

A Comprehensive Method for Calculating Impact of Coal Dust on the Marine Environment

YAO Wenwei^{1, a}, YING Chao^{1, b} and ZHAO Xin^{1, c}

¹*Zhejiang Institute of Hydraulics & Estuary, Hangzhou, China*

^awwwyao230@163.com, ^b 28447353@qq.com, ^c 3989373@qq.com

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Abstract. The coal dust will cause pollution of the marine environment when the coal wharf of a coastal power plant is operated. The coal loss in the process of unloading in the wharf was estimated through the standard formula, and then the amount of coal dust into the sea was determined. By the combined force of gravity and wind, the coal dust would land on the surface of the sea, the horizontal distance of the landing point and the coal wharf can be calculated by the empirical formula, then the source range of coal dust into the sea was generalized. The Lagrangian particle tracking method was used in the calculation of the diffusion process of the suspended coal particles, The concentration range of suspended coal particles was obtained.

Introduction

Coal is the most important part in China's energy structure, the total amount of coal consumption accounted for about 64% [1] of total energy consumption in 2015. In order to facilitate the transport of coal, China's large-scale coal-fired power plants are mainly concentrated in the eastern coastal areas, almost all these power plants have built large dedicated coal wharf, the unloading process of coal from ship to the coal yard was often accompanied by dust, previous studies have focused on the atmospheric environment impact caused by dust [2,3], however coal dust is also a pollution source to the marine environment, dust from wharf to sea to eventually deposited in the seabed will have an impact on water quality and sediment quality. Therefore, a coastal coal power plant in Zhejiang province was studied as a case, the suspended and diffusion process was studied by the combining use of empirical formula and numerical simulation method, and the result can provide a reference for assessing the impact of coal dust on the marine environment.

Calculation of Coal Dust into Sea. Coal particles whose size less than 200μm was produced in the unloading and stacking process of coal, and those particle was likely to be raised under the action of mechanical action of wind and other effects, quantity of dust was mainly related to wind speed, moisture content of the coal and the unloading height, it can be estimated by the following formula [4]:

$$Q = 0.03V^{1.6}H^{1.23}e^{-0.28W} \quad (1)$$

Where Q is the amount of dust (kg/t); V is the actual wind speed (m/s); W is the coal moisture content (%); H is the loading and unloading height (m). The annual average wind speed near the project area was about 5.0m/s; the moisture content of coal when it arrive at the wharf was about 8-10%, for a negative side, we take 8%; the height of the grab unloader operation was about 1~3m, for a negative side, 3m was taken. Then Q can be estimated as 0.18kg/T.

The coal wharf was composed of two 35,000-ton berths, equipped with four bridge type grab ship unloaders, nominal production rate of two of which was 1600t/h, the other two was 1500t/h. The maximum loading and unloading coal per hour was 6200t, it all means the maximum loss 1102.5kg/h.

Table 1. The percentage of typical coal dust in different size particle distribution

Particle size(μm)	0-10	10-30	30-50	50-70	70-90	90-100	100-200	>200
Percentage(%)	2.2	4.5	4.4	3.5	4.3	2.1	21	20

Table 1 are typical percentage of coal dust of different particle size distribution, the particle size of less than 200 μm content in 42% in the total quantity of dust in the unloading operation, the density of coal dust is about 1.38g/cm³. When the grab unloaders are unloading the coal, a reflection plate which can suppress the dust through spraying is set surrounding the feeding funnel and the dust suppression efficiency is about 85%[5], the source of coal dust into the sea to be suspended can be calculated by the above date, and the source is 0.0193 kg/s.

Numerical Model.

2-D Hydrodynamic Module. The model is based on the solution of 2-D incompressible Reynolds averaged Navier-Stokes equations. Integration of the horizontal momentum equations and the continuity equation over depth the following 2-D shallow water equations are obtained[6]:

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = hS \quad (2)$$

$$\begin{aligned} \frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{v}\bar{u}}{\partial y} = & f\bar{v}h - gh\frac{\partial h}{\partial x} - \frac{h}{r_0}\frac{\partial p_a}{\partial x} - \frac{gh^2}{2r_0}\frac{\partial r}{\partial x} + \frac{t_{sx}}{r_0} - \frac{t_{bx}}{r_0} - \\ & + \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy}) + hu_s s \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{u}\bar{v}}{\partial x} + \frac{\partial h\bar{v}^2}{\partial y} = & -f\bar{u}h - gh\frac{\partial h}{\partial y} - \frac{h}{r_0}\frac{\partial p_a}{\partial y} - \frac{gh^2}{2r_0}\frac{\partial r}{\partial y} + \frac{t_{sy}}{r_0} - \frac{t_{by}}{r_0} - \\ & + \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy}) + hv_s s \end{aligned} \quad (4)$$

Where: t is the time; x, y are the Cartesian co-ordinates; η is the surface elevation; d is the still water depth; $h = \eta + d$ is the total water depth; u, v are the velocity components in the x, y direction; $f = 2\Omega \sin \Phi$ is the Coriolis parameter (Ω is the angular rate of revolution and Φ the geographic latitude); g is the gravitational acceleration; ρ is the density of water; ρ_0 is the reference density of water; the lateral stresses T_{ij} include viscous friction, turbulent friction and differential advection.

Particle Tracking Module. In the Particle Tracking Module a Lagrangian discrete-parcel method is used, the coal dust is represented by a large ensemble of small parcels. Every particle's transportation is governed in a random walk model. The position $x(t)$ of each particle in a random walk model is described by the non-linear Langevin equation[7]:

$$\frac{d\mathbf{x}}{dt} = A(\mathbf{x}, t) + B(\mathbf{x}, t)\mathbf{x}(t) \quad (5)$$

Where $A(\mathbf{x}, t)$ is a known vector representing the deterministic forces that act to change $x(t)$, $B(\mathbf{x}, t)$ is a known tensor that characterizes the random forces, and $\xi(t)$ is a vector composed of random numbers that represent the random nature of tidal mixing which, when averaged over sufficiently long time and space scales, becomes effectively random.

Eq.5 becomes equivalent to the stochastic differential equation

$$d\mathbf{x} = A(\mathbf{x}(t), t)dt + B(\mathbf{x}(t), t)dW(t) \quad (6)$$

Where $dW(t)$ is the random Wiener process. The mean value of $dW(t)$ is zero and the mean square is proportional to dt . The simplest discretization of Eq.6 is the explicit Euler scheme for stochastic differential equations.

$$\Delta\mathbf{x} = \mathbf{x}_n - \mathbf{x}_{n-1} = A(\mathbf{x}_{n-1}, t_{n-1})\Delta t + B(\mathbf{x}_{n-1}, t_{n-1})\sqrt{\Delta t}Z_n \quad (7)$$

Where Z_n is vector of one, two, or three independent random numbers depending on the dimensionality of the problem form a distribution with zero mean and unit variance.

In the limit when the number of particles is infinite and the time step is infinitely small, Eq.7 is equivalent to the Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x_i} (A_i f) = \frac{\partial^2}{\partial x_i \partial x_j} \left(\frac{1}{2} B_{ik} B_{jk} f \right) \quad (8)$$

Where $f(\mathbf{x}, t | \mathbf{x}_0, t_0)$ is the conditional probability density function.

Model Parameters.

The Range of Coal Dust into Sea. Once the coal dust particle was raised, it drift under the effect of wind, and gradually settle to the ground or sea surface due to its own gravity, the distance between the starting point to the fall point is the drift distance in the air medium. The settling velocity of the coal dust particle in the air can be estimated by the Stokes settling velocity formula[8]:

$$V_g = \frac{d_i^2 r g}{18m} \quad (9)$$

Where V_g is the settling velocity of a coal particle; d_i is diameter of particle (m); ρ is the density of coal (kg/m^3); g is the gravitational acceleration (m/s^2); μ is the dynamic viscosity of air ($\text{Pa}\cdot\text{s}$). According to the model proposed by Walker[9]: coal dust particle do linear motion to the surface of the sea by the combined action of mean wind velocity V_w and settling velocity V_g , it is assumed that coal particle to do straight trajectory with average inclination angle $\text{tg}^{-1}(v_g v_w^{-1})$ [10] in normal distribution:

$$\Phi = \text{tg}^{-1}(H \cdot X^{-1}) - \text{tg}^{-1}(V_g \cdot V_w^{-1}) \approx H \cdot X^{-1} - V_g \cdot V_w^{-1} \quad (10)$$

Where, H is the height of particle source; X is horizontal distance of coal particles moving in the air. When the deviation angle $\Phi = 0$,

$$X = H \cdot V_w \cdot V_g^{-1} \quad (11)$$

According to the above formulas, the horizontal distance X can be estimated. Table 2 is the settling velocity of particles with different diameters and horizontal distances of particles moving in the air for those different size particles.

Table 2. Settling velocity of particles and its horizontal distances of particles moving in the air

Diameter (μm)	Settling velocity(m/s)	Wind scale /typical wind speed (m/s)				
		2/2.5	3/4.3	4/6.8	5/8.5	6/12.5
<20	0.012	3125	5375	8500	10625	15625
20-60	0.109	344	592	936	1170	1720
60-100	0.284	132	227	359	441	660
100-150	0.556	67	116	183	229	337
150-200	0.833	45	77	122	153	225
>200	1.667	22	39	61	76	112

The smaller the particle size and the greater the wind speed, the farther the horizontal distance. The particle whose diameter less than $20\mu\text{m}$ can move 3.1km from the wharf until settle on the sea surface under the constant wind speed 2.5m/s, while under strong wind (12.5m/s), the distance is about 15km, however because of the smaller proportion of this scale coal dust, the generalized of source position in the numerical model of these particle will not be considered.

According to the measured wind data statistics, the annual average wind speed is about 5.0m/s, taking wind scale 3 and $100\mu\text{m}$ for characterizing the wind speed and the particle size respectively, the distance can be estimated as about 200m. The source position of the coal particles can be generalized as a circle whose radius is 200m and the center of the circle is the center of the wharf. Because of the different size of particles, the source positions are set in 80 points, which located in

four circles and their radius is 50m,100m,150m and 200m respectively, each circle aliquot taken 20 points, the position of these points is showed in Fig.1. It is assumed that the coal dust into the sea uniform distribution in the 80 points.

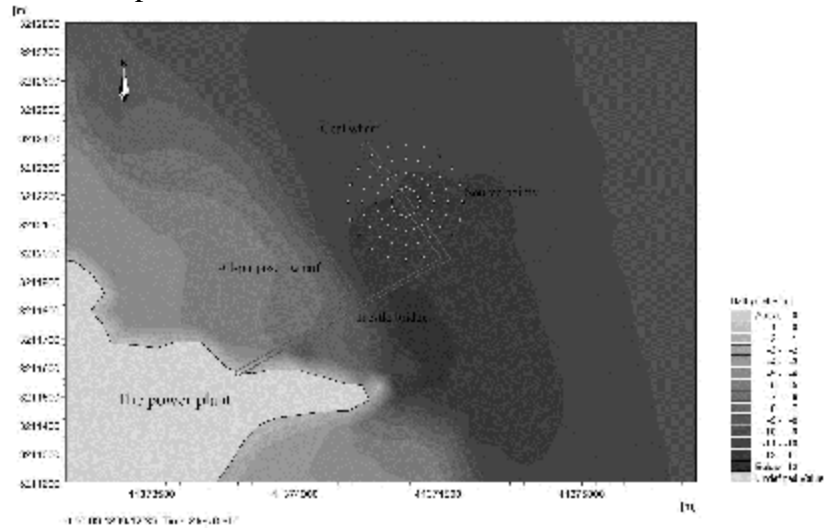


Fig.1 Sketch of the generalized points of coal dust source on the sea surface

The Settling Velocity of Coal Particle in Seawater. The settling velocity of the coal dust particle in the seawater can also be estimated by the Stokes settling velocity formula:

$$w_s = \frac{gd^2(r_m - r_w)}{18\mu} \quad (12)$$

Where w_s is the settling velocity of coal particle in seawater; r_m is the density of coal(kg/m^3); r_w is the density of seawater; μ is the dynamic viscosity of seawater. The settling velocity of different sizes can be calculated by Eq.12, and the result is shown in Tab.3. Settling velocity of different sizes are quite different, the smaller the particle size, the smaller settling velocity, the longer the time suspended in the water.

The average depth at the front of the wharf is about 12m, so 0 ~ 40 μm coal dust will sink onto the seabed in about 43 hours, 161 ~ 200 μm coal dust will sink onto the seabed within 0.5 hours, the resuspension of the coal particles were not considered. The pollution source is divided into 5 parts, 0 ~ 40 μm , 41 ~ 80 μm , 81 ~ 120 μm , 121 ~ 160 μm and 161 ~ 200 μm represent five different particle size range of coal dust, all the separated result will be added to calculate the maximum envelope area of the concentration of suspended coal particles.

Table 3 settling velocity of coal particles in seawater with different sizes

Size range(μm)	Characteristic size (μm)	Settling velocity(m/s)
0~40	20	7.84×10^{-5}
41~80	60	7.06×10^{-4}
81~120	100	1.96×10^{-3}
121~160	140	3.84×10^{-3}
161~200	180	6.35×10^{-3}

Mesh Setting. The domain of the numerical model is shown in Fig.2, the computational domain area is about 11939 km^2 . Unstructured triangular meshes is used in the model, in order to ensure the accuracy of the simulation, the mesh is as fine as 5m at the region around the wharf. A flow field of 15 consecutive days which has been validated was used as the hydrodynamic condition, the unloading operation of coal in the wharf was assumed continuous, the model calculates 15 days to analyze the suspension of coal dust in seawater.

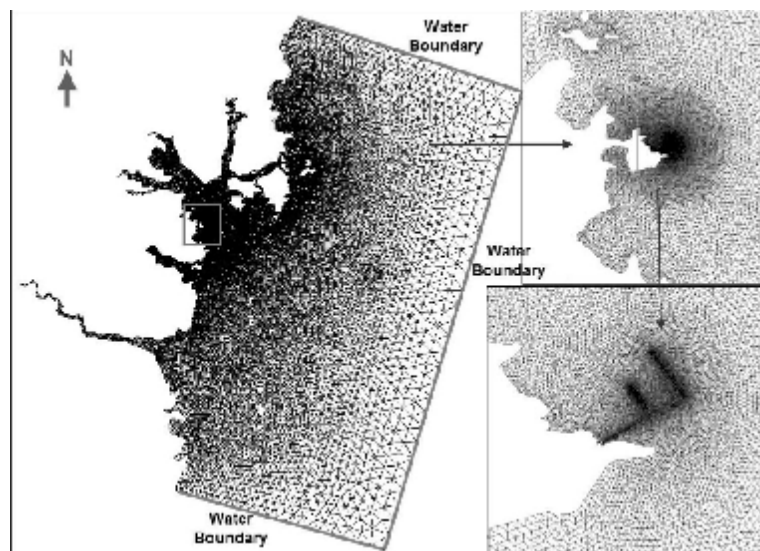


Figure 2 Sketch of computational region and mesh

Calculation Result. Due to the effect of flood and ebb tidal current, the coal dust that was suspended in seawater would be drifted along with the tidal current. The transport direction of the suspended particles was almost consistent with the direction of the tidal current. It was shown in Figure 3 that the concentration of suspended particles in seawater in the condition of the continuous unloading operation on the wharf, and statistics of the envelope areas of different concentrations levels was shown in Table 4.

Table 4 statistics of the envelope areas of concentrations levels of suspended coal particles

concentration (mg/L)	≥ 0.05	≥ 0.10	≥ 0.15	≥ 0.20	≥ 0.40
Envelope area (km ²)	0.405	0.102	0.053	0.032	0.007

The diffusion range of the suspended particle was primarily limited to the region of about 1km around the wharf .Because of the great efficiency of dust suppression device, the amount of coal dust that can drift into the sea surface was small, only 0.0193kg/s, and the settling velocity of coal particles in seawater was comparatively fast. The envelope areas which have a concentration greater than 0.05mg/L、 0.1mg/L and 0.2mg/L were 0.405 km2、 0.102 km2 and 0.007 km2 respectively.

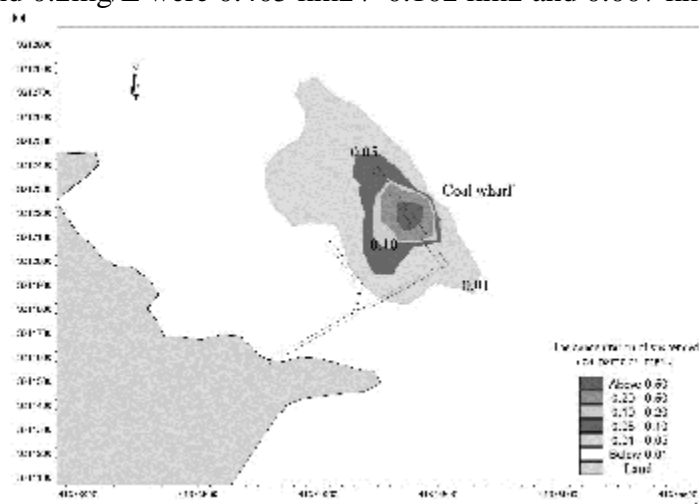


Fig.3 Envelope areas of concentration of suspended coal particles

Conclusions

The process of coal dust affect the marine environment was described as three steps: first of all drift down to the sea from the operation zone of the wharf, second suspended in seawater and drift along with tidal current and finally sunk onto the seabed under its own gravity. In the first step, a standardized formula was used to estimated the amount of raised coal dust that can drift into sea and

the range of dust that reach the surface of sea was generalized as a circle through the Stokes formula and Walker's model. In the second step, a Lagrangian particle tracking method based on a 2-D hydrodynamic model was established to simulate the diffusion of suspended coal particles. Through this method the maximum possible suspension concentration of coal particle can be estimated, the result can be used to assess the impact of coal dust on the marine environment on the operation of coal wharf.

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