinges on both sides of the pipe with respect to the fault [20], are considered in the analytical methodologies. Nevertheless, the pipeline behavior would be dominated by global buckling and local buckling under compressive fault movement. In this situation, the analytical solutions are no longer applicable and numerical methodologies are used.

When a pipeline crosses a seismic area, several active tectonic faults will be encountered. Therefore in practice, beam-type numerical model is applied by design engineers due to its high efficiency. Many researchers have proposed beam-type numerical models to study pipelines subjected to fault movement [5,21–23]. Besides being highly efficient, the beam-type model is capable of incorporating the geometric and material nonlinearity [5], global buckling of the pipeline [21] and the formation of plastic hinges in the pipe due to incrementally applied fault movements [22].

A pipeline subjected to compression in addition to material

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deformation will undergo local buckling. In this case, the beam or pipe element may lead to errors [5]. Therefore, the continuum model (pipe modeling with shell elements and the surrounding soil with solid elements) are employed when additional parameters, such the native soil properties and the trench dimensions, are available and need to be considered. Results of the continuum models were validated by experimental results and good agreement was obtained for both small-scale experiment [4] and large-scale experiment [6,9]. Using the continuum models, many researchers [24–27] investigated the mechanical behavior of buried steel pipelines crossing active strike-slip faults. Local buckling was observed at relatively small fault displacements and the influence of crossing angle on pipeline local buckling was examined. Besides, effect of the ends' constrains of the buried pipeline was considered and proved significant. Since the continuum models are computing expensive, the pipelines are always very short, with length of tens of the pipeline diameters. Meanwhile, the end conditions of the pipeline segment were fixed [25,26], or modeled with equivalent nonlinear springs [24]. Nevertheless, the mathematical solutions of the equivalent nonlinear springs are only applicable for straight pipeline with ideal longitudinal pipe-soil interaction.

Beam-type models may provide efficient and reasonable predictions of the pipeline responses [5,21], while they lack sufficient details of cross-sectional distortion and local buckling of the pipelines. The shell-type continuum models can rigorously model the pipe-wall deformation, while they are computing expensive. Therefore, a method which can combine the advantages of the beam-type and shell-type models could be helpful. Considering that the plasticity and cross-sectional deformation occurs only near the fault crossing and can be neglected farther away, Karamitros et al. [16] developed a hybrid model with the commercial code MSC/NASTRAN. In their model, the pipeline near the fault plane is modeled with shell elements, while the other segments farther away from the fault plane are modeled with beam elements. The shell segment and the beam segments are connected with rigid bar elements. The hybrid model not only improves the computing efficiency without reducing in accuracy, but also solves the challenge of ends' constrains of the pipeline.

In this paper, a similar beam-shell coupling scheme based on the Vector Form Intrinsic Finite Element (VFIFE or V-5) method is proposed. Similar to the coupling scheme of Karamitros et al. [16], rigid connection between the shell segment and the beam segment is used. Whereas in the present scheme, the rigid connection is realized by controlling the node motion in the coupling plane, instead of connecting the segments with rigid bar element. The material and geometric nonlinearities are considered and the pipe-soil interaction is modeled with soil springs. Details about the VFIFE method and the beam-shell coupling scheme will be introduced. Subsequently, considering different performance criteria: the local buckling, the tensile strain limit and the flattening parameter limit, effects of fault displacement, crossing angle and fault dip angle on the maximum allowable fault displacement will be examined.

2. Numerical method

In recent years, Ting, Shih [28–30] proposed the Vector Form Intrinsic Finite Element (VFIFE) method, which was used to analyze the mechanical responses of pipelines [31–33]. In this paper, a FORTRAN procedure of the VFIFE 3D beam element and the VFIFE 3D triangular shell element are developed, together with a beam-shell coupling scheme. All the necessary calculations are performed using the FORTRAN procedure developed by the authors. The VFIFE method and the beam-shell coupling scheme are briefly introduced below. Refer to literatures [28–31,34,35] for details about the VFIFE method.

2.1. VFIFE method

As shown in Fig. 1(a) and Fig. 2(a), a pipeline is decomposed to finite mass particles linked by 3D beam element and 3D shell elements, respectively. Corresponding to conventional FEM, a mass particle is also called a node in this paper. In Fig. 1(b) and Fig. 2(b), t_a and t_i are the starting and ending time of a movement, respectively. The time from t_a to t_i is discretized into a series of small time steps dt divided by t_b, t_c, t_d, ..., t_i. During one time step $t_c \le t \le t_d$, the state at t_c, instead of the starting state at t_a, is taken as the initial state. Shape and position of a pipeline are described by tracing the nodal movements, which are computed following the Second Newton's Law:

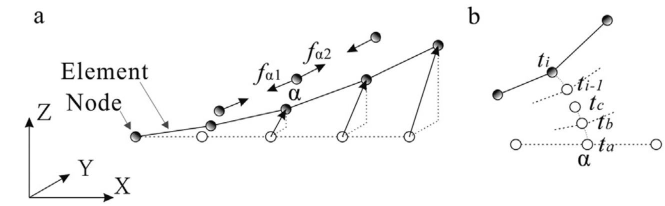

Fig. 1. Structural and movement discretization of beam elements in the VFIFE method: (a) structural discretization; (b) movement discretization.

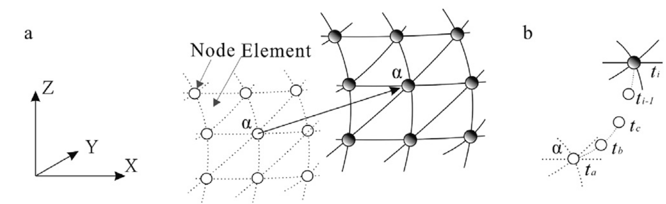

Fig. 2. Structural and movement discretization of shell elements in the VFIFE method: (a) structural discretization; (b) movement discretization.

$$\mathbf{M}_\alpha \frac{d^2\mathbf{d}_\alpha}{dt^2}(t) = \mathbf{P}_\alpha(t) + \mathbf{f}_\alpha(t) \quad (\alpha = 1, 2, 3, \dots, N) \tag{1}$$

$$\mathbf{I}_\alpha \frac{d^2\mathbf{\theta}_\alpha}{dt^2}(t) = \mathbf{Q}_\alpha(t) + \mathbf{m}_\alpha(t) \quad (\alpha = 1, 2, 3, \dots, N) \tag{2}$$

where α is the node number and t is time; $\mathbf{M}_\alpha$ is the mass matrix; $\mathbf{d}_\alpha$ is the nodal position; $\mathbf{P}(t)$ is the external force; $\mathbf{f}(t)$ is the internal force; $\mathbf{I}_\alpha$ is the rotational inertia matrix; $\mathbf{\theta}_\alpha$ is the rotational vector; $\mathbf{Q}_\alpha$ and $\mathbf{m}_\alpha$ are the external and the internal moments matrix, respectively. The mass matrix and the rotational inertia matrix are calculated out following Appendix A.

2.1.1. Internal forces

The internal forces applied on a node are composed of the forces from its adjacent elements:

$$\mathbf{f}_\alpha = \sum_{i=1}^{N} \mathbf{f}_\alpha^i \tag{3}$$

$$\mathbf{m}_\alpha = \sum_{i=1}^{N} \mathbf{m}_\alpha^i \tag{4}$$

where N is the number of the elements adjacent to node α, $\mathbf{f}_\alpha{}^i$ and $\mathbf{m}_\alpha{}^i$ are the force component and the moment component applied on node α from the i^{th} adjacent element, respectively.

Different from other intrinsic formulations, the elements are deformable and the shape functions satisfy the continuity condition in the VFIFE method. The node displacement in a time step is composed of element deformation and rigid element motion [35]. The rigid element motion is irrelevant with the element internal forces and therefore, it is eliminated with fictitious reversed motion. After the elimination, the element deformation is obtained and the element internal forces can be calculated out with the element deformation. See Appendix B and Appendix C for details about calculating the internal forces of the beam and shell elements, respectively.