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A method for the approximation of oil binder fall trajectory

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Abstract

The following paper presents a novel method for approximating the fall trajectories of small, lightweight oil binders, used during oil spill clean-up operation at sea. Due to the weight, size and shape of the binders, the fall trajectory is highly dependent on the direction and strength of the wind, as well as the rotations and positions of individual binders when dropped. Since a large quantity of tightly packed binders are dropped at once, it is highly inconvenient to calculate the precise trajectory of each binder when its exact initial rotation and position inside the container are not known. The aim of this study is to predict the exact moment and position of the drop, as well as the oil binders' spread, considering wind conditions, airplane velocity and height.

Introduction

Oil spills pose a threat to society and the environment in all parts of the world and the current state of marine technology for oil spill control is mostly based on mechanical or chemical treatment of oil spills. The BioBind project, which started in 2011 and lasted for 3 years, aimed to develop a fast oil spill response system with good performance even in high sea state conditions, using biodegradable, wood-fibre based oil binders (Unbehaun et al., 2014). As a result, a system for fighting oil spills was proposed (Figure 1). This system consists of:

- low-cost airborne analysis and monitoring of the oil spill and oil binders;
- biogenic and biodegradable oil binders in combination with oil degrading microorganisms;
- airborne deployment of oil binders;
- seaborne recovery of oil binders with a netboom;
- onshore recovery of oil binders with vacuum technology;
- sea state forecast and drift modelling (Baltic Sea & North Sea).

One of the problems not solved during the BioBind project is prediction of the movement of oil binders during the drop phase and on the water surface. A mathematical model that takes into account wind force and direction, velocity of the airplane and surface current is required to precisely establish the time and position of the drop as well as the size and location of the oil binder cluster after a given time. The following paper focuses on modelling the fall trajectories of oil binders from the moment of drop from the airplane to the moment of contact with the water surface. Further work will focus on modelling the behaviour of oil binders on the water surface for given wind and surface current conditions.

Assumptions

One of the main goals of the BioBind project was to develop an oil binder based on biogenic and biodegradable material. The resulting oil binder is a small, square pad made from wood fibres with dimensions of 5 cm × 5 cm × 0.4 cm and a density ranging from 250 to 280 kg·m^{-3} (Figure 2). The motion of such bodies has been shown to display a chaotic nature (Auguste, Magnaudet & Fabre, 2013), influenced heavily by the Reynolds number, calculated as $R = Ud/\nu$, where U is the mean vertical

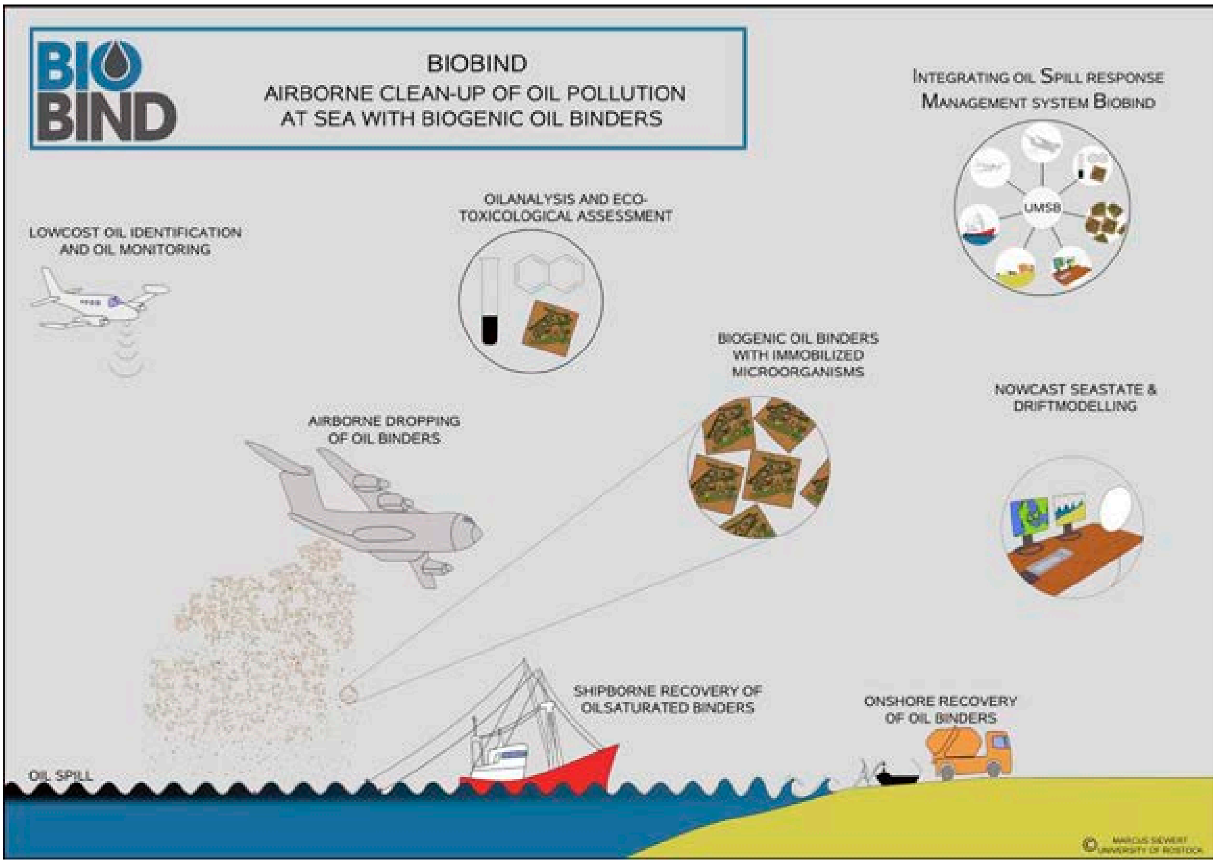

Figure 1. Diagram detailing the airborne clean-up of oil pollution proposed in the BioBind project (Siewert, Powilleit & Saathoff, 2014)

Figure 2. Wood-fibre based oil binder

disk velocity, d – its diameter and ν – the kinematic viscosity of the fluid/air. It has been shown that this apparently complex behaviour can be reduced to a series of one-dimensional maps, which display a discontinuity at the crossover from periodic to chaotic motion (Field et al., 1997). This, however, was observed for Newtonian fluids and without any external disturbance, hence such an approach could not be applied in our research since a single oil binder pad is highly influenced by the wind during its drop phase. Martin et al. (Martin, Umetani & Bickel, 2015) proposed a data-driven pipeline to model and acquire the aerodynamics of three-dimensional rigid objects, including aerodynamic forces, such as drag and lift, for any incoming wind direction using a novel representation based on spherical harmonics. This technique acquires the aerodynamic properties of an object simply by capturing its falling motion using a single camera. Such an approach is valid for a single object and a given wind strength and direction; however, during oil spill clean-up, thousands of oil binders are dropped from a plane. This cluster of oil binders disturbs the wind flow, hence it is invalid to assume the same wind strength and direction for each single oil binder in the cluster.

Taking the above into consideration, the authors decided to model the spread of the oil binder cluster based on empirical data from experimentation. The research focused on two main factors that can influence the oil binder's drop trajectory, namely:

1. Airplane velocity, which is, at the same time, the initial horizontal (parallel to the sea's surface) velocity of the oil binder;
2. Wind strength and direction.

Method

The proposed method allows for calculation of the coordinates from where the oil binders should be dropped. The results were determined on the basis of the predicted fall trajectories of oil binders with consideration of the different initial conditions. Factors, potentially influencing fall trajectory, considered in the analysis were:

- horizontal speed of the airplane;
- wind speed and direction;
- height of the drop.

Relationships describing the influence of the identified parameters were established on the basis of experimentation which was carried out in two steps. In the first step, the influence of the initial horizontal speed was examined; in the second step, wind speed and direction were concerned. The height of the drop was taken into consideration in both steps.

To examine the influence of the initial horizontal speed on the fall trajectory, a dedicated measuring system was built. It consisted of an original device capable of giving the binders' initial speed; a slow motion video camera and reference line allow for initial speed calculation. The binder-firing device is a kind of slingshot with a horizontally aligned barrel that can shoot oil binders with different applied force, the height of the barrel can also be adjusted according to research assumptions. To assess the relationships between initial speed, height and fall trajectories, trials were carried out with different initial conditions (initial speed and height). A schematic of the measuring system used in the experiment is presented in Figure 3. The precise initial speed and fall trajectory were determined on the basis of the analysis of the slow-motion records from the video camera. The distance the oil binders fell to the ground was measured with a tape.

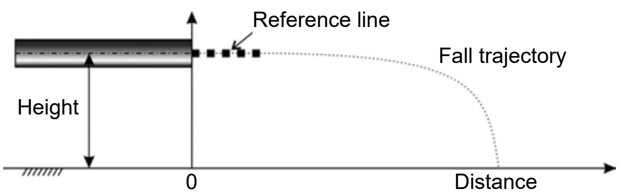

Figure 3. Scheme of initial horizontal speed influence measuring system

The second step of the experiment deals with assessing the influence of external conditions on the fall trajectory of the oil binders. On the basis of observation and specifics of the free fall phenomenon, it was assumed that the direction of the fall is in line with the wind direction. To determine the relationship between wind strength, drop height and fall trajectory, an experiment was carried out. During the experiment, binders were dropped from a height (Figure 4) at different wind speeds measured at

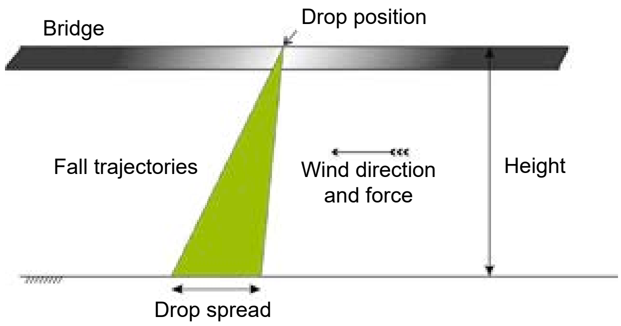

Figure 4. Scheme of experiment for wind force and height of drop influence assessment

two heights (at drop height and ca. 2 m above the ground level). The fall trajectories of the binders were determined on the basis of recordings from two perpendicular video-cameras. Additionally, the maximum spread of the oil binders was measured on the ground. The results of the second part of the experiment allow for assessment of the position and spread of the drop for different heights and wind speeds.

Results

The results of measurements taken while dropping oil binders at a certain initial horizontal speed are presented in Table 1. The initial speed calculations showed an average speed equal to 9.25 mps ± 2.70 mps. The observed distance for three different heights of drop are shown in Figure 5.

To evaluate the influence of the initial speed of the oil binders on the distance covered by a binder, Pearson correlation coefficients (PCC) were calculated for 105 cm and 210 cm drop height. The achieved results (PCC = 0.35 for 105 cm and PCC = 0.05 for 210 cm) show that it can be assumed that because of the light weight of the binders and the high air resistance, the initial speed does not influence the distance covered by an oil binder significantly. Further research concerning larger samples and higher initial speeds should be carried out to confirm this assumption.

Table 1. The results of measurements of the distance (*x*) for various initial speeds (*v*) and drop heights (*y*)

Shot No.	1	2	3	4	5	6	7	8	9	10	11	12
v [m/s]	5	5	5	6	6	6	8	8	8	9	9	10
y [cm]	105	105	105	210	210	210	162	162	178	105	105	105
x [cm]	250	325	355	530	575	600	265	270	300	410	415	250

Shot No.	13	14	15	16	17	18	19	20	21	22	23
v [m/s]	10	10	12	12	12	12	12	12	12	12	12
y [cm]	105	105	105	105	105	210	210	210	210	162	162
x [cm]	305	320	255	440	590	450	745	750	380	270	275

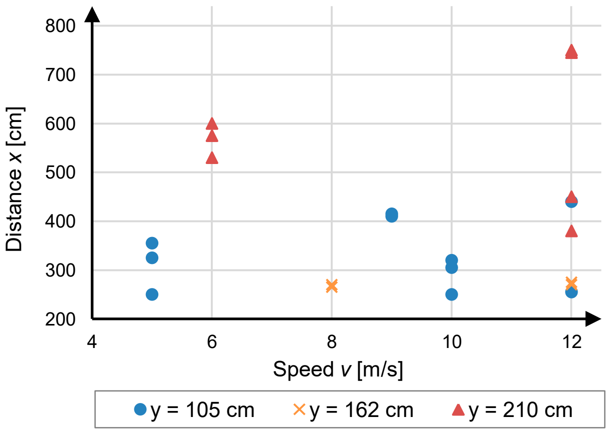

Figure 5. Distance (*x*) in relation to the initial speed (*v*) and height of drop (*y*)

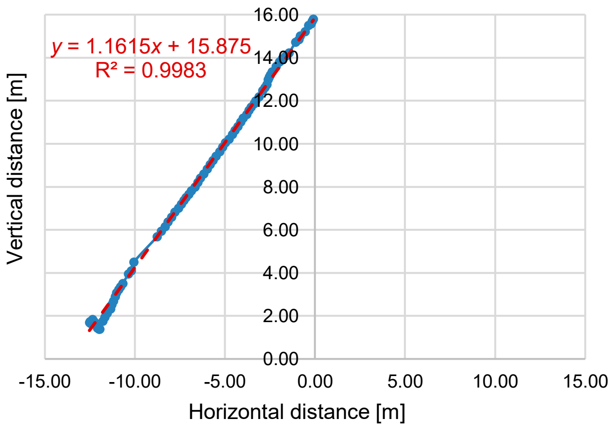

Figure 6. The fall trajectory of an individual oil binder pad at the constant speed of wind of about 1.5 mps

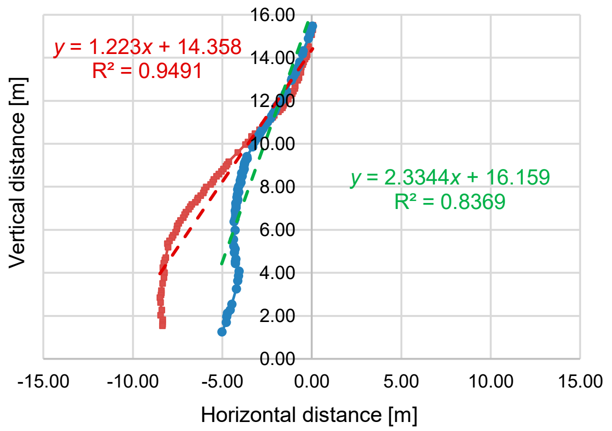

Figure 7. The fall trajectories of two extreme oil binder pads (with regards to the final spread on the ground) for constant wind speed of about 1 mps

The next step was to drop individual oil binder pads and to analyse their fall trajectory on the basis of a frame by frame video analysis. Analysis of the relationship between initial drop height and vertical distance travelled, at a constant wind speed of about 1.5 mps (Figure 6), shows that this relationship is approximately linear.

In the last stage of the experiment, 20 to 100 oil binder pads were dropped at various wind speeds. Two extreme situations for constant wind speed (Figure 7) and for variable wind speed (Figure 8) are shown.

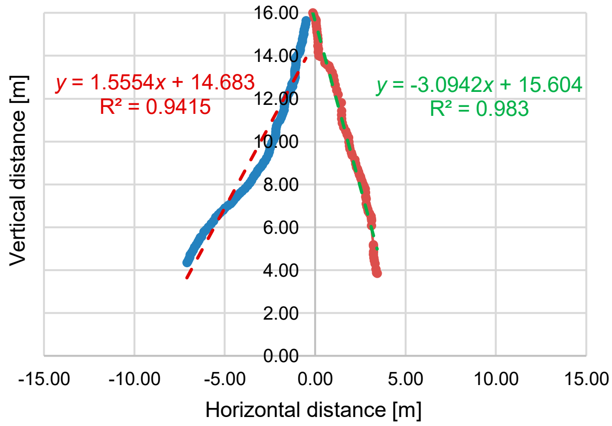

Figure 8. The fall trajectories of two extreme oil binder pads (with regards to final spread on the ground) for variable wind speeds of 1–4 mps

Conclusions

The main goal of this research, for which preliminary results are presented, was to develop an easy to use, simplified model that enables prediction of actual and future positions of a large number of oil binders dropped from a plane and an evaluation of the position from where these oil binders should be dropped to reach a given location in a given time. The goal of the research and the large number of oil binders required the use of empirical data from experimentation instead of a theoretical description of the falling trajectories of individual oil binders.

The results of the research showed that the fall trajectory of oil binder pads may be approximated to be a linear function, the shape of whose exact plot depends on wind speed and direction as well as on the speed and the direction of the individual oil binder pad rotations. Such rotation is of a random character and depends on the initial conditions of the drop, including the position of an individual oil binder pad, the number of and the force of deflection from other oil binder pads in the area. It can be assumed that the fall trajectory does not depend on the initial speed; this result however, is only valid for the presented initial speeds and drop heights. Further research is required to validate this finding for conditions representing oil spill clean-up operations more closely. The horizontal distance travelled by the oil binders during their fall depends more on their initial orientation than on their initial horizontal speed. Oil binders which take off horizontally have a significant rotational speed in the vertical axis, so they fly the longest distance.

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