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# 2 Novel Application of Laboratory 3 Instrumentation Characterizes Mass Settling 4 Dynamics of Oil-Mineral Aggregates (OMAs) 5 and Oil-Mineral-Microbial Interactions

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## 39 ABSTRACT

40 It is reasonable to assume that microbes played an important role in determining  
41 the eventual fate of oil spilled during the 2010 *Deepwater Horizon* disaster, given  
42 that microbial activities in the Gulf of Mexico are significant and diverse. However,  
43 critical gaps exist in our knowledge of how microbes influence the biodegradation  
44 and accumulation of petroleum in the water column and in marine sediments of the  
45 deep ocean and the shelf. Ultimately, this limited understanding impedes the ability to  
46 forecast the fate of future oil spills, specifically the capacity of numerical models to  
47 simulate the transport and fate of petroleum under a variety of conditions and regimes.

48 By synthesizing recent model developments and results from field- and laboratory-  
49 based microbial studies, the Consortium for Simulation of Oil-Microbial Interactions  
50 in the Ocean (CSOMIO) investigates (a) how microbial biodegradation influences  
51 accumulation of petroleum in the water column and in marine sediments and  
52 (b) how biodegradation can be influenced by environmental conditions and impact  
53 forecasts of potential future oil spills.

54 **Keywords:**

## 23 Laboratory Flocculation 24 Experiments

25 **C**ritical to oil-mineral-microbial  
26 interactions is a process whereby cohe-  
27 sive sediment particles do not behave  
28 as individual, dispersed particles but  
29 instead tend to stick together. This  
30 process is known as flocculation, and  
31 the resultant floc sizes and settling  
32 velocity are much greater than those  
33 of the individual constituent parti-  
34 cles, but their overall floc effective  
35 density is less (e.g., Dyer & Manning,  
36 1999; Manning & Dyer, 1999).  
37 When oil droplets are contained by  
38 flocs of cohesive sediment and/or

55 marine snows, oil sedimentation can  
56 occur and provide an unexpected  
57 pathway in the oil budget calculation  
58 (Daly et al., 2016; Muschenheim &  
59 Lee, 2002; Passow & Ziervogel,  
60 2016). A novel high-resolution floc  
61 video instrument originally designed  
62 to determine the spectral characteris-  
63 tics of flocculating cohesive sediments  
64 has, for the first time, been applied to  
65 study floc size distribution and set-  
66 tling dynamics of oil-mineral aggre-  
67 gates (OMAs). The results of this  
68 study inform the development of  
69 efficient and accurate algorithms for  
70 simulating the formation and settling  
71 of these flocs.

72 As part of the Consortium for  
73 Simulation of Oil-Microbial Inter-  
74 actions in the Ocean (CSOMIO), a  
75 series of laboratory flocculation exper-  
76 iments with seawater, crude oil, and  
77 cohesive sediment mixtures (mineral  
78 clay and artificial extracellular poly-  
79 meric substances) have been conducted  
80 at the Center for Applied Coastal Re-  
81 search, University of Delaware, using  
82 the LabSFLOC-2 (the second genera-  
83 tion of the LabSFLOC [Laboratory  
84 Spectral Flocculation Characteristics  
85 instrument; Manning, 2015], devel-  
86 oped by Manning, 2006). In these  
87 experiments, the LabSFLOC-2 instru-  
88 ment, a digital video microscope and

Q1

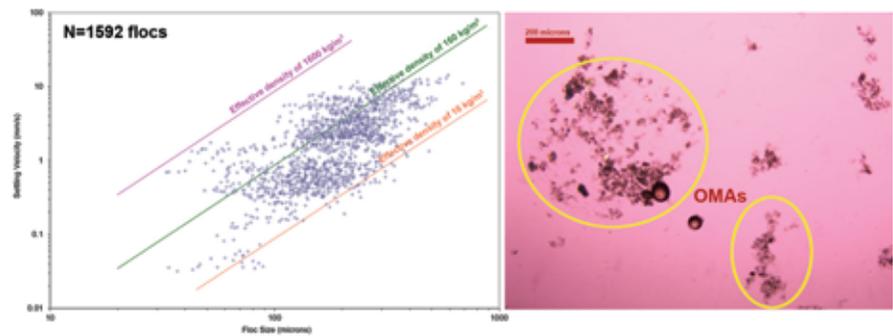
89 processing package, makes it possible to  
 90 obtain high-quality floc population  
 91 data (e.g., individual floc size, settling  
 92 velocity, density, mass), as well as sup-  
 93plementary individual floc information  
 94 including floc porosity, floc mass, frac-  
 95tural dimension, floc shape, and mass  
 96 settling flux. Manning et al. (2010)  
 97 and Manning et al. (2017) provide  
 98 further details of the floc acquisition  
 99 procedures and postprocessing compu-  
 100tations, respectively. LabSFLOC-2  
 101 provides data for many important as-  
 102pects of flocculation. These floc data  
 103 are necessary to comprehensively assess  
 104 and characterize oil-mineral-microbial  
 105 settling dynamics and to improve the  
 106 parameterization (Manning & Dyer,  
 107 2007; Soulsby et al., 2013) and calibra-  
 108tion (Baugh & Manning, 2007) of  
 109 numerical models. Additionally, the  
 110 digital microscope images help us better  
 111 understand the visible floc structure of  
 112 OMAs.

## 113 Laboratory Experiments 114 Utilizing the 115 LabSFLOC-2 Instrument

116 Mass settling dynamics of oil-  
 117 mineral flocs are observed using the  
 118 LabSFLOC-2 system (Figure 1),  
 119 which measures an entire floc popula-  
 120tion for each sample being assessed.  
 121 LabSFLOC-2 utilizes a low intrusive  
 122 2.0-MP Grasshopper monochrome  
 123 digital video camera to optically ob-  
 124serve individual flocs (e.g., Manning  
 125 & Dyer, 2002) as they settle in a  
 126 350 mm high  $\times$  100 mm square  
 127 Perspex settling column. The video  
 128 camera, positioned nominally 75 mm  
 129 above the base of the column, views  
 130 all particles in the center of the column  
 131 that pass within a 1-mm depth of field,  
 132 45 mm from the Sill TZM 1560 high-  
 133 magnification (nominal 5- $\mu$ m pixel  
 134 resolution) telecentric (maximum

## FIGURE 1

The LabSFLOC-2 setup on the desk beside the stir jar system for real-time samplings (photo provided by Prof. A. J. Manning).



135 pixel distortion of 0.6%), 0.66 (1:1.5)  
 136 magnification, F4, macro lens.

137 A suspension containing oil-mineral-  
 138 microbial flocs is initially introduced  
 139 to the LabSFLOC-2 column, while a  
 140 suspension is extracted from the  
 141 jar fluid using a specially modified  
 142 Serological TD-EX 20°C 50-ml  
 143 maximum-capacity sterile pipette.  
 144 This process has proved to be mini-  
 145mally intrusive for flocs, relying only  
 146 upon settling due to gravity and thus  
 147 avoiding the need for additional  
 148 fluid or turbulence transfer. The  
 149 LabSFLOC-2 instrumentation is  
 150 located close and adjacent to the stir  
 151 jar system, as this minimizes the time  
 152 needed to transfer floc samples to the  
 153 LabSFLOC-2 settling chamber and  
 154 any potential disruption during the  
 155 subsequent floc settling process.

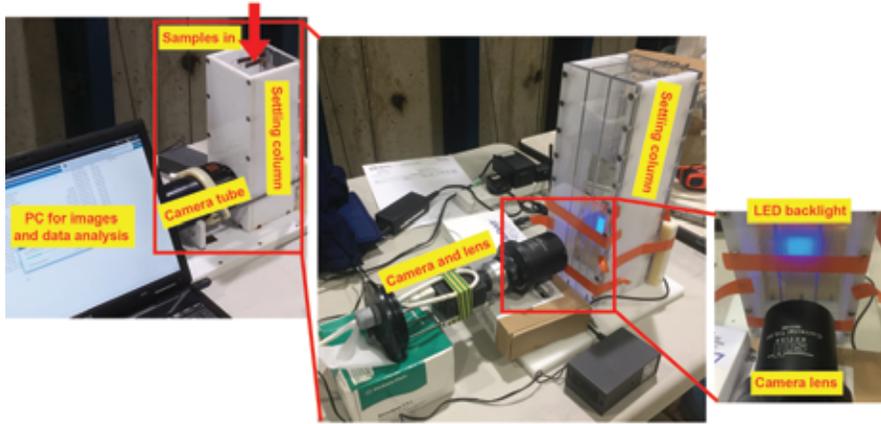
156 The camera views through an aper-  
 157 ture in the settling column wall at a  
 158 depth of 230 mm below the column  
 159 water surface. It records all settling  
 160 flocs/particles in the center of the  
 161 column, which pass within a 1-mm  
 162 focal depth of field, 45 mm (focal  
 163 length) from the camera lens. The  
 164 total image size is nominally 6 mm  
 165 high and 8 mm wide. During sam-  
 166 pling, a pipette is filled to produce a  
 167 fluid head of 50 mm, which results in

168 a video image control sample volume  
 169 nominally of 400 mm<sup>3</sup> (1-mm image  
 170 depth and 6-mm nominal video  
 171 image width, with a nominal 50-mm  
 172 high suspension extracted with a mod-  
 173 ified pipette). This control volume  
 174 permits the LabSFLOC-2 calculated  
 175 total floc mass to be accurately mass-  
 176 balanced with the nominal suspended  
 177 particulate matter concentration uti-  
 178 lized in the jar test under examination.  
 179 The LabSFLOC-2 camera can view  
 180 particles as small as 5  $\mu$ m and as large  
 181 as 8 mm. Settling velocities ranging  
 182 from 0.01 to 45 mm·s<sup>-1</sup> can be mea-  
 183 sured by the LabSFLOC-2, and the  
 184 system can operate within floc sus-  
 185 pended particulate matter concentra-  
 186 tions of a few milligrams per liter,  
 187 with a practical upper operating limit  
 188 of ~200 g·l<sup>-1</sup>.

189 Settling flocs are viewed as silhou-  
 190 ettes (to reduce image smearing) result-  
 191 ing from a 43  $\times$  35 mm, homogeneous  
 192 blue (470 nm), back-illumination  
 193 LED panel located at the rear of the  
 194 settling column. The digital floc im-  
 195 ages are captured as non-Codec com-  
 196 pressed AVI files at a frame rate of  
 197 7.5 Hz (one frame is 0.04 s), at a reso-  
 198 lution of 1,600  $\times$  1,200 pixels, with an  
 199 individual pixel nominally represent-  
 200 ing 5  $\mu$ m (confirmed by independent

## FIGURE 2

Sample from an oil-bentonite case. The left plot shows the floc size and settling velocity scatters of each calculated floc. The three diagonal lines present contours of Stokes settling velocity calculated with a constant effective density (i.e., floc bulk density minus water density): pink =  $1,600 \text{ kg}\cdot\text{m}^{-3}$  (equivalent to a quartz particle), green =  $160 \text{ kg}\cdot\text{m}^{-3}$ , and red =  $16 \text{ kg}\cdot\text{m}^{-3}$ . The right image is the generated OMAs as seen by the digital microscope camera (approximately  $\times 40$ ).



calibration), connected and streamed to a laptop PC, and recorded on the internal hard drive.

The present system not only produces visible floc individual images (e.g., Figure 2, right) but also reveals all other essential quantitative floc properties. The uncompressed images are then analyzed with MATLAB software routines. During postprocessing, the HR Wallingford Ltd. DigiFloc software version 1.0 (Benson & Manning, 2013) and JavaScript can be used to semiautomatically process the digital recording image stack to obtain floc size and settling velocity spectra (e.g., Figure 2, left for oil-bentonite flocs). A modified version of Stokes' law (Stokes, 1851) permits an accurate estimate of individual floc effective density (Manning et al., 2013), which can then be utilized to calculate floc mass. In the oil-bentonite sample, resultant floc sizes (nominally mass-balanced to a suspended particulate matter concentration of  $1,000\text{-mg}\cdot\text{l}^{-1}$  bentonite and 1 ml of Texas crude oil) ranged between

## Summary

In the first attempt to apply the LabSFLOC-2 system in an oil-mineral flocculation study, we have combined state-of-the-art technologies/instruments in order to expand our knowledge of oil-sediment-microbial interactions and the vertical transport of oil. The preliminary laboratory experiments demonstrate that these systems can be used to produce and characterize mass settling dynamics of OMAs. Future experiments will use different oil, sediment, and microbial characteristics and turbulence levels. Statistical data on settling dynamics provided by LabSFLOC-2 will allow for a systematic analysis of the role that each factor plays in determining the resultant settling dynamics. Mov-

ing forward, these technologies have the potential for applications to a carefully designed test matrix in order to calibrate a given modeling framework for oil-sediment-microbial interactions.

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