INTRODUCTION

Crude oil pipeline with long distance and large drop in height generally adopts the operation mode of filling water first and then jacking water by crude oil for part of the pipeline, and water resources can be greatly saved by adopting partial pipeline filling\(^\text{1,2}\). The water-filling process can flush and clean the pipeline to ensure that the quality of oil in the pipeline will not be affected and is used to test the pressure of the large-drop pipe to ensure the safe delivery of oil; additionally, we can use the water column to establish back pressure to prevent oil vaporization. But during the water-filling process, crude oil pipelines with complex topography are prone to undulating slug flow or severe slug flow, which causes the flow and tube pressure to fluctuate drastically, and the operating noise increases\(^3\), affecting the safety of pipelines and equipment. Therefore, it is necessary to pay special attention to the influence of huge height differences and undulating topography on the water-filling process when adopting a water-filling operation mode for part of the whole pipeline that has the large drop. Moreover, when the waterhead overturns the high point and underrushes in the pipe without enough back pressure, this will greatly impact the low point of the pipe and endanger pipe safety.

Deng and other scholars\(^4,6\) mentioned that during the transportation of large-drop pipelines, the phenomenon of

**Abstract**

To explore the problem of the slack flow and waterhead having a huge impact on the low point of a pipeline during the water-filling process of a large-drop pipeline, the crossing section of the Nujiang China-Myanmar crude oil pipeline (for which the maximum height difference is 1480 m) is taken as an actual case, and water filling of an oil pipe segment with a large drop is simulated based on an OLGA multiphase flow transient simulation. The maximum velocity, pressure, and corresponding liquid holdup at different low points of the pipeline are studied, and the variations of water flow velocity, pressure, and liquid holdup with time at different low points under different load conditions are obtained. A stress analysis of the pipeline is performed through CAESAR II. The results showed that, when the volume flow rate was 900-2000 m\(^3\)/h, the probability of slug flow in pipe could be reduced by 57%. Meanwhile, the tube pressure fluctuation and damage to the pipeline and equipment are reduced and pipeline transportation efficiency is improved, thereby providing an effective basis for engineering practice.

**KEYWORDS**

large-drop pipeline, slack flow, water filling, waterhead impact
LIU et al.

negative pressure or pressure drop to the saturated vapor pressure of water is easy to occur at the high point of the pipeline and near the high point and the gas dissolved in the water will escape to form a steam cavity. Because of the difference in density and pressure, this part of the air mass stays at the high point of the pipeline, and slack flow will occur in some sections near the high point or at the high point\(^\text{7,8}\); when the pressure is high, a small amount of gas is absorbed by the water. The liquid after the higher point will form a waterfall flow in the tube, and under the action of its own kinetic energy and gravity, the liquid will accelerate downward, producing a large impact load on the low point of the pipeline, which will cause the pipeline to be overpressured at a low point.\(^\text{9,10}\) This condition is not conducive to the safe operation of the pipeline. The water-filling process of the large-drop-in-height pipe is shown in Figure 1.

The water-filling process of a large-drop pipe forms a gas-liquid two-phase flow of "water-driving gas" under the difference of gas-liquid two-phase density and pressure at the high point of the pipeline.\(^\text{11-13}\) Schmidt\(^\text{14}\) pointed out that the most complicated problem of gas-liquid two-phase flow is slug flow. Liquid slug flow is most common at offshore platform risers and uphill sections of large-drop pipes. The existence of slug flow will impact and oscillate the pipeline, which will affect its safety. For this reason, the hydraulic characteristics of the slug flow through the ascending pipeline are studied experimentally. Payne et al\(^\text{15}\) pointed out that pipelines inevitably have to go through areas with large terrain fluctuations. Pressure drop loss and liquid holdup prediction are issues that must be considered in the design of two-phase flow pipelines. Ju et al\(^\text{16}\) established a flow pattern, pressure gradient, and liquid holdup calculation model of gas-liquid two-phase flow in a gas-liquid choke pipe section and compiled relevant calculation programs. Based on actual engineering data, numerical simulation was conducted, providing a theoretical basis and solution for prevention of air resistance in the heavily fluctuated section of the large-drop pipeline when it was put into operation. Guo\(^\text{17}\) studied the flow problem of liquid push gas when a large-drop pipeline was put into operation and simulated the relevant parameters of the liquid push gas flow process with the western product oil pipeline as an example. Liu et al\(^\text{1}\) simulated the commissioning process of crude oil in large-drop pipelines and analyzed the flow pattern changes and pressure changes of oil and water in the pipelines. Zhang et al\(^\text{18}\) studied the gas-liquid two-phase flow law and its influencing factors in different types of pipelines and established an undulating pipeline model to simulate gas-liquid two-phase flow in the undulating pipeline. Wang et al\(^\text{19}\) established a corresponding mathematical model for the gas-liquid two-phase flow problem in the undulating pipe section and used a numerical simulation method to elucidate the whole process of liquid-filled flow and the variation of hydrothermal parameters under the condition of a stagnation airbag. The influence of the undulating terrain and a large-drop difference of the western pipeline on pipeline liquid filling during the production process were analyzed by Zhang et al\(^\text{20}\) However, their research was limited to the engineering observational data, and the problems were not abstracted into mathematical models for comparison.

In recent years, many scholars\(^\text{21-24}\) have studied the flow state of pipelines by using CFD numerical simulation methods, and some scholars\(^\text{25-28}\) have proposed the method of mathematical model prediction for this problem, which provides a new idea for us to solve multiphase flow problems.

It can be seen from the preceding analysis that the existing studies on multiphase flow during the commissioning of large-drop crude oil pipelines are based on the operation of gas-liquid mixtures in pipes. However, when we study the water-filling process of large-drop pipe, as a result of the empty-tube water-filling process, air is filled in the tube before water filling, and the filling process is actually a multiphase flow process of "water-driving air." When the waterhead overtops the high point, the water-air interface evolves into a waterfall flow pattern and accelerates downward under the action of its own gravity and kinetic energy, producing a large impact load on the low point of the pipeline, which will cause the pipeline to be overpressured at a low point. Therefore, we propose a new calculation method for this problem and innovatively study the maximum velocity at low point, the corresponding liquid holdup, and the impact load of the waterhead on the low point, which can provide technical means and theoretical basis for other large-drop pipelines.

**FIGURE 1** Large-drop-in-height pipe water-filling process
Based on the actual geometry and geographic data of the crossing section of the Nujiang China-Myanmar crude oil pipeline, we used OLGA 7.0 to simulate the steady-state and transient operation of the water-filling process of a large-drop pipeline, predicting the maximum water filling and filling time in the process, analyzing the change rule of pressure, flow, liquid holdup, and flow pattern. We used CAESAR II software to obtain the impact load of water flow on different low points of a large-drop pipe under different load conditions with tube soil action taken into consideration. By combining the engineering case and a comparison of the simulation results with the actual data, we obtained the allowable throughput range of a large-drop pipe.

2 PHYSICAL MODEL AND BOUNDARY CONDITIONS

2.1 Physical model

At present, many scholars have used OLGA to conduct a large number of numerical simulation calculations on gas-cap emptying, pigging, and other fields, and CAESAR II stress analysis software has also been widely applied to stress analysis of buried pipelines, which shows that the OLGA and the CAESAR II numerical simulation results are in good agreement with experiment results. We will use these software packages to build a computational model of the pipeline.

As shown in Figure 2, the water-filling pipe segment of a typical large-drop pipe contains two important low points: low elbow #1 and low elbow #2 (the first low point of the downhill section and the lowest point of the pipeline, respectively). The pipeline diameter used in the simulation was 813 mm according to the actual situation. The total length of the pipeline was 29 000 m and the pipeline buried. Because of the height difference, there is no need to use an air compressor at the inlet.

OLGA Basic File model was selected in the modeling process of OLGA software, and the channel grid was partitioned into 299 segments by using Discretize, an internal tool of OLGA. And the model includes the mixing of liquid and gas in the later continuous running process. After OLGA software modeling is completed, the “Verify” option in the OLGA software is clicked to verify the validity of the built model, and according to the comparison between the actual date and simulated date of valve stations A and B, their relative deviation is about 0.307% and 0.76%, respectively, which proves the accuracy of the model used in this paper.

In the water-filling process, the long-distance water flow makes its load time much longer than the dynamic abrupt change time. The impact load of water flow on the low point is regarded as static load, acting on the bend in the form of external concentrated force. As the whole section of Nujiang crossover pipes is laid in a buried way, soil constraints are added to the pipeline. And to ensure accuracy calculation, the node spacing of the pipeline model is set to 20m, and a CAESAR II model was constructed as shown in Figure 3.

2.2 Boundary conditions

During the waterfall flow, interphase slip exists at the water-gas interface. Therefore, for the interface boundary conditions, the interphase slip model in the OLGA software remains the default state, that is, NOLSIP is set to OFF. The initial condition is the empty pipe state.

The inlet and the outlet boundary condition are set as the mass flow source and the pressure node, respectively. As the filling process is a multiphase flow process of "water-driving air," two fluid packages are prepared by using PVTSIM software: the transport medium (water) and air. The basic components of water and atmosphere are input into PVTSIM, the upper and lower pressure boundaries are 0.1 and 10 MPa, respectively, and the upper and lower limits of temperature are 10 and 50°C, respectively. Then, the fluid packet that transports medium water and air is input to the inlet flow node and outlet pressure node, respectively, aiming to simulate the process of water-driving air in the actual water-filling process.

As a result of the empty-tube water-filling process, air is filled in the tube before water filling, and air on the right side of the pipe is squeezed by water and discharged to the atmosphere through the end of the pipe with the process of continuous water filling. There is no obvious air segment in the pipe and no air resistance is formed, so there is no need to use an air release valve, just be aware of the steam hole at the high point of the pipe due to the difference in pressure and density.
The design and boundary condition parameters of the target water-filled pipeline are listed in Tables 1 and 2, respectively. Except for the parameters shown in Tables 1 and 2, the other values in OLGA (such as the heat transfer coefficient) remain the default values.

The whole section of Nujiang crossover pipes is laid in a buried way, and its main constraint is soil constraint. The soil parameters are listed in Table 3.

## 3 | MATHEMATICAL MODEL

### 3.1 | Water-filling process

During the large-drop-in-height pipe-filling process, the waterhead will quickly undershoot after passing through the point, decreasing the pressure at the high point of the pipe rapidly. When the pressure is lower than the saturated vapor pressure of water, the bubbles dissolved in the water will escape to form steam holes. When the pressure is greater than the saturated vapor pressure of water, the bubbles will dissolve to form a liquid. A phase transition occurs between water and water vapor under pressure changes, forming a typical gas-water two-phase flow. Based on this, a corresponding gas-liquid two-fluid transient flow model is established and cited by many scholars, which proved the accuracy of the formula.

The gas-phase continuity equation is.

$$\frac{\partial}{\partial t} (\rho_g \phi) + \frac{\partial}{\partial x} (\rho_g \phi u_g) = \Delta m_{gl}$$

(1)

The liquid-phase continuity equation is.

$$\frac{\partial}{\partial t} (\rho_l \phi_l) + \frac{\partial}{\partial x} (\rho_l \phi_l v_l) = H_l$$

(2)

The relationship between volume gas content and volume liquid volume friction is as follows:

$$\phi + H_l = 1$$

(3)

In which \(g\) is the gas phase; \(l\) is the liquid phase; \(\phi\) is the volume gas content; \(H_l\) is the liquid volume fraction; \(\rho_g\) and \(\rho_l\) are gas and liquid density, respectively (kg/m³); \(\Delta m_{gl}\) is the net mass transfer from gas phase to liquid phase (kg/(m³·s)); and \(\Delta m_{lg}\) is the net mass transfer from liquid phase to gas phase (kg/(m³·s)).

The gas momentum conservation equation is.

$$\frac{\partial}{\partial t} (\rho_g \phi u_g) + \frac{\partial}{\partial x} \left( \rho_g \phi u_g^2 + \rho_g \phi u_g \frac{\partial P_g}{\partial x} \right) + \tau_{gw} S_g + \tau_{tg} S_g$$

$$= -\rho_g \phi g \sin \alpha - \phi \rho_g \frac{\partial P_g}{\partial x} + \Delta m_{gl} \phi_l u_l$$

(4)

The liquid momentum conservation equation is.

$$\frac{\partial}{\partial t} (H_l, \rho_l u_l) + \frac{\partial}{\partial x} \left( H_l, \rho_l u_l^2 + \rho_l \phi_l \frac{\partial P_l}{\partial x} \right) + \tau_{lw} S_l + \tau_{tl} S_l$$

$$= -H_l \phi g \sin \alpha - H_l \frac{\partial P_l}{\partial x} + \Delta m_{lg} \phi_g u_g$$

(5)

In which \(\rho_g\) and \(\rho_l\) are the gas- and liquid-phase pressure, respectively (Pa); \(\tau_{gw}\) is the shear force between gas phase and tube wall (N/m); \(\tau_{lw}\) is the shear force between liquid
phase and tube wall (N/m); $\tau_i$ is the shear force at the gas-liquid interface (N/m); $S_l$ is the liquid-phase wetted perimeter; $S_g$ is the gas-phase wetted perimeter; and $S_i$ is the gas-liquid interface wetted perimeter.

The gas-phase energy conservation equation is:

$$\frac{\partial}{\partial x} \left[ \rho_g v_g \left( h_g + \frac{v_g^2}{2} \right) \right] + \rho_g v_g \phi g \sin \alpha = Q_{wg} + E_{lg} + W_g \tag{6}$$

The liquid-phase energy conservation equation is:

$$\frac{\partial}{\partial x} \left[ H_l \rho_l v_l \left( h_l + \frac{v_l^2}{2} \right) \right] + H_l \rho_l v_l g \sin \alpha = Q_{nl} + E_{il} + W_l \tag{7}$$

where

$$Q_{wg} = -q_{wk} S_k, \quad E_{lg} = -q_l S_l + \Delta m_{gl} \left( h_l + \frac{v_l^2}{2} \right),$$

$$E_{il} = q_l S_l - \Delta m_{lg} \left( h_l + \frac{v_l^2}{2} \right), \quad W_g = -\frac{\partial (\rho_g v_g)}{\partial x} - \tau_i S_l v_l,$$

$$W_l = -\frac{\partial (H_l \rho_l v_l)}{\partial x} - \tau_i S_l v_l \tag{8}$$

In which $Q_{wg}$ is the amount of heat exchanged between gas phase and tube wall, $J/(m^3\cdot s)$; $Q_{nl}$ is the amount of heat exchanged between liquid phase and tube wall, $J/(m^3\cdot s)$; $E_{lg}$ and $E_{il}$ are the rate of energy transfer between the liquid phase and the gas phase, respectively, $J/(m^3\cdot s)$; $W_g$ and $W_l$ are work done per unit volume of gas phase and liquid phase, respectively, $J/(m^3\cdot s)$; $q_{wk}$ is the heat flux between liquid phase and tube wall ($J/(m^2\cdot s)$); $q_{lg}$ is the heat flux between gas phase and tube wall, ($J/(m^2\cdot s)$); $q_l$ is the heat flux between gas and liquid phase interfaces ($J/(m^2\cdot s)$); $h_g$ and $h_l$ are specific enthalpy values of gas phase and liquid phase, (J/kg); $l$ is the specific enthalpy values of gas and liquid at the interface, (J/kg); for the liquid, k is equal to $l$; and for the gas, k is equal to $g$.

In the water-filling process, the pressure at each point of the pipeline changes with the filling time, and the air in front of the water flow is compressible gas.\cite{26,34} The air state equation is shown in formula (9):

$$PV = ZnRT$$

molar volume of gas, (m$^3$/kmol); $Z$ is the gas compressibility factor; $n$ is the amount of gaseous substance; $T$ is the gas temperature, K; and $R$ is the gas constant, 0.813KJ/(kmol·K).

For the two-fluid (gas-liquid) model, in the first step, the pipeline is discretized into numerous control body units by using a staggered grid. Variables such as density, pressure, and temperature are stored in the center of the control body, and variables such as flow rate and flow rate are stored at the boundary of the control body. In the second step, the differential equations are integrated over the control body length and time to obtain a set of linear algebraic equations. In order to use a large time step, an implicit format is used for the time, and then, the upwind difference algorithm is used to associate the convection term variable with the node value.

### 3.2 Water flow impact mathematical model

#### 3.2.1 Soil load

The whole section of Nujiang crossover pipes is laid in a buried way. Using the Marston model, the vertical earth pressure at the top of the pipe is uniformly distributed in any depth plane in the pipe trench. The top of the pipe is subjected to the full earth pressure, and the force balance equation of the micro-element is established at any position above the pipe to obtain the vertical earth pressure at the position, thereby obtaining the maximum vertical soil load per unit length of the pipe:\cite{35}

$$W_v = C_d \left( \gamma_o B - 2c \right) B \tag{10}$$

where

$$C_d = \frac{1 - \exp \left( -2k_o \frac{\mu B}{B} \right)}{2k_o \mu} \tag{11}$$
with 

$$k_a = \tan^2 \left( \frac{\pi}{4} - \frac{\phi}{2} \right)$$  \hspace{1cm} (12)$$

In which $M_v$ is the vertical earth pressure received by a unit length of pipe (kN/m); $C_d$ is the load coefficient (dimensionless); $\gamma_{so}$ is the bulk density of the backfill soil (kN/m$^3$); $B$ is the width of trench at top of pipe (m); $C$ is the viscosity of the backfill soil (kPa); $k_a$ is the proportion of active lateral unit earth pressure to vertical pressure; $\mu$ is coefficient of friction between the backfill and the trench wall (dimensionless); $H$ is pipe top buried depth (m); $\phi$ is soil internal friction angle (rad); and $D$ is outer diameter (m).

Under the action of internal pressure and hydraulic head impact force, the large-drop pipe may be relatively displaced from the soil. The earth pressure on the pipe is not evenly distributed along the pipe circumference, making it necessary to characterize the uneven distribution from the actual situation. First, the radial and axial earth pressure values are determined, and the earth pressure in the other directions comprises the radial and axial projection values. The friction force for a unit pipe length is given by.

$$f = \frac{\pi}{2} \mu_2 \gamma_{so} DH_0 \left( 1 + k_a \right) + \mu_1 G_g$$  \hspace{1cm} (13)$$

In which $f$ is the frictional force on a length of unit pipe (kN/m); $G_g$ is the total gravity per unit length of the pipe structure including the insulating layer, the steel pipe, and the medium inside the pipe (kN/m); $\mu$ is coefficient of friction between pipe and soil (dimensionless).

### 3.2.2 Gravity load of pipes and conveying medium water

The crude oil pipeline of the Nujiang crossover pipes is built on a steep slope. When the slope is stable, the weight of the pipeline can be regarded as evenly loaded by the soil. Gravity has little influence on the stress analysis of the pipeline with a large drop. However, because the pipeline is a giant U-shaped pipeline extending a long distance and with a large dip angle, the effect of gravity on the pipeline itself cannot be ignored. The total force of gravity per unit length of the pipe structure, including the insulating layer, the steel pipe, and the medium inside the pipe, can be expressed as.

$$G_g = \gamma_s \pi \left( D - t \right) t + \sum_{i=1}^{n} \gamma_i \pi \delta_i \left( D + \sum_{j=1}^{i} \delta_j + \sum_{j=1}^{i-1} \delta_j \right)$$ \hspace{1cm} (14)$$

In which $G_g$ is bulk density of steel (N/m$^3$); $\gamma_i$ is material bulk density of layer $i$ outside the pipe (N/m$^3$); $\delta_i$ and $\delta_j$ are material thicknesses of layers $i$ and $j$ outside the pipe (m); and $n$ is total layers of material outside the pipe.

During the water-filling process, the waterhead will produce a huge impact load on the bottom bend of the pipeline. This load may exceed the design limit, causing the pipeline stress to be too large. The load of the water flow can be expressed as.

$$F_G = m_w g \cos \alpha$$ \hspace{1cm} (15)$$

The gravitational force of the water flow is related to the length of the liquid bomb, the liquid-holding rate, and the diameter of the pipe and can be expressed as.

$$m_w g \cos \alpha = \rho_l H_l L_s A_g \cos \alpha$$ \hspace{1cm} (16)$$

Because the liquid holdup and water flow length are constantly changing with the filling time, combining Equations (15) and (16) gives the gravity load of water flow on pipelines with a large-drop difference:

$$F_G(t) = [m_p + \rho_l H_l(t)L_s(t)A_g] \cos \alpha$$ \hspace{1cm} (17)$$

In which $F_G$ is gravity load caused by water flow to a large-drop pipe (N); $m_p$ is water mass (kg); $g$ is acceleration of gravity (m/s$^2$); $\alpha$ is pipeline inclination (°); $L_s$ is length of the liquid segment (m); and $A$ is pipe cross-sectional area (m$^2$).

#### 3.2.3 Waterhead to low point elbow impact load

The impact load of the water flow on the elbow is mainly reflected in the normal force acting on the elbow surface. The micro-element between the head and the tail of the water flow passing through the low point bend of the large-drop pipe is the control body. As shown in Figure 4, it is assumed that the density of water flow and the pressure difference before and after the water flow do not change with time and that the temperature does not change during the impact process. The momentum conservation equation at the micro-element section of the elbow is obtained from the momentum conservation principle$^{36}$:

$$dF_{nf} - \rho_l H_{li} A_l g ds \cos \alpha = \rho_l H_{li} A_l \frac{v_j^2}{r} ds$$ \hspace{1cm} (18)$$

In which $r$ is the curvature of the pipeline elbow; $DF_{nf}$ is impact load of the liquid bomb micro-element on the pipe low point elbow (N); $H_{li}$ is liquid holdup of liquid bomb micro-unit; $v_j$ is liquid bomb velocity (m/s); $ds$ is length of
liquid bomb micro-element at the pipe elbow (m); r is radius of curvature of the pipeline elbow (m); and $i$ is $i$th infinitesimal segment.

4  |  RESULTS AND DISCUSSION

4.1  |  Maximum water filling and water-filling stability time

Figure 5 shows the total water content-time relation curves for different volume flows. It can be seen from the figure that the water-filling amount in the pipeline under different volume flows shows a trend of linear increase and then stable fluctuation at a certain value. This is due to the empty-tube water-filling process and the volume flow is constant before the pipeline is full, the water-filling amount in the pipeline increases linearly with the progress of the water-filling process, when the water filling is stable; because of the slack flow at the high point of the pipeline and the pressure fluctuation, the water filling in the pipe fluctuates around a certain value with the water filling continues. The higher the volume flow rate is, the faster the liquid-holding capacity in the tube increases; the faster the water-filling rate is, the more intense the fluctuation will be. However, determining the water-filling stabilization time only by the change of the liquid-holding capacity in the tube is inaccurate.
It is considered in this study that, when the water-filling process is stable, all the flow and operating parameters in the pipeline (e.g., fluid holdup in the branch, the pressure distribution along the line, and the flow distribution across the line) will change from an unstable state to a stable one at almost the same time. Figure 6 shows how the operating parameters change with time under the condition of the same volume flow rate (900 m$^3$/h).

It can be seen from Figure 6 that, although the maximum values of pressure and flow at different positions of the pipeline are different, all the parameters change from a drastic change state to a steady state almost at the same time. For example, the pressure at low point 1 increased to 10.38 MPa at 12.92 hours and 10.39 MPa at 13.1 hours. The pressure at low point 2 increased to 11.98 MPa at 12.92 hours and 11.99 MPa at 13.1 hours. The flow at low point 1 was 900.26 m$^3$/h at 12.92 hours and 936.79 m$^3$/h at 13.1 hours, with a relative rate of change of only 3.9%. The flow at low point 2 was 901.34 m$^3$/h at 12.92 hours and 936.79 m$^3$/h at 13.1 hours, with a relative rate of change of only 3.78%. Although all the parameters at the time node are not fixed values, after the time node, they change from dramatic undulation (traffic) and increase (pressure) to tiny fluctuations about a certain value, and the flow at different positions is almost equal, so the time node is the interval at which the stability state of the water-filling process is reached.

In addition, as the crossing section of the Nujiang China-Myanmar crude oil pipeline is a typical U-type pipe, the waterhead will quickly undershoot after passing through the high point. When the current reaches low point 1, its maximum velocity of 26.94 m/s causes the flow to exceed 6000 m$^3$/h, and the change curves of flow at different low points in Figure 6 refer to the changes of the total flow in the pipe at different low points. When the water-filling process is stable, the total flow in the tube tended to be stable, and the flow change curves at low point 1 and low point 2 coincide. It can be seen from Figure 6 that the liquid holdup is 100% at low points 1 and 2 after water-filling stabilization, which is in a full tube state, while the liquid holdup at the high points 1 and 2 is 7.8% and 92%, respectively; after water filling is stable, there is an slack flow phenomenon at the high point of the pipeline. When pipeline includes the gas part, the flow rate at different locations cannot be same.

The simulation results of the corresponding water-filling stability time, maximum water-filling amount, maximum velocity at the low point, and pressure for each volume flow are summarized in Table 4.

From Table 4, one can see that, with the increase in the volume flow rate, the maximum amount of filling water inside the pipe increases, the required water-filling stability time decreases, the maximum flow velocity reaching low point 1 decreases, and the maximum pressure at the low point increases. The maximum pressures are all lower than the designed pressure of the pipe of 15 MPa. When the pipe is filled with water for 30 hours, it has reached a stable state under various flow conditions.

### 4.2 Pressure monitoring

Because the water-filling process is affected by the large drop in height, a waterfall flow is formed in the tube after the waterhead passes through the top point, as shown in Figure 7. The pipe is full of air before water filling; under the action of its own gravity, the waterhead quickly undershoots and rapidly squeezes the air inside the pipe, causing the pipeline to be overpressured at a low point. Therefore, in the process of water filling, it is necessary to pay close attention to the pressure changes of the two important low points of the pipeline (the first low point of the downhill section and the lowest point of the pipeline) to prevent the pressure from exceeding the design limit.

It can be seen from Figure 7 that, at the initial stage of water filling, there are many slack flows in this section and, during the water-filling process, the low point of the pipeline is filled first. Because of the different weights of the conveying medium at different positions of the pipeline, the pressure at different positions of the pipeline varies greatly. In the following, we will study the changes of liquid holdup and pressure along the pipeline under different volume flow rate conditions when water filling occurs for 3 hours.

| Volume flow (m$^3$/h) | Water-filling stability time (h) | Maximum water-filling amount (m$^3$) | Proportion of maximum water filling to pipeline capacity (%) | Maximum velocity (m/s) | Maximum pressure (MPa) |
|----------------------|----------------------------------|--------------------------------------|-----------------------------------------------------------|-----------------------|-----------------------|
|                      |                                  |                                      |                                                           | Low point 1 | Low point 2 | Low point 1 | Low point 2 |
| 900                  | 12.93                            | 12 070.81                           | 87.60                                                     | 26.94      | 53.31      | 10.39      | 11.99      |
| 1300                 | 8.99                             | 12 141.62                           | 88.11                                                     | 25.99      | 12.42      | 10.44      | 12.01      |
| 1700                 | 6.97                             | 12 198.75                           | 88.53                                                     | 23.50      | 12.65      | 10.53      | 12.05      |
| 2100                 | 5.71                             | 12 281.44                           | 89.13                                                     | 23.05      | 15.69      | 10.63      | 12.09      |
| 2500                 | 5.05                             | 12 363.52                           | 89.73                                                     | 21.97      | 12.89      | 10.68      | 12.13      |
Curves of the hydrostatic pressure distribution along the pipeline under different flows 3h after commissioning are shown in Figure 8. Since the pressure at different positions of the pipeline first increases and then fluctuates at a certain value with the progress of water-filling process, combined with the water-filling stability time under the condition of different volumes, we can know that the water-filling process has not reached a stable state when the water is filled for 3 hours. And the pressure at each point along the pipeline in Figure 8 is the pressure value for commissioning 3h, not the maximum pressure at each point. When the flow is 900 m³/h, the pressure at low point 1 of the pipeline is 1.7 MPa, the pressure at low point 2 is 1.2 MPa, and thus, the pressure at low point 1 is higher than that at low point 2. According to the curve of liquid holdup rate under the condition of 900 m³/h in Figure 8, the waterhead has just passed low point 1 and has not reached low point 2; yet, the pressure at low point 2 is caused by the compressed air in the tube. When the flow is 2500 m³/h, the pressure at low point 1 of the pipeline is 3.38 MPa, the pressure at low point 2 is 4.1 MPa, and thus, the pressure at low point 2 is higher than that at low point 1. According to the curve of liquid holdup rate under the condition of 2500 m³/h in Figure 8, at this time, the waterhead almost reached the end of the pipeline, and the liquid-holding rates at low points 1 and 2 are 100% and 99.99%, respectively. Both low points are in the full pipe state, and, because the height of low point 2 is lower than that of low point 1, the pressure at low point 2 is higher than that at low point 1, and low point 2 exhibits the highest pressure in the whole line. It is not difficult to see that, with the decrease in elevation, the pipeline pressure gradually increases and, with the increase in elevation, the pipeline pressure gradually decreases, and so the changes of hydrostatic pressure along the pipeline under different volume flow conditions are consistent.

Figure 10 shows the hydrostatic pressure distribution along the pipeline when the water-filling stage reaches a stable state. The pipe pressure and liquid holdup rate under the various volume flow rate conditions in the figure no longer exhibit any changes, and the pipe pressure curves after low point 1 almost coincide. According to the liquid holdup rate curve, there are bubbles in the downhill pipe section before low point 1. When the water filling is stable, the bubbles have accumulated at the high point of the pipeline, forming an air mass, which reduces the pipeline pressure.

In addition, after water filling is stabilized, the liquid-holding rate of the whole pipeline is not 100% but is <100% at the high point of each pipeline, especially, at the high point of the downhill pipe before low point 1, where the rate is only 5.4% (900 m³/h), as shown in Figure 11. This indicates that there is a serious gas accumulation problem at the high point of the pipeline, which has an important influence on the production of the crude oil pipeline. If the gas at the high point of the pipeline is not discharged in time during production, it will seriously affect the downstream pumping station equipment and cause air resistance and other undesirable phenomena. Therefore, changes of the liquid holdup rate and flow regime of the pipeline under different volume flow rate conditions will be studied in the following.

### 4.3 Holdup and flow regime

Figure 12 shows the holdup distribution along the pipeline when the water-filling stage reaches a stable state. In the figure, points with higher elevation have a lower liquid holdup, such as at the pipeline inlet, where the rate is only 9.6% (900 m³/h). High points of the pipeline with severe fluctuation have a lower liquid holdup, such as the first high point after low point 1, where the rate is only 10.1% (900 m³/h). This means that the pressure and topography determine the direction of the bubble, not the point at which the elevation is higher, but the point at which the bubble is concentrated. The higher the terrain, the lower the pressure, and the smaller the angle of the pipe is, the easier it is to accumulate gas at the high point. For example, the height of high point 1 is greater than that of high point 2, and the pressure of high point 1 is lower than that of high point 2, so the liquid holdup of high point 1 is lower than that of high
**FIGURE 8** Pressure distribution curves along the pipeline under different flows 3 h after commissioning

**FIGURE 9** Time-dependent curves of hydrostatic pressure at the top elbow 1 and the low elbow 1 of the pipeline under different volume flow rates

**FIGURE 10** Pressure distribution curves along the pipeline under different flows 30 h after commissioning (steady state)
However, the pipe angle at high point 3 is too large, so bubbles are easily carried away by liquid flow and gas cannot gather there. Therefore, although the height of high point 3 is greater than that of high point 2, there is no gas accumulation there.

In the downhill section before low point 1, the distribution of liquid holdup under the water-filled stable state differs with different volume flow rates. The liquid holdup of the top point was the lowest under 900 m$^3$/h and the highest under 2500 m$^3$/h. This is because the higher the volume flow rate is, the higher the water flow rate is, and the easier it is to take away the bubbles generated during the water-filling process, so fewer bubbles gather at high points and the liquid-holding rate is higher.

To better understand liquid holdup along the pipeline, the distribution of liquid holdup across the line under different production times and volume flow rates was simulated. As shown in Figure 13, the liquid holdup at the end of the pipe section is still changing after water filling is stabilized. Therefore, a monitoring point was added at the end of the pipe section to observe the liquid holdup of the section as a function of time, as shown in Figure 14.
Figure 14 clearly shows the variation of liquid holdup at the end of the pipe under different volume flow rate conditions. When the output is <1700 m³/h, the liquid holdup at the end of the pipe section under the condition of water-filling stability is very stable, remaining at 100%. When the volume flow rate is 2100 m³/h, the liquid holdup when the waterhead reaches the end of the pipe segment is not stable and fluctuates violently from 15h. However, when the volume flow rate is 1700 m³/h, the liquid holdup at the end of pipe is very stable and begins to fluctuate after 35 hours of production. When the volume flow rate is 2500 m³/h, the liquid holdup when the waterhead reaches the end of the pipe segment is not stable and fluctuates violently from 11h. The change in liquid holdup is likely to be related to the flow regime. If the flow in the section is laminar or annular flow, liquid holdup cannot sharply fluctuate, and it is likely that the flow regime changes there as the volume flow rate increases. Therefore, the flow regime of this section and the pressure fluctuation closely related to the flow regime are tracked. Figures 15 and 16, respectively, show the flow regime and pressure fluctuation curve at the end of the pipe section under each volume flow rate.

In Figure 15, the value 1 represents laminar flow (stratified flow), 2 represents annular flow, 3 represents slug flow, and 4 represents bubble flow. With the increase in the flow volume, the final flow regime at the end of the pipe section changes successively from laminar flow to bubble flow to slug flow. The lower the volume flow rate is, the longer the bubble flow lasts, and the slower the transition to the slug flow regime is. As can be seen from Figure 16, the pressure at the end of the pipeline gradually fluctuates with the increase in the volume flow rate. According to the upslope of the section with increasing elevation and the analysis of solitary waves on the stratified flow interface by Taitel et al., when the output increases, the water flow speed increases. Under the action of the Bernoulli effect,
the pressure on the wave surface changes, and when the suction force generated by the pressure changes acts on the water wave and overcomes gravity (stabilizing the boundary wave), the Kelvin-Helmholtz instability occurs, that is, the Kelvin-Helmholtz instability of the interface wave, so the interface wave grows until the liquid plug is formed.

In other words, when the gas-liquid flow volume in the tube is relatively small, the flow behaves as stratified flow, and the gas velocity equals the liquid velocity (as shown in Figure 17 for gas and liquid velocity under flow volumes of 900-1300 m³/h).

When the volume flow is increased, the wetted perimeter is increased (the liquid level is higher), the gas velocity gradually increases. At this time, as a consequence of the Bernoulli effect, the increase in gas velocity causes the pressure here to decrease, and the wave of liquid in the tube intensifies. The liquid wave peak blown by the airflow may reach the top of the tube, because gravity acting on the liquid will suppress the increase in the wave. However, when the velocity of the gas gradually becomes greater than that of the liquid (such as the gas and liquid velocity at 1700 m³/h in

**FIGURE 16** Hydrostatic pressure fluctuation curves at the end of the pipeline under different volume flow rates

**FIGURE 17** Gas velocity and liquid velocity vs filling time at the end of the pipeline under different loads
Figure 17), the Bernoulli effect is further aggravated, and the suction force generated by the pressure changes acts on the surface of the water wave and overcomes gravity. The wave is further enlarged, and, at higher liquid levels, the crest reaches the top of the tube from time to time. At this point, the lower velocity waves block the passage of the high-velocity airflow and then are blown away by the airflow, carrying away a portion of the liquid. The trapped liquid is dispersed into droplets or forms a foam with the gas, at which point the mixture continues to flow upward, the pressure gradually decreases, the gas expands continuously, small bubbles accumulate into large bubbles, and the large bubbles merge into air masses and airbags until they occupy the entire pipe cross section. The larger the volume flow rate is, the stronger the gas-liquid carrying capacity in the pipe is, and the faster the slug flow is formed.

Gas-liquid alternating flow is the flow characteristic of slug flow. When slug flow occurs in the pipe, the pressure and flow fluctuate greatly, and the pipe under slug flow is subjected to intermittent shock stress and strong pipe vibration occurs. In addition, the appearance of slug flow will increase the pressure drop along the line, aggravate tube wall corrosion, cause great damage to the pipeline and corresponding equipment, and affect the normal operation of downstream process devices. It can be seen that, if the liquid-filled output is too large, it will cause severe fluctuations of pressure and velocity in the uphill pipe, which will induce severe slug flow and endanger the safety of the pipeline.

4.4 Waterhead impact stress

To obtain a safe water-filling condition and ascertain the effect of the waterhead on the low point impact load of the large-drop pipe during the water-filling process, we studied the impact force of the liquid-filled water head on the low point under the conditions of different velocities and liquid holdup at different volume flows and applied the maximum impact force of the water flow to the low point as a concentrated force. Combined with the soil constraint of the pipeline, the stress distribution at different low points of the water-filled pipeline with large drop is obtained through static analysis. The stresses of the waterhead on the low point of different pipelines versus time under different volume flow rate conditions are shown in Figures 18 and 19.

The simulation results for the maximum impact force at the low point, the liquid holdup of the pipeline corresponding to the maximum impact force, and the velocity corresponding to the maximum impact force are given in Tables 5 and 6.

It can be seen from Table 5 that, with the increase in volume flow rate, the impact force of the waterhead after passing through the high point on the bottom of the pipeline also increases, but the maximum axial stress and hoop stress of the entire pipe system do not change. A completely buried pipeline is wrapped by soil and is mainly subjected to static friction of the soil to constrain the displacement of the pipeline. The pipeline is mainly affected by the gravity load of the conveying medium water entering the pipe, and the impact load as a concentrated load has little effect on the pipeline.
5  |  CONCLUSIONS

OLGA 7.0 was used to simulate and contrastively analyze the water-filling process of an oil pipeline with complex topography under different transportation volume conditions. The following conclusions are drawn:

1. During the water-filling process of an oil pipeline with complex topography, if the exhaust is not carried out in time, even if the water filling is stable, there will still be a serious slack flow in the downhill pipeline, and like at the end of the pipe, there will always be a gas plug.

2. The existing studies on multiphase flow during the commissioning of large-drop crude oil pipelines are based on the operation of gas-liquid mixtures in pipes, and we innovatively study the multiphase flow problem of “water overhead air” in the process of filling water into production. In view of the problem that the water-air interface evolves into a waterfall flow pattern under the action of its own gravity and kinetic energy after the waterhead over the high point, which causes great impact load on the low point of the pipe, there will always be a gas plug.

3. At the end of the pipeline, serious slug flow will gradually form with the increase in volume flow rate, when the volume flow of pipeline is greater than 2000 m³/h, it will cause drastic fluctuations of pressure and velocity in the upslope pipe, which will induce serious slug flow and endanger the safety of the pipeline.

ACKNOWLEDGMENT
This work was supported by the Sichuan Provincial Applied Basic Research Project (2019YJ0352).

CONFLICT OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID
Enbin Liu https://orcid.org/0000-0002-8624-836X
Bingyan Guo https://orcid.org/0000-0001-9398-6830
Yong Peng https://orcid.org/0000-0002-8568-7651

REFERENCES
1. Liu E, Peng Y, Shan C, et al. Analysis of the role of the isolation ball in the process of pushing the water from the oil pipeline with complex terrain. Ener Rep. 2020;6:265–274.
2. Liu E, Lv L, Ma Q, Kuang J, Zhang L. Steady-state optimization operation of the west–east gas pipeline. Adv Mech Eng. 2019;11(1):1687814018821746.
3. Taitel Y, Simkhis M, Tevelev A, et al. Transient gas liquid flow in hilly terrain pipelines. Int J Multiph Flow. 2016;86:21-27.
4. Deng T, Gong J, Yu D, et al. Influence of complex terrain on the pressure test and drainage of long-distance gas pipeline. Oil Gas Storage Transport. 2014;12:1326–1330.

| TABLE 5  | Simulation results for low point 1 under different volume flow rates |
|---|---|---|---|---|---|---|
| Volume flow (m³/h) | Maximum impact force (N) | Liquid holdup corresponding to the maximum impact force (%) | Velocity corresponding to the maximum impact force (m/s) | Axial stress (MPa) | Circumferential stress (MPa) | Allowable stress (MPa) |
|---|---|---|---|---|---|---|
| 900 | 10 931.78 | 1.4 | 26.94 | 78.67 | 162.60 | 482.63 |
| 1300 | 12 922.34 | 1.9 | 26.5 | | | |
| 1700 | 16 259.63 | 3.5 | 23.6 | | | |
| 2100 | 16 769.60 | 4.1 | 24.3 | | | |
| 2500 | 17 600.13 | 7.2 | 21.7 | | | |

| TABLE 6  | Simulation results for low point 2 under different volume flow rates |
|---|---|---|---|---|---|---|
| Volume flow (m³/h) | Maximum impact force (N) | Liquid holdup corresponding to the maximum impact force (%) | Velocity corresponding to the maximum impact force (m/s) | Axial stress (MPa) | Circumferential stress (MPa) | Allowable stress (MPa) |
|---|---|---|---|---|---|---|
| 900 | 8366.67 | 2.2 | 15.2 | 78.68 | 162.60 | 482.63 |
| 1300 | 12 645.77 | 15.8 | 11.7 | | | |
| 1700 | 11 301.6 | 0.0 | 24.9 | | | |
| 2100 | 13 326.21 | 5.0 | 13.1 | | | |
| 2500 | 10 408.65 | 7.2 | 12.9 | | | |
5. Pothof IWM, Clemens FHLR. Experimental study of air–water flow in downward sloping pipes. *Int J Multiph Flow*. 2010;37(3):278-292.

6. Yang Y, Li J, Wang S, et al. Understanding the formation process of the liquid slug in a hilly-terrain wet natural gas pipeline. *Journal of Environmental. Chem Eng*. 2017;5(5):4220-4228.

7. Gong J, Yu D. Gasification process of pipeline during pressure transient. *J Petrochem Univ*. 2000;13(2):50-56.

8. Liu E, Li W, Cai H, et al. Formation mechanism of trailing oil in product oil pipeline. *Processes*. 2019;7(1):7.

9. Liu E, Ma X, Zhou M. Analysis of discharge process of oil pipeline with complex topography. *Energy Reports*. 2019;5:678-687.

10. Sun Y, Wang Z, Wang L, et al. Analysis and dispose during production and operation of lancheng oil pipeline. *Pipeline Techn Equipment*. 2016;1:19-21.

11. Zhang X, Bo YU, Qiu D, et al. Numerical study on the gas-liquid two phase flow in pipeline commissioning. *J Petrol Sci Res*. 2013;2(4):181-184.

12. Laanearu J, Annus I, Koppel T, et al. Emptying of large-scale pipe-line by pressurized air. *J Hydr Eng*. 2012;138(12):1090–1100.

13. Tijsseling AS, Hou Q, Bozkus Z, et al. Improved one-dimensional models for rapid emptying and filling of pipelines. *J Press Vessel Technol Transact ASME*. 2016;138(3):031301.

14. Schmidt Z, Brill JP, Beggs HD. Experimental study of two-phase normal slug flow in a pipeline-riser pipe system. *J Energy Res Technol*. 1981;103(1):67.

15. Payne GA, Palmer CM, Brill JP, et al. Evaluation of inclined-pipe, Schmidt Z, Brill JP, Beggs HD. Experimental study of two-phase normal slug flow in a pipeline-riser pipe system. *J Energy Res Technol*. 1981;103(1):67.

16. Laanearu J, Annus I, Koppel T, et al. Emptying of large-scale pipeline by pressurized air. *J Hydr Eng*. 2012;138(12):1090–1100.

17. Tijsseling AS, Hou Q, Bozkus Z, et al. Improved one-dimensional models for rapid emptying and filling of pipelines. *J Press Vessel Technol Transact ASME*. 2016;138(3):031301.

18. Schmidt Z, Brill JP, Beggs HD. Experimental study of two-phase normal slug flow in a pipeline-riser pipe system. *J Energy Res Technol*. 1981;103(1):67.

19. Laanearu J, Annus I, Koppel T, et al. Emptying of large-scale pipeline by pressurized air. *J Hydr Eng*. 2012;138(12):1090–1100.

20. Tijsseling AS, Hou Q, Bozkus Z, et al. Improved one-dimensional models for rapid emptying and filling of pipelines. *J Press Vessel Technol Transact ASME*. 2016;138(3):031301.

21. Peng S, Chen Q, Zhen C, et al. Analysis of particle deposition in a natural gas transmission station. *Oil Gas Sci Technol Revue d’IFP Energ Nouvelles*. 2019;74:70.

22. Zhang X, Bo YU, Qiu D, et al. Numerical study on the gas-liquid two phase flow in pipeline commissioning. *J Petrol Sci Res*. 2013;2(4):181-184.

23. Laanearu J, Annus I, Koppel T, et al. Emptying of large-scale pipeline by pressurized air. *J Hydr Eng*. 2012;138(12):1090–1100.

24. Tijsseling AS, Hou Q, Bozkus Z, et al. Improved one-dimensional models for rapid emptying and filling of pipelines. *J Press Vessel Technol Transact ASME*. 2016;138(3):031301.

25. Qiao W, Yang Z. An improved dolphin swarm algorithm based on kernel fuzzy c-means in the application of solving the optimal problems of large-scale function. *IEEE Access*. 2019;8:2073–2089.

26. Qiao W, Yang Z. Forecast the electricity price of U.S. using a wavelet transform-based hybrid model. *Energy*. 2019;193:116704.

27. Liu E, Kuang J, Peng S, Liu Y. Transient operation optimization technology of gas transmission pipeline: a case study of west-east gas transmission pipeline. *IEEE Access*. 2019;7:112131–112141.

28. Qiao W, Yang Z, Kang Z, Pan Z. Short-term natural gas consumption prediction based on Volterra adaptive filter and improved whale optimization algorithm. *Eng Appl Artif Intell*. 2020;87:103323.

29. Guo R, Zhang W, Jiang J, et al. Numerical simulation of mobile pipeline gas-gap emptying based on OLGA. *J Chem Eng Chinese Univ*. 2017;31(2):337–345.

30. Ali SF, Yeung H. Experimental investigation and numerical simulation of two-phase flow in a large-diameter horizontal flow line vertical riser. *Pet Sci Technol*. 2010;28(11):1079–1095.

31. Davoudi M, Heidari Y, Mansoori SAA. Field experience and evaluation of the south pars sea line piggging, based on dynamic simulations. *J Nat Gas Sci Eng*. 2014;18:210–218.

32. Ni H-F, Ren B. Application of CAESAR II in reconstruction of natural gas transportation pipeline. *Petrochem Equip*. 2018;47(1):32–37.

33. Zhang D, Mu WB, Sun DQ. Petroleum Pipeline Displacement Analysis and Optimization Based on CAESAR II. *Petro & Chemical Equipment*. 2019;22(10):60-66–70. http://kns.cnki.net/kcms/detail/detail.aspx?FileId=HSFF201910020&DbName=CJFF2019

34. Liu E, Lv L, Yi Y, Xie P. Research on the steady operation optimization model of natural gas pipeline considering the combined operation of air coolers and compressors. *IEEE Access*. 2019;7:83251–83265.

35. Liu S, Pu H, Liu S, et al. Stress analysis method of buried pipeline. *Oil Gas Storage Transport*. 2012;4:274–278, 327-328.

36. Liu X. Study on safety piggging scheme of China-Myanmar natural gas pipeline with large drop. Southwest Petroleum University. 2017. http://kns.cnki.net/kcms/detail/detail.aspx?FileName=1017108563.nh&DbName=CMFD2017.

37. Liu EB, Yan S, Peng SB, et al. Noise silencing technology for manifold flow noise based on ANSYS fluent. *J Nat Gas Sci Eng*. 2016;29(2):322–328.

38. Peng S, Liu EB, Xian W, et al. Dynamic simulation of an underground gas storage injection-production network. *J Environ Biol*. 2015;36(4):799–806.

39. Liu W, Zhang ZX, Fan JY, Jiang DY. Daemen JJK. Research on the stability and treatments of natural gas storage caverns with different shapes in bedded salt rocks. *IEEE Access*. 2020;8:18995–19007.