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A Comprehensive Prediction Model of Hydraulic Extended-Reach Limit Considering the Allowable Range of Drilling Fluid Flow Rate in Horizontal Drilling

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Hydraulic extended-reach limit (HERL) model of horizontal extended-reach well (ERW) can predict the maximum measured depth (MMD) of the horizontal ERW. The HERL refers to the well's MMD when drilling fluid cannot be normally circulated by drilling pump. Previous model analyzed the following two constraint conditions, drilling pump rated pressure and rated power. However, effects of the allowable range of drilling fluid flow rate ($Q_{min} \le Q \le Q_{max}$) were not considered. In this study, three cases of HERL model are proposed according to the relationship between allowable range of drilling fluid flow rate and rated flow rate of drilling pump (Q_r). A horizontal ERW is analyzed to predict its HERL, especially its horizontal-section limit (L_h). Results show that when $Q_{min} \le Q_r \le Q_{max}$ (Case I), L_h depends both on horizontal-section limit based on rated pump pressure (L_{h1}) and horizontal-section limit based on rated pump power (L_{h2}); when $Q_{min} < Q_{max} < Q_r$ (Case II), L_h is exclusively controlled by L_{h1}; while L_h is only determined by L_{h2} when $Q_r < Q_{min} < Q_{max}$ (Case III). Furthermore, L_{h1} first increases and then decreases with the increase in drilling fluid flow rate, while L_{h2} keeps decreasing as the drilling fluid flow rate increases. The comprehensive model provides a more accurate prediction on HERL.

Longer horizontal-section length of horizontal extended-reach well (ERW) often means higher oil and gas output, and is also an economical choice for oil field development[1]. However, drilling engineers have no idea how far the horizontal ERW can extend. The hydraulic extended-reach limit (HERL) theory of the horizontal ERW can be used to predict the maximum measured depth (MMD) of horizontal ERW from the perspective of hydraulics, especially the bearing capacity of drilling pump.

Wang and Guo (2008) first proposed the concept and the computational model of HERL theory[2]. The HERL theory of the horizontal ERW can be summarized as follows. The horizontal ERW cannot extend without limitation. Drilling pump will stop circulating drilling fluid when the total pressure losses of circulation system exceed the rated pressure of drilling pump, which is a critical point. The measured depth of the horizontal ERW at the critical point is defined as the HERL of the horizontal ERW. In other words, the HERL of the horizontal ERW refers to the well's MMD when the drilling fluid cannot be normally circulated by drilling pump. The HERL is mainly related to the total pressure losses of circulation system and the rated pressure of the drilling pump. Later in 2009, Guo and Wang (2009) applied the HERL theory to the Liuhua field in the South China Sea[3]. They analyzed the ERW's HERL based on the established HERL model. Gao *et al.* (2009) also introduced and analyzed the concept and influence factors in the HERL model for horizontal ERW[4]. Sun (2013) further developed the HERL model, he regarded the rated power of drilling pump as a new constraint condition[5]. The HERL model based on new constraint condition is also introduced. However, these studies only consider the effects of rated pressure of

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drilling pump and rated power of drilling pump on the HERL model; the allowable range of drilling fluid flow rate, an important hydraulic parameter range, was not taken into consideration.

Each drilling pump has a maximum output power, known as the rated power of drilling pump P_r. Meanwhile, each drilling pump also possesses several cylinders with different diameters, and every cylinder has a certain allowable pressure, which is called the rated pressure of drilling pump p_r. The drilling fluid flow rate Q under the conditions of P_r and p_r is called the rated flow rate of drilling pump Q_r. In general, P_r, p_r and Q_r have the following relationship.

$$P_r = p_r Q_r \tag{1}$$

When $Q \le Q_r$, the pump pressure is restricted by the allowable pressure of cylinder, the maximum pump pressure can only reach the rated pump pressure of drilling pump p_r. Then the pump power keeps increases with the increase in drilling fluid flow rate Q until $Q = Q_r$, namely the rated power of drilling pump P_r is reached, and the drilling fluid flow rate Q at this time is the rated flow rate of drilling pump Q_r. In brief, p_r is the major constraint condition when $Q \le Q_r$. In contrast, the pump power is maintained at P_r when $Q > Q_r$, the pump pressure keeps decreasing as drilling fluid flow rate Q increase. In other words, P_r becomes the main constraint condition when $Q > Q_r$[6].

As mentioned above, the rated pump pressure of drilling pump p_r and the rated power of drilling pump P_r as two constraint conditions of HERL model for horizontal ERW are provided under the conditions of $Q \le Q_r$ and $Q > Q_r$ respectively. However, the effects of allowable range of drilling fluid flow rate on the HERL model are not considered. During the drilling process, the drilling fluid flow rate Q has a theoretical range, namely the allowable range of drilling fluid flow rate. Specifically, too small Q cannot meet the needs of hole cleaning; however, if Q is too large, the bearing capacity of the drilled formation may be threatened. The allowable range of drilling fluid flow rate is expressed in Eq. (2).

$$Q_{\min} \le Q \le Q_{\max} \tag{2}$$

where $Q_{\min}$ is the lower limit of drilling fluid flow rate, L/s; $Q_{\max}$ is the upper limit of drilling fluid flow rate, namely the upper limit considering the bearing capacity of drilled formation, L/s.

The main purpose of this paper is to establish a more comprehensive and accurate model of HERL for horizontal ERW according to the relationship between the above allowable range of drilling fluid flow rate and the rated flow rate of drilling pump Q_r. Moreover, the bearing capacity of existing hydraulic equipment can also be evaluated based on the established HERL model, avoiding the situation that the designed horizontal-section length exceeds the limit extension ability provided by the available drilling pump.

Results

HERL model. For a horizontal ERW, the lengths of vertical section and deviated sections can be obtained by an inclinometer before drilling into the horizontal section. Therefore, we mainly analyze the well's horizontal-section limit L_h, which can be expressed in Eq. (3).

$$\begin{cases} L_h = L_{h1} = \dfrac{p_r - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, \ (Q \le Q_r) \\ L_h = L_{h2} = \dfrac{\frac{P_r}{Q} - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, \ (Q > Q_r) \\ Q_{\min} \le Q \le Q_{\max} \end{cases} \tag{3}$$

where L_h is the horizontal-section limit, m; L_{h1} is the horizontal-section limit based on rated pump pressure, m; L_{h2} is the horizontal-section limit based on rated pump power, m; p_r is the rated pressure of drilling pump, MPa; P_r is the rated power of drilling pump, kW; Δp_g is surface pipeline pressure drop, MPa; Δp_b is bit pressure drop, MPa; Δp_{stv} is the drill string pressure losses of vertical section, MPa; Δp_{std} is the drill string pressure losses of deviated sections, MPa; Δp_{av} is the annular pressure losses of vertical section, MPa; Δp_{ads} is annular pressure losses of small-inclination section, MPa; Δp_{adl} is annular pressure losses of large-inclination section, MPa; $\left(\frac{\Delta p}{\Delta L}\right)_{sth}$ is drill string pressure loss gradients in horizontal section, MPa/m; $\left(\frac{\Delta p}{\Delta L}\right)_{ah}$ is annular pressure loss gradients in horizontal section, MPa/m.

According to the relationship between the allowable range of drilling fluid flow rate $Q_{\min} \le Q \le Q_{\max}$ and the rated flow rate of drilling pump Q_r, the Eq. (3) can be divided into the following three Cases, including $Q_{\min} \le Q_r \le Q_{\max}$, $Q_{\min} < Q_{\max} < Q_r$ and $Q_r < Q_{\min} < Q_{\max}$. They are expressed in Eqs (4)–(6).

Case I: $Q_{\min} \le Q_r \le Q_{\max}$;

Casing program	Bit size/mm	Casing outer diameter/mm	Casing depth/m
Conductor	558.8	476.3	30
Surface casing	444.5	339.7	700
Intermediate casing	311.2	244.5	2407
Open hole	215.9	—	—

Table 1. Design table of casing program.

Variables	Value	Unit
Inclination at KOP	0	°
L_v	1956.3	m
Build rate	20.55	°/100 m
Inclination at target base	90	°
True vertical depth D_v	2241	m
Horizontal displacement before the horizontal section	280	m
Drilling fluid density ρ_m	1.35	g/cm^3
Cuttings density ρ_s	2.5	g/cm^3
Flow behavior index n	0.7365	—
Consistency coefficient K	0.7565	Pa·s^n
Fracture pressure equivalent density ρ_f	1.91	g/cm^3
Designed horizontal-section length L_{h0}	1500	m
Drill pipe outer diameter D_i	139.7	mm
Drill pipe rotation speed N	40	rpm
Rate of penetration ROP	10	m/h
Rated pump pressure p_r	39	MPa
Rated pump power P_r	1323	kW

Table 2. List of input data for modeling.

$$L_h = \begin{cases} L_{h1} = \dfrac{p_r - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, (Q_{\min} \le Q \le Q_r) \\ L_{h2} = \dfrac{\frac{P_r}{Q} - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, (Q_r < Q \le Q_{\max}) \end{cases} \tag{4}$$

where Q_r is rated flow rate of drilling pump, L/s.

Case II: $Q_{\min} < Q_{\max} < Q_r$;

$$L_h = L_{h1} = \frac{p_r - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - \left(\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl}\right)}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, \quad (Q_{\min} \le Q \le Q_{\max} < Q_r) \tag{5}$$

Case III: $Q_r < Q_{\min} < Q_{\max}$;

$$L_h = L_{h2} = \frac{\frac{P_r}{Q} - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}}, (Q_r < Q_{\min} \le Q \le Q_{\max}) \tag{6}$$

Application example. For a horizontal ERW, the established HERL model is used to predict the well's HERL, especially the horizontal-section limit. The specific data of this well is listed in Tables 1 and 2[7], and schematic overview of the horizontal ERW is illustrated in Fig. 1.

First of all, the authors assume that the fracture pressure in the horizontal section is identical, otherwise inconsistent comparison conditions will occur when the parameters sensitivity analysis is carried out. Meanwhile, the bearing capacity of drilled formation and the needs of hole cleaning should be considered to determine the allowable range of drilling fluid flow rate.

The specific calculation results show that the lower limit based on the needs of hole cleaning Q_{hc} is 29.6 L/s, the lower limit considering the bearing capacity of drilled formation $Q_{\min-df}$ is 27.1 L/s, and the upper limit of drilling fluid flow rate $Q_{\max}$ is 39 L/s. Therefore, the allowable range of drilling fluid flow rate ranges from 29.6 L/s to 38.5 L/s. Moreover, according to the conditions given in Tables 1 and 2, the rated pressure of drilling pump p_r is

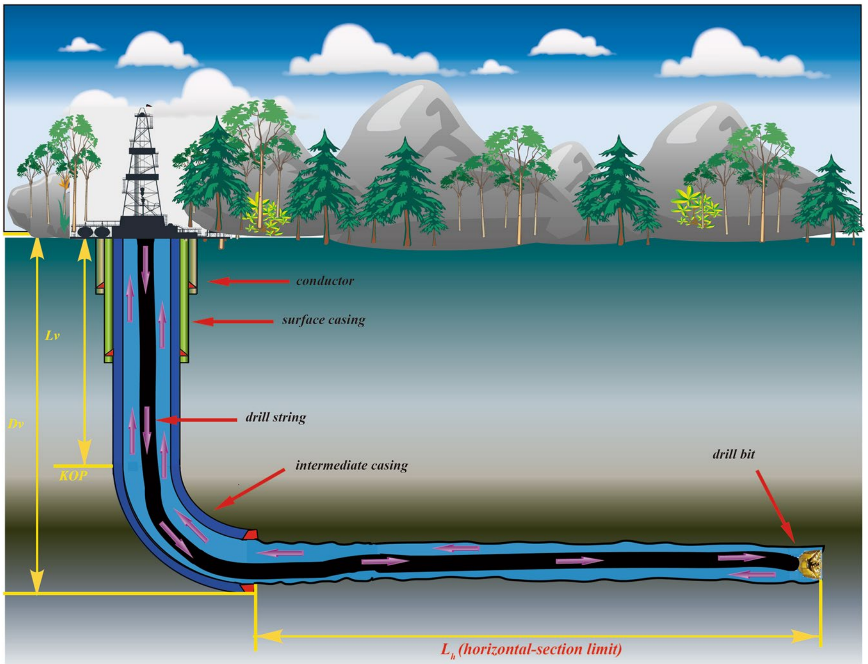

Figure 1. Schematic overview of the horizontal extended-reach well.

39 MPa, the rated power of drilling pump P_r is 1323 kW, so the rated flow rate of drilling pump Q_r is 34 L/s. Depending on the relationship between allowable range of drilling fluid flow rate and the rated flow rate of drilling pump Q_r, the HERL model belongs to Case I, which can be determined by Eq. (4). Effects of drilling fluid flow rate on the horizontal-section limit based on rated pump pressure L_{h1} and the horizontal-section limit based on rated pump power L_{h2} are shown in Fig. 2a, which is also the schematic overview of the situation of $Q_{\min} \le Q_r \le Q_{\max}$ (Case I).

As shown in the Fig. 2a, the horizontal-section limit based on rated pump pressure L_{h1} first increases and then decreases with increase in drilling fluid flow rate; meanwhile, the horizontal-section limit based on rated pump power L_{h2} keep decreasing as drilling fluid drilling fluid flow rate increases when $Q_{\min} \le Q_r \le Q_{\max}$. The abscissa value of the intersection between these two curves is the rated flow rate of drilling pump Q_r (34 L/s). The HERL, especially the horizontal-section limit is mainly dependent on L_{h1} when Q ranges from $Q_{\min}$ to Q_r ($Q_{\min} \le Q \le Q_r$), which is indicated by the yellow dotted area in the Fig. 2a. However, the HERL especially the horizontal-section limit mainly depends on L_{h2} if Q ranges from Q_r to $Q_{\max}$ ($Q_r < Q \le Q_{\max}$), which is indicated by the blue dotted area in the Fig. 2a. Furthermore, both $L_{h1\max}$ (the maximum horizontal-section limit based on rated pump pressure) and $L_{h2\max}$ (the maximum horizontal-section limit based on rated pump power) are larger than $L_{h\max}$ (the maximum horizontal-section limit). $L_{h\max}$ can be obtained at Q_r (34 L/s). Specifically, $L_{h1\max}$ is 5270 m, $L_{h2\max}$ is 5955 m, while $L_{h\max}$ is 5068 m. Considering the lengths of vertical section and deviated sections, each drilling fluid flow rate corresponds to a well's HERL, and the maximum HERL of the horizontal ERW is 7463 m, which can also be obtained at Q_r (34 L/s).

Discussion

In order to analyze the effects of different parameters on the HERL especially the horizontal-section limit of horizontal ERW, parameters sensitivity analysis is discussed. Furthermore, results simulated by the established model are also compared with the results of the previous model that did not consider the allowable range of drilling fluid flow rate.

Effects of rate of penetration on HERL. Rate of penetration (ROP) is of significance to the economic benefits in drilling engineering. First, allowable ranges of drilling fluid flow rate under different ROPs (6 m/h, 8 m/h, 10 m/h) are listed in Table 3.

As shown in Table 3, the lower limit of drilling fluid flow rate $Q_{\min}$ gradually increases and the upper limit of drilling fluid flow rate $Q_{\max}$ keeps decreasing as ROP increases. In other words, the window of drilling fluid flow rate becomes narrower. The effects of different ROPs on L_{h1} and L_{h2} are shown in the Fig. 2b.

As shown in the Fig. 2b, L_{h1} first increases and subsequently decreases with the increase in drilling fluid flow rate, whereas L_{h2} keep decreases with the increase in drilling fluid flow rate. Moreover, both L_{h1} and L_{h2} have a negative correlation with ROP under the condition of identical drilling fluid flow rate, since the annular cuttings and the annular pressure losses increase with the increase in ROP. In addition, ROP has no effects on the rated flow rate of drilling pump Q_r, and $Q_r = 34$ L/s. The horizontal-section limit here can be determined by the Eq. (4) (Case I), and the maximum horizontal-section limit $L_{h\max}$ can be achieved at Q_r with different ROPs.

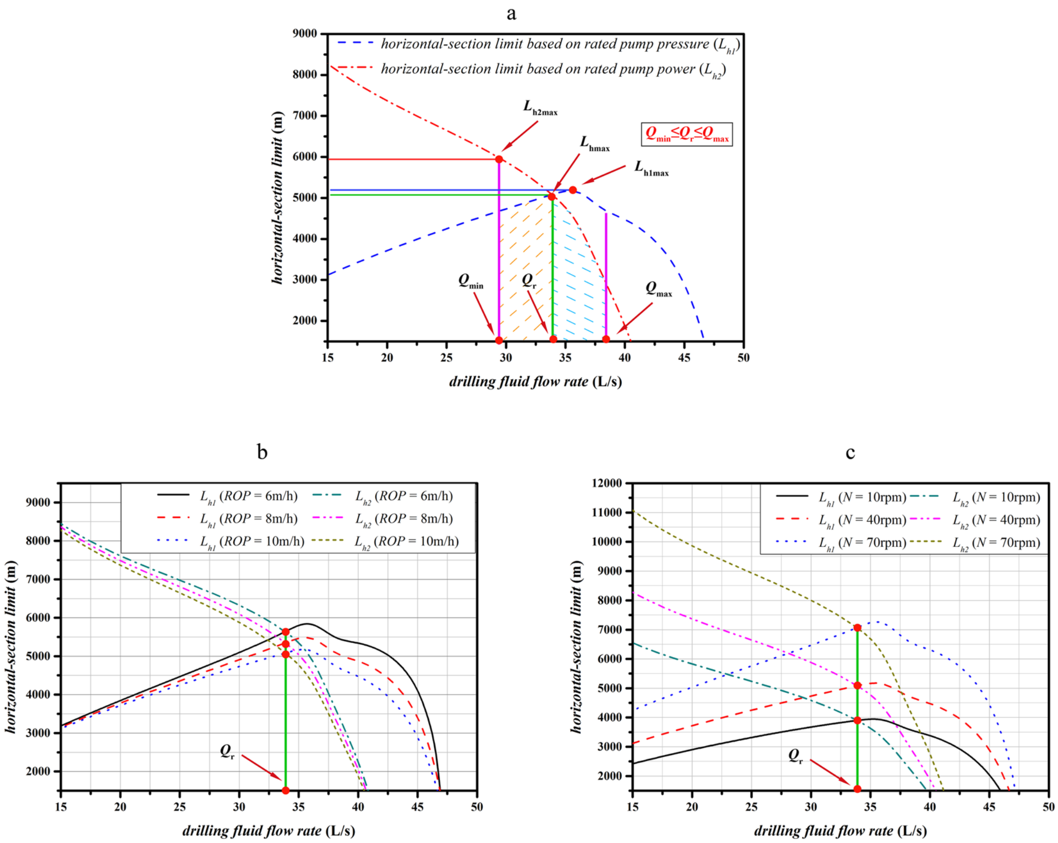

Figure 2. Effects of drilling fluid flow rate on L_{h1} and L_{h2} & the schematic overview of the situation $Q_{min} \leq Q_r \leq Q_{max}$ (Case I). (**a**) Effects of drilling fluid flow rate on L_{h1} and L_{h2}; (**b**) Effects of different ROPs on L_{h1} and L_{h2}; (**c**) Effects of different drill pipe rotation speeds on L_{h1} and L_{h2}.

Variables	Results	Lower limit of drilling fluid flow rate Q_{min} (L/s)			Upper limit of drilling fluid flow rate Q_{max} (L/s)	Rated flow rate Q_r (L/s)	Situation	Case
		$Q_{min\text{-}df}$	Q_{hc}	Q_{min}				
ROP (m/h)	6	26.1	28.6	28.6	40.0	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	8	26.4	29.1	29.1	39.2	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	10	27.1	29.6	29.6	38.4	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
N (rpm)	10	31.5	31.1	31.5	40.9	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	40	26.9	29.6	29.6	41.3	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	70	21.1	28.2	28.2	41.8	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
p_r (MPa)	39	27.1	29.6	29.6	38.5	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	34	27.1	29.6	29.6	38.5	39	$Q_{min} < Q_{max} < Q_r$	II
	31	27.1	29.6	29.6	38.5	43	$Q_{min} < Q_{max} < Q_r$	II
P_r (kW)	1323	27.1	29.6	29.6	38.5	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	1049	27.1	29.6	29.6	38.5	26.9	$Q_r < Q_{min} < Q_{max}$	III
	726	27.1	29.6	29.6	38.5	18.6	$Q_r < Q_{min} < Q_{max}$	III
L_{h0} (m)	1500	27.1	29.6	29.6	38.5	34	$Q_{min} \leq Q_r \leq Q_{max}$	I
	3000	34.9	29.6	34.9	37.6	34	$Q_r < Q_{min} < Q_{max}$	III
	6000	—	29.6	—	—	34	—	—

Table 3. Allowable ranges of drilling fluid flow rate under different parameters.

Effects of drill pipe rotation speed on HERL. Results of allowable ranges of drilling fluid flow rate under different drill pipe rotation speeds (10 rpm, 40 rpm, 70 rpm) are listed in Table 3.

Table 3 shows that the lower limit of drilling fluid flow rate Q_{min} decreases and the upper limit of drilling fluid flow rate Q_{max} increases with the increase in drill pipe rotation speed *N*. In other words, the window of drilling fluid flow rate becomes wider. The effects of different drill pipe rotation speeds on L_{h1} and L_{h2} are shown in Fig. 2c.

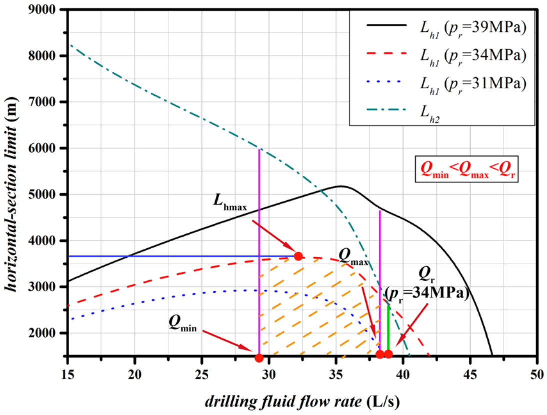

Figure 3. Schematic overview of the situation $Q_{min} < Q_{max} < Q_r$ (Case II) and effects of different rated pump pressures on L_{h1} and L_{h2}.

Similarly, the Fig. 2c shows that L_{h1} begins to decrease as drilling fluid flow rate increases after L_{h1} reached its upper limit, whereas L_{h2} has a consistent negative correlation with drilling fluid flow rate. Moreover, the rotation of drill pipe is conductive to the efficiency of hole cleaning, as a result of which both L_{h1} and L_{h2} increase with the increase in drill pipe rotation speed N under the condition of identical drilling fluid flow rate. Furthermore, drill pipe rotation speed also has no effects on rated flow rate of drilling pump Q_r. The horizontal-section limit here can also be determined by the Eq. (4) (Case I) and the maximum horizontal-section limit L_{hmax} can be achieved at $Q_r = 34$ L/s with different drill pipe rotation speeds.

Effect of rated pressure of drilling pump on HERL. The rated pressure of drilling pump p_r, an important parameter of the HERL model, has great effects on the HERL of horizontal ERW especially the horizontal-section limit L_h. First of all, allowable ranges of drilling fluid flow rate under different rated pump pressures are calculated and listed in Table 3.

Table 3 shows that p_r has no effects on hole cleaning and the bearing capacity of the drilled formation. Moreover, different p_r correspond to different Q_r. Specifically, $Q_r = 34$ L/s when $p_r = 39$ MPa, $Q_r = 39$ L/s when $p_r = 34$ MPa and $Q_r = 43$ L/s when $p_r = 31$ MPa. The situation of $p_r = 39$ MPa is exactly the same as that in Fig. 2a. The situation of $p_r = 34$ MPa is focused in this part, the horizontal-section limit L_h can be calculated by Eq. (5) since $Q_{\min} < Q_{\max} < Q_r$. The effects of different rated pump pressures on L_{h1} and L_{h2} are illustrated in Fig. 3, which is also the schematic overview of situation $Q_{\min} < Q_{\max} < Q_r$ (Case II).

Figure 3 shows that L_{h1} first increases, but later decreases with the increase in drilling fluid flow rate, while L_{h2} keep decreasing as drilling fluid flow rate increase. Moreover, the higher p_r corresponds to the greater L_{h1} when drilling fluid flow rates are the same. However, p_r has no effects on L_{h2}.

According to the Eq. (5), the horizontal-section limit totally depends on L_{h1} when $Q_{\min} < Q_{\max} < Q_r$ (Case II), which is indicated by the yellow dotted area in the Fig. 3. Therefore, the maximum horizontal-section limit $L_{h\max}$ can be obtained at the drilling fluid flow rate Q when $L_{h1\max}$ is achieved rather than at the rated flow rate of drilling pump Q_r.

Effect of rated power of drilling pump on HERL. Firstly, allowable ranges of drilling fluid flow rate under different rated pump powers P_r are calculated. Which situation the HERL belongs to and which kind of HERL model needs to be adopted can be determined according to the relationships between these allowable ranges of drilling fluid flow rate and the rated flow rate of the drilling pump Q_r.

Table 3 shows that rated pressure of drilling pump P_r has no effects on hole cleaning and the bearing capacity of drilled formation. The rated flow rate of drilling pump $Q_r = 34L$/s when $P_r = 1323$kW, $Q_r = 26.9L$/s when $P_r = 1049$kW and $Q_r = 18.6L$/s when $P_r = 726$kW. Their HERL Cases are listed in Table 3. The situation of $P_r = 1049$kW is focused in this part, which belongs to the situation of $Q_r < Q_{\min} < Q_{\max}$ (Case III), and the horizontal-section limit can be determined by Eq. (6). The effects of rated pressure of drilling pump P_r on L_{h1} and L_{h2} are shown in Fig. 4a.

Similarly, the Fig. 4a shows that L_{h1} first increases and subsequently decreases with the increase in drilling fluid flow rate, whereas L_{h2} has a consistent negative correlation with drilling fluid flow rate. Moreover, the higher rated pressure of drilling pump P_r means the greater L_{h2} with identical drilling fluid flow rate. However, P_r has no effects on L_{h1}.

According to the Eq. (6), the horizontal-section limit L_h depends entirely on L_{h2} when $Q_r < Q_{\min} < Q_{\max}$, which is indicated by the yellow dotted area in the Fig. 4a. Therefore, the maximum horizontal-section limit $L_{h\max}$ can be obtained at the drilling fluid flow rate Q when $L_{h2\max}$ is achieved rather than the rated flow rate of drilling pump Q_r. The Fig. 4a shows that the horizontal-section limit L_h at Q_r is larger than $L_{h\max}$ when $P_r = 1049$kW. Therefore, if the allowable range of drilling fluid flow rate is not considered, and taking the horizontal-section

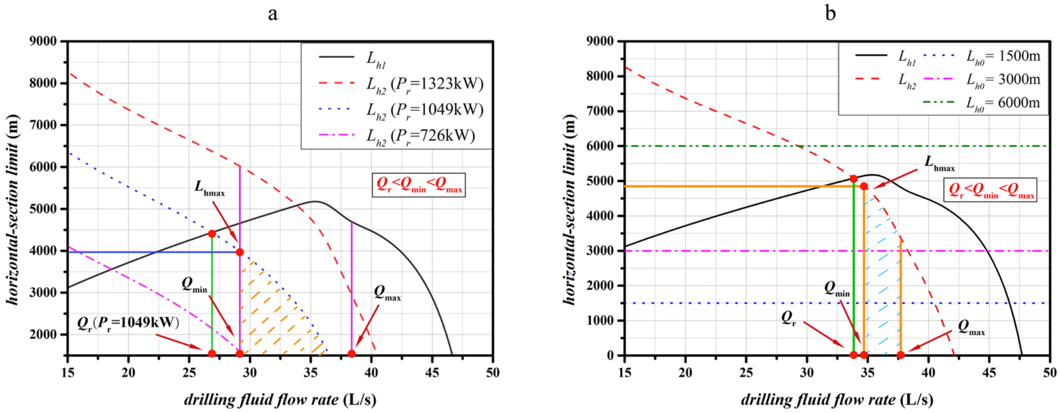

Figure 4. Schematic overview of the situation $Q_r < Q_{min} < Q_{max}$ (Case III). (**a**) Effects of different rated pump powers on L_{h1} and L_{h2}; (**b**) Effects of different designed horizontal-section lengths on L_{h1} and L_{h2}.

limit L_h at Q_r as the $L_{h\max}$ when $P_r = 1049$kW, it will result in the designed horizontal-section length L_{h0} being larger than the horizontal-section limit L_h that can be achieved, and causing safety hazards.

Effects of designed horizontal-section length on HERL. In general, different designed horizontal-section lengths L_{h0} have great effects on drilling operations. In the part of application example, the designed horizontal-section length L_{h0} is 1500 m. Allowable ranges of drilling fluid flow rate under different designed horizontal-section lengths (1500 m, 3000 m, 6000 m) are listed in Table 3.

Table 3 shows that the window of drilling fluid flow rate becomes narrower when the designed horizontal-section length L_{h0} increases. Effects of different designed horizontal-section lengths L_{h0} on the horizontal-section limit based on rated pump pressure L_{h1} and the horizontal-section limit based on rated pump power L_{h2} are illustrated in Fig. 4b.

As shown in the Fig. 4b, after the increase of L_{h1} in the first stage, it begins to decreases as drilling fluid flow rate increase, while L_{h2} keep decreasing as drilling fluid flow rate increases. When $L_{h0} = 3000$ m, the lower limit of drilling fluid flow rate $Q_{\min}$ is 34.9 L/s, and the rated flow rate of drilling pump Q_r is 34 L/s, which belongs to the situation of $Q_r < Q_{\min} < Q_{\max}$ (Case III). The horizontal-section limit L_h here can be determined by Eq. (6), and it is mainly dependent on L_{h2} (seen from the Fig. 4b). The maximum horizontal-section limit $L_{h\max}$ can be achieved at the lower limit of drilling fluid flow rate $Q_{\min}$, rather than the rated flow rate of drilling pump Q_r.

As shown in Table 3, the situation of $L_{h0} = 1500$ m is analyzed in the part of application example. However, drilling fluid flow rate window closed when $L_{h0} = 6000$ m. At this point, the bottom hole pressure with any drilling fluid flow rate will exceed the bearing capacity of drilled formation. Moreover, there is no intersection between the curve of L_{h1} and the straight line of $L_{h0} = 6000$ m, indicating that drilling pump can no longer work at the rated pressure state of 39 MPa regardless of any drilling fluid flow rate.

Comparison of the established model and the previous model. In the previous model, since the allowable range of drilling fluid flow rate is not considered, the drilling fluid flow rate Q can be considered in the range of zero to infinity, including the rated flow rate of drilling pump Q_r. The maximum horizontal-section limit $L_{h\max}$ is achieved at Q_r when the allowable range of drilling fluid flow rate is not considered. In other words, the previous model can be taken as the Case I in the established model in this study. The previous model has been applied in the South China Sea. If the rated power of drilling pump P_r is 1049 kW and other conditions remain the same as those in the application example, $L_{h\max}$ is 4438 m based on the previous model, which can be obtained at Q_r of 26.9 L/s. But in fact, the lower limit of drilling fluid flow rate $Q_{\min}$ is 29.6 L/s, namely $Q_r < Q_{\min} < Q_{\max}$, which can also be considered as the Case III of the established model in this study. And $L_{h\max}$ is 3908 m based on the established model, which is achieved at $Q_{\min}$ (Fig. 4a). Therefore, the designed measured depth cannot be drilled if the designed horizontal-section length L_{h0} is 4100 m, or even resulting in drilling hazards.

Therefore, the effects of allowable range of drilling fluid flow rate must be considered to establish the more comprehensive and accurate HERL model. Failure to consider the allowable range of drilling fluid flow rate may result in problems of wellbore cleaning or borehole instability, and it is also unclear that what is the main constraint condition for HERL model of horizontal ERW and which kind of HERL model should be adopted.

In this study, the allowable range of drilling fluid flow rate is taken into account to establish a more comprehensive and accurate HERL model of horizontal ERW. Depending on the relationship between the allowable range of drilling fluid flow rate and the rated flow rate of the drilling pump, three kinds of HERLs model are established. Specifically, both the horizontal-section limit based on rated pump pressure L_{h1} and the horizontal-section limit based on rated pump power L_{h2} should be considered when $Q_{\min} \le Q_r \le Q_{\max}$, L_{h1} is the main factor when $Q_{\min} < Q_{\max} < Q_r$ while L_{h2} is the main factor when $Q_r < Q_{\min} < Q_{\max}$.

The horizontal-section limit based on rated pump pressure L_{h1} first increases and subsequently decreases with the increase in drilling fluid flow rate, whereas the horizontal-section limit based on rated pump power L_{h2} keep decreases with the increase in drilling fluid flow rate. In addition, greater rated pump pressure drilling pump p_r means greater L_{h1}. Similarly, the greater rated pump power P_r corresponds to the greater L_{h2}. Moreover, both L_{h1} and L_{h2} show negative correlation with ROP but have positive correlation with drill pipe rotation speed N. However, both the ROP and the drill pipe rotation speed have no effects on the rated flow rate of drilling pump Q_r. In order to achieve larger HERL, it is necessary to improve the rated pressure of drilling pump p_r and rated power of drilling pump P_r as much as possible; in addition, lower ROP and higher drill pipe rotation speed are also necessary.

For a horizontal ERW, the designed horizontal-section length L_{h0} should be less than the maximum horizontal-section limit $L_{h\max}$ It is prone to safety hazards if the designed horizontal-section length is longer than the maximum horizontal-section limit which can be achieved in actual drilling operation. Therefore, it is of great significance to accurately predict the HERL by selecting comprehensive and appropriate constraint conditions.

Method

Modified model of HERL.

Constraint conditions. Three constraint conditions for HERL model are given by combining the previous studies and the allowable range of drilling fluid flow rate. They can be also expressed in Eq. (7).

(1) When several drilling pumps work together, the actual pump pressure cannot exceed anyone of these rated pump pressures;
(2) When several drilling pumps work together, the actual pump power cannot exceed the sum of these rated pump power of all drilling pumps;
(3) The drilling fluid flow rate should be within an allowable range of drilling fluid flow rate. On one hand, drilling fluid flow rate should meet the needs of hole cleaning, on the other hand, wellbore pressure should not exceed the bearing capacity of drilled formation.

$$\begin{cases} p_{ac} \leq \min(p_{r1}, p_{r2}, \ldots p_{rn}), (n = 1, 2, \ldots) \\ P_{ac} \leq P_{r1} + P_{r2} + \ldots + P_{rn}, \ (n = 1, 2, \ldots) \\ Q_{\min} \leq Q \leq Q_{\max} \end{cases} \quad (7)$$

where p_{ac} is actual pressure of drilling pump, MPa; p_r is rated pressure of drilling pump, MPa; P_{ac} is actual power of drilling pump, kW; P_r is rated power of drilling pump, kW; Q is drilling fluid flow rate, L/s; $Q_{\min}$ is lower limit of drilling fluid flow rate, L/s; $Q_{\max}$ is upper limit of drilling fluid flow rate, L/s.

The actual power of drilling pump P_{ac} and the rated pressure of drilling pump p_{ac} are shown in Eq. (8) and Eq. (9) respectively.

$$P_{ac} = p_{ac} Q \quad (8)$$

$$p_{ac} = \Delta p_g + \Delta p_b + \Delta p_{st} + \Delta p_a \quad (9)$$

where Δp_g is surface pipeline pressure drop, MPa; Δp_b is bit pressure drop, MPa; Δp_{st} is drill string pressure losses, MPa; Δp_a is annular pressure losses, MPa. The Eq. (7) can be modified as Eq. (10).

$$\begin{cases} p_{ac} = \Delta p_g + \Delta p_b + \Delta p_{st} + \Delta p_a \leq \min(p_{r1}, p_{r2}, \ldots p_{rn}), (n = 1, 2, \ldots) \\ P_{ac} = p_{ac} Q \leq P_{r1} + P_{r2} + \ldots + P_{rn}, (n = 1, 2, \ldots) \\ Q_{\min} \leq Q \leq Q_{\max} \end{cases} \quad (10)$$

HERL based on rated pump pressure.

According to the first constraint condition, the actual pump pressure cannot exceed anyone of these rated pump pressures when several drilling pumps work together. The first constraint condition can be expressed in Eqs (11) and (12).

$$p_{ac} = \Delta p_g + \Delta p_b + \Delta p_{st} + \Delta p_a \leq \min(p_{r1}, p_{r2}, \ldots p_{rn}), (n = 1, 2, \ldots) \quad (11)$$

$$p_{ac} = \Delta p_g + \Delta p_b + \sum_{i=1}^{j} \frac{\Delta p_{sti}}{\Delta L_i} L_i + \sum_{i=1}^{j} \frac{\Delta p_{ai}}{\Delta L_i} L_i \leq \min(p_{r1}, p_{r2}, \ldots p_{rn}), (n = 1, 2, \ldots) \quad (12)$$

where $\frac{\Delta p_{sti}}{\Delta L_i}$ is drill string pressure loss gradients in several parts of drill string, MPa/m; $\frac{\Delta p_{ai}}{\Delta L_i}$ is annular pressure loss gradients in several parts of annulus, MPa/m.

For a horizontal ERW, we mainly analyze its horizontal-section limit L_h. If merely one drilling pump is considered, its rated pressure is p_r, the horizontal-section limit based on rated pump pressure L_{h1} under the first constraint condition can be expressed in Eq. (13).

$$L_{h1} = \frac{p_r - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}} \tag{13}$$

where Δp_{stv} is drill string pressure losses of vertical section, MPa; Δp_{std} is drill string pressure losses of deviated sections, MPa; Δp_{av} is annular pressure losses of vertical section, MPa; Δp_{ads} is annular pressure losses of small-inclination section, MPa; Δp_{adl} is annular pressure losses of large-inclination section, MPa; $(\Delta p/\Delta L)_{sth}$ is drill string pressure loss gradients in horizontal section, MPa/m; $(\Delta p/\Delta L)_{ah}$ is annular pressure loss gradients in horizontal section, MPa/m. Their calculation methods refer to the following literatures (Wang and Liu, 1995; Kelessidis *et al.*, 2011; Fan, 2013; Erge *et al.*, 2015)[8–11].

HERL based on rated pump power. According to the second constraint condition, the actual pump power cannot exceed the sum of these rated pump power of all drilling pumps when several drilling pumps work together. The second constraint condition can be expressed in Eqs (14) and (15).

$$P_{ac} = p_{ac} Q \le P_{r1} + P_{r2} + \ldots + P_{rn}, \ (n = 1, 2, \ldots) \tag{14}$$

$$P_{ac} = p_{ac} Q = \left(\Delta p_g + \Delta p_b + \sum_{i=1}^{j} \frac{\Delta p_{sti}}{\Delta L_i} L_i + \sum_{i=1}^{j} \frac{\Delta p_{ai}}{\Delta L_i} L_i\right) Q \le P_{r1} + P_{r2} + \ldots + P_{rn}, \ (n = 1, 2, \ldots) \tag{15}$$

For a horizontal ERW, we mainly analyze its horizontal-section limit L_h. Similarly, if merely one drilling pump is considered, its rated power is P_r, the horizontal-section limit based on rated pump power L_{h2} under the second constraint condition can be expressed in Eq. (16).

$$L_{h2} = \frac{\frac{P_r}{Q} - \Delta p_g - \Delta p_b - (\Delta p_{stv} + \Delta p_{std}) - (\Delta p_{av} + \Delta p_{ads} + \Delta p_{adl})}{\left(\frac{\Delta p}{\Delta L}\right)_{sth} + \left(\frac{\Delta p}{\Delta L}\right)_{ah}} \tag{16}$$

Allowable range of drilling fluid flow rate. According to the third constraint condition, the actual drilling fluid flow rate should be within an allowable range of drilling fluid flow rate. On one hand, the drilling fluid flow rate should meet the needs of hole cleaning. On the other hand, the wellbore pressure should not exceed the bearing capacity of drilled formation.

Upper limit. In general, greater drilling fluid flow rate often means better state of hole cleaning. However, there is an upper limit for drilling fluid flow rate since the too high drilling fluid flow rate poses a great threat to the bearing capacity of drilled formation due to the exceeded annular drilling fluid velocity. The upper limit of drilling fluid flow rate $Q_{\max}$, namely the upper limit considering the bearing capacity of drilled formation can be determined based on the open hole extended-reach limit (OHERL) theory.

The OHERL theory can be summarized as follows. The horizontal ERW cannot extend without limitation, the drilled formation will be fractured if the bottom hole pressure exceeds the fracture pressure, which is a critical point, and it can be expressed in Eq. (17)[7, 12–14].

$$0.00981[\rho_s C_s + \rho_m (1 - C_s)] D_v + \left(\Delta p_{av} + \sum_{i=1}^{j} \Delta p_{adi} + \Delta p_{ah}\right) = 0.00981 \rho_f D_v \tag{17}$$

where ρ_s is solids density, namely cuttings density, g/cm3; ρ_m is drilling fluid density, g/cm3; C_s is solid volumetric concentration, %; Δp_{av} is annular pressure losses of vertical section, MPa; Δp_{adi} are annular pressure losses of several deviated sections, MPa; Δp_{ah} annular pressure losses of horizontal section at the critical point, MPa.

In general, the horizontal-section limit based on OHERL theory should be larger than the designed horizontal-section length L_{h0}. The limit values of drilling fluid flow rate can be obtained when the horizontal-section limit based on OHERL theory equals L_{h0}, which is obtained from Eq. (18).

$$\frac{0.00981 \rho_f D_v - 0.00981[\rho_s C_s + \rho_m (1 - C_s)] D_v - (\Delta p_{av} + \sum_{i=1}^{j} \Delta p_{adi})}{(\Delta p/\Delta L)_{ah}} = L_{h0} \tag{18}$$

The results show that there are two limit values of drilling fluid flow rate, the larger of which can be taken as the upper limit of drilling fluid flow rate $Q_{\max}$, namely the upper limit considering the bearing capacity of drilled formation.

Lower limit. If the drilling fluid flow rate is too small, the hole cleaning condition becomes worse. Moreover, both the annular pressure losses and the bottom hole pressure are increased, which will also pose a great threat to the drilled formation. Therefore, two factors should be considered to determine the lower limit of drilling fluid flow rate. On one hand, the lower limit considering the bearing capacity of drilled formation $Q_{\min-df}$ can be obtained based on the above OHERL theory. On the other hand, considering the needs of hole cleaning, the lower

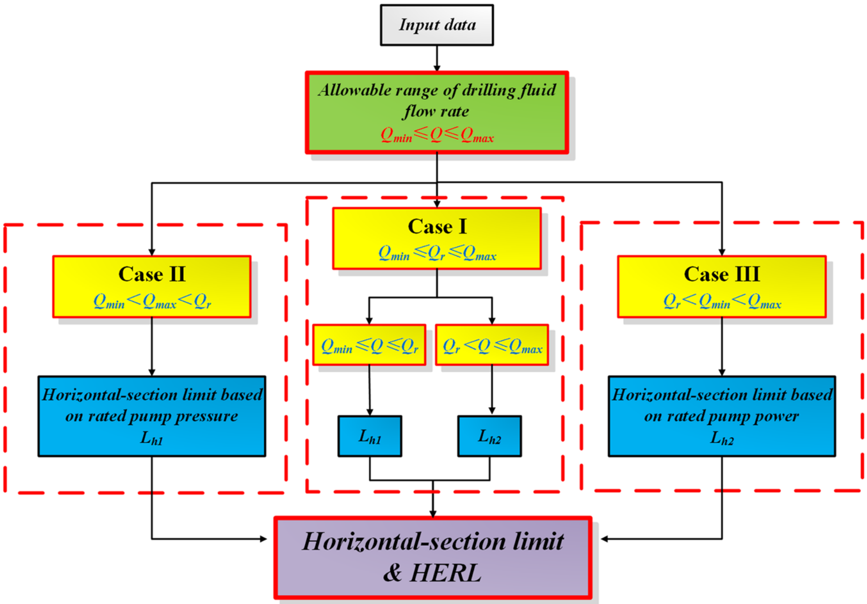

Figure 5. Flow chart of the calculation procedure.

limit based on the needs of hole cleaning Q_{hc} can be obtained. The lower limit of drilling fluid flow rate $Q_{\min}$ can be obtained by Eq. (19).

$$Q_{\min} = \max\left(Q_{\min-df}, Q_{hc}\right) \tag{19}$$

The lower limit considering the bearing capacity of drilled formation $Q_{\min-df}$ can also be determined by the OHERL theory. The lower limit value of drilling fluid flow rate which satisfies the Eq. (18) can be regarded as the $Q_{\min-df}$.

The horizontal ERW requires a certain amount of annular drilling fluid flow rate in order to meet the needs of hole cleaning, so there exists a lower limit based on the needs of hole cleaning Q_{hc}. The predecessors have made lots of researches in this field (Li and Liu, 1994; Larsen *et al.*, 1997; Wang and Song, 2003; Li *et al.*, 2010)[15–18]. According to the difference of deviation angle and annular size, the authors divide the whole sections of horizontal ERW into the vertical and small inclination section, the large inclination section, and the horizontal-section (Xin *et al.*, 2016c)[13]. Therefore, $Q_{\min 1}$ (the lower limit of drilling fluid flow rate in vertical section and small-inclination section), $Q_{\min 2}$ (the lower limit of drilling fluid flow rate in large-inclination section) and $Q_{\min 3}$ (the lower limit of drilling fluid flow rate in horizontal section) can be achieved. The minimum one can be taken as the lower limit of drilling fluid flow rate $Q_{\min}$, which is given by Eq. (20).

$$Q_{hc} = \max(Q_{\min1}, Q_{\min2}, Q_{\min3}) \tag{20}$$

The calculation procedure is summarized as follows and shown in Fig. 5.

(1) Determine the allowable range of drilling fluid rate $Q_{\min} \le Q \le Q_{\max}$ by considering the needs of hole cleaning and the bearing ability of drilled formation;
(2) Determine the relationship between $Q_{\min} \le Q \le Q_{\max}$ and the rated flow rate of the drilling pump Q_r;
(3) Determine which situation the HERL belongs to and which kind of HERL model is to be adopted, then calculate the horizontal-section limit L_h of the horizontal ERW;
(4) If $Q_{\min} \le Q_r \le Q_{\max}$ (Case I), calculate L_h using Eq. (4); if $Q_{\min} < Q_{\max} < Q_r$ (Case II), calculate L_h using Eq. (5); if $Q_r < Q_{\min} < Q_{\max}$ (Case III), calculate L_h using Eq. (6).

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Author Contributions

Xin Li and Deli Gao developed the model; Xin Li wrote the main manuscript; Deli Gao supervised the project and Xuyue Chen revised the manuscript. All the authors reviewed the manuscript.

Additional Information

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