

Bidirectional Coupling Analysis of Support Pipeline for Shock Damping of Dilute Debris Flow

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Abstract: With the frequent occurrence of geological disasters and extreme weather, pipeline failure accidents and secondary disasters caused by debris flow continue to occur. Aiming at the impact of thin debris flow on support pipeline, a multi-physical coupling model of debris flow and support pipeline with vibration reduction is established based on the expansion flow model. The expansive fluid model is used to simulate the stress of the support pipeline under the action of thin debris flow. The results show that the impact effect of thin debris flow slurry on the support pipeline is concentrated at the inlet surface of the pipeline and the support, and gradually decreases to both ends. As the velocity of debris flow slurry increases, the stress acting on the support pipeline also increases. When the flow field tends to be stable, the load acting on the support pipeline maintains a stable value. The leading effect of debris flow slurry is the most serious damage to the support pipeline. The research results have a certain reference value for the impact of dilute debris flow in support pipeline.

Keywords: Dilute debris flow, Shock absorbing support pipe, Fluid-structure coupling, Numerical simulation.

1. Introduction

With the rapid increase in the length of oil and gas pipelines in all regions of the country, debris flow disasters occur frequently in complex geological sections such as hills, mountains and rivers, which seriously endangers the safe operation of pipelines. In 2021, 154 mudslide disasters occurred in oil and gas pipelines nationwide, 12% more than in 2020, with frequent accidents occurring in mountainous and hilly areas in southwest and northwest China.

Under the action of debris flow, the support pipeline is affected by the shear stress impact of the faucet slurry, which leads to the plastic deformation of the stressed part of the pipeline, resulting in the pipeline deformation and rupture, which leads to the pipeline leakage and explosion accident, secondary pollution endangers the surrounding environment, and affects the safety of people's lives and property. In this paper, a multi-physical field coupling model of debris flow slurry and vibration damping support pipeline is established based on the actual working conditions to study the mechanical properties of the vibration damping support pipeline under the action of thin debris flow, which is of great significance for the safe operation of the pipeline.

At present, scholars at home and abroad have made a lot of research on the mechanics model of thin debris flow. In 1970, Johnson [1] proposed the Bingham viscous fluid model based on the non-Newtonian fluid of debris flow and established the debris flow motion equation for the first time to solve the maximum velocity of debris flow. In 1978, Takahashi [2] proposed the Bagnold expansion flow model based on the expansion flow of dilute debris flow, and solved the average velocity and fluid velocity of debris flow according to the equation of debris flow motion. In 1986, Chen [3] proposed a general Viscous plastic flow model of debris flow based on Bingham fluid equation and obtained the numerical solution of the model. In 1997, Iverson [4] proposed "momentum conservation equation of mixed flow theory" for debris flow based on the principle of energy conservation, and calculated the velocities of solids and liquids in debris flow respectively. Hong kai Chen [5] analyzed the mechanism of debris flow

movement and explained various debris flow phenomena in movement based on the equivalent two-phase flow model.

With the extensive application of finite element software simulation in debris flow analysis, many scholars simplified the overall movement of debris flow as rocks and studied the process of rockfall impacting the pipeline. For example, Jian Xiong [6] used LS-DYNA software to simulate the process of rockfall impacting the buried pipeline. Jie Zhang [7] established the calculation model of the spherical rockfall impact pipeline, and carried out numerical simulation and analysis on the dynamic response process of the pipeline. Hong Chao Ding [8] simulated the impact of viscous debris flow slurry on buried pipelines by simplifying the slurry into Bingham fluid and discretizing it into SPH particles. A large number of studies have focused on the action of viscous debris flow slurry and rocks on buried pipelines respectively. At present, there is a lack of systematic research on the continuous impact of thin debris flow slurry on vibration reduction support pipelines at home and abroad.

Considering the continuous impact of thin debris flow slurry on the support and vibration damping frame pipeline, a multi-physical coupling model of thin debris flow and vibration damping support pipeline is established in this paper to study the mechanical characteristics of the support pipeline under the action of thin debris flow slurry.

2. Basic Theory

2.1. Basic principles of fluid-structure coupling calculation

The solid structure will deform or move under the action of the flow field, which in turn will affect the flow field and lead to the change of the flow field, which in turn will change the size and distribution of the fluid load acting on the solid structure, thus forming the interaction and mutual influence between the fluid and the solid structure. That is, Fluid Structure (FSI) [9].

The fluid-structure coupling problem can be defined by its coupling equations, which include both the fluid domain and the solid domain. On the premise of satisfying the three basic

conservation laws of mass, energy and momentum, fluid dynamics derived three basic equations, namely, mass conservation equation, energy conservation equation and momentum conservation equation, which can be expressed by the following general equation [10]

$$\frac{\partial (\rho\phi)}{\partial t} + \text{div} (\rho\mathbf{u}\phi) = \text{div} (\Gamma \text{grad}\phi) + S \quad (1)$$

Where: ρ is the density of mass; ϕ is general purpose variable, which can represent variables such as the components (u, v, w) and temperature T of the velocity vector u in the x, y and z directions; Γ is the generalized diffusion coefficient; S is the generalized source term; grad stands for the tonsure ; div stands for divergence, defined

$$\text{div} (\alpha) = \partial\alpha_x/\partial x + \partial\alpha_y/\partial y + \partial\alpha_z/\partial z$$

The solid part can be derived from Newton's second law, namely

$$\rho_s \ddot{\mathbf{d}}_s = \nabla \cdot \boldsymbol{\sigma}_s + \mathbf{f}_s \quad (2)$$

Where: ρ_s is solid density; \mathbf{f}_s is the volume vector; $\boldsymbol{\sigma}_s$ is Cauchy stress tensor; \mathbf{d}_s is the acceleration vector.

The fluid-structure coupling must meet the basic principle of conservation, which is manifested at the coupling interface. The displacement d, stress τ , temperature T, heat flow q and other variables of fluid domain and solid domain should also be equal or conserved [10].

$$\left. \begin{cases} \tau_f \cdot \mathbf{n}_f = \tau_s \cdot \mathbf{n}_s \\ d_f = d_s \\ q_f = q_s \\ T_f = T_s \end{cases} \right\} \quad (3)$$

Where: The left of the formula represents the fluid domain, represented by the subscript f; Formula right represents the solid domain, denoted by subscript s.

Equations 1-3 constitute the basic governing equations of fluid-structure coupling analysis. By combining the above equations, the parametric solutions of fluid-structure coupling analysis can be obtained according to the actual coupling situation and given the boundary conditions and initial parameters. According to the different methods of governing equation solving, the fluid-structure coupling method can be divided into direct coupling method and separation method. The direct coupling method puts the solid, fluid and their coupling effects into the same governing equation, and solves the variables of the fluid domain and the solid domain at the same time. In this way, the method is ideal in theory because there is no time lag in solving the problem. But the Computation Structural Mechanics (CSM) and the Computation Fluid Dynamics (CFD), both of which are difficult to use with direct coupling solutions, are mostly complicated in actual fluid-structure coupling problems. really comes together, so this method is suitable for relatively regular fluid, solid coupling phenomena with very simple

boundary conditions. On the contrary, the separation method does not need coupling equations, but solves the governing equations of solids or fluids in sequence according to the set order. The calculation results of the solid domain and fluid domain are exchanged and transferred through the fluid-solid interface (therefore, it is also called the load transfer method). After each step reaches convergence, the next step is solved until the final stable result is obtained. The separation method has a time lag. Since the coupling equation is not solved, the energy on the coupling interface is not completely conserved. However, the separation method can be modified slightly and directly use the existing CSM and CFD software, and the memory required for solving is also low.

2.2. ANSYS fluid-structure coupling solution process

Under the platform of ANSYS Workbench, using the existing transient structure analysis module and fluid analysis module, the separation method is used to analyze the complex fluid-structure coupling model. Figure 1 shows the data transfer relationship for the bidirectional fluid-structure coupling analysis. This paper uses ANSYS Mechanical-CFX two-way fluid-structure coupling to analyze the interaction between debris flow and support pipeline [11].

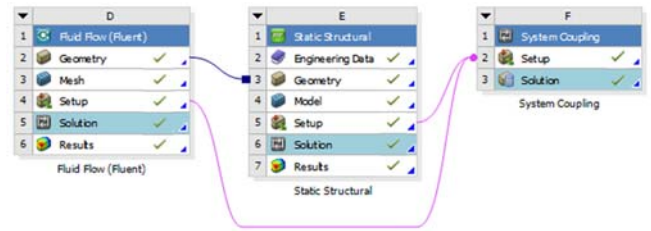


Figure 1. ANSYS bidirectional fluid-structure coupling data transfer diagram

3. Rheological Characteristics and Computational Modeling of Debris Flow Slurry

3.1. Vibration reduction support pipeline

Engineering background: Because it is not affected by groundwater level, soil quality, terrain and other pipelines, and has simple structure and convenient maintenance, bracket laying has been widely used in specific locations. In this paper, the mechanical properties of a common support pipeline under the impact of dilute debris flow are analyzed. Rubber damping pad has high elasticity, viscoelasticity and good damping characteristics, and it has the advantages of small cost, easy installation, etc. In order to make the pipeline can bear more transverse impact force, this paper adds rubber damping pad structure on the rigid support.

3.2. Analysis Objects

The stone pier at the bottom of the support is 2.3m high and 1m in diameter. The stone pier is made of C30 concrete. The thickness of the damping rubber cushion is 50mm, the Poisson's ratio is 0.49, the density is 1600kg/cm³ and the elastic modulus is 6.1MPa. X70 steel pipe with diameter of 508mm and wall thickness of 9.5mm is selected for the pipe. No load is used in the calculation, and only the dead weight of the structure is calculated. The steel of the bracket is Q345b, the density is 7850kg/cm³, the elastic modulus is 210GPa and Poisson's ratio is 0.3. The pipe and the vibration damping

rubber pad clamp are restrained by small friction, and the bracket and the vibration damping rubber pad clamp are fixed

connections.

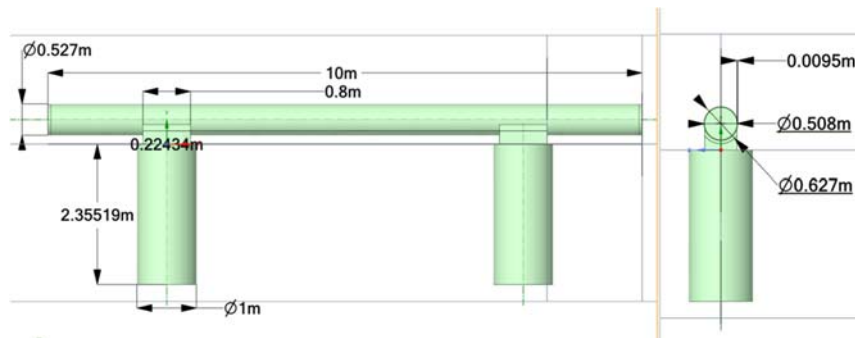


Figure 2. Constitutive model of the pipe of the damping support

3.3. Characteristics of debris flow slurry

The dilute debris flow in literature [12] is taken as the research object. The viscosity is 0.1Pa·s, the bulk density is 1300KN/m³, and the flow velocity is 12m/s-15m/s.

The common physical models of debris flow include expansion flow model, Bingham body model, two-phase flow model and particle flow model, among which expansion flow model is more suitable for thin debris flow slurry. The rheological characteristics of the expansion model [13] can be expressed as

$$\tau = \tau_y + \eta (\dot{\gamma})^n \quad (4)$$

Where: τ is shear stress, Pa; τ_y is the yield stress, Pa; η is viscosity, Pa·s; $\dot{\gamma}$ is the shear rate, s⁻¹.

3.4. Coupling model establishment

To simplify the analysis, it is assumed that the debris flow basin is a rectangular section, 16m wide and 40m long in which the inlet is 20m away from the support pipeline, and the depth of the debris flow is 3m. The lower 3m is debris flow, and the upper about 1m is air.

There are four main types of boundary conditions in CFX: Inlet, Outlet, Wall and Fluid-cylinder-interface. In mudstone drainage basin, the inlet boundary condition is set as the velocity condition, and the flow velocity is 12m/s-15m/s. Outlet boundary conditions relative pressure is zero; The boundary conditions of the top surface, ground and side were set as Wall. The contact surface between the pipe bracket and the fluid domain is set as the fluid-cylinder-interface. The numerical calculation model is shown in Figure 3.

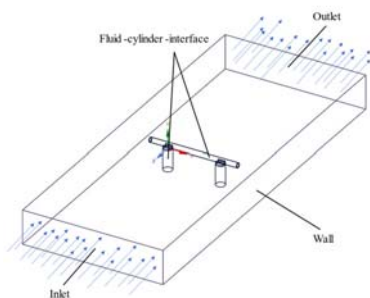


Figure 3. Fluid-structure coupling model of debris flow and support pipeline

4. Calculation Results and Discussion

4.1. Analysis results of flow field

Figure 4-6 shows the flow field trace line, three-dimensional rendering of debris flow slurry and pressure cloud diagram at the interface when the flow rate $t=10s$ and 12m/s.

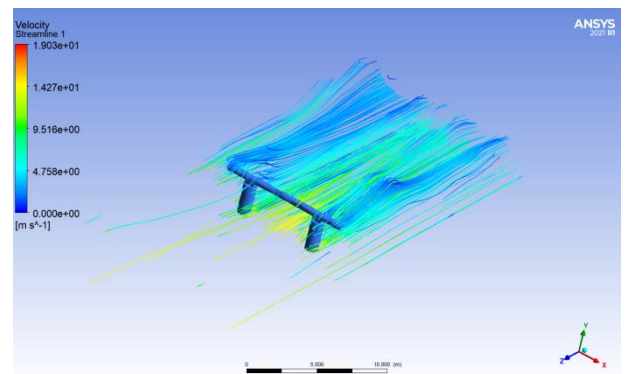


Figure 4. Debris flow trace line

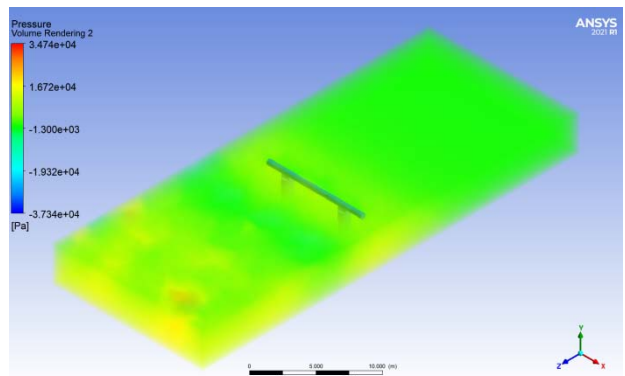


Figure 5. Three-dimensional rendering of debris flow slurry

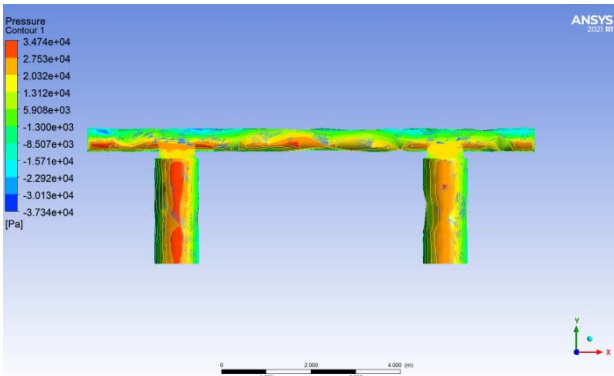


Figure 6. Pressure cloud diagram at the fluid-structure interface

As can be seen from Figure 4-6, debris flow slurry mainly acts on the oncoming side of the fluid-structure coupling interface.

4.2. Stress and strain of support pipeline

Under the impact of dilute debris flow, the support pipeline is under eccentric compression. CFX can directly monitor the stress of the support pipe in the process of calculation and analysis. Figure 7-10 shows the stress distribution cloud diagram of the pipeline after the flow field reaches a stable state when $t=15s$ and $v=12-15m/s$. It can be seen from the figure that the stress on the support pipe is concentrated in the area where the pipe and support are connected to meet the flow, and gradually decreases towards both ends. According to the calculation results in the solid domain, the bending moment distribution state of the bracket pipe can be extracted. Figure 11 and 12 show the equivalent stress and strain time history curve acting on the bracket pipe when the inlet velocity changes from 12m/s-15m/s. It can be seen from the trend that with the increase of flow rate, the stress acting on the support pipe also increases. The impact of debris flow faucet on the support pipeline is the most obvious. When the inlet speed is large, the speed of the debris flow faucet is fast, and the instantaneous impact effect on the support pipeline is obvious. For example, when $t \leq 5m/s$ and $v=12-14m/s$, the instantaneous impact effect of the faucet changes exponentially. From $t=8s$, the flow field tends to be stable, and the stress acting on the support pipe remains unchanged. When $v=15m/s$ and $t=1s$, the maximum stress generated by faucet impact is 82MPa, and the bending moment has exceeded the elastic limit load of 80MPa. Elastic deformation occurs in the support pipeline, and the maximum value is 0.0012m/m. When t is at 1-3s, the stress acting on the pipe shows a "wavy" trend change due to the continuous impact of slurry and the joint action of pipeline resilience. When $t \geq 5s$, the flow field tends to be stable, and the load acting on the support pipe remains stable.

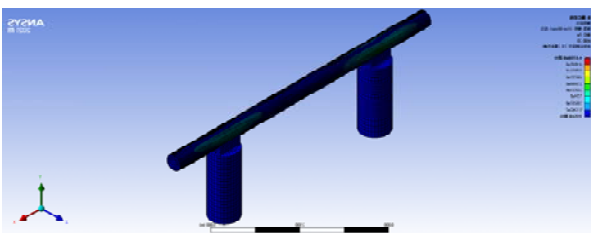


Figure 7. Stress nephogram of 12m/s pipeline

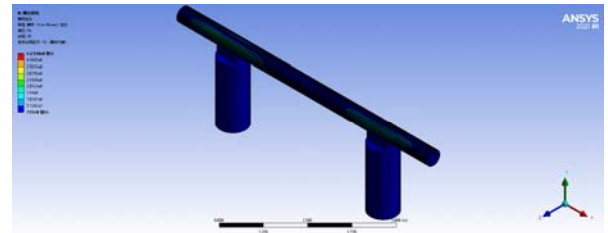


Figure 8. Stress nephogram of 13m/s pipeline

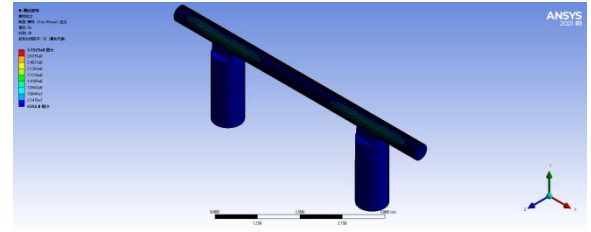


Figure 9. Stress nephogram of 14m/s pipeline

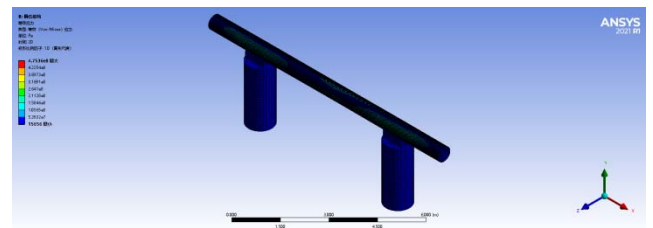


Figure 10. Stress nephogram of 15m/s pipeline

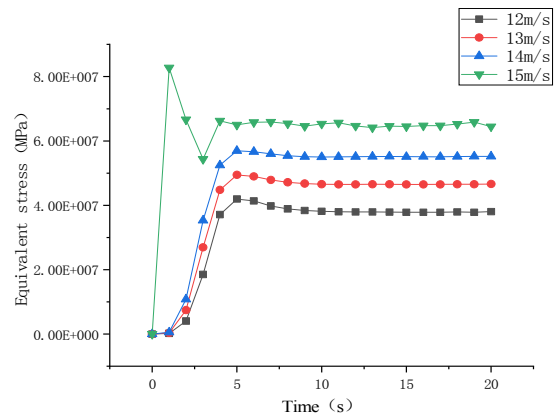


Figure 11. Stress time history curves of support pipes at different speeds

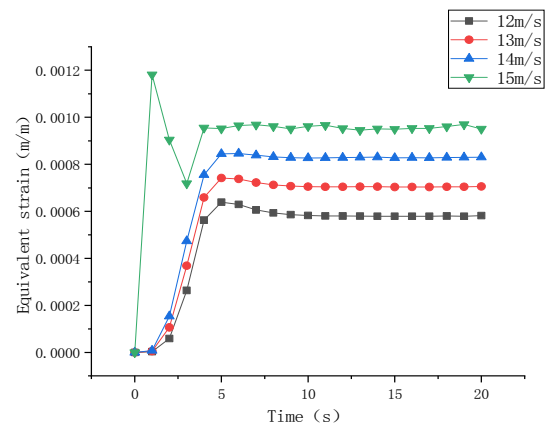


Figure 12. Strain time history curves of bracket pipelines at different speeds

4.3. Displacement analysis of support pipeline

Figure 13-16 shows the total deformation nephogram of the support pipeline at different flow rates. As can be seen from the figure, under the impact of dilute debris flow slurry, the instantaneous impact force generated by the faucet has an overall impact on the support pipeline, and the displacement at the intersection of the pipeline and the support reaches the maximum, and gradually decreases to the two ends. Figure 17 shows the displacement time-history curve of the pipeline at different flow rates. According to Figure 17, when $t \leq 5s$ and $v \leq 14m/s$, the displacement of support pipeline increases with the increase of debris flow impact velocity. Due to the spigot impact effect of debris flow slurry, the instantaneous impact force of the support pipeline is relatively large, and the displacement of the support pipeline changes exponentially. When $t \geq 6s$ and $v \leq 14m/s$, the flow field tends to be stable and the displacement of the support pipeline remains unchanged. When $v = 15m/s$ and $t = 1s$, elastic deformation occurs and displacement changes, and the maximum value is 0.017m. When t is in the range of 1-3s, the displacement of the support pipe changes in a "wavy" trend due to the continuous impact of slurry and the joint action of pipeline resilience. When $t \geq 5s$, the flow field tends to be stable, and the displacement of the bracket pipe remains unchanged.

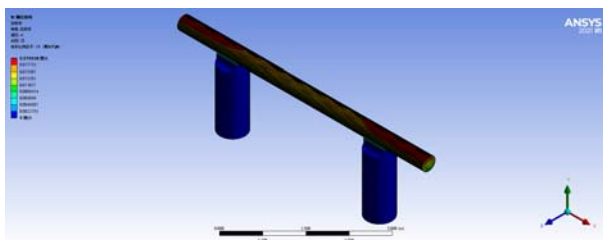


Figure 13. Total deformation cloud map of 12m/s pipeline

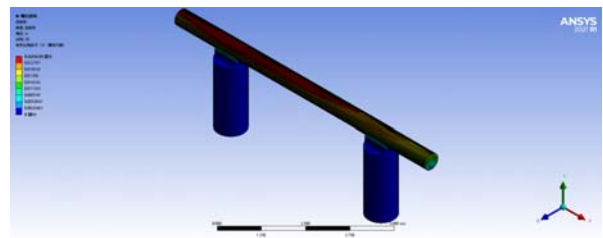


Figure 14. Total deformation cloud map of 13m/s pipeline

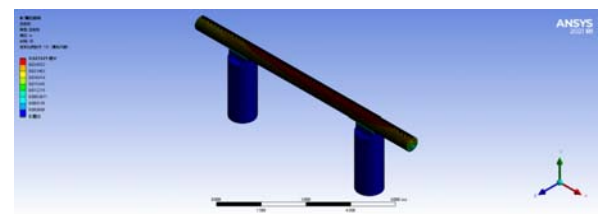


Figure 15. Total deformation cloud map of 14m/s pipeline

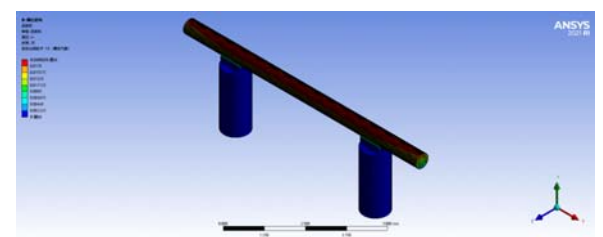


Figure 16. Total deformation cloud map of 15m/s pipeline

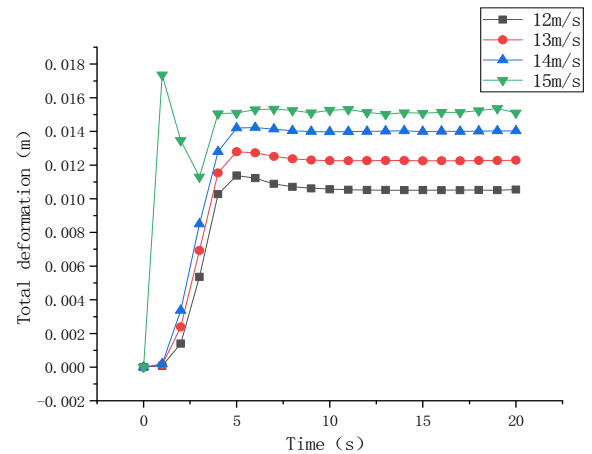


Figure 17. Displacement time-history curves of pipelines at different speeds

5. Summary

Based on the fluid-structure coupling theory, ANSYS-CFX was used in this paper to simulate the coupling between thin debris flow and support pipeline, and the response of thin debris flow slurry to impact support pipeline structure under different flow rates was analyzed, and the following conclusions were drawn:

(1) The impact effect of dilute debris flow slurry on the support pipeline is concentrated at the inlet surface where the pipeline and support meet, and gradually decreases to both ends.

(2) As the velocity of debris flow slurry increases, the stress acting on the support pipeline also increases. When the flow field tends to be stable, the load acting on the support pipeline maintains a stable value; The leading effect of debris flow slurry is the most serious damage to the support pipeline.

(3) When the inlet velocity is greater than 14m/s, elastic deformation occurs in the support pipeline under the impact effect of the debris flow tap, which may lead to the plastic failure of the pipeline structure. However, the nonlinear influence of materials was not considered in this study, and the whole process from impact to failure of the structure was not completely simulated. Therefore, it is necessary to further analyze the influence of material nonlinear on the flow field and the coupling effect of the two when the velocity is high.

(4) The rocks in the actual debris flow slurry are numerous and of different sizes, and the rocks in the debris flow have a significant impact on the pipeline, but the impact of rocks on the support pipeline is not considered in this paper.

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