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Excavation-Impact Failure Thresholds for the Shaanxi-Beijing Line 4 Gas Pipeline: A Finite-Element Study

Hongwei Rao
School of Petroleum and Natural Gas Engineering, Southwest Petroleum University, Chengdu 610500, China
Email: 1351191558@qq.com

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Abstract

The Shaanxi-Beijing Line 4 gas pipeline is a strategic supply route serving Beijing and surrounding areas. Much of the 1,098 km alignment crosses rural land, where excavation, agricultural work, and vehicle traffic repeatedly trigger the distributed warning system. This condensed study screens these third-party activities and focuses on the most credible immediate threat: direct contact between an excavator tooth and a pressurized buried pipe. A three-dimensional finite-element model representing the tooth-pipe-soil interaction was developed in ABAQUS for an X80 steel pipe with a 1,220 mm outside diameter, a minimum wall thickness of 18.4 mm, and an operating pressure of 12 MPa. Model validation against the analytical pressure stress produced a 1.4% difference. The simulation identified load thresholds of approximately 450 kN for the onset of plastic deformation, 698 kN for localized necking, and 1,446 kN for puncture. These thresholds support graded alarm response and field intervention, while their use should remain limited to the modeled geometry, material data, and boundary conditions.

Keywords

Natural Gas Pipeline; Third-Party Damage; Excavation Impact; Finite-Element Analysis; X80 Steel; Failure Threshold

1. Introduction

Long-distance pipelines provide a closed, economical, and land-efficient means of transporting natural gas, but their expanding footprint also increases exposure to construction and agricultural activity. Third-party interference is especially important because it can remove protective soil, damage the coating, dent the pipe wall, or directly puncture a pressurized line. The consequence can range from accelerated external corrosion to leakage, fire, explosion, and supply interruption [2,13,14].

Line 4 of the Shaanxi-Beijing system has an annual delivery capacity of about 30

billion m^3 and is central to peak-season supply security in the capital region [1]. Its route crosses Shaanxi, Inner Mongolia, Hebei, and Beijing, with substantial rural mileage beyond continuous on-site supervision. The pipeline also represents the prevailing design direction of Chinese trunk gas systems: large diameter, high pressure, high-strength X80 steel, and long-distance operation. A defensible estimate of damage thresholds is therefore useful both for Line 4 and for comparable assets.

Previous studies have emphasized index-based risk ranking, fault trees, fuzzy evaluation, Bayesian networks, and monitoring systems [2-7]. Finite-element work has examined local indentation and puncture, yet field decision-making still benefits from explicit load intervals linked to successive deformation states [8-12]. The objective here is to connect observed third-party activity with a mechanics-based classification of elastic response, yielding, necking, and puncture under a direct excavator-tooth strike.

2. Field Activity Screening and Study Scope

2.1. Warning records and seasonal pattern

A fiber-optic warning system records ground vibration and displacement along the line. In 2020, the Anping Station-to-Valve Station 33 segment generated more than 900 alarms: over 500 from rural work, over 250 from mechanical operations, and over 100 from vehicle passage. Activity peaked during spring cultivation, early-summer harvesting and land leveling, and the September-October harvest.

Table 1. Screening of recurrent third-party activities

Activity class	Observed pattern	Potential damage mechanism	Scope decision
Mechanical work	>250 alarms; concentrated in farming and construction periods	Direct tooth contact, indentation, coating loss, or puncture	Primary modeled hazard: excavator strike
Rural manual work	>500 alarms; strong spring/autumn seasonality	Hand-tool impact is possible but generally lower energy	Screened out of detailed simulation
Vehicle passage	>100 alarms; road traffic is comparatively random	Repeated surface loading and possible fatigue accumulation	Recognized as a separate future study

2.2. Hazard selection

Routine cultivation and factory vibration can trigger the system without contacting a pipe buried at least about 0.8 m. Manual digging has a similar contact geometry to machine excavation but substantially less available force. By contrast, an excavator can rapidly remove the cover and apply a concentrated load through a hard tooth. This combination of exposure, concentrated contact, and high force makes excavator interference the most credible source of immediate wall failure in the screened dataset.

Heavy vehicles may cross local roads to avoid inspection stations, and repeated loading deserves attention even when a single pass does not produce a stress-strain failure. Because the original numerical work did not complete a fatigue analysis,

vehicle loading is not combined with the excavation model in this condensed paper. This separation avoids implying that a static puncture threshold also represents a fatigue limit.

2.3. Analytical approach

The modeled sequence assumes that most cover has been removed and one tooth moves vertically into the pipe crown. The analysis establishes the internal-pressure stress, applies the local strike, and aligns the force history with material-response stages. The resulting thresholds are case-specific screening values, not universal design limits.

3. Finite-Element Model

3.1. Materials and constitutive representation

Soil was represented by a Drucker-Prager elastoplastic model, the X80 pipe by its reported stress-plastic-strain relation, and the excavator tooth as rigid. Table 2 summarizes the principal inputs.

Table 2. Principal model parameters

Component	Parameter	Value	Modeling role
Soil	Density; elastic modulus; Poisson ratio	1,850 kg/m^3; 20 MPa; 0.40	Bulk stiffness and inertia
Soil	D-P friction angle; flow-stress ratio; dilation	28.7°; 1.0; 0°	Pressure-sensitive plasticity
Pipe	Grade; outside diameter; minimum wall	X80; 1,220 mm; 18.4 mm	Structural geometry
Pipe	Yield strength; elastic modulus; Poisson ratio	538 MPa; 210 GPa; 0.30	Elastic-plastic response
Operation	Internal pressure	12 MPa	Initial in-service stress
Contact	Pipe-soil friction coefficient	0.40	Interface constraint
Tooth	Height; bottom/top width; thickness	200; 4/80; 50 mm	Concentrated contact geometry
Loading	Tooth velocity and direction	0.15 m/s; vertical	Dynamic indentation/puncture

3.2. Geometry, contacts, and boundary conditions

The coupled tooth-pipe-soil model fixed the outer soil boundary, used frictional pipe-soil contact, and drove the tooth downward at 0.15 m/s. A near-vertical strike provided a reproducible baseline, while mesh refinement was concentrated around the high-gradient contact zone.

3.3. Pressure-state validation

At 12 MPa internal pressure, the thin-wall von Mises solution was 362 MPa and the finite-element result was 357 MPa, a difference of about 1.4%. This check supports the initial pressure state, although it does not independently validate the puncture failure law.

4. Failure Evolution and Load Thresholds

4.1. Stress and deformation sequence

Before contact, the pressurized pipe maintained an equivalent stress of about 357 MPa. Once the tooth engaged the crown, local stress rose rapidly. The response first remained recoverable, then crossed the yield condition and accumulated plastic strain. With continued penetration, deformation localized around the contact point and the wall entered a necking stage. The reported maximum stress reached approximately 596 MPa before the local element response collapsed as puncture occurred.

The reaction force on the rigid tooth was extracted from the simulation. By Newton's third law, its magnitude equals the load applied to the pipe in the opposite direction. Aligning the force-time and stress-time histories yielded three transition loads that divide the response into four practical states.

Table 3. Load-based classification of the simulated pipe response

Applied tooth load	Dominant response	Structural interpretation	Operational implication
<450 kN	Elastic deformation	Wall returns toward its initial shape after unloading in the idealized model	Inspect coating and geometry; do not assume zero damage
450-698 kN	Plastic deformation	Permanent denting/yielding begins	Treat as integrity-threatening damage
698-1,446 kN	Localized necking	Load-bearing cross-section progressively weakens	Urgent isolation and engineering assessment
>1,446 kN	Puncture / complete local failure	Tooth penetrates the wall	Emergency response and shutdown

4.2. Interpretation

For the modeled 18.4 mm minimum wall thickness, 450 kN marks irreversible deformation, 698 kN pronounced localization, and 1,446 kN puncture. Even sub-puncture events may leave dents, coating damage, or residual strain. Although ordinary excavators often develop less than 300 kN and very large machines may approach the puncture range, consequence also depends on tooth geometry, angle, support, cover, dynamics, pressure, and wall tolerance; equipment identification must therefore be paired with integrity inspection.

5. Engineering Implications, Limitations, and Conclusions

5.1. Risk-based use of the thresholds

Alarm frequency alone is not failure probability: frequent farming activity is usually low energy, whereas less frequent excavator contact can be catastrophic. Escalation should combine activity type, equipment, proximity, cover depth, and persistence. The modeled intervals provide a graded mechanics layer: plausible loads below 450 kN still justify inspection; 450-698 kN indicates permanent deformation; 698-1,446 kN a severe localized state; and credible loads above 1,446 kN puncture-oriented emergency action.

5.2. Limitations and future work

The simplified crown-strike model omits oblique gouging, sliding, welds, corrosion, residual stress, imperfections, coating response, strain-rate calibration, and crack growth; soil support and boundaries are also idealized. Experimental puncture tests and mesh-objectivity studies are required before the thresholds are treated as design values. Future work should separately model vehicle fatigue and develop fragility curves across wall thickness, pressure, tooth geometry, strike angle, and soil condition.

Vehicle passage was identified as a separate recurring hazard, but its main concern is repeated loading and fatigue rather than a single indentation event. Future work should combine measured axle spectra, burial depth, soil stiffness, traffic repetitions, and existing defects in a cumulative-damage framework. Sensitivity studies should also vary wall thickness, internal pressure, tooth radius, strike angle, and soil condition. These extensions would convert the present case-specific thresholds into probabilistic fragility curves suitable for wider network application.

5.3. Conclusions

The warning records identified excavation and vehicle passage as the priority third-party hazards, while the completed finite-element scope addressed excavator contact. The Line 4 model matched the analytical pressure stress within 1.4% and resolved elastic response, yielding, necking, and puncture at approximately 450, 698, and 1,446 kN. Used with inspection and uncertainty controls, these staged thresholds support earlier, risk-based response to rural-corridor alarms.

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Note: Chinese-language titles have been translated for this condensed English manuscript. Bibliographic details follow the source document.