

# Study on the Separate Characteristics of Oil Spill Driven by Combined Water and Wind in Braided Rivers

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**Abstract:** In general, there are many bifurcations in natural rivers. When the oil spilled accident occurred at the upstream of bifurcation and was not controlled in time, the pollution scale would be expanded and the treatment would become harder as the oil slick entered into braided river driven by combined water and wind. To Study the separate law at the bifurcation in rivers, a two-dimensional numerical simulation model of oil spilled was established by oil particle model theory on the basis of two-dimensional hydrodynamic model. The quantitative relationship between the oil separate ratio and the flux ratio, velocity ratio, width ratio was obtained driven by water. The wind effect on the proportion of oil separate was also discussed based on the oil spilled numerical simulation. This study will provide technical support for forecast and response of oil pollution in braided rivers.

## 1 Introduction

The simulation model of sudden oil spill pollution incident is an important content of oil slick emergency control and disposal system construction. The rapid quantitative formula of oil slick based on control parameters can predict the migration and expansion process of oil slick in water and provide decision support for emergency disposal.

In recent years, sudden water pollution incidents have occurred in rivers, lakes, water diversion projects and other water areas in China, which have seriously affected the water environment of the waters and the drinking water supply along the river. It has become the current focus of attention in response to sudden water pollution incidents. For this, domestic scholars have focused on the research of water hydrodynamic characteristics, engineering regulation, pollutant transport and diffusion characteristics, pollution disposal technologies and devices (Lian, et al., 2006; Lian, et al., 2013; Gu, et al., 2011; Tao, et al., 2013). Sudden oil pollution is one of the main types of sudden water pollution in rivers. For sudden oil pollution incidents in river systems, realizing the characteristics of oil pollution and identifying the range of oil pollution is the basis for rapid and efficient pollution disposal. The earliest proposed oil slick center-of-gravity trajectory combined with the oil slick expansion empirical formula method, the equivalent ellipse of the oil spill area is given by extending the empirical formula, and the oil pollution range is obtained after being added to the oil-oil center drift position. But it only applies to open water

areas such as the ocean and estuary. The oil slick dynamics model method has operational limitations, because it assumes that the oil slick is a continuum during the change and movement process, and can not consider the oil slick fracture process.

Based on the Lagrangian theoretical system, the oil particle model discretizes the oil spill into a large number of oil particles. The oil slick expansion is simulated by the random movement of oil particles, and the calculation efficiency is high (Zhang, et al., 2008), which has become the mainstream method for the current study on oil spill numerical simulation.

REINALDO (Reinaldo, et al., 1999) designed a fourth-order Runge-Kutta method to calculate oil particles to improve the calculation accuracy of river oil spill simulation. M.SAYED (M.SAYED, et al., 2008) developed a simple and easy oil spill simulation model based on oil particle model theory. providing decision support for oil pollution disposal in the St. Lawrence River.

In China, relevant scholars (Jiang, 2007; Zhang, et al., 2010; Zhao, et al., 2012) take the tidal reach of Huangpu river, the Yangtze river, the Han river and the Three-Gorges reservoir as examples, and use the oil particle model to carry out the oil spill numerical simulation study of sudden oil spill accident, and the research results lay a foundation for the emergency response and disposal of oil spill pollution in multiple types of waters.

At present, the river oil spill simulation is mostly based on the typical section of the river, and there is a lack of the research results on the oil spill separate characteristics of

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the braided rivers. Based on this, the paper has developed the study on the separate characteristics of oil spill driven by combined water and wind in braided rivers.

Based on the two-dimensional hydrodynamic model of braided river, a numerical simulation model is established by using the theory of oil particle model.

Firstly, the influence of oil spill expansion time on oil flow shunt is analyzed, and then the oil separate ratio under different flow, velocity and braided width is studied, and the influence of wind on oil spill separate characteristics is also analyzed. The research results are expected to provide technical support for the prediction of the impact range of oil spills in the braided river and the disposal of oil pollution.

## 2 Numerical Simulation Model

### 2.1 Two-Dimensional flow equation

Equation of continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0 \quad (1)$$

Equations of motion:

$$\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{v}\bar{u}}{\partial y} = -gh \frac{\partial \eta}{\partial x} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial x} \quad (2)$$

$$-\frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial x} - \frac{\tau_{bx}}{\rho_0} - \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy})$$

$$\frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{u}\bar{v}}{\partial x} + \frac{\partial h\bar{v}^2}{\partial y} = -gh \frac{\partial \eta}{\partial y} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial y} \quad (3)$$

$$-\frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial y} - \frac{\tau_{by}}{\rho_0} - \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy})$$

in which,  $h = \eta + d$  is total water depth;  $d$  is static water depth;  $\eta$  is water level;  $u$ 、 $v$  is the velocity of  $x$ 、 $y$  direction, respectively;  $T_{xx}$ 、 $T_{yy}$ 、 $T_{xy}$  is the horizontal viscous stress term;  $\tau_{bx}$ 、 $\tau_{by}$  is the shear force of the bed surface;  $\bar{u}$ 、 $\bar{v}$  is the average velocity in the direction of depth.

### 2.2 the migration and expansion simulation model of oil spill

#### (1) Expansion

After the spilled oil enters the water, the spread area of oil slick with the change of time can be calculated with modified Fay's gravity-viscous formula:

$$\frac{dA_{oil}}{dt} = K_a A_{oil}^{1/3} \left( \frac{V_{oil}}{A_{oil}} \right)^{4/3} \quad (1)$$

in which,  $A_{oil} = \pi R_{oil}^2$ , is the spread area of oil slick,  $m^2$ ;  $R_{oil}$  is the radius of oil slick,  $m$ ;  $K_a$  is the coefficient,  $s^{-1}$ .

#### (2) Advection Transport and Turbulent Diffusion

Oil slick transport refers to the translatory movement of oil particles under the influence of wind, surface

current, and waves in the surrounding waters. The formula for calculating the drifting velocity of the oil slick is:

$$\vec{U} = \vec{U}_a + \vec{U}' \quad (2)$$

in which,  $\vec{U}_a$  is the translatory velocity of the surface current and wind,  $m/s$ ;  $\vec{U}'$  is the horizontal turbulent diffusion velocity,  $m/s$ .

The translatory velocity is calculated by the following weight formula:

$$\vec{U}_a = K_s \vec{U}_s + K_w \vec{U}_w \quad (3)$$

$$\vec{U}_s = (1-j)(1-k)u_1 + j(1-k)u_2 + (1-j)k \cdot u_3 + j \cdot k \cdot u_4 \quad (4)$$

in which,  $\vec{U}_s$  is the surface velocity of the canal segment,  $m/s$ ;  $K_s$  is water-driven drift impact factor, set at 1.15(Zhao, et al., 2012);  $\vec{U}_w$  is the wind velocity 10m above the water surface,  $m/s$ ;  $K_w$  is wind-driven drift impact factor, generally set at 0.02~0.03;  $u_1$ ,  $u_2$ ,  $u_3$ ,  $u_4$  are velocity components.

The turbulent diffusion rate of the oil slick is calculated using random step. The formula for calculating the diffusion rate is:

$$\Delta S = [R]_0^1 \sqrt{12D_h \Delta t} \quad (5)$$

in which:  $[R]_0^1$  is a random number from 0 to 1,  $D_h$  is the horizontal diffusion coefficient.

Distributed formula of oil slick displacement:

$$L_{x(\Delta t)} = U_{ax} \Delta t + \Delta S \cos \theta$$

$$L_{y(\Delta t)} = U_{ay} \Delta t + \Delta S \sin \theta \quad (6)$$

in which,  $L_{x(\Delta t)}$  and  $L_{y(\Delta t)}$  are displacement in the direction of  $x$  and  $y$ , respectively;  $U_{ax}$  and  $U_{ay}$  are advection velocity components in the direction of  $x$  and  $y$ ;  $\theta = 2\pi[R]_0^1$ .

The new position of the  $i^{\text{th}}$  oil particle moving from moment  $n$  to moment  $n+1$  is:

$$X_i^{n+1} = X_i^n + L_{x(\Delta t)}$$

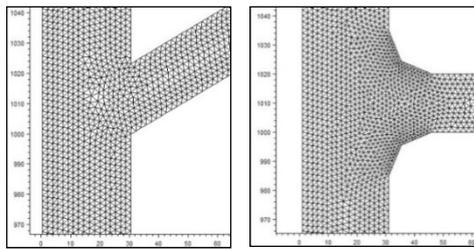
$$Y_i^{n+1} = Y_i^n + L_{y(\Delta t)} \quad (7)$$

in which,  $X$  and  $Y$  are the coordinates of oil particles.

## 3 Study on separate characteristics driven by flow

### 3.1 Setting of research object and simulation parameter

As shown in Fig.1, the study on the oil spill separate characteristics of the braided river was carried out with the example of oblique branch and vertical branch.



(a) oblique; (b) vertical  
**Fig.1** The forms of braided rivers

**Tab.1** Parameters for oil spilled numerical simulation

Type of oil spill	Oil Spill Quantity /m <sup>3</sup>	$D_L$ /m <sup>2</sup> /s	$D_T$ /m <sup>2</sup> /s	Water Temperature /°C	Air Temperature /°C
instantaneous	10	0.25	0.1	20	20

Notes:  $D_L$ ,  $D_T$  are the longitudinal and transverse expansion coefficients of the oil slick.

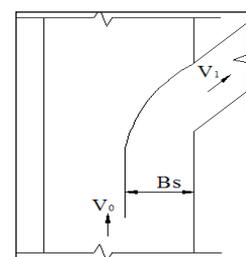
**Tab.2** Conditions of hydrodynamic simulation

Scenario	Type of braid	The main channel before the braided			The braided river		
		Flow $Q_0$ / m <sup>3</sup> /s	Width $B_0$ /m	Velocity $V_0$ /m/s	Flow $Q_1$ / m <sup>3</sup> /s	Width $B_1$ /m	Velocity $V_1$ /m/s
1	oblique	200	50	0.847	59.11	40	0.675
2		200	50	0.846	67.01	40	0.693
3		200	50	0.848	78.02	40	0.720
4		200	50	0.840	84.76	40	0.737
5		200	50	0.838	94.24	40	0.763
6		200	50	0.830	108.67	40	0.800
7		200	50	0.827	124.81	40	0.825
8		200	50	0.835	66.31	30	0.714
9		200	50	0.846	101.28	50	0.697
10		100	30	0.488	40.00	23	0.481
11	vertical	100	30	0.493	30.00	36	0.318
12		100	30	0.486	40.00	36	0.320
13		100	30	0.482	50.00	36	0.675

The numerical simulation of oil spill only considers the physical change process of expansion and drift, and ignores the chemical change process of oil spill evaporation, dissolution and emulsification. The main parameters of the model are shown in table 1. By changing the boundary conditions of the two-dimensional hydrodynamic numerical simulation model, the hydrodynamic data under different diverging conditions are obtained as shown in table 2.

### 3.2 The influence of oil slick expansion time on the oil separate ratio

As shown in Fig. 2, the flow would be separated in the channel branches. The distribution of surface separate width determines the amount of oil entering the channel branches (Cao, et al., 2003). The oil slick expansion time is the primary factor influencing the oil distribution within the braided river width.



**Fig.2** The sketch of  $B_s$

Based on the condition of scenario 3, by changing the distance between the oil spill point with the branch inlet, the influence of the oil slick expansion time on the oil distribution rules is simulated. Simulation results is shown in Table 3. Time revised coefficient is defined as the ratio of the oil separate ratio of each operating scenario to the oil separate ratio of the scenario 3-6.

It can be seen from Table 3 that as the oil slick expansion time increased, the amount of separated oil increase gradually; when the oil slick expansion time is greater than 1600s, the amount of separated oil tends to be

stable.

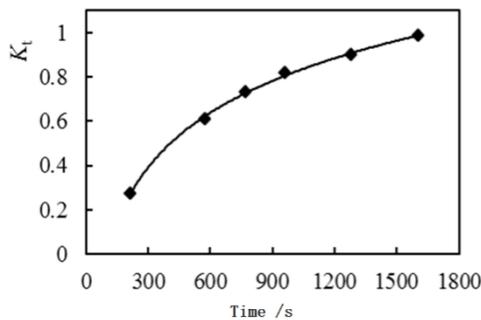
When  $t \leq 1600s$ , the relationship between the time revised coefficient of the oil separate ratio and the oil slick expansion time is shown in Fig.3.

When the oil slick expansion time  $t < T$ , the relationship expression between the time revised coefficient of the oil separate ratio and the oil slick expansion time is as:

$$K_t = a \ln(t) + b \quad (8)$$

**Tab.3** Spread time effect on the oil distribution

scenario	Spread time t/s	Oil volume of braided river $W_1/m^3$	Oil volume of the main channel $W_0/m^3$	Oil separate ratio $K_{oil}=W_1/W_0$	$K_t$
3-1	212	1.180	10.00	0.118	0.272
3-2	572	2.298	9.997	0.230	0.609
3-3	772	2.637	9.979	0.264	0.734
3-4	962	2.852	9.977	0.289	0.817
3-5	1278	3.033	9.920	0.306	0.902
3-6	1584	3.233	9.870	0.328	1
3-7	1604	3.187	9.810	\	\
3-8	2158	3.155	9.807	\	\
3-9	2218	3.170	9.790	\	\
3-10	2590	3.242	9.757	\	\
3-11	2764	3.247	9.735	\	\



**Fig.3** Time revised coefficient

### 3.3 Study on the separate characteristics of oil driven by water flow

The influence of water flow on oil separate ratio is mainly reflected in the separate width. Literature (Yang, et al., 2006) studies have shown that the surface split width increases with the increase of the separate ratio  $\eta = V_1 / V_0$ . Under different hydrodynamic conditions, the larger  $V_1$  is, the larger  $B_s$  is, and the larger the oil volume  $W_1$  flow into the braided river is. The flow rate  $Q_1$  and width  $B_1$  of the braided river will have a significant effect on the split velocity  $V_1$ .

Based on the scenario 1~13, the oil spill point is set at the central position of the river at 2km upstream of the braided inlet (the same as scenario 3-6 in table 3). The simulation results of oil separate ratio under various hydrodynamic conditions are shown in table 4.

Where  $a$ 、 $b$ 、 $T$  are related to the width of the main channel.

The value of the parameter when the main channel width is 50m:

$$a = 0.357; b = -1.632; T = 1600s$$

The value of the parameter when the main channel width is 30m:

$$a = 0.223; b = -0.543; T = 1100s$$

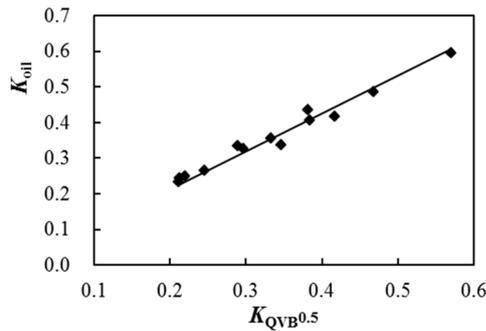
Draw the relationship between  $K_{oil}$  and  $K_{QVB^{0.5}}$ ,

$$K_{QVB^{0.5}} = \frac{Q_1 V_1 B_1^{0.5}}{Q_0 V_0 B_0^{0.5}}$$

where,

**Tab.4** The result of simulation for oil separate

scenario	Oil volume of braided river $W_1$	Oil volume of the main channel $W_0$	Oil separate ratio $K_{oil}=W_1/W_0$	$K_{QVB^{0.5}}$
1-1	2.297	9.793	0.235	0.211
2-1	2.628	9.877	0.266	0.245
3-6	3.233	9.87	0.328	0.296
4-1	3.508	9.86	0.356	0.332
5-1	4.01	9.862	0.407	0.383
6-1	4.777	9.829	0.486	0.468
7-1	5.862	9.854	0.595	0.557
8-1	2.445	9.84	0.248	0.22
9-1	4.105	9.857	0.416	0.417
10-1	3.332	9.915	0.336	0.346
11-1	2.398	9.867	0.243	0.212
12-1	3.292	9.852	0.334	0.289
13-1	4.287	9.86	0.435	0.382



**Fig.4** The relationship between  $K_{oil}$  and  $K_{QVB}^{0.5}$

The Fig.4 shows: the oil separate ratio  $K_{oil}$  and  $K_{QVB}^{0.5}$  are approximately linear, and the relationship between the two is as shown in equation (9).

$$K_{oil} = kK_{QVB}^{0.5} \quad (9)$$

$k = 1.06$  can be obtained by linear fitting of figure 4 data points.

#### 4 Study on the separate characteristics of oil spill driven by combined water and wind

The influence of wind on the proportion of oil separation is reflected in changing the oil distribution within the width of flow split. Based on the flow condition of scenario 3, the oil spill point is set at the central location 2km away from the upstream of the branch inlet. The simulation results of oil separate are shown in table 5.

**Tab.5** Oil separate result driven by combine water-wind

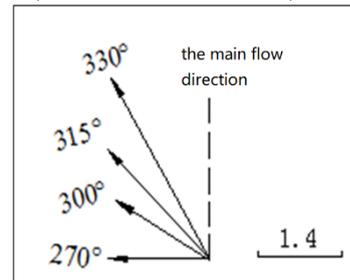
scenario	Wind condition			Oil volume of braided river $W_1/m^3$
	Wind speed m/s	wind direction	Time /min	
3-6	\	\	\	3.233
3-12	1	0°	35	3.138
3-13	5	0°	35	3.167
3-14	10	0°	35	3.133
3-15	1	45°	35	3.810
3-16	5	45°	35	4.742
3-17	10	45°	35	5.297
3-18	2.7	330°	35	0
3-19	2	315°	35	0
3-20	1.5	300°	35	0
3-21	1.4	270°	35	0
3-22	1.8	270°	30	0
3-23	5.0	270°	25	0

It can be seen from the simulation results in table 5 that the influence of wind on oil separate ratio is related to the size of wind speed, wind direction and the acting time of wind:

(1) Comparing the scenarios of 3-12~3-14, it can be known that when the wind and the main river flow are in the same direction, and the influence of wind speed on the

oil separate ratio can be neglected; Comparing the scenarios of 3-15~3-17, it shows when the wind deflects towards the distributary reach., the amount of oil volume in the braided river increases as the wind speed increases.

(2) Comparing the critical scenarios of 3-18~3-23 which the separate oil amount are zero, it can be seen that when the wind field action time is the same (scenarios of 3-18~3-21), the components of the vertical speed of the wind speed are the same, as shown in Fig. 5. When the greater the wind speed, the shorter the time required for the wind field (scenarios of 3-21~3-23).



**Fig.5** The vector diagram of critical wind speed

#### 5 Conclusion

In this paper, a widely used oil particle model is adopted to study the separate characteristics of oil slick in braided river. The research results can provide the basis for the prediction of the oil spill range and the disposal of oil spill in the braided river. The specific research conclusions are as follows:

(1) Under the driving of water flow, the longer the oil film expansion time, the more adequate the oil slick expansion; Under the condition of oil slick sufficiently expansion, the oil separate ratio  $K_{oil}$  is linear with  $K_{QVB}^{0.5}$ .  $K_{QVB}^{0.5}$  is the product of flow separate ratio  $Q_1/Q_0$ , velocity ratio  $V_1/V_0$  and river width ratio's 0.5th power  $(B_1/B_0)^{0.5}$ .

$$K_{oil} = 1.06K_{QVB}^{0.5};$$

(2) Under the combined driving of water and wind, the influence of wind on the oil separate ratio is related to the magnitude of wind speed, wind direction and action time of wind field. Under the same conditions of wind field action, when the wind is biased towards the braided river,  $K_{oil}$  increases with the increase of wind speed; When the wind deviates from the braided river,  $K_{oil}$  decreases with the increase of wind speed; When the component perpendicular to the shore of the wind are the same, the wind has the same influence on the oil separate ratio.

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