Dynamics and strain-based design of the large-diameter pipe under the impact of a falling rock

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Abstract: Falling rocks are one of the essential causes to pipeline failures in the most frequently occurring geological disasters and the pipes in a thin-shell structure can hardly resist the huge impact energy. The traditional design are conducted by keeping the maximum stress smaller than the material strength which is too conservative to make a full use of the pipeline. In this work, codes for the explicit dynamics based on the Lagrange algorithm are adopted to numerically simulate the impact of falling spherical stones on the large diameter pipe with the consideration of nonlinearity of big deformation. Dynamic responses of the pipe as well as strains on pipe’s cross section are discussed in detail. Influences on the pipe strains from factors like impact speed, stone size and moving direction are investigated. Results show that, most significant effect is from the diameter-thickness ratio of the pipe and it shows the resistant capability of the pipe drops exponentially with the decreasing of the thickness and the ratio is recommended to be chosen in a range of 40–60. Eccentricity also effects the strains exponentially and the impact extent is greatly reduced with the eccentricity being smaller than 50%. Safety check is carried out by an ultimate-strain criterion and so, the ultimate size and velocity of the falling stone are got. What is done in this paper is expected to be of referential values for geological disaster resistant design of pipeline.

1. Introduction
The damages on the pipelines from the falling rocks in the geological disasters including landslides and debris flows are mainly caused by the transient impacts which can easily result in failure of the pipe. Both laboratory tests and computations have been conducted. Qixin Yang & Shubao Guan adopted a method by a gravity hammer to fall freely onto the soil groove to investigate the influence of the falling stone impulsive force to the gallery structure\textsuperscript{[1]}. By the test, the experimental formula of calculating falling stone impulsive force was given. Di Prisco & Galli conducted a small scale plane-strain text in the laboratory and the lateral response curves of pipe in the varying buried depth under motivations in different directions were obtained\textsuperscript{[2]}. Although many tests have been conducted, imperfections always exist for the laboratory tests. Due to the complex factors in the falling rocks in the real happening geological disasters such as huge impact energy, transient interacting time and complicated interactions, it is hard to be simulated by the laboratory tests. Thereupon, numerical simulations are being adopted more and more widely and of course, it is no exception for the impacts
of the falling rocks in the geological disasters. Plassiard & Donze used the discrete element method (DEM) to simulate the impact process of the falling stones on the protective embankment[3]. Xuejing Deng et al. numerically simulated the impacts of falling rocks on the buried pipelines by the DEM software 3DEC and investigated the factors effecting the surface soil pressure and the pipe information[4]. Hongyuan Jing did some research work on the stress responses of the gas pipeline under the impact of falling stones by the ANSYS/DYNA[5]. Min Lou & Haiqin Ming also used the ANSYS/DYNA to simulate the damage of the subsea pipeline under the impact of heavy objects[7].

In the design of oil & gas pipeline, the traditional stress-based standards appear to be conservative compared with the strain-based standards. The deformation resistant capability of the pipe materials is more fully used and meanwhile, the structural stability is remained in the stain-based standards which could be applied in the areas like landslides and frost regions where large deformations may more likely occur. For now, dozens of pipelines have been designed by the strain-based methods and applied in the areas containing potential geological disasters[7-13]. However, focus on the impact of falling rocks on the pipe has not been attracted enough.

2. Explicit dynamic FEM Modeling

2.1. Lagrange explicit algorithm

By the principle of the virtual work, the discrete control equations in Lagrange, given as

\[ u(x,t) = N(X)u(t) = \sum_i N_i(X)u_i(t) \]

\[ \varepsilon = \sum_i \frac{\partial N_i}{\partial X} u_i \]

\[ \sigma = [D] \varepsilon \]

\[ [D] = \frac{E(1-\mu)}{(1+\mu)(1-2\mu)} [\mu] \]

\[ f^m_{int} = \int B^T \sigma d\Omega \]

\[ f^e_{ext} = \int_\Omega \rho N^T b d\Omega + \int_\Omega N^T \tau d\xi \]

\[ M_e = \int_\Omega \rho N^T N d\Omega \]

\[ M\ddot{u} + f^m_{int} = f^e_{ext} \]

Equation (1) ~ (3) respectively are the node force in the cell, node force out of the cell and cell mass matrix. Equation (4) is the momentum equation where the \( u(x, t) \) is the trial function of the node displacement, the \( N_i(X) \) is the interpolating function, \( \dot{u}_i(t) \) is the node displacements. \( \varepsilon \) is the node strain and \( \sigma \) is the cell stress. \( f^m_{int} \) is the node force in the cell and \( f^e_{ext} \) is the node force out of the cell. \( B \) is the strain matrix and \( b \) denotes the volume force. \( \int_\Omega N^T b d\Omega \) is the node force caused by the boundary conditions, \( M_e \) is the lumped mass matrix and \( \ddot{u} \) is the node acceleration.

2.2. FEM simulation model

In this section, we use the explicit dynamic FEM codes to simulate the impact process of the falling rocks on the bare pipe and investigate the large deformation and stress distribution of the pipe. Furtherly, the applicability of the pipe is verified by the utmost strain rule and the factor influences of the falling rock such as speed, size and impacting direction on the resulting strain of the pipe is discussed in detail. In the simulation, the falling rock is simplified to be an ideal sphere in the diameter of 0.6m and the diameter and the wall thickness of the X80 pipe are 1219mm and 22mm, respectively. Other parameters used in simulations are given in table 1. The falling sphere is taken as a rigid body and the rock is falling to the pipe with its centroid moving perpendicularly to the pipe axis. Figure 1 shows the simulation model and grids.
3. Influences of parameters during the impact
In this section, the impacting speed of 10m/s of the rock with diameter of 0.6m are adopted as the initial speed of the falling rock. Five moments in the impacting process are taken and shown in figure 2. From the stresses and deformations in figure 2, the point contact is happening in the initial moment and in the second moment, the stress sharp rises from 0 to 27.2MPa in 3ms with an unconspicuous deformation. However, significant deformation happens to the pipe wall at the impacting point in next moment and the stress spreads. From the fourth and fifth moment, the pipe wall recovers to some extent and the stress goes down responsively, however, permanent plastic deformation has been produced.

3.1. Ratio between pipe diameter and wall thickness $R_{wt}$
According to the requirement for $R_{wt}$ for being over 20, values of 20, 40, 60, 80 and 100 are chosen for simulations and the corresponding wall thickness will be 60.95mm, 30.48mm, 20.32mm, 15.24 mm and 12.196mm respectively. The maximum effective strain is extracted. Figure 3 shows the displacements of the contacting cells along the impacting direction with varying $R_{wt}$, which reflects the subsidence depth of the pipe wall at the impacting point. Maximum subsidence depths are used in figure 4 and the fitting curve is obtained. From figure 3 and 4, it can be easily seen that, with an increasing $R_{wt}$, the subsidence depth rises quickly which means, with a small $R_{wt}$, the pipe owns a better capability to resist the impact of a falling rock. From the curves, $R_{wt}$ is suggested to be chosen during the range of 40–60.
3.2. Impacting direction

The impacting of the falling rock can cause different consequences in different directions. In our work, the eccentricity ratio is taken to describe the impact direction which is the ratio of actual eccentricity to the maximum one, given as:

$$H_R = \frac{H}{r+R} \times 100\%$$

(8)

where $H$ denotes the eccentricity which is the horizontal projected distance between the centers of the rock and the pipe cross section; $r$ is the radius of the rock and the $R$ denotes radius of the pipe. In this case, five values of 10%, 30%, 50%, 70% and 90% are chosen.

$$y=0.0047-0.0103*0.0038^x$$

$y=0.121-0.0024*exp(4.092*x)$

Figure 3. Subsidence depth at the impact point versus impacting time

Figure 4. Final subsidence depth at the impact point versus $R_{wt}$

Figure 5. Sectional deformations of the pipe versus impact directions

Figure 6. subsidence depth versus time with varying eccentricity

Figure 7. Final subsidence depth with varying versus eccentricity
Figure 5 shows the stress and deformations of final moments of the impacts with different $H_R$. With a bigger $H_R$, which means the rock laterally contacts the pipe, the impact will cause a smaller impact because only partial impacting energy is transferred to the pipe. Figure 6 shows the displacements of the contacting cell under different $H_R$. By extracting the maximum subsidence depth, figure 7 and corresponding fitting curve are obtained. It can be seen that, the subsidence depth decreases exponentially with the increasing $H_R$. The 50% of $H_R$ is more likely to be a watershed because a sharp decrease happens when is $H_R$ smaller than 50%.

3.3. The size and speed of the falling rock

For a pipe with specific $R_{wt}$ and other parameters, there are critical values of the size and speed of the falling rock that the pipe can resist. In this section, the 0.0054 axial strain is chosen to be the permissible maximum value to judge the resistant capability of the pipe to the falling rock. Parameters are same to those in section 2.2 except the varying diameter and falling speed of the rock.

From figure 8 obviously, a faster moving and bigger rock results in a larger axial strain and curves are linear. Extracting the permissible axial strain, figure 9 is got. From figure 9, the pipe can resist a fast impacting speed of the rock when its diameter is smaller than 1.0m. A fitted equation is given in figure 9 and for specific pipe and falling rock, the permissible impacting speed of the rock can be determined by the equation.

4. Conclusions

In this work, we discussed the dynamics and parameters effects during the impacting process of the falling rock onto a pipeline. From the strain-based standards, the permissible speed and the diameter of the falling rock can be determined by the fitted equations. The results and corresponding advices may provide some engineering reference.

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