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Dynamic response of buried gas pipeline under excavator loading: Experimental/numerical study

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ABSTRACT

Recently, the ongoing mining risk and damage quantitative assessment methods for buried gas pipelines are mostly implemented on the static test data. Naturally, dynamic experimental results may help to enhance the fidelity of the evaluation strategy. The excavator-pipeline-soil test system in this paper is designed to detect the impact digging force, which is derived from the liquid pressure oscillation of hydro-cylinders and the inertial force of mining equipment. The dynamic loading coefficient and impact force under various mining modes are evaluated by experimental and multibody dynamics software, and the results are subsequently verified by comparison with a series of LS-DYNA modeling responses. It should be stressed that the obvious growth of dynamic digging force is as important as the critical resistant analysis to the buried gas pipeline. Thus, one can establish more confident judgments with regard to ground mining protection and damage assessment.

1. Introduction

The frequency of pipeline external incidents was increasing in the past decade. However, such incidents are hard to predict and prevent due to the high uncertainty of inference by ground activities. Based on the 1249 incidents in the PID (pipeline incident databases) from 1970 to 2010, the statistical analysis made by EGIG (European Gas pipeline Incident data Group) companies demonstrates that approximately 48% of pipe accidents were caused by external interference, which was equivalent to the total frequency of other known accidents [15]. PHMSA (Pipeline & Hazardous Materials Safety Administration), as a member of the U.S. DOT (Department of Transportation), described the external interference as excavation damage. Among the accidents reported from 1993 to 2012, approximately 18.7% and 20.4% accidents occurred in pipelines and gas pipelines, respectively [31]. The high external accident frequency for pipelines also exists in other developed countries which already have an advanced pipeline system, such as Canada, Australia and Russia, etc. Among these damages, excavation loading has become the main risk of pipe defects, which can be caused by the behaviors of mining, sloping, trenching, drilling, etc. Recently, gas and oil pipeline laying in China has become faster and faster with rapid economic development; for example, the mileage of pipeline will be up to 150,000 km in 2015, which may increase the risk of pipeline external interference dramatically since the urban expansion. It is regrettable that no specific pipeline incident database was created in China, even after 1000 pipe accidents have occurred from 1995 to 2012. A report from the UPCC (Underground Pipeline Committee of China Association of City Planning) indicates that approximately 10% of incidents are due to the defects of the pipe body itself, and over 70% are attributable to the external interference that may come from natural disaster, artificial sabotage and third-party operations. Related report found that “there is an excavator worked near the pipeline as the most

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possible scenario before the accident was found in the urban gas pipeline system." In the period from 2009 to 2013 in China, 27 casualty-related underground pipe accidents occurred in China with 117 people killed, and it seems that this number will increase in the next decade as a result of an increase in the miles of oil/gas transportation. According to database statistics, the underground utilities in the city are more vulnerable to excavators; however, more serious consequences may be produced from long distance, high inner pressure gas pipelines that evolve mechanical defects, including coating spalling and local dent and gouge. Therefore, prevention strategy, as well as the quantitative evaluation after damage, cannot be taken lightly.

Pipe resistance to external interference such as hydraulic excavators has been carried out by several research groups and corporations with different damage modes. EPRG (European Pipeline Research Group) developed a "pipe aggression" test rig to perform static and dynamic digging experiments. Their recommendations included a complete test database for pipeline engineers in-situ, as well as semi-empirical prediction equitation about the dent resistance, gouge resistance, dent and gouge combination resistance and puncture resistance [8–10,32,36,37]. Battelle laboratories have undertaken research dealing with the dents, dent and gouge combinations and punctures, and carried out the internal pressures effecting analysis of the pipeline under the dent behavior. Moreover, puncture resistance of the pipelines were tested and simulation under quasi-static conditions was also carried out, and the results showed that pipes with the largest wall thicknesses exhibited the greatest puncture resistance [1,25,27]. Beside puncture damage, BG (British Gas) has researched the damage modes of plain dents and dent and gouge combinations, as well as the dent and gouge combination fatigue safety topic with other organizations; meanwhile, the standards that outline procedures for the inspection and repair of damaged steel pipelines were set [3,11,17,22,23]. COGE (Centre for Oil and Gas Engineering) of Australia started the testing and FE (Finite Element) simulation project in 1997 named "Pipeline Resistance to External Interference", in which the parameter study for pipe response under excavator loading was carried out. Another result of the research is that the standard AS2885-1997 for oil-gas pipelines in Australia was set as a guideline to avoid external damage. A number of other parties have contributed toward the research on external interference of pipelines [4–7,34]. GRI (Gas Research Institute) in Chicago undertook third-party damage management mode research on gas pipelines by MFL-based work [30]. PRC (Pipeline Research Committee) of the American Gas Association forced the failure stress prediction of steel pipe with dent and gouge damage [1]. The Gas and Fuel Corporation of Victoria undertook experimental tests on the effect of a range of excavators striking buried pipelines [18].

The multi-body behavior of excavator tooth impact on the buried steel pipeline not only damages the pipe but may also break down the excavator mechanical system. Quantitative assessment based on the experimental/simulation therefore becomes the indispensable. I.B. Iflefel and J. Błachut [2,20] conducted some experimental and numerical investigations on plain and gouged dents found in steel pipes. Daniel C. Brooker [4–7] has paid more attention on the numerical modeling and experimental verification of pipeline punctures under excavator loading. Other researchers examine the structural response of internally pressurized tubes under lateral loads modeled with nonlinear shell finite elements and a simplified analytical model [13,14,19,24], as well as conducting a digging limiting load evaluation with the strength criterion for cracked and crackless pipelines [35].

It is indeed important for quantitative dynamic analysis to be conducted on pipelines under real mining situations; however, this has not yet been reported. The static-dynamic in-site full scale test study on the response of a buried gas pipeline under the impact of a hydraulic backhoe was carried out in this article. The real digging force in a specific working condition is the most concerned value under study, which is so difficult to find an analytical solution that an experimental/numerical method has become the better choice. When the excavator bucket reached the buried gas pipeline, extra loading will be produced due to the liquid pressure oscillation of the hydro-cylinder and the inertial force of excavator system, which will result in a growth spurt of the digging force. Therefore, both a pseudo-static test and dynamic tests with 21 conditions were conducted in total with different design operations. A multi-body impact model was also developed by ADAMS to reproduce the mining behavior by the test data. Verification was placed into the last step by a finite element code.

In the following sections, Section 2 briefly introduces the definition of digging force on the pipeline, as well as the resultant dynamic loading coefficient. Section 3 describes the excavator test scheme and results, which include the deformation and vibration of pipeline under static and dynamic cases. Section 4 modeling the excavator load by ADAMS multibody model. Section 5 addresses the verification analysis for digging force by finite element method, whose results seems reasonable. Some conclusions are given in Section 6.

2. Digging force definition

As mentioned before, in reality the digging force is mainly contributed from two parts: one is the impact force caused by the liquid impulsive, i.e., F_{d1}; the other is the inertial force of the excavator bucket, i.e., F_{d2}. The main reason for the former part is that the zero liquid velocity during impaction leads to a sharp pressure change in the cylinders. The extra force component F_{d1} by liquid compression can be calculated by the following formula:

$$F_{d1} = F_r \Delta K_{d1} = F_r \frac{\Delta P}{P} = F_r \frac{\rho v a}{P} \tag{1}$$

where F_r indicates the rated digging force of the excavator and P, ρ and v are the working pressure, oil density and flow velocity, respectively. a is the propagating velocity of the sound wave in oil, which can be calculated by $a = C/\sqrt{1 + kd/(E\delta)}$ and is determined by the bulk modulus k of oil, wall thickness δ and inner diameter d of a cylinder, Young's modulus E of the cylinder material, and the propagate velocity of sound wave in liquid C.

The second part of the digging force is in the form of inertial force. In the view of the energy conservation law, the total energy before impaction should be converted into elastic deformation energy when the tooth comes into contact with a barrier. It is assumed