Experimental and numerical study of shallow-buried high-density polyethylene pipeline under collapse touchdown impact

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Abstract
The debris from structures produced during the blasting demolition of engineered buildings (structures) may fall near buried pipelines, which threaten the integrity of the buried gas pipeline. In this paper, the dynamic response of nearby shallow-buried high-density polyethylene (HDPE) gas pipelines under collapse impact loads was investigated. The stress-strain curve and material parameters of the HDPE pipe were obtained through uniaxial tensile tests. The strain distribution of buried pipelines under collapse loading was obtained. Subsequently, a 3D nonlinear finite element (FE) model of a buried HDPE pipeline impacted by a collapsed body was established. Finally, the effects of the impact velocity, touchdown angle, touchdown mode, offset distance, and pavement structure on the mechanical behavior of buried HDPE pipelines were analyzed in detail. The results show that, as the touchdown velocity and angle of the collapsed body increase, the von Mises stress of the pipeline is significantly affected. The pipe section close to the center of the impact zone tends to be damaged due to the von Mises stress reaching the maximum tensile strength. The maximum von Mises stress of the pipeline that is impacted by the edge of the collapsed body is the smallest, but the buried pipeline undergoes the largest displacement. The rigidity of the overlying pavement structure has a significant impact on the reliability of the buried HDPE gas pipeline. The stress concentration areas of buried pipelines mainly appear on the top, bottom, and the arches of the pipeline.

KEYWORDS
blasting collapse, finite element analysis, HDPE gas pipeline, impact test, mechanical property, uniaxial tensile test

1 | INTRODUCTION
High-density polyethylene (HDPE) pipelines have been widely employed in urban gas pipe networks due to their excellent characteristics.¹ ¹ With the continuous expansion of the scale of urban construction and the rapid development of blasting technology, an increasing number of older high-rise buildings (structures) have been
demolished by blasting. However, there are some uncertainties in how blasting demolition can affect the safety of adjacent gas pipelines. Figure 1 shows an urban gas pipeline sited near building (or structures) to be demolished by controlled blasting. Urban gas PE pipelines have a much lower strength than metal pipeline. When these shallow-buried flexible pipelines are impacted by a collapsed structure, severe stress/strain concentrations, excessive deformations, or even rupture may occur, which greatly increases the probability of accidents. Thus, it is necessary to investigate the mechanical response and structural reliability of buried natural gas PE pipelines under collapse impact loads.

Researchers have conducted some investigations on the mechanical response of PE pipelines subjected to external short-term loads and long-term loads. Tafreshi and Khalaj experimentally studied the mechanical response of buried PE pipes under repeated vehicle loads. In a full-scale test, Zhou et al investigated the structural response of a 600-mm diameter lined-corrugated HDPE pipe subjected to differential ground movements associated with a normal fault. Xia et al presented a theoretical method based on the Winkler model and the Timoshenko beam theory to calculate the effect of blasting loads induced by blasting the rock overlying a buried HDPE pipeline. Li et al and Liu et al analyzed the mechanical failure process of PE gas pipelines under the action of a third-party excavation load. Wang et al used numerical modeling to investigate the bending moment in HDPE pipes that was caused by traffic loading, and proposed an empirical method to predict the maximum bending moment. Liang et al studied the distribution of stress, strain, and displacement in buried PE pipes under above-ground loading. Wu et al and Zhou et al studied the mechanical behavior of gas PE pipes and HDPE double-wall corrugated pipes under land subsidence. Fei et al studied the time-dependent performance of steel-reinforced HDPE (SRHDPE) pipes and developed an empirical relationship between vertical arching factor and the equivalent stiffness coefficient. Elshesheny et al used three-dimensional finite element models to investigate the numerical behavior of buried flexible HDPE pipes in sand beds under cyclic loading. Zha and Jar developed a model based on the extended finite element method (XFEM) to study the fracture behavior of pre-cracked PE pipe under foundation settlement. Zhang et al used continuum damage mechanics to quantitatively analyze the distribution of damage caused by flattening of natural gas PE pipelines.

There has only been a little research on the effects of the collapse of buildings and their effect on the surrounding underground pipelines during blasting demolition. Long et al not only analyzed the patterns of the ground shock caused by the demolished chimney, but also deduced the dynamic response relationship between the subterranean pipeline and the ground vibration. Ge et al used both experimental and numerical methods to study the impact of the collapse of a viaduct after blasting on a concrete pipeline and proposed a comprehensive plan to protect buried pipelines. Wang et al investigated the strain distributions of buried steel pipelines under collapse impact loads; they combined experimental and numerical simulations. Nevertheless, the majority of the previous studies have focused on water supply and drainage PE pipes, assessing the mechanical behavior of pipelines under long-term loads such as land subsidence due to geological disasters and cyclic traffic loads. However, the analysis and investigation of shallow-buried HDPE urban gas pipelines under instantaneous impact loads due to the collapse of structures is lacking.

This work has therefore employed an experimental approach and numerical simulations to investigate the mechanical response of shallow-buried HDPE pipeline under collapse impact loads. Initially, a uniaxial tensile test and an impact test using a drop hammer on a SDR17 PE pipe (standard dimension ratio) were combined. A rigorous 3D nonlinear finite element (FE) model of a buried HDPE pipeline impacted by a collapsed body was established. Subsequently, several typical touchdown modes for the collapsed bodies were incorporated into the FE model. Finally, the effects of impact velocity, touchdown modes, pipeline offset distance, and other parameters that affected the pipeline were examined in detail. The research outcomes provide an important reference for the evaluation of safety in buried pipelines and the formulation of...
safety protection strategies during blasting demolition. At the same time, these findings will contribute to the development of management of the integrity of urban gas pipelines and the formulation of relevant safety specifications.

2 | HDPE PIPE TENSILE EXPERIMENT

2.1 | Test preparation and design

In this experiment, the stress-strain relationship of the polyethylene pipe was measured by a universal testing machine under specified conditions. The experimental method was in accordance with the provisions of GB/T8804-2003. The specific parameters used are shown in Table 1.

PE100 grade pipe was selected for the tensile tests, and the latest sizes SDR17 (standard dimension ratio) and DN160 (nominal outer diameter) in the piping specification were selected. Due to its rate dependence, the stretching rate has an obvious influence on the tensile properties of the polyethylene material. Therefore, the polyethylene samples stretched at different stretching rates to obtain the stress-strain relationship of the material. The samples were stretched using the SANS-CMT4304 electronic universal testing machine (see details Table 2).

Due to the temperature sensitivity of HDPE materials, the temperature of the experiment was controlled to reduce the influence of the temperature. Therefore, before starting the experiment, the sample remained in the same environment for more than six hours. The specimens were then subjected to tensile tests at six tensile rates, 3 mm/min, 10 mm/min, 30 mm/min, 50 mm/min, 100 mm/min, and 300 mm/min. The corresponding strain rates are $1 \times 10^{-3}/s$, $3 \times 10^{-3}/s$, $1 \times 10^{-2}/s$, $2 \times 10^{-2}/s$, $3 \times 10^{-2}/s$, and $1 \times 10^{-1}/s$. Since this study focuses on the performance of the material before and after yielding, the experiment only needs to be carried out until the engineering strain is about 0.2.

2.2 | Test results and discussion

Figure 2 shows the stress-strain curve for the PE100 pipe at different stretching rates. It can be seen that different stretching rates result in significantly different stress-strain curves for the polyethylene pipe, which means that there is a clear rate dependence. As the tensile rate of the sample increases, the total stress value in the sample also increases, and a steeper slope of the curve before yielding, which means that the elastic modulus increases. The highest point of the curve is the yield stress of the pipe at different stretching rates. The faster the stretching rate, the greater the stress when the material yields; the specimens are necked and deformed. To obtain the true stress-strain curve of the pipe, it is necessary to consider the uniform deformation of the cross-section of the HDPE pipe material before yielding. According to the calculation method of GB/T1040, the Poisson’s ratio is taken as 0.4. The relationship between the engineering stress and strain and real stress and strain is as follows.

$$
ε_{true} \int_{L_0}^{L} \frac{dL}{L} = \ln \left( \frac{L}{L_0} \right) = \ln \left( \frac{L_0 + ΔL}{L_0} \right) = \ln(1 + ε)
$$

where, $ε_{true}$ is the true stress, Pa; $ε_{true}$ is the true strain; $σ$ is the engineering stress; $ε$ is the engineering strain; $μ$ is Poisson’s ratio; $L$ is the length of the sample, m; $L_0$ is the initial length of the sample, m; $ΔL$ is the deformation of the sample, m.

According to Equations (1) and (2), the values of the tensile test results of the material are transformed, and the true stress-strain curve of the PE samples under different strain rates is obtained, as shown in Figure 2B.

During the experiment, the yield strength of the HDPE pipe material was recorded. After several tests, the average values were calculated and it was found that there is a logarithmic relationship between the yield stress of the HDPE pipe and the tensile rate, as shown in Figure 3.

According to the tensile test data and standard GB/T1040, the elastic modulus of the pipe was calculated. The average value of the slope of the interval between $ε_1 = 0.05\%$ and strain $ε_2 = 0.25\%$ on the stress-strain curve was calculated. In summary, the mechanical material parameters of HDPE pipes are listed in Table 3.

2.3 | Failure criterion

Tensile testing of the pipe is used to directly observe the macroscopic behavior of the pipe during shear yield. When the applied load reaches its yield stress, the HDPE pipe yields but does not fail immediately. The pipe has undergone significant plastic deformation at the yield point, where a necking phenomenon has occurred, and the pipe wall has obviously weakened. This means that the pressure-bearing capacity of the pipeline has been reduced, and the pipeline will be more susceptible to failure. Therefore, the stress failure criterion was selected to judge the safety of HDPE pipeline. The equivalent stress is chosen as the von Mises equivalent stress, which is expressed as follows:
\[ \sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \leq \sigma_y \quad (3) \]

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the three principal stresses of the element body respectively, and \( \sigma_{eq} \) is the equivalent stress. If the pipeline is in a safe state, the von Mises equivalent stress should be less than the yield stress \( \sigma_y \).

### 3 | IMPACT EXPERIMENT FOR BURIED PIPELINE

#### 3.1 | Test preparation and design

This experiment used a free-fall hammer to impact the shallow-buried pipeline, simulating the force on a pipeline from the impact of a collapsed building or structure. The impact mechanism and impact characteristics of the model load are consistent with the impact of building collapse.\(^2\)\(^7\) The layout before the experiment is depicted in Figure 4.

The stress and strain distribution of the HDPE pipes was obtained by the resistance strain-stress method. First, a strain gauge was attached to the top and bottom of the pipe in the middle section of the pipe. When the collapsed body touches the ground, the small deformations recorded by the resistance strain gauge on the buried HDPE pipeline will change. These are converted into a voltage signal that measures the strain value. Finally, the strain is converted to stress according to Equations (4) and (5).

**Main strain:**

\[ \varepsilon_1 = \varepsilon_0, \varepsilon_2 = \varepsilon_9, \gamma_{xy} = 0 \quad (4) \]

**Principal stress:**

\[ \sigma_1 = \frac{E (\varepsilon_0 + \mu \varepsilon_9)}{1 - \mu^2}, \sigma_2 = \frac{E (\varepsilon_9 + \mu \varepsilon_0)}{1 - \mu^2} \quad (5) \]

where \( \varepsilon_1 \) and \( \varepsilon_0 \) are the first principal strains, which is the hoop strain; \( \varepsilon_2 \) and \( \varepsilon_9 \) are the second principal strain, which is the axial strain; \( \gamma_{xy} \) is shear strain; \( \sigma_1 \) is first principal stress.

This experiment used a 1/2 bridge connection, and temperature compensation was performed to eliminate the influence of temperature. According to the HDPE requirements, the resistance strain gauge was of the 120-10AA type and its physical parameters are listed in Table 4. The Tester’s TST5912 dynamic signal experiment and analysis device were adopted.

The HDPE pipe size used was DN110, SDR17, and the initial buried depth was 25 cm. The drop weight was cast iron, with a mass of 20 kg, and the length, width, and height were 22 cm \( \times \) 15 cm \( \times \) 12 cm, respectively. In addition, the model test used Yangtze River sand from Chengdu as the filling material in the model box. The sand was air-dried and passed through a 2 mm sieve before the test. The values of soil material parameters are listed in Table 5.

Finally, the different heights for the hammer drop to simulate a collapsed body (25 cm, 50 cm, 75 cm, 100 cm, and 125 cm) and the buried depth of the pipeline (19.5 cm and 25 cm) were designated. The strain at different positions of the pipeline and the depth of the soil depression were collected. Figure 5 presents a photograph of the experimental process.

#### 3.2 | Test results

Multiple collapse touchdown tests were conducted, and the data were collected; repeated tests and invalid experimental results were excluded. The stresses and soil depression values measured are summarized in Table 6. It can be seen from the experimental results that the peak stress at

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**Table 1** Dimension parameters of tensile specimens (mm)

| Symbol | Description               | Size (mm) |
|--------|---------------------------|-----------|
| A      | Minimum total length      | 150       |
| B      | End width                 | 20 ± 0.2  |
| C      | Parallel section length   | 60 ± 0.5  |
| D      | Parallel part width       | 10 ± 0.2  |
| E      | Large radius              | 60        |
| F      | Distance between markings | 50 ± 0.5  |
| G      | Distance between fixtures | 115 ± 0.5 |
| H      | Wall thickness            | Pipe wall thickness |

**Table 2** Parameters of SANS-CMT4304 Universal experimental testing machine

| Maximum test force | Displacement accuracy | Relative error | Deformation resolution | Deformation rate adjustment range | Accuracy class |
|--------------------|-----------------------|----------------|------------------------|-----------------------------------|----------------|
| 30 kN              | 0.03 μm               | ±0.1%          | 1/300,000 FS           | 0.02–5%FS/s                      | 0.5            |
the top of the pipe is greater than the stress at the bottom of the pipe. The peak stress of the pipeline decreases, and the soil depression at the impact center increases with the increase in the height of the collapse.

3.3 | Simulation of touchdown process

3.3.1 | Finite element model

1. Model size

According to the size of the soil box in the experiment, a rammer-tube-soil three-dimensional finite element model with a buried depth of 25 cm was established in the commercial finite element software ABAQUS. The size of the soil model was 1 m in length and width and 0.7 m in height. The drop hammer size was 22 cm × 15 cm × 12 cm. The pipeline size was the same as in the experiments.

2. Loads and interaction between pipe and soil

In the numerical analysis, the bottom of the total model was fully consolidated. The upper surface is a free surface without any constraints. Displacement constraints were imposed on other surfaces of the soil, with the ends of the pipe restrained in the pipe longitudinal direction. The drop hammer was considered to be a rigid
In the model, the surface-to-surface contact type was selected for the pipe-soil contact, with the outer surface of the pipe as the main surface and the inner surface of the soil as the secondary surface. The mechanical constraint was carried out by the motion contact method, and the contact attribute defines the normal behavior and the tangential behavior. Normal behavior was defined as "hard" contact, while tangential behavior was defined by "penalty". The friction coefficient between the pipe and the soil was taken as 0.4. The acceleration due to gravity was set at 9.8 m/s².

3. Mesh division

Both the pipe and the soil were modeled as solid elements. The mesh of the pipeline and the local soil was a mesh refinement. Considering the accuracy and efficiency of the calculation, the grid used an eight-node linear hexahedral linear reduction integration unit (C3D8R). The quality of the mesh was then verified using the mesh check tool.

3.3.2 Comparison of results

Finite element models with the collapse heights of 25 cm, 50 cm, 75 cm, 100 cm, and 125 cm were used. The finite element calculations were compared with the experimental results; the comparison is shown in Figure 6.

It can be seen from Figure 6A that, with the increase in the collapse height, the maximum stress of the pipe located in the center of the impact area increases, and the measured value is consistent with the numerical simulations. The finite element simulation yields slightly larger results than the measured experimental values, with a minimum error of 4.3%, and a maximum error of 8.4%. It can be seen from Figure 6B that the sag value of the soil after impact tests and from the simulation increases with an increase in the collapse height; the experimental results are in good agreement with the simulation results.
As mentioned above, the average error of the finite element results is less than 10%, and the simulation results are close to the experimental test data, which verifies the accuracy of the finite element model and shows that it can be used for engineering simulations.

### TABLE 4 Physical parameters of resistance strain gauge

| Resistance | Long × width | Voltage | Sensitivity coefficient | Material       | Mechanical lag | Strain limit   |
|------------|--------------|---------|-------------------------|----------------|----------------|---------------|
| 120 Ω      | 14.5 × 5.1 mm| 3–10 V | 2.0%                    | Phenolic-Epoxy | 1.2 μm/m       | 20,000 μm/m   |

### TABLE 5 Soil parameters

| Density (kg m⁻³) | Proportion | Relative compactness | Internal friction angle (°) | Elastic modulus (kPa) | Poisson's ratio | Cohesion (kPa) |
|------------------|------------|---------------------|-----------------------------|-----------------------|----------------|----------------|
| 1600             | 29.3       | 0.7                 | 18.4                        | 20,000                | 0.4            | 29.3           |

### FIGURE 5 Experiment process of the drop-hammer impacting the pipeline

(A) Pipeline before the experiment

(B) Drop-hammer impact process

(C) Pipeline after the experiment

### TABLE 6 Test results of impact of rammer on shallow-buried pipelines

| Number | Drop weight (kg) | Buried depth (cm) | Collapse height (cm) | Depth of soil depression (cm) | Peak stress at pipe top (MPa) | Peak stress at bottom of pipe (MPa) |
|--------|------------------|-------------------|----------------------|-------------------------------|-------------------------------|----------------------------------|
| 1      | 20               | 25                | 25                   | 0.7                           | 3.5                           | 1.3                              |
| 2      | 20               | 25                | 50                   | 1.3                           | 5.2                           | 1.9                              |
| 3      | 20               | 25                | 75                   | 1.7                           | 6.2                           | 2.4                              |
| 4      | 20               | 25                | 100                  | 1.9                           | 6.9                           | 2.6                              |
| 5      | 20               | 25                | 125                  | 2.5                           | 8.1                           | 3.0                              |
| 6      | 20               | 19.5              | 25                   | 0.5                           | 5.4                           | 2.2                              |
| 7      | 20               | 19.5              | 50                   | 1.2                           | 7.7                           | 3.0                              |
| 8      | 20               | 19.5              | 75                   | 1.5                           | 8.0                           | 3.5                              |
| 9      | 20               | 19.5              | 100                  | 2.1                           | 9.8                           | 4.05                             |
| 10     | 20               | 19.5              | 125                  | 2.4                           | 10.4                          | 4.4                              |

4 | NUMERICAL SIMULATION OF COLLAPSE IMPACT

Using the powerful calculation and analysis functions of the finite element software, the mechanical response of the
collapsed body impacting the pipeline under the influence of different parameters can be thoroughly studied to clarify the crucial parameters, and the countermeasures were proposed. The impact on the buried pipeline can be simplified to the process of a semi-infinite body being impacted. As a semi-infinite space, the soil is only part of the scope of this research. According to the results of previous research and trial calculations, the selection of the size range of the finite element model adopts the truncated boundary analysis method. The model size is taken as length 15 m, height 7.5 m, and width 15 m. The shape of the collapsed structure was mostly in the form of a flat rectangular parallelepiped, such as from viaducts, and load-bearing walls therefore, the collapsed body was set as a low-height rectangular parallelepiped, with a length of 2 m, a height of 0.5 m, and a width of 1 m. Referring to standard GB50028, the minimum covering thickness (from the road surface to the top of the pipe) where the motor vehicle weight cannot reach is not less than 0.3 m, and the general overlying thickness is 0.8 m; the soil thickness covering the pipe was therefore set to 0.8 m in the model. The pipeline pressure was set to 0.4 MPa for medium pressure A grade.

The settings of the load, meshing fineness, and material parameters of the finite element model refer to the values in the numerical simulation above. The overall finite element model is depicted in Figure 7.
5 | RESULTS AND DISCUSSION

5.1 | Dynamic response of a buried pipeline subjected to touchdown loads

The left half of the cross-sectional symmetry of the HDPE pipe at the center of the ground impact was divided into three areas A, B, and C, as shown in Figure 8A. According to the usual collapse height from a viaduct under blasting demolition, a model was designed where the collapse touchdown velocity was 10 m/s, the operating pressure of the gas pipeline was 0.4 MPa, the thickness of the overburden was 0.8 m, and the pipeline is located directly under the impact.

Figure 8A illustrates the von Mises stress of a shallow-buried HDPE gas pipeline at different times. The results show that the collapsed body touched the ground at a vertical velocity of 10 m/s within 0.01 s. The buried HDPE gas pipeline was affected by the surrounding soil pressure and internal pressure before impact with the ground when the pipeline stress was about 2.8 MPa. After the collapsed body touches the ground (see Figure 8A), the stress at the top of the pipe A, the arch line B, and the bottom C of the pipe, first drops and subsequently rises rapidly. This is because the internal pressure of the pipe offsets a part of the impact of the external load, after which the influence of the external load dominates. The three stresses at A, B, and C reached their maximum values almost at the same time, at $1.7 \times 10^{-2}$ s, and the stress on the inner wall of the tube arch was the greatest. This is because the rigidity of the HDPE pipeline is not sufficient to transmit a large load, and the impact load can only be accommodated through flattening deformation. These results show that the B area of the pipeline is most likely to fail after an impact load, due to damage or yielding.

Figure 8B depicts the von Mises stress of the pipeline at different times. The stress on the Z-X plane of the inner wall of the pipeline center is shown by the polar coordinate diagram. At $1.7 \times 10^{-2}$ s, the stress on both sides of the pipeline is obviously higher than at other times. At other times, the maximum stress of the pipeline mainly appeared at the top and bottom of the pipeline, but did not exceed 8 MPa. This is because, after the soil and the pipeline are subjected to the momentary force, they continue to vibrate and produce relative displacements due to the impact force, which causes fluctuations in the pipeline stress. As the vibration weakens, the stress in the buried pipeline also gradually decreases. In addition, the stress on the pipeline decreases along the axial direction.

The maximum deformation and final deformation of the pipeline are shown in Figure 9. The area of the pipeline located in the center of the impact zone experiences the largest deformation. In the axial direction, away from the impact center, the deformation of the pipeline gradually transitions to zero at 1.4 m. In addition, due to the rebound effect of the pipeline and the soil itself, the difference between the maximum deformation and the final deformation of the pipeline is relatively large.

5.2 | Parametric Analysis

5.2.1 | Touchdown velocity

When a structure is demolished by blasting, the height of the collapse is different, and the impact force experienced by the buried pipeline is also different. The range of impact velocities was set to between 5 m/s and 17 m/s. The overburden thickness was set to 0.8 m, and the pipeline pressure was fixed at 0.4 MPa.
Figure 10 depicts the maximum von Mises stress occurring at the pipeline locations A, B, and C after the collapse touchdown but with different impact velocities. The results show that, with the increase in the impact velocity, the stress at the center of the impact area increases significantly. When the velocity increases uniformly, the maximum stress in the buried pipeline increases approximately linearly. As the impact velocity of the collapse increases, the maximum stress on the pipe sides obviously increases more. It must be pointed out that when the velocity is 16 m/s, the maximum stress at pipe location B is 24.64 MPa, and the pipe has yielded. Therefore, in any engineering endeavor, the impact velocity of the collapsed body should be reduced as much as possible to protect the pipeline.

5.2.2 | Touchdown impact angle

Due to the uncertainty of the relative position of the collapsed structure and the degree of disintegration when a building is demolished, the collapsed body may impact the buried HDPE pipeline at different angles and velocity. Therefore, finite element impact models with different impact angles were established. A schematic diagram of an inclined impact is shown in Figure 11.

The maximum von Mises stress of a shallow HDPE pipe with differing impact angles is depicted in Figure 12. It can be seen that under different impact angles, the maximum von Mises stress appears at different positions in the pipeline. When the impact angle is 15°, the highest stress concentration in the pipeline is on the inner wall.
When the impact angle is increased, the maximum stress in the HDPE pipe increases; the maximum stress is gradually transferred to the inner wall surface of the pipe arch line, while the area of stress concentration decreases along the axial direction of the pipeline. When the impact angle is less than 15°, the maximum stress difference at different velocities is not obvious. It is worth noting that when the pipeline is impacted at a vertical angle at 18 m/s, the maximum stress is 26.5 MPa, and the HDPE pipeline is dangerously compromised due to yielding. Therefore, the closer the pipeline is to the demolished structure, the greater the possible impact angle and the less safe it is.

5.2.3 | Touchdown impact mode

The size and shape of the collapsed bodies are different when urban buildings (structures) are collapsed during blasting demolition, resulting in different contact surfaces when the collapsed material touches the ground. The contact mode between the collapsed bodies and the soil can be summarized into three types: plane contact, edge contact, and arc contact. Therefore, three different finite element models of blasting demolition collapse and touchdown methods were designed. The volume of each collapsed body is the same; other parameters remain unchanged.

Figure 13 shows the maximum von Mises stress and displacement cloud diagrams for shallow-buried HDPE
gas pipelines under different touchdown modes; the impact velocity was set as 14 m/s. The results show that the time and location of the maximum stress in the pipeline is different under different touchdown modes. For the plane mode, the maximum stress occurs at the side of the pipe at 6 e−3 s, but the pipeline has not undergone significant deformation at this time. For the other two touchdown modes, the maximum stress appears at the bottom of the pipe at a time of 2.73 e−2 s, with maximum displacement occurring after the maximum stress time.

Figure 14 depicts the trend of the maximum von Mises stress of the pipeline with the touchdown velocity under different touchdown modes. Under each of the three touchdown modes, the maximum equivalent stress in the pipeline increases with an increase in the touchdown velocity. When compared with the edge and arc surface touchdown, the stress in the buried pipeline in the plane touchdown mode is significantly increased. The maximum von Mises stress in the pipeline caused by edge contact to the soil is the smallest. This is because the plastic deformation generated by the soil in the depression above the buried pipeline is large, and part of the collapse potential energy is transferred to the energy dissipation of the plastic depression. In addition, sharp and irregular edges and corners may pierce the soil and directly cause plastic damage to the shallow-buried HDPE pipe.

5.2.4 Touchdown offset distance

The distance between the collapsed body and the buried gas pipeline is an important factor affecting the safe operation of the pipeline during building collapse and disintegration. This distance is shown in Figure 15. Therefore, different finite element models were run, with the distance between the center of the collapsed body and the axis of the pipeline at 0 m, 0.4 m, 0.8 m, 1.2 m, 1.6 m, 2 m, 2.4 m, 2.8 m, and 3.2 m. The touchdown mode was plane contact, and the other parameters remained unchanged.

Figure 16 represents the trend of the maximum von Mises stress of the HDPE pipeline with the offset distance. It can be seen from Figure 16A that when the impact velocity is constant, and the distance between the collapsed body and the buried pipeline increases, the maximum stress in the pipeline decreases. In the interval of 0-0.8 m from the center of the laterally offset pipeline, the maximum stress of the pipeline is high and the trend is obvious. The stress tends to be stable and basically the same (P > 1.6 m). The locations of the stress concentration areas of the pipeline are different at
Figure 13: Distribution of maximum von Mises stress and displacement cloud diagrams of HDPE pipeline under different slump touchdowns.

Figure 14: Variation of maximum von Mises stress in an HDPE pipeline at different impact velocities and different slump touchdowns.
different offset distances. The time required to reach the maximum stress in the pipeline is delayed as the offset distance increases. It must be pointed out that when the collapsed body is near the center of the pipe, the pipe yields. Therefore, during a blasting and demolition project, the collapse direction of the structure should be as far away as possible from the gas pipeline. When it is unavoidable, a cushion layer should be laid over the buried pipeline for protection.

Figure 16B shows the displacement of the pipe at the moment of maximum stress. The displacement of the pipeline along the axial direction is different at different offset distances. The time required to reach the maximum stress in the pipeline is delayed as the offset distance increases. It must be pointed out that when the collapsed body is near the center of the pipe, the pipe yields. Therefore, during a blasting and demolition project, the collapse direction of the structure should be as far away as possible from the gas pipeline. When it is unavoidable, a cushion layer should be laid over the buried pipeline for protection.

Figure 16B shows the displacement of the pipe at the moment of maximum stress. The displacement of the pipeline along the axial direction is different at different
offset distances. When the touchdown offset distance is 0.4 m, part of the collapsed body is still above the pipeline, so the pipe displacement is still relatively large. The most significant interval for the pipeline displacement is \([-1.2 \ m, 1.2 \ m]\). When the offset distance exceeds 1.2 m, the displacement of the pipeline decreases significantly.

5.2.5 | Pavement structure layer

The pavement layer above the buried pipeline has an obvious influence on the buried HDPE pipeline. Common hardened roads are semi-rigid roads and rigid roads, namely asphalt roads and cement concrete roads. The parameters of each structural layer are shown in Table 7. The minimum soil thickness required to cover a polyethylene gas pipeline is not less than 1.5 m when crossing urban highways.

In order to more clearly reflect the difference in the dynamic response of pipelines beneath different types of roads, the collapse velocity was set at 15 m/s, the thickness of the overburden was set to 1.5 m, and other parameters remained unchanged.

Figure 17 depicts the dynamic response of the maximum von Mises stress and displacement of the pipeline over time under different pavement structures. The results show that the HDPE pipes have different response times to reach the maximum von Mises stress under different pavement structures. The first stress peak of the pipeline located below a cement concrete pavement after 0.006 s is 5.3 MPa, that is, the pipeline reacts promptly to the collapse load. Subsequently, the maximum value of the von Mises stress in the pipe appears at the top of the pipeline at 0.014 s, an increase of 20%. The maximum stress in the pipeline under a semi-rigid asphalt pavement is 8.42 MPa. The peak stress of the pipeline is largest below an unhardened road surface, while the von Mises stress response of the pipeline is the slowest. In addition, the stress fluctuations in the unhardened pavement are obvious, while the stress fluctuations of the semi-rigid and rigid pavement are gentler.

It can be seen from Figure 17B that the effects of different pavement structures on the pipeline displacement are ranked as follows: unhardened pavement > asphalt > cement. In summary, it shows that the hardened pavement has an obvious protective effect on the buried HDPE gas pipeline under collapse impact.

5.2.6 | Thickness of covering soil

In order to analyze the effect of soil thickness on the mechanical response of the top of buried gas pipelines, the soil thickness above the pipeline was set to 0.3 m, 0.6 m, 0.8 m, 0.9 m, 1.2 m, 1.5 m, 2 m, and 2.5 m. Other parameters remained unchanged.

Figure 18 shows the variation of the maximum stress and displacement of the pipeline with the depth of the overlying soil. It can be seen from the figure that the maximum von Mises stress and displacement of the pipeline decreases with an increase in the depth of the covering soil. The amount of impact energy consumed by the soil increases as the buried depth of the pipeline increases. When the overburden depth is less than 0.6 m, the pipeline
FIGURE 17  Maximum von Mises stress and displacement of pipelines with time under different pavement types
will always be greatly affected by the collapse load. The change in the maximum von Mises stress change for pipelines is no longer obvious when the cover soil thickness is greater than 1.5 m. Overall, the maximum stress is reduced by 64.1%. The maximum displacement of the pipeline decreased as the covering soil thickness increased, which was a decrease of 86.6%. Therefore, it is recommended that the soil cushioning layer above the pipeline be increased to at least 1.5 m.

6 | CONCLUSION

In this paper, experiments and finite element simulations were used to study the dynamic response of shallow HDPE pipelines under blasting demolition collapse loads. The effects of different parameters on the stress and displacement of HDPE pipes were also analyzed. The following conclusions can be drawn:

1. According to the characteristics of the pipe in the uniaxial tensile test, a stress failure criterion was proposed. The strength is significantly reduced after the pipe yields. The yield strength and elastic modulus of pipes increase as the stretching rate increases. The numerical simulation results are consistent with the experimental data, which shows that the finite element model that considers the actual pipe-soil interaction relationship can accurately simulate the mechanical behavior of the pipeline.

2. The maximum von Mises stress of the pipeline increases significantly with an increase in the touchdown velocity of the collapsed body. The increase in the touchdown angle is equivalent to the increase in the vertical touchdown velocity. Therefore, the probability of pipeline failure due to attaining yield strength increases.

3. When the distance between the collapsed body and the pipeline is less than a critical value (1.2 m), the pipeline stress concentration is obvious; some safety measures should be taken to protect the pipeline. The most dangerous position in the pipeline is transferred from the pipe arch line to the inner surface in the touchdown direction.

4. Three different modes of the collapsed body hitting the soil are summarized. The stress in the pipeline due to plane touchdown is the largest, but the displacement is the smallest; when the edge of the collapsed body hits the soil, the plastic energy absorbed by the soil increases significantly, minimizing the stress in the pipeline. Here, the pipeline has the largest displacement, and there is danger of direct damage to the pipeline through the soil.

5. Different pavement structural layers above the soil covering the buried pipeline have different protective effects on the pipeline. A rigid road surface reduces the maximum stress, displacement, and stress fluctuation of the pipeline, affording greater protection to the pipeline. In addition, increasing the buried depth of the pipeline contributes to a reduction in the effects on the pipeline due to a collapse load.

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CONFLICTS OF INTEREST
The authors declare that they have no conflicts of interest.

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