Development of Ishikawa Diagram of Oil Spreading in the Sea

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Abstract. The spread of an oil slick over the water surface is a complex process that is systematically described by the Ishikawa diagram. An oil slick moves across the surface under the influence of forces acting on every particle in the sea. The development of the Ishikawa diagram describes the causes, sub-causes, sub-sub-causes... to level 5th causes. Consequence, i.e. the problem in this case, in Ishikawa diagram is spreading oil slicks in the sea. Theoretical framework for development of the Ishikawa diagram defined through mathematical equations shows that the spreading of oil slicks in the sea depends on sea pressure, friction force, Coriolis force, buoyancy force, equation of state, tangential stresses due to wind action (wind currents), tidal forces, tension force and diffusion.

1. Introduction
Petroleum crude oil is an oil obtained from a well, before any cleaning, separation and refining. The chemical composition of crude oil depends on the type of oil, the original maturity of organic matter and its preservation in reservoir rocks and the conditions in the sedimental environment [1, 2].
In the last twenty years, governments and activists around the world started to pay a lot of attention to sea pollution due to major accidents that have caused major sea pollution. Serious oil pollution of the sea can occur during the transport of crude oil in tankers and tanker accidents, and large-scale oil pollution is also possible in case of shore platform accidents, drilling rigs and wells, oil transfuse from tankers to tanks at fuel terminals or at old and dilapidated refineries on the coast [3]. Small oil spills in marinas are not reported because they occur regularly and are usually not reported if they don’t induce major environmental problems.
The spreading of an oil slick on the water surface can be caused by the action of various forces, such as wind force, water currents, tides, waves, etc. [4]. During the oil slick spread process, many natural processes could change the volume and physicochemical characteristics of the oil slick. [4,5].
The rate of oil slick expansion is affected by many factors, the main division being the causes of horizontal shear, the causes of vertical expansion, and the tension force. Oil floating on the surface of the sea endangers plants and animals with its physical properties, because it endangers photosynthesis, respiration and nutrition. The recovery time of the area after contamination depends on fast and efficient cleaning. Good and accurate prediction of oil slick spread can significantly shorten the time required for cleaning.

2. Theoretical framework
Oil slicks are transported over long distances by the action of sea currents and mixing. They float on the surface, which is the result of buoyancy due to the lower density than the density of the sea. They expand and increase due to the forces of tension and diffusion, and due to the horizontal shear caused by the
spatial variability of the flow itself. Horizontal sea currents are formed under the influence of: generating forces such as horizontal variability of sea pressure (gradient currents), tangential stresses due to wind action (wind currents) and tidal forces (tidal currents or currents of sea ages); relaxing forces that occur at the edges of the sea, but also within the sea between particles; and Coriolis forces caused by the rotation of a system of water masses.

The generating forces are:
- horizontal variability of sea pressure (gradient currents),
- tangential stresses due to wind action (wind currents) and
- tidal forces (tidal currents or currents of sea ages).

The sum of the generating, relaxing, and Coriolis forces defines motion in the sea in space and time. The open sea is dominated by: pressure gradient force and Coriolis force. These two forces in the horizontal plane in stationary motion define geostrophic currents, whose relative value are calculated using the values of temperature and salinity. The direct transfer of substances and pollutants in the vertical plane takes place due to the action of vertical changes in density and buoyancy. On large spatial scales, upwelling and downwelling processes occur as a result of horizontal forces and mass conservation, while on smaller spatial scales, vertical movements occur under the influence of diffusion and instability processes in vertical density distribution [6].

2.1. Sea pressure, friction force, Coriolis force and buoyancy force
Movement of the sea is influenced by forces acting on each particle in the sea [6] such as gravity which acts directly on vertical movements, but also changes the pressure of horizontal movement by changing the pressure; pressure gradient force which is a consequence of different density and altitude of the sea and therefore the weight of the sea column in an area; friction force which is a relaxing force that redistributes energy in the sea and is influenced by viscosity and turbulent motions, but also by the force of the wind tension on the surface of the sea that transfers energy from the atmosphere; and Coriolis force, a pseudo-force that occurs due to the rotation of the reference system i.e. due to the Earth's rotation, and is dependent on the speed of rotation and latitude.

All these forces cause changes in motion of the sea in space and time. Therefore, the equations of motion of the sea can be written as:

$$\frac{dV}{dt} = -\frac{1}{\rho} \nabla p - 2\Omega \times V + g + F_t$$

where V - velocity vector; ρ - sea density; p - sea pressure; Ω - the angular velocity vector of the Earth's rotation; g - gravity vector; and F_t - represents all other forces (friction force, etc.).

The following is obtained in the Cartesian system:

$$\frac{dU}{dt} + U \frac{dU}{dx} + V \frac{dU}{dy} + W \frac{dU}{dz} = -\frac{1}{\rho} \frac{dp}{dx} + 2\Omega \cdot \nu \cdot \sin \phi + F_x$$

$$\frac{dV}{dt} + U \frac{dV}{dx} + V \frac{dV}{dy} + W \frac{dV}{dz} = -\frac{1}{\rho} \frac{dp}{dy} - 2\Omega \cdot \nu \cdot \sin \phi + F_y$$

$$\frac{dW}{dt} + U \frac{dW}{dx} + V \frac{dW}{dy} + W \frac{dW}{dz} = -\frac{1}{\rho} \frac{dp}{dz} - g - 2\Omega \cdot \nu \cdot \cos \phi + F_z$$

By linearizing this system, and integrating by a homogeneous layer, shallow fluid equations are obtained:

$$\frac{dU}{dt} = -g \frac{\delta \xi}{\delta x} + \frac{1}{\rho \cdot H} (\tau_x - \tau_{x,H})$$

$$\frac{dV}{dt} = -g \frac{\delta \xi}{\delta y} + \frac{1}{\rho \cdot H} (\tau_y - \tau_{y,H})$$

where: U and V - averaged velocities in the shallow fluid layer; H - layer thickness; τ_x and τ_y - wind tension components at the surface of the layer; τ_{x,H} and τ_{y,H} - friction components at the bottom of the layer; and f - Coriolis parameter (f = 2Ω \cdot \sin \phi).

In hydrostatic equilibrium (pressure at a certain depth depends only on the weight of the sea column) [7]:

$$\frac{dV}{dt} = -\frac{1}{\rho} \nabla p$$
\[-\frac{1}{\rho} \frac{\partial p}{\partial z} - g = 0\] (7)

In addition to the equations of motion, the law of conservation of mass (principle of mass conservation) also applies in the sea [8]:

\[\frac{1}{\rho} \frac{\partial \rho}{\partial t} + \frac{\delta U}{\delta x} + \frac{\delta V}{\delta y} + \frac{\delta W}{\delta z} = 0\] (8)

which for incompressible fluids is reduced to:

\[\frac{\delta U}{\delta x} + \frac{\delta V}{\delta y} + \frac{\delta W}{\delta z} = 0\] (9)

and in the shallow fluid equations it is in the form:

\[\frac{\delta H U}{\delta x} + \frac{\delta H V}{\delta y} + \frac{\delta \zeta}{\delta t} = 0\] (10)

The laws of conservation of salt and heat also apply in the sea [9]:

\[\frac{dS}{dt} = I + P\] (11)

\[\frac{dT}{dt} = I + P\] (12)

where: S – salinity; T – temperature; I - source of salt and heat; and P - abyss of salt and heat.

Finally, the system of equations of motion of the sea is complemented by the equation of state.

2.2. Equation of state

On average, seawater is a mixture of 96.5% pure water (H\(_2\)O) and 3.5% other ingredients, such as salts, dissolved gases, organic substances and undissolved particles. The physical properties of pure water are defined by the shape of the constituent molecules, and the essential property that defines the kinematics and dynamics of the sea and ocean is the dependence of sea density on the aggregate state of water and temperature. Namely, the density of liquid water is significantly higher than ice, while the density of sea water is always highest at the freezing point, for salinities higher than 25 [6].

The main physical properties of the sea are salinity, temperature and density. A simple definition of salinity is the ratio of the total amount of solute (in grams) to a given amount of seawater (in kilograms). Therefore, salinity is a dimensionless quantity. In the early 20\(^{th}\) century, salinity was defined as the amount of solute in grams per kilogram of seawater, when all carbonates were converted to oxides, bromine and iodine were replaced by chlorine, and all organic matter was oxidized. Due to the constant ratio of individual dissolved components (chlorine, bromine and iodine), the parameter chlorinity was determined (total amount of halides in 1 kg of sea water) [10]. Empirical relations determined salinity from chlorinity, for example UNESCO (1962) gave the relation \(S = 1.80655 \times C\) (total amount of halides in 1 kg of seawater) [11]. The relationship was kept constant for the parameter chlorinity. Since seawater is a guide, and its conductivity depends on the amount of solutes, the "practical salinity 1978" is defined, which is still the official definition of seawater salinity [11]:

\[S = 0.008 - 0.1692 R_T^2 + 25.3851 R_T + 14.0941 R_T^3 - 7.0261 R_T^4 + 2.7081 R_T^5 + 0.261 R_T^6 + \Delta S\] (13)

\[R_T = \frac{C(S,T,0)}{C(KCl,T,0)}\] (14)

\[\Delta S = \left[\frac{T - 15}{1 + 0.0162(T - 15)}\right] + 0.0005 - 0.0056 R_T^2 - 0.0066 R_T - 0.0375 R_T^3 + 0.632 R_T^4 - 0.0144 R_T^6 + 0.5^{\frac{6}{2}}\] (15)

where: S – salinity; C (S, T, 0) - conductivity of the seawater sample at temperature (°C) and standard atmospheric pressure (1013 hPa); and C (KCl, T, 0) - conductivity of the standard potassium chloride solution at temperature (°C) and standard atmospheric pressure (1013 hPa).
Density is one of the most important parameters that define the dynamic properties of the sea and ocean. Even small horizontal differences in density, caused, for example, by different heat balances on the surface, can cause very strong currents in the sea. Density is a function of sea salinity, temperature and pressure (seawater equation or "International equation of state 1980") [12]:

$$\rho(S,T,p) = \frac{\rho(S,T,0)}{1 - \frac{K(S,T)}{ho(S,T,p)}}$$

(17)

where: $\rho(S,T,0)$ and $\rho(S,T,p)$ - salinity, temperature and pressure functions,

Assuming that $p = 0$, a $\sigma_T$ value (density reduced by 1000 kg/m$^3$) is used instead of density, because then the amount of density is independent of the sampling depth.

The simplified form of the state equation (17) can be linear [13]:

$$\rho = \rho_0(1 - \alpha T + \beta S), \alpha = 0.0002, \beta = 0.0008$$

(18)

or nonlinear:

$$\sigma_T = 28.152 - 0.07357 - 0.00469T^2 + (0.802 - 0.002T)(S - 35)$$

(19)

The layer of temperature discontinuity is also called thermocline, salinity of halocline, and density of pycnocline, and their consequence is the appearance of baroque flow. Barotropic (a barotropic fluid) is a state of the sea whose surfaces of equal density (isopic) are parallel to surfaces of equal pressure (isobars) [14]. Therefore, the slope of the isopic depends exclusively on the slope of the sea surface, while the flow that occurs due to the action of the horizontal pressure gradient is called barotropic.

Barotropic flow is constant throughout the sea column in which barotropy is preserved. This flow is characteristic of vertically homogeneous seas, or in individual homogeneous layers, which is most often the result of the process of vertical convection and mixing of water masses in the colder part of the year. In contrast, baroclinity is a state of the sea in which surfaces of equal density intersect surfaces of equal pressure [15]. This situation is common in stratified seas, and in such situations the current changes with depth. This flow is called barocline flow, and it occurs due to the sea pressure gradient caused by spatial changes in sea density on isobaric surfaces [16].

2.3. Tangential stresses due to wind action (wind currents)

The wind energy blowing over the sea surface is transferred partly to the energy of short-period surface waves and partly to the energy of wind currents. The action of wind on the surface of the sea is the result of frictional force (wind tension):

$$T = C_D \cdot \rho_A \cdot U \cdot |U|$$

(20)

where: $C_D$ - drag coefficient; $\rho_A$ - air density; and $U$ - wind vector.

In 1905, V. Walfid Ekman was the first to write a paper on the effect of wind on motion in the sea [17]. Ekman assumed the stationarity of motion in a deep homogeneous sea, taking the constant value of the member of the vertical viscosity:

$$T_{xz} = \rho \cdot A_z \frac{\delta U}{\delta z}$$

$$T_{yz} = \rho \cdot A_z \frac{\delta V}{\delta z}$$

(21)

(22)

where: $T_{xz}$ and $T_{yz}$ - stress components (viscosity) inside the sea, on the surface they represent components of wind tension; and $\rho$ - sea density.

With the neglect of other terms, the equations of motion (21), (22) pass into:

$$f v + A_z \frac{\delta^2 U}{\delta z^2} = 0$$

$$-f u + A_z \frac{\delta^2 V}{\delta z^2} = 0$$

(23)

(24)

where is: $f$ - Coriolis parameter ($f = 2\Omega \sin \phi$).

When the wind blows to the north ($T = T_{yz}$), the solution is:
\[ u = V_0 e^{az} \sin \left( \frac{\pi}{4} - az \right) \]  
\[ v = V_0 e^{az} \cos \left( \frac{\pi}{4} - az \right) \]

where:

\[ V_0 = \frac{\tau}{\rho \sqrt{f A z}} \]  
\[ a = \sqrt{\frac{f}{2 A z}} \]  
\[ T = C_D \rho_a U^2 \]

and U - wind speed over the sea.

The main properties of Ekman's solution of wind currents are:

- the surface current is deflected by 45° to the right with respect to the wind direction, and
- the current velocity decreases exponentially with depth, while the current vector rotates clockwise (Ekman's spiral).

The total transport of water masses caused by the wind is directed 90° to the right in the northern hemisphere, so in the case when the wind blows along the coast, leaving it on the right side, there is a downwelling, and in the opposite wind upwelling. Also, on the high seas there is a Ekman pumping that causes vertical movements of water due to the horizontal variability of the wind field over a certain area.

2.4. Tidal forces

The tidal force is caused by the gravitational attraction of water masses by the Sun and the Moon, and by the centrifugal force that occurs due to the rotation of the Earth and the Moon, i.e. the Earth and the Sun around a common center of mass. Its action has a periodic character, with the most pronounced half-day and daily components.

The tidal force is a combined gravitational and centrifugal force that acts on water bodies on Earth. Namely, the motion of water masses is affected by the gravitational attraction of the Sun and the Moon, which is variable and depends on their positions in relation to the Earth, and the centrifugal force created by the Earth's revolution. Therefore, the tidal force is of variable character in space and time, and dominates the horizontal movement of water masses, thus causing fluctuations in sea levels and sea currents.

2.5. Tension force and diffusion

Surface tension decreases with increasing temperature and addition of surfactants. The rate of diffusion of a substance in a given direction is proportional to its concentration gradient (Fick's 1st law of diffusion), and generally increases with increasing temperature (because particles move faster) and decreases with increasing density. Experiments have shown that the higher the pressure above the liquid and the lower the temperature of the liquid, the higher the amount of absorbed gas in the liquid.

3. Conceptual model

The Ishikawa diagram was used to develop the conceptual model (Figure 1) and analyse causes and effects. Each cause has sub-causes, which are a source of variation. The causes are grouped into main categories. Although originally developed as a quality control tool, this technique can be used just as well for other purposes [18].

The visual representation of the causes provided by this method facilitates the analysis of their mutual relationship and significance. It graphically illustrates the relationship between the consequence and all the factors influencing the consequence.

Constructing a diagram consists of following steps:
1. Identifying the consequence (problem) - e.g. the spread of an oil slick
2. Identification of the cause - e.g. horizontal shear, surface tension, vertical movement,
3. Identification of other factors that affect the occurrence of the cause – e.g. temperature, salinity, generating forces, etc.
The identification of other factors influencing the occurrence of causes is most easily carried out by a series of question “Why?”. Making such a diagram is in itself of an educational nature, because through making it one can learn numerous specificities, i.e. the causes of the problem. Based on this diagram, various possible causes can be examined, confirmed or ruled out, with the purpose of concentrating on the severity of certain causes, thus is helpful tool for both the diagram maker and the reader. The main disadvantage of diagrams is that, when it comes to a complex problem which has many possible causes and sub-causes, the diagram is opaque and cumbersome. However, the application of this diagram is very good when it comes to complex systems, because it provides very useful visualization of complex systems making it more understandable.

**Figure 1** Ishikawa diagram

Main causes (level 1 causes) of oil slick spread in the sea are horizontal shear, vertical expansion and tension force each of which is formed by sub-causes (level 2 causes). Horizontal shear is build up by generating forces, geostrophic currents and friction force; Vertical expansion is composed of diffusion, Coriolis force, buoyancy forces and vertical changes in density; and sub-causes of the Tension force are temperature, strength of attractive forces and nature of matter. According to Ishikawa, the least effect is caused by the horizontal shear.

Sub-causes (level 2) of Vertical expansion also have their sub-causes (level 3), hence diffusion depends on temperature, pressure, density and concentration gradient, while Coriolis force depends on geographic latitude and the speed of the Earth’s rotation.

Although, Horizontal shear (level 1 cause) has only three sub-causes (level 2), each of them has their own sub-causes (level 3) consist of their own sub-causes (level 4) and so on. Gradient currents depend on sea density, air density and sea level; tidal forces depend on centrifugal force and gravity; and wind currents depend on Coriolis force (which depends on geographic latitude and the speed of the Earth’s rotation – a level 5 sub-causes) and friction forces-wind tension (dependent on wind vector, air density...
and drag coefficient – also a level 5 sub-causes). Therefore, Ishikawa diagram is often used also to detect attainable elements that could reverse or stop the process.

4. Conclusion

As shown above, the main spread causes of the oil slick spread shown by the Ishikawa diagram are Tension force, Vertical expansion and Horizontal shear. Effects of wind energy, tides and surface tension are also recorded in the Ishikawa subsystems. Since the most common cause (sub-cause) affecting the oil slick spread – Coriolis force caused by the Earth’s latitude and rotation speed – is unchangeable, diagram analysis suggests to put more efforts toward causes that could be locally altered by deliberate action, such as temperature, pressure and the composition of the slick.

5. References

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