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Simulating dispersion of oils from a subsea release comparing mechanical and chemically enhanced dispersion — An experimental study of the influence of oil properties

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ABSTRACT

The main objective with subsea mechanical dispersion (SSMD) is to influence the fate of an oil spill in the marine environment by significantly reducing oil droplet sizes from subsea release of oil. Earlier studies have indicated that the capability of SSMD to reduce oil droplet sizes is comparable to subsea dispersant injection (SSDI).

Earlier testing of SSMD has mainly used a low viscus paraffinic oil. Focus for this study was to study SSMD and SSDI effectiveness using five oil types spanning out a wide variation of relevant oil properties. Effectiveness was quantified as the reduction in oil droplet sizes measured by a Silhouette camera. Testing of the two technologies were completed in the same experiment on a simulated subsea release.

The results show a variation in effectiveness for both technologies as a function of oil properties. SSMD and SSDI showed comparable effectiveness for all oils tested.

1. Introduction

The background for this paper is research exploring the potential of using mechanical devices for creating dispersions of oil in response to a subsea oil and gas release. This response option is called subsea mechanical dispersion (SSMD) and the main objective is to reduce the oil droplet sizes from a subsea oil release, thereby influencing the fate and behaviour of the released oil in the marine environment.

The technology presented in this paper is a product of an extensive R&D program (2012–2020) and the initial feasibility study was initiated by BP as a post Deep Water Horizon (DWH-2010) oil spill activity in 2012 focusing on screening possible technologies for SSMD. The following three technologies were tested as a part of the initial feasibility study (Davies et al., 2015; Brandvik et al., 2016):

1. Mechanical shear (an industry high-speed mixer marinised for tank testing),
2. Ultrasonication (a marinised industry probe)
3. Water jetting (performed by pumps, hoses, and nozzles)

Both small-scale laboratory testing, and modelling indicated high effectiveness using water jetting for SSMD. This together with the equipment survey pointing at water jetting as an operationally viable method motivated further work on this technology. In the case of water jetting, subsea pumps, short hoses, and suitable nozzles were used to direct a water jet of ambient sea water towards the released oil to enhance the droplet breakup in the oil jet. If the momentum flux of the water jet is completely entrained in the oil jet, the momentum flux in the new combined oil and water flow will be increased causing an enhanced droplet breakup. For this enhanced breakup to be successful and produce significantly smaller droplets the energy in the water jet has to be sufficiently high and operational factors like treatment location (relative to the release) and alignment of nozzles has to be optimal.

An important part of the initial feasibility study was to study possible differences in coalescence between chemically enhanced dispersions (SSDI) and mechanically generated dispersions (SSMD). An extensive study was performed using a large experimental tower basin (6 m high, 3 m in diameter, containing 43,000 l of natural sea water) with a factorial design contained 8 settling experiments varying oil droplet size (250 and 25 µm), concentration (400 and 20 ppm) and finally dispersion type (SSMD and SSDI). In each experiment oil droplets were monitored in two different heights in the six meter high tower basin for 3–5 days. A

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small increase in coalescence for the mechanically generated droplets was only observed for the small droplets (25 μm), high concentration (400 ppm) experiment. These experiments are only representative for conditions very close to the subsea release where the distances between the droplets are small and was not identified as a limiting factor for further development of the SSMD technology (Davies et al., 2015). This large dataset is now being analysed in more detail and the experimental data are compared against modelling of rise velocities and coalescence and will be published as a separate paper.

Exploring the effect of different nozzle types, water jetting rates, alignment, and treatment positions relative to the oil release were also a part of this research program. Experiments were performed at different scales and also with combined releases of oil and gas in a pressurised tank. The program also included large-scale testing at the Ohmsett facility to verify the main findings from the small- and medium-scale laboratory testing. A summary description of the different phases of this research program and the main findings regarding SSMD effectiveness can be found in Brandvik et al. (2021b, 2023).

The energy from a water jet was already studied in the early 1980s to enhance dispersion of surface oil slicks, often in connection with using dispersant under calm sea condition to add extra energy (Belore, 1987). This concept was followed up in the next decades with focus on how to utilise the effect of cavitating jets (Kato, 2001) and different devices to increase the shear forces between the water jet and the surface oil (Kato et al., 2006). However, it proved challenging to break and mechanically disperse emulsified, and viscous oil slicks with the energy available in water jets. However, the energy is sufficient to disperse the warm and low viscosity oil from a subsea release. SSMD could also benefit from the concentrated release and the high turbulence already available, similar to SSDI. The authors have not been able to find earlier studies focusing on mechanical devices to disperse subsea releases of oil.

Using subsea dispersant injection (SSDI) to reduce oil droplet sizes from a subsea oil release is a well proven technology with a documented ability to reduce oil droplet sizes and thereby influence volume and distribution of the resulting surface oil. Unfortunately, no systematic oil droplet data were obtained during the DWH-2010 oil spill, but both remote sensing data showing reduced occurrence of surface oil during SSDI (MacDonald et al., 2015; Svejkovsky et al., 2023) and analysis of air monitoring data from response vessels showing reduced airborne VOC (Zhao et al., 2021) are strong indirect proof of high SSDI effectiveness. Laboratory- and modelling studies focusing on the conditions during DWH-2010 indicate a high SSDI effectiveness (Aprin et al., 2015, Socolofsky et al., 2015, Testa et al., 2016, NASEM, 2019, Cooper et al., 2021, Brandvik et al., 2021a).

An alternative response technique like SSMD could be beneficial in some situations, for example due to regional legislation limiting the use of SSDI or in release scenarios with very low release velocities where low SSDI effectiveness is expected due to insufficient turbulence for both dispersant-oil mixing and droplet break-up. There is also a significant operational advantage to avoid transporting large quantities of chemical dispersants to an often remote offshore spill site. The total amount of chemical dispersant injected subsurface during DWH-2010 was estimated to 3000 m^3 (Lehr et al., 2010). Dispersant availability could also be a limiting factor in some large-scale scenarios, especially since one of the major producers earlier this year terminated their dispersant production line (Nalco, 2023).

The research to develop the technology and document SSMD effectiveness have so far focused on low viscosity oils, with testing performed with a light paraffinic crude (Oseberg Blend). The viscosity for this oil at the most used test temperatures (8–12 °C) has been approximately 10 mPa•s (or cP) measured at a shear rate of 10 s^{-1}. The justification for using a single oil has been that this oil is a representative oil type for a large flowrate subsea blow-out scenario. However, we expect that SSMD effectiveness will vary with varying oil properties, in a similar manner as earlier observed with SSDI (Belore, 2014; Brandvik et al., 2018; Brandvik et al., 2019a).

Similar to SSDI the effectiveness of SSMD is determined by a reduction in oil droplet sizes. Since experiments in different laboratory settings generate a wide range of oil droplet sizes a relative measure called the d_{50}-ratio (d_{50}-untreated/d_{50}-treated) is used to quantify the effectiveness.

The work presented in this paper has focus on SSMD effectiveness on a broad selection of oil types. Five different oil types have been selected to span a wide variation of relevant and important oil properties (viscosity, interfacial tension, pour point, density, content of asphaltenes and waxes).

To ease the interpretation of the variations in SSMD effectiveness as a function of oil properties we also included testing of SSDI effectiveness on the same oil types with three different commercially available and globally stockpiled dispersants (Corexit 9500, Finasol OSR-52 and Dasic Slicgone NS). The dispersants were tested using the same experimental setup and conditions (oil release rates and oil droplet quantification) as used for the SSMD experiments.

2. Experimental

Experiments are performed at a medium-scale basin facility at SINTEF Ocean, Trondheim, Norway. This facility identified as “SINTEF Wave basin” has also earlier been used to study SSMD effectiveness. A summary description of the facility and further details might be found in an earlier paper describing similar experiments (Brandvik et al., 2023).

2.1. SINTEF wave basin

This basin is a 14-m long wave basin or flume comprised of stainless steel with large glass windows on both sides. The flume is 0.5 m wide, 10 m long and 2 m deep with a “double bottom” to facilitate circulation. During experiments, sea water was filled to 1.5 m above the bottom (or 1 m above the “double bottom”), which corresponds approximately to 11 m^3 of seawater. In the lower compartment (“double bottom”) propellers are installed to provide circulation within the basin. This usually give 5–6 min of continuous experimental time, with a clean water background, before small oil droplets start to recirculate in the system, see Fig. 2.1. Further details can be found in Supplemental information Fig. S.1, Fig. S.2 in the and in Brandvik et al., 2023.

Fig. 2.2 shows the setup of the experiments in more detail. Both the system for water jetting (SSMD) and for dispersant injection (SSDI) are shown. SSMD effectiveness was dependent on water jetting nozzle alignment, distances above and between water jetting nozzle and oil release nozzle. Experience from earlier studies and from initial experiments in this study identified the following optimal conditions: The water nozzle was positioned 10 oil release diameters (D_{oil}) above the oil release nozzle with a distance to the center of the oil release of $3D_{oil}$.

Performing down-scaled experiments in a laboratory, trying to simulate full-scale processes can be challenging. In these laboratory experiments, scaling from field conditions was done by using the release diameter for the oil (D_{oil}) as a scaling factor. The “distances” referred to in Fig. 2.2 are relative to an oil nozzle diameter of 5 mm. Close to the release opening, in the jet zone of the release, this scaling approach was regarded to be highly relevant. Higher above the release, where a plume behaviour dominates, other scaling approaches could probably be more relevant (Papanicolaou and List, 1988).

To evaluate the optimum height or vertical distance for the water jetting above the oil release a series of experiments were performed. The optimum height based on the d_{50} of the dispersed oil droplets was determined to 10 D_{oil}. This is probably also dependant on the type, configuration and number of water jetting nozzles. It was challenging for the water jet to cover the entire radius or width of the oil plume if the nozzle was located too high above the release, while a position too close to the oil nozzle probably missed the advantage of a primary oil droplet formation taking place higher above the nozzle.

A series of experiments were also performed to optimise the

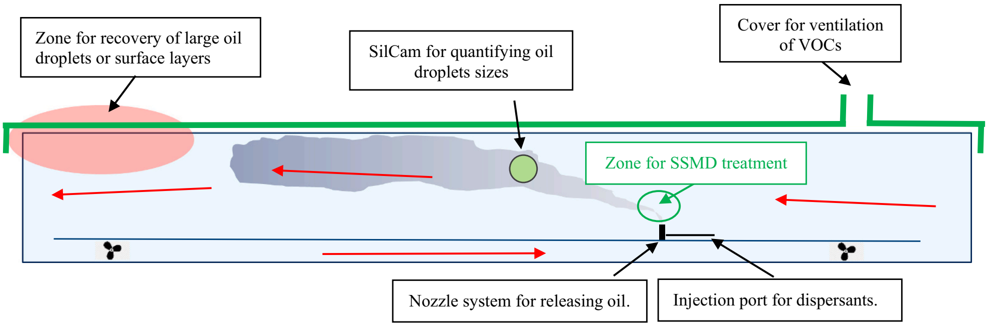


Fig. 2.1. Principal sketch of how the wave basin was used to simulate oil droplet formation from a subsea release and quantify effectiveness of SSDI and SSMD.

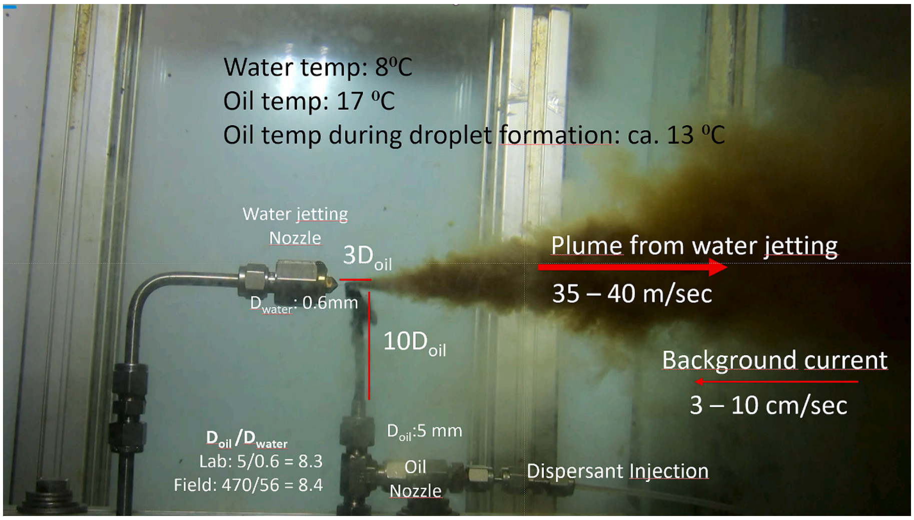


Fig. 2.2. Basic setup for testing in SINTEF Wave basin showing the oil release nozzle, the water jetting nozzle and the dispersant injection tube. The distance measures are given in D_{oil}.

horizontal distance from the water jetting nozzle and the centre of the rising oil jet or plume. The kinetic energy or turbulent dissipation rate of the water jet is reduces with the distance from the nozzle (z) with a power of four $(z/D_{water})^{-4}$ so increasing the distance is not favourable (Or et al., 2011). On the other side we need a certain width of the water jet to cover the radius of the rising oil plume. Experiments showed that for the used round single nozzle a distance of $3D_{oil}$ was optimal.

The dispersants were injected into the oil stream 6 D_{oil} before the outlet of the oil release nozzle, see Fig. 2.2. Earlier projects have identified this as the most effective injection method called simulated injection tool (SIT), see Brandvik et al., 2018. This simulates dispersant injection with a 2–3 m long tube inserted down into the opening of the oil release, for example a blow-out prevented (BOP).

In an experimental system like shown in Fig. 2.1 with a horizontal plume of oil droplets, separation based on differences in oil droplet size and rise velocities, can be an experimental challenge. The background current was adjusted so representative parts of the plume was monitored by the stationary SilCam (see Fig. 2.1). The challenge is larger with plumes from untreated oil due to larger differences in oil droplet sizes and rise velocities. The separation is significantly lower for oil plumes after treatment (SSDI or SSMD) due to reduced oil droplet size and their reduced span in rise velocities relative to the higher internal turbulence in the plume, see also Figs. S.2, S.3 and S.4.

The experimental conditions for both types of experiments (SSMD/SSDI) are listed in Table 2.1.

Table 2.1
Experimental conditions for SSMD and SSDI experiments.

Parameter	Values/range
Oil release nozzle size (D_{oil})	5 mm
Oil flow rate	1.3 l/min
Oil release velocity	1.1 m/s
Water nozzle size (D_{water})	0.6 mm
Expected untreated oil droplet sizes[1]	5–8 mm (d_{50})
Nozzle position	Single horizontal, 10 D_{oil} above oil release
Water jetting range	45–55 % (of oil release rate)
Water jetting velocities[2]	35–40 m/s
Expected SSMD/SSDI oil droplet size range[3]	0.100–0.800 mm (d_{50})
Oil types	Five different oil types (see Table 2.3)
Dispersants tested (SSDI)	Corexit 9500A, Finasol OSR-52 and Dasic Slickgone NS
Dispersant injection[4]	Simulated insertion tool (1 %)

[1] Based on modified Weber scaling (Johansen et al., 2013).

[2] Water jetting velocity is higher than the velocity where cavitation could be initiated. However, large scale experiments at Ohmsett indicate that the influence from cavitation (additional droplet splitting) on SSMD effectiveness is very low (see Brandvik et al., 2023).

[3] Based on earlier experiments with Oseberg blend (Brandvik et al., 2021b, 2023).

[4] Dispersant injection, simulated insertion tool — SIT (Brandvik et al., 2018).

2.2. Scaling between lab experiments and full-scale conditions

In this study we focused on using oil droplet sizes for untreated oil, representative for a low velocity blow-out (similar to DWH-2010), and keeping the relationship between the oil release diameter (D_{oil}) and water jetting nozzles (D_{water}) similar to a full-scale release (470 mm oil release and 56 mm single water nozzle), see Table 2.2 and Fig. 2.2. This was done to ensure that the coverage of a single water jetting nozzle during the laboratory experiments was comparable to a full-scale application.

2.3. Quantification of effectiveness — reduction in oil droplet sizes

The wide oil droplet size range generated in this study (up to multiple millimetres) is outside the specification of light scattering instruments traditionally used for particle size characterisation (Agrawal and Pottsmith, 2000; Karp-Boss et al., 2007; Graham and Nimmo-Smith, 2010). The SINTEF Silhouette Camera (SilCam) is described in Davies et al., 2017 and has successfully been used for quantifying oil droplets and gas bubbles in multiple oil spill related applications over a wide particle size range (Ahnell et al., 2018, Brandvik et al., 2019a, b, c, 2021a, b, 2023). The SilCam has also been used to quantify other marine particles (for example plankton, fish eggs and microplastics, see Fragoso et al., 2019, 2022, Brakstad et al., 2020, Saad and Stahl, 2020).

The experiments presented in this paper have been performed continuously. Meaning that experimental conditions like water jetting rate, background current, oil- or dispersant type have been varied while the oil release and the oil droplet distribution has been continuously monitored. Each experimental period (with one set of conditions) typically lasted for 60–90 s. The first 30–60 s were used to adjust and stabilise the conditions to optimise plume monitoring and the last 30 s were needed to collect droplet data. Averaging data over 30 s usually provided sufficient statistical material for calculating particle size distributions.

The SilCam instrument used to quantify the larger droplets from the reference experiments with release of untreated oil had a low resolution (107–12,000 μm) while the instrument used to quantify the smaller droplets from the SSMD/SSDI experiments had a medium resolution (56–8000 μm). Further details regarding the SilCam specifications and resolutions can be found in Davies et al. (2017).

The reduction in oil droplet sizes is used to quantify the effectiveness of SSMD and SSDI. To create a relative measure independent of the sizes of the untreated oil droplets the ratio between the untreated to treated droplets (d_{50}-ratio) is used in tables/figures in this study. d_{50}-ratio = d_{50}-Untreated droplets/d_{50}-Treated droplets.

However, due to the low release velocity and corresponding low Weber number for some of the oils used in these experiments (1.1 m/s and ⟨200), some of the untreated oil droplets were large and unstable. The largest droplets generated could be larger than the stable droplets size (d_{max}) for this oil as calculated according to Hu and Kinter (1955). The droplet sizes measured with the SilCam close to the release nozzle can for this reason overestimate the droplet sizes due to later secondary breakup of the larger unstable droplets. For example, the measured d_{50} for untreated Grane (8 mm) is large compared to a d_{max} of 10 mm indicating that many of the larger droplets in this distribution is larger than d_{max}. Modified Weber scaling (Johansen et al., 2013) predicts a stable droplet size with a d_{50} of 4.8 mm for these release conditions. Using these unstable oil droplets as reference distributions could overestimate the relative effectiveness for both SSMD and SSDI. For this reason we have used the predicted untreated droplet sizes (Johansen et al., 2013) for calculating the d_{50}-ratio, see Table S.1.

This is done to avoid overestimating effectiveness (d_{50}-ratio) for both SSDI and SSMD and using modified Weber scaling for predicting oil droplet sizes have in earlier studies showed a high correlation to experimental data from large-scale experiments at Ohmsett (Brandvik et al., 2021a) and the algorithm is implemented in multiple models for subsea releases (Socolofsky et al., 2015).

Table 2.2
Comparison of a full-scale field case and with our medium-scale laboratory conditions.

Full-scale blow-out scenario	Medium-scale lab. scenario
1. Oil release diameter: 470 mm[1]	1. Oil release diameter: 5 mm
2. Oil flow rate: 11,500 m^3/day	2. Oil flow rate: 1.3 l/min
3. Re_{oil}[4]: 32k	3. Re_{oil}[4]: 600
4. Water nozzles: 56 mm[2]	4. Water nozzles: 0.6 mm
5. D_{oil} to D_{water} ratio: 8.4	5. D_{oil} to D_{water} ratio: 8.3
6. Total water jetting capacity	6. Total water jetting capacity
• 4 m^3/min pump capacity[3] (50 % of oil rate)	• 0.59–0.70 l/min (45–55 % of oil rate)
7. Water jetting velocity: 25–35 m/s	7. Water jetting velocity: 35–41 m/s
8. Re_{water}: 1200 k (27 m/s)	8. Re_{water}: 16 k (35 m/s)
9. Ration $Re_{water/oil}$: 38	9. Ratio $Re_{water/oil}$: 32

[1] Reference is an unrestricted BOP.
[2] Design suggestion for a SSMD prototype.
[3] Capacity for available subsea pumps.
[4] Oseberg from Table 2.3 is used to calculate the Reynolds numbers (*Re*).

2.4. Oil types

As discussed earlier, most of the previous research performed on the SSMD technology has focused on low viscosity oils. All the testing at SINTEF has been performed with a light paraffinic crude (Oseberg Blend). However, we expect SSMD effectiveness to vary with varying oil properties, in a similar manner as earlier observed with SSDI (Belore, 2014; Brandvik et al., 2018; Brandvik et al., 2019a). In a research program focusing on SSDI effectiveness, funded by the American Petroleum Association (2015–19), five oil types, including Oseberg blend, were used to span out a wide variation of oil properties (Brandvik et al., 2019a). These oils represent a broad selection of oil types and should be representative for a large number of oils worldwide. We have used the same oil types in this study, see Table 2.3, but we have substituted Troll B with another Norwegian naphthenic crude, Wisting Central.

- Paraffinic crude oil (e.g. Oseberg): Rich in paraffins and saturated components.
- Waxy crude oil (e.g. Norne): Rich in waxes (higher saturated components > C_{20}), high pour point.
- Naphtenic crude oil (e.g. Wisting Central): Biodegraded, rich in saturated cyclic components, branched alkanes and often aromatic components. Very low in waxes and a corresponding low pour point.
- Asphaltenic crude oil (e.g. Grane): Rich in polar resins and asphaltenes and high density.
- Condensate (e.g. Kobbe): Very light hydrocarbon, low in polar resins, asphaltenes and waxes and low density.

The SINTEF ID for each oil type (see Table 2.3) was tracked during the experimental work in this study and each experiment was linked to this ID.

2.5. Dispersants

To better evaluate the variations in SSMD effectiveness as a function of oil properties we also performed SSDI effectiveness testing for the same oil types. This enabled us to directly compare SSMD- and SSDI effectiveness, since the chemical dispersants were tested using the same experimental setup regarding oil release rates and oil droplet quantification. Three commercially available dispersants were selected for the testing as they are stockpiled worldwide by several major oil spill response providers. These stockpiles are integrated in oil spill contingency of most major energy companies. The selected dispersants were:

1. Corexit 9500A

Table 2.3
Oil properties for the five oil types used in this study.

	Oseberg blend[1] (Paraffinic) 2017-2492	Grane[2] (Asphaltenic) 2015-0061	Kobbe[3] (Light paraffinic) 2006-1061	Norne blend[4] (Waxy) 2017-3365	Wisting Central[5] (Naphthenic) 2016-0320
Density (kg/L)	0.832	0.941	0.797	0.860	0.838
Pour Point (°C)	−6	−24	−36	21	−36
Interfacial tension (mN/m)	17	11	15	20	30
Viscosity (mPa·s), shear rate 10 s^{-1}, 13 °C	9.6	593	5.3	40	10
Asphaltene (wt%)	0.3	1.4	0.03	0.3	0.05
Waxes (wt%)	3.2	3.2	3.4	4.2	0.71

The oil property data in this table is from earlier reports describing weathering properties of different oil types: 1: Leirvik and Resby, 2007, 2: Strøm, 2013, 3: Moldestad and Sørheim, 2008 4: Sørheim et al., 2010, and 5: Sørheim and Bakken, 2017.

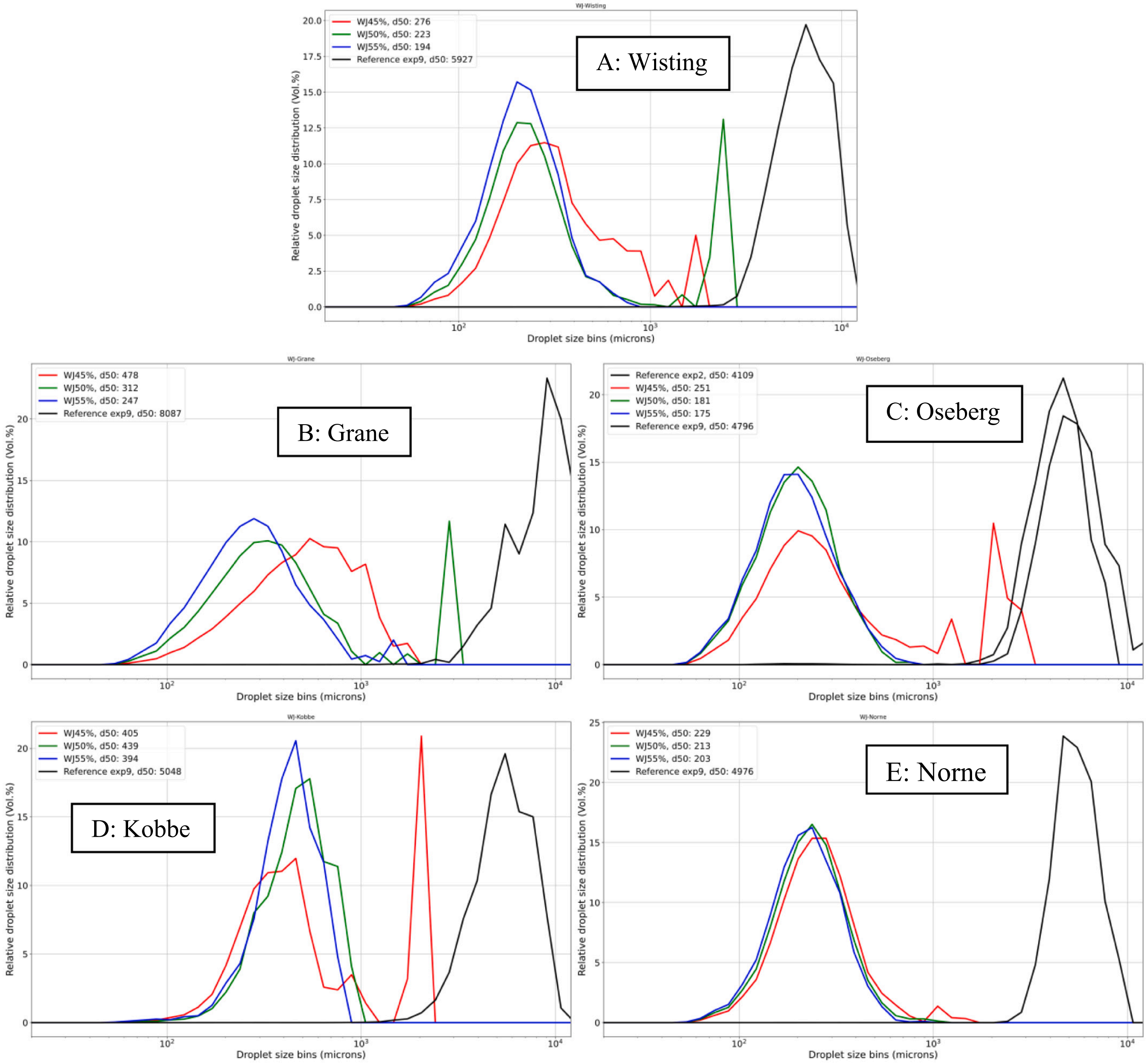


Fig. 3.1. SSMD: Oil droplet size distributions of untreated oil (black lines) and after 45, 50 and 55 % water jetting (coloured lines) for the five oil types. d_{50} from the volume distributions (based on 50 % cumulative area) are listed in upper left corner.

2. Dasig Slickgone NS
3. Finasol OSR-52

3. Results and discussion

The experimental results from testing of SSMD and SSDI effectiveness on the five oil types are discussed in the following three sections:

1. Effectiveness of subsea mechanical dispersion (SSMD) as a function of water jetting (WJ) rate
2. Effectiveness of subsea dispersant injection (SSDI) for the three dispersants
3. Comparison of SSDI and SSMD effectiveness.

3.1. *SSMD effectiveness as a function of water jetting rate*

Effectiveness of SSMD illustrated as reduction in oil droplet sizes is presented in Fig. 3.1 and summarised as d_{50}-ratio in Table 3.1 for all the five oil types.

The experiments presented in Fig. 3.1 show that the measured oil droplet sizes (d_{50}) generally are reduced from 5 to 8 mm for the untreated oils to 0.2–0.5 mm after SSMD. We also observe a systematic shift towards smaller oil droplets as water jetting rate increases from 45 % to 55 %. The average reduction in oil droplet sizes (d_{50}-ratio) for all five oil types is ranging from 15 for the lowest water jetting (45 %), via 18 (50 %) to 20 for the most powerful water jetting (55% WJ), see Table 3.1.

For most of the oil types we observe a low number of large oil droplets for the lowest water treatment rates, see example in Oseberg in Fig. 3.1. These large droplets represent untreated or partly treated oil, when not all the released oil has been treated by the water jet. This is more frequent at lower water jetting rates.

As discussed in Section 2.3, we have chosen to use the predicted droplet sizes instead of the measured droplet sizes for the untreated oils, see also Fig. S.4 and Table S.1 in the supplemental material for further details.

Table 3.1 shows that increasing water jetting within the 45–55 % range increases the effectiveness. This is expected since the kinetic energy (e) available for droplet splitting is highly dependent on the water velocity ($e = ½\, m \bullet v^2$). Where m is the mass of water and v is the water velocity. This means that increasing the water jetting from 45 % to 50 % and 55 % (or from 35 to 38 and 41 m/s) increases the kinetic energy available for enhanced droplet splitting with approximately 31 % and 67 %. This supports the general trend for all oil types that the SSMD effectiveness (d_{50}-ratio) increases with increasing water jetting rate from.

However, earlier experiments indicate that this increase in SSMD effectiveness as a function of water jetting rate has an upper limit where further increase in water jetting will not produce smaller droplets (Brandvik et al., 2023). This is also indicated with a clear difference between the oil types included in the study. Increasing water jetting shows a high effect on the asphaltenic, and viscous Grane (593 mPa•s) with a d_{50}-ratio increasing from 11 to 20 (see individual d_{50} values in Fig. 3.1B and ratios in Table 3.1), while with the low viscosity Kobbe (5 mPa•s) a similar increase in water jetting has limited effect on reduction in oil droplet sizes (see Fig. 3.1D and in Table 3.1).

Table 3.1
SSMD Effectiveness expressed as d_{50}-ratio for the five oil types.

	Relative values (d_{50}-ratio)				
	WJ45%	WJ50%	WJ55%	Average	StDev
Wisting	19.2	23.8	27.3	23.4	4.1
Oseberg	15.1	21.0	21.7	19.3	3.6
Kobbe	8.9	8.2	9.1	8.7	0.5
Grane	10.5	16.0	20.2	15.6	4.9
Norne	19.7	21.1	22.2	21.0	1.3
Average	14.7	18.0	20.1	17.6	2.9

The pour point of the waxy Norne is high (21 °C), but in these experiments the oil was injected at 20 °C and the temperature during initial droplet formation and water jetting (<10 release diameters above oil nozzle, see Fig. 2.2) was estimated to 13 °C. This temperature is probably not sufficiently low, compared to the pour point, to strongly influence droplet formation during the water jetting.

The light oil or condensate Kobbe has a d_{50} after SSMD treatment around 400 μm which is comparable to, or even larger than the viscous Grane (see Fig. 3.1B and D). This is surprising since the relative dispersed oil droplet size (d_{50}/D_{oil}) are expected to be proportional to the viscosity of the oil (Johansen et al., 2013). However, this light oil has a very low content of polar material to stabilise newly formed droplets, and this could be one factor (see Table 2.3). Especially during the initial phase of droplets formation where distances between the droplets are small, chemical stabilisation to avoid coalescence could be a significant factor. Formation of larger droplets than expected for the Kobbe oil is also observed for SSDI experiments in both this study (see Fig. 3.2) and in earlier studies of SSDI (Brandvik et al., 2015). The reduced density of the light oil could also influence the oil droplet sizes towards larger sizes, since dispersed oil droplet size (d_{50}/D_{oil}) are proportional to oil density (Hinze, 1955).

3.2. *SSDI effectiveness for selected dispersants*

Oil droplet distributions for untreated oil together with distributions after dispersant injection for the three dispersants (Corexit 9500, Dasic NS and Finasol OSR-52) are presented in Fig. 3.2 and in Table 3.2.

The experiments presented in Fig. 3.2 show both a variation in SSDI effectiveness within the tested oil types and between the three dispersants. The effectiveness is generally high for the naphthenic Wisting and paraffinic Oseberg (viscosity: 10 mPa•s) but some reduced for the viscous Grane (viscosity: 593 mPa•s) and the waxy Norne (viscosity: 40 mPa•s), especially for Dasic NS and Finasol OSR-52. As observed for the SSMD experiments (Section 3.1), the light oil Kobbe gives surprisingly large droplets after dispersant injection. The droplet sizes (d_{50}) for Corexit are similar for both Kobbe and the viscous Grane, see Fig. 3.2. Unexpected large droplets for Kobbe have also been observed in earlier studies of SSDI effectiveness (Brandvik et al., 2015).

Similar as for the SSMD experiments we have chosen to use the predicted droplet sizes (Johansen et al., 2013) instead of the measured large and unstable droplets from the untreated reference experiments to calculate the d_{50}-ratios in Table 3.2 below.

For all oil types, treatment with Corexit 9500 produced smaller or similar droplets (d_{50}) compared to the two other dispersants. The average d_{50}-ratio for all oil types (Table 3.2) indicate that Corexit 9500 has a higher effectiveness on this selection of oil types compared to the other two products. The average d_{50}-ratio for Corexit 9500 is 22 versus 16 and 12 for Dasic NS and Finasol OSR-52. For the viscous Grane and especially the waxy Norne we observe a larger difference in droplet formation between the three dispersants. The dispersants with reduced effectiveness on the waxy Norne (see Fig. 3.2E) formed larger droplets and droplets of irregular shape, see also SilCam images in Figs. S.7 and S.8 in the supplemental material.

3.3. *Comparison of SSDI and SSMD*

The water jetting- (SSMD) and dispersant injection (SSDI) experiments were performed with the same experimental set-up (see Fig. 2.1 and Fig. 2.2). The SSMD and SSDI testing were also performed as a part of the same basin experiment, water jetting was performed first (45, 50 and 55 %) and then after turning water jetting off, switching directly over to dispersant injection. Identical analytical equipment was used to monitor reduction in oil particle sizes (SilCam). A series of

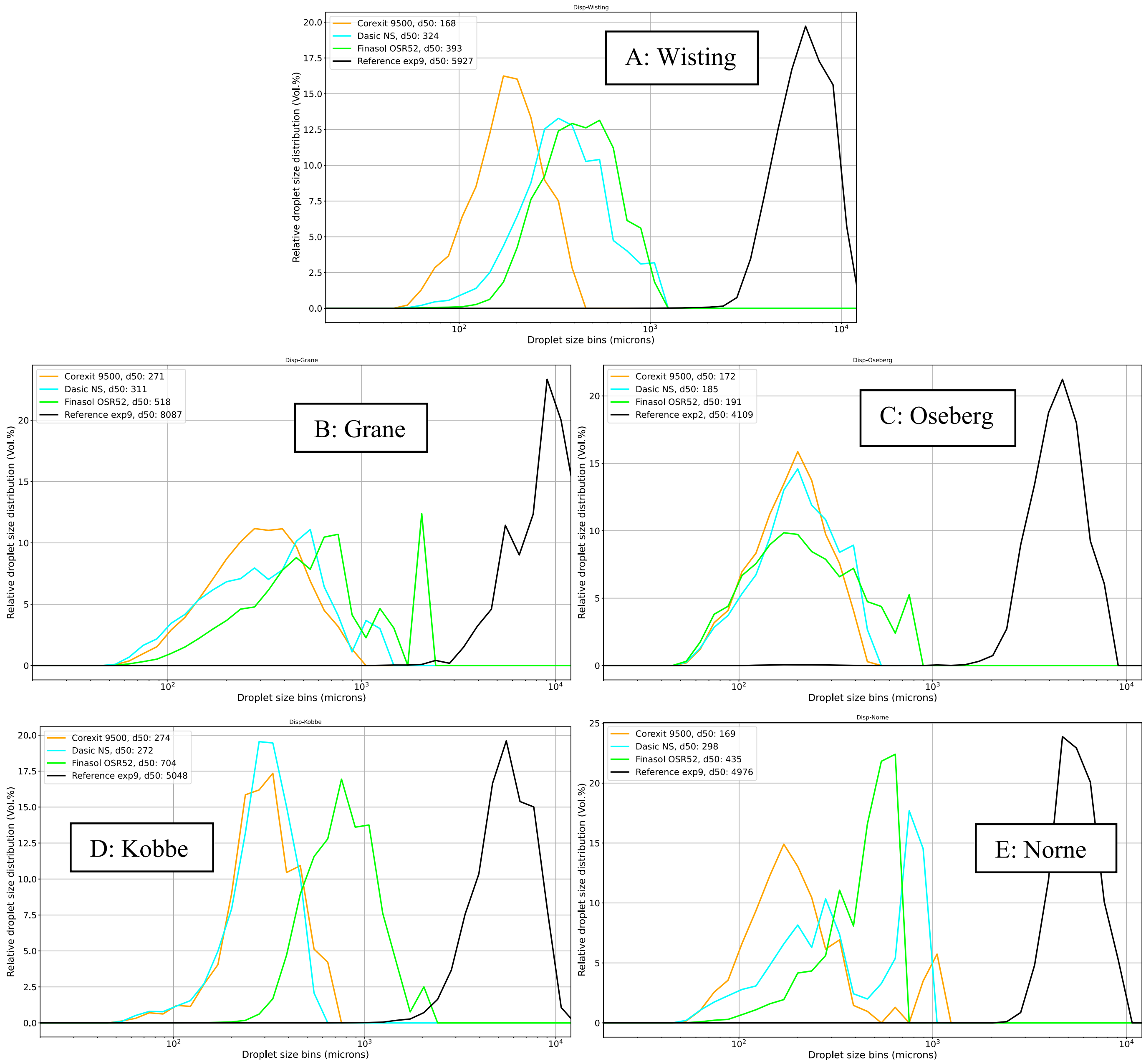


Fig. 3.2. SSDI: Droplet size distributions of untreated oil (black lines) and after 1 % dispersant injection with the three dispersants (coloured lines) for the five oils. d_{50} from the volume distributions (based on 50 % cumulative area) are listed in upper left corner.

Table 3.2
SSDI effectiveness expressed as d_{50}-ratio for the five oil types.

	Relative values (d_{50}-ratio)				StDev
	Corexit 9500A	Dasic NS	Finasol OSR-52	Average	
Wisting	31.5	16.4	13.5	20.5	9.7
Oseberg	22.1	20.5	19.9	20.8	1.1
Kobbe	13.1	13.2	5.1	10.5	4.7
Grane	18.5	16.1	9.7	14.7	4.6
Norne	26.6	15.1	10.3	17.4	8.4
Average	22.4	16.3	11.7	16.8	5.7

representative SilCam images for the naphthenic Wisting are shown in Fig. 3.3. Although it is difficult to select representative single images from a 30 s monitoring period (120–300 images), we observe a clear relationship between the visual impression of the oil droplet sizes in Fig. 3.3 and the resulting droplet size distributions for Wisting in Fig. 3.1 and Fig. 3.2. The images of Finasol OSR-52 and Dasic NS seem to contain larger particles compared to the image of Corexit 9500 and all have smaller particles than the image of the untreated oil. Similar images for the other four oil types are given as Supplementary information (Fig. S.5 to Fig. S.8).

Selected oil droplet size distributions are illustrated for comparison of SSMD and SSDI in Fig. 3.4. The most effective water jetting (55 %) and the most effective dispersant (Corexit 9500) are compared with untreated reference distributions for all oil types. Similar comparisons for the two other dispersants, Finasol OSR-52 and Dasic NS are presented in Fig. S.9. In Fig. 3.4. the SSMD distributions (solid lines) are in some cases (Grane and Oseberg) indicating smaller or equal oil droplets compared to the SSDI distributions (dotted lines), while SSDI gives slightly smaller droplets for Wisting, Kobbe and Norne. The largest differences are for the viscous Grane, where SSMD is better and for the

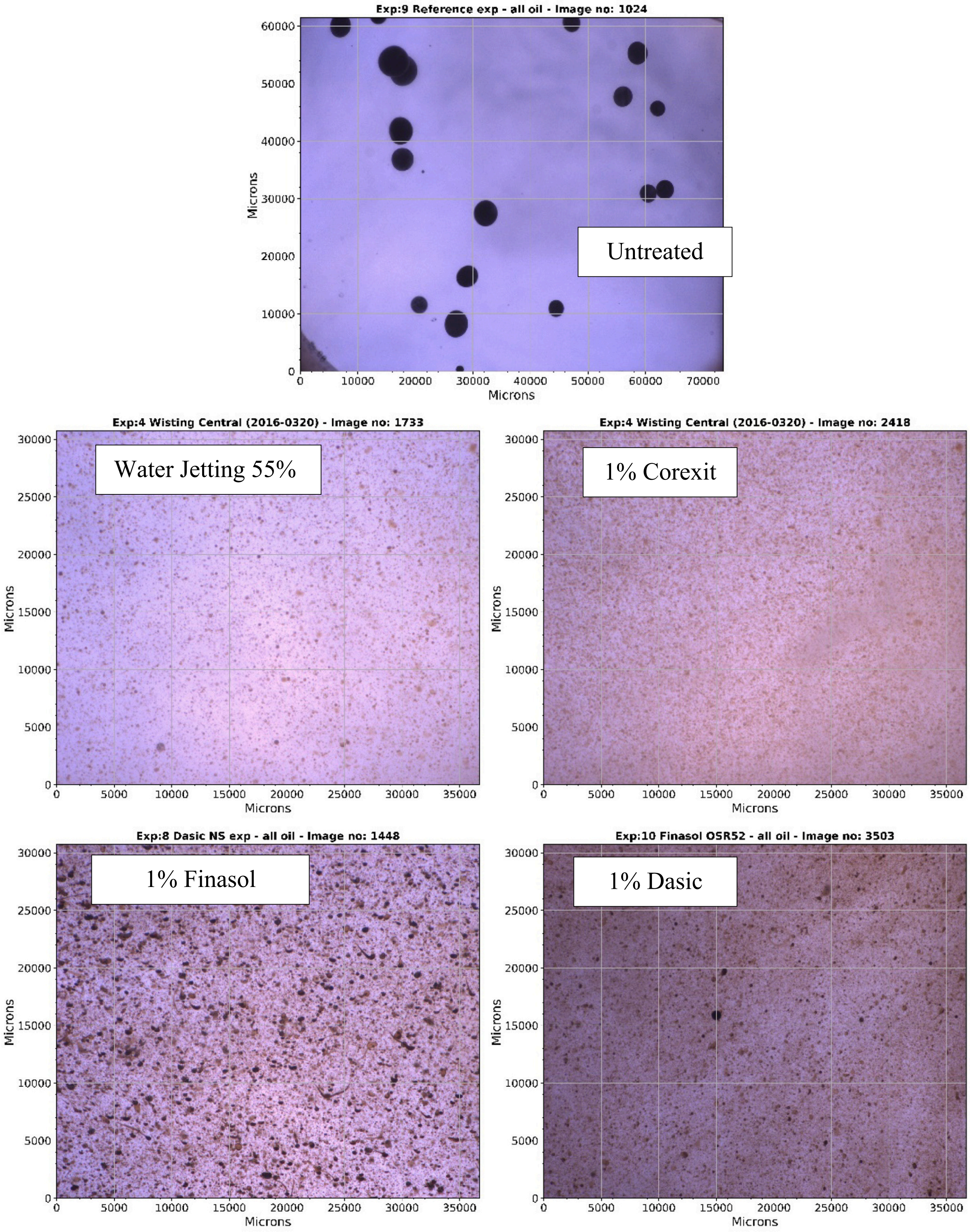


Fig. 3.3. Comparison of SSMD and SSDI for the Wisting oil: Representative SilCam images for untreated oil, after mechanical dispersion (55 % water jetting) and 1 % dispersant injection Corexit 9500, Finasol OSR52 and Dasic NS. NB! Image of untreated oil is from a low resolution SilCam and has a larger scale.

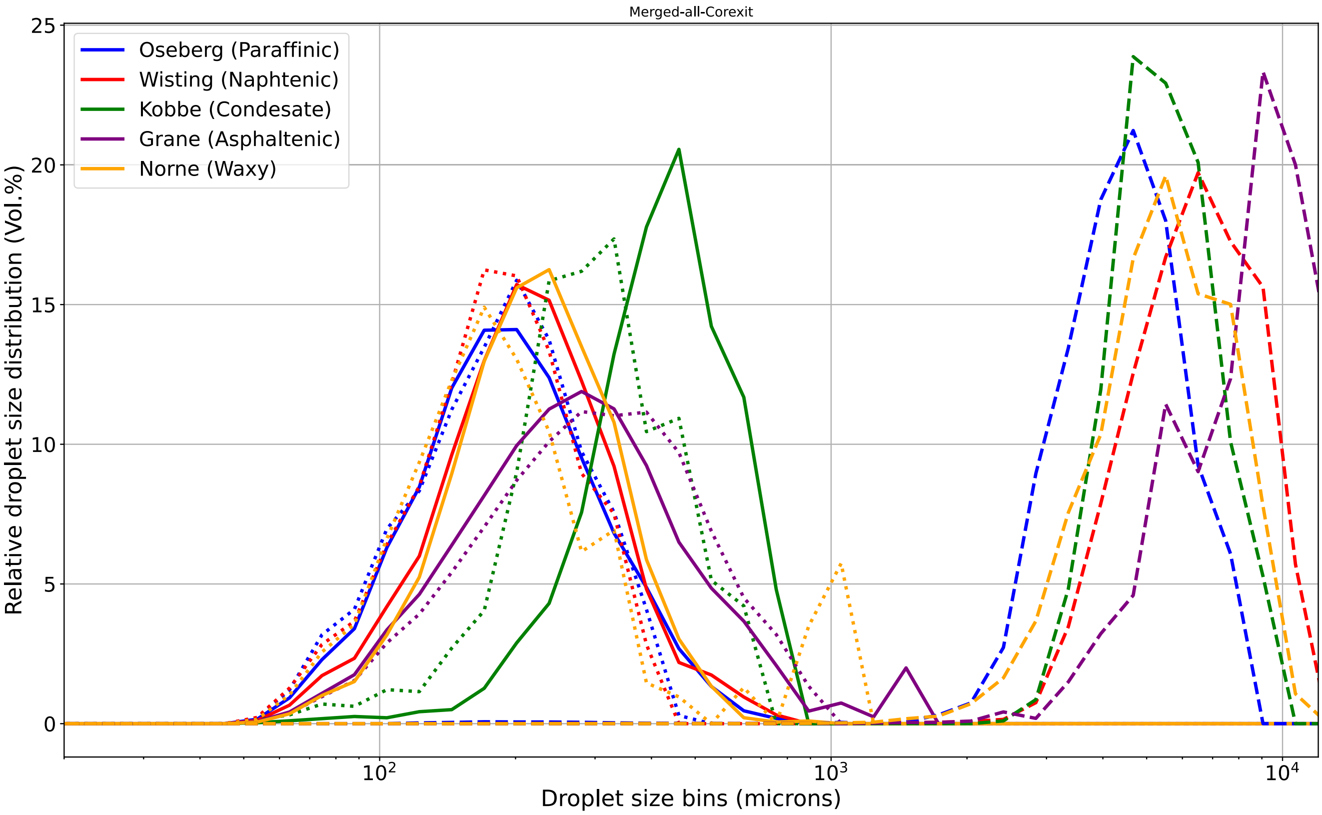


Fig. 3.4. Summary of both SSDI-effectiveness (1 % Corexit 9500, dotted lines) and SSMD effectiveness (55 % water jetting, solid lines) compared to untreated oils (dashed lines) for all five oil types. Relative droplet size distribution (volume %) illustrates the reduction in oil droplet sizes.

light oil Kobbe, where SSDI is better.

To simplify comparison of the oil droplet distributions the mean droplet size or d_{50} of the distributions can be compared to d_{50} for untreated oil (d_{50}-ratio), see Fig. 3.5A which presents the data from Table 3.1 and Table 3.2. This figure compares d_{50}-ratio for both SSMD and SSDI for all oil types and illustrates again a general increase in SSMD effectiveness with increasing water rate (45–55 %) and that Corexit 9500 seems to offer the highest dispersant effectiveness for this selection of oil types.

To compare SSMD and SSDI on a more general basis, average results (45–55 % WJ) and average for all three dispersants are presented in Fig. 3.5B. We observe generally very similar results as observed earlier, SSMD are best for 3 oils (Wisting, Grane and Norne) while SSDI is best with Oseberg and Kobbe. The average differences in d_{50}-ratio between the technologies are small, SSMD being slightly better than SSMD (0.8) but probably not significant. No replicate experiments were performed so the statistical significance of the differences cannot be determined. In Fig. 3.5C we compare the best options from each technology (Corexit 9500 versus 55 % WJ). The dispersant offers higher effectiveness in 4 of 5 cases and SSMD is only better for the viscous Grane. The average difference is small (2.3) and is also in this case probably not significant. For both SSMD and SSDI we observe a reduced effectiveness on the viscous Grane and the light oil or condensate Kobbe.

One notable difference between SSMD and SSDI is the large variation in effectiveness between the oil types for the three surfactants. The average d_{50}-ratio for the five oil types is 20 for SSMD (55 % WJ, Table 3.1), while it varies between 12 and 22 for the three dispersants (Table 3.2). This indicate that selecting the best dispersant for the actual oil type is important to achieve high SSDI effectiveness.

To link this comparison of SSMD and SSDI with previous studies, the 50%WJ and Corexit 9500 experiments (from Fig. 3.1 and Fig. 3.2) are compared to similar experiments from earlier large-scale studies at Ohmsett with 51%WJ in 2019 (Brandvik et al., 2023) and 1 %-Corexit 9500 in 2015 (Brandvik et al., 2021a). All pair of experiments comparing SSDI-SSMD were performed with similar oil release conditions, oil droplet quantification and oil type.

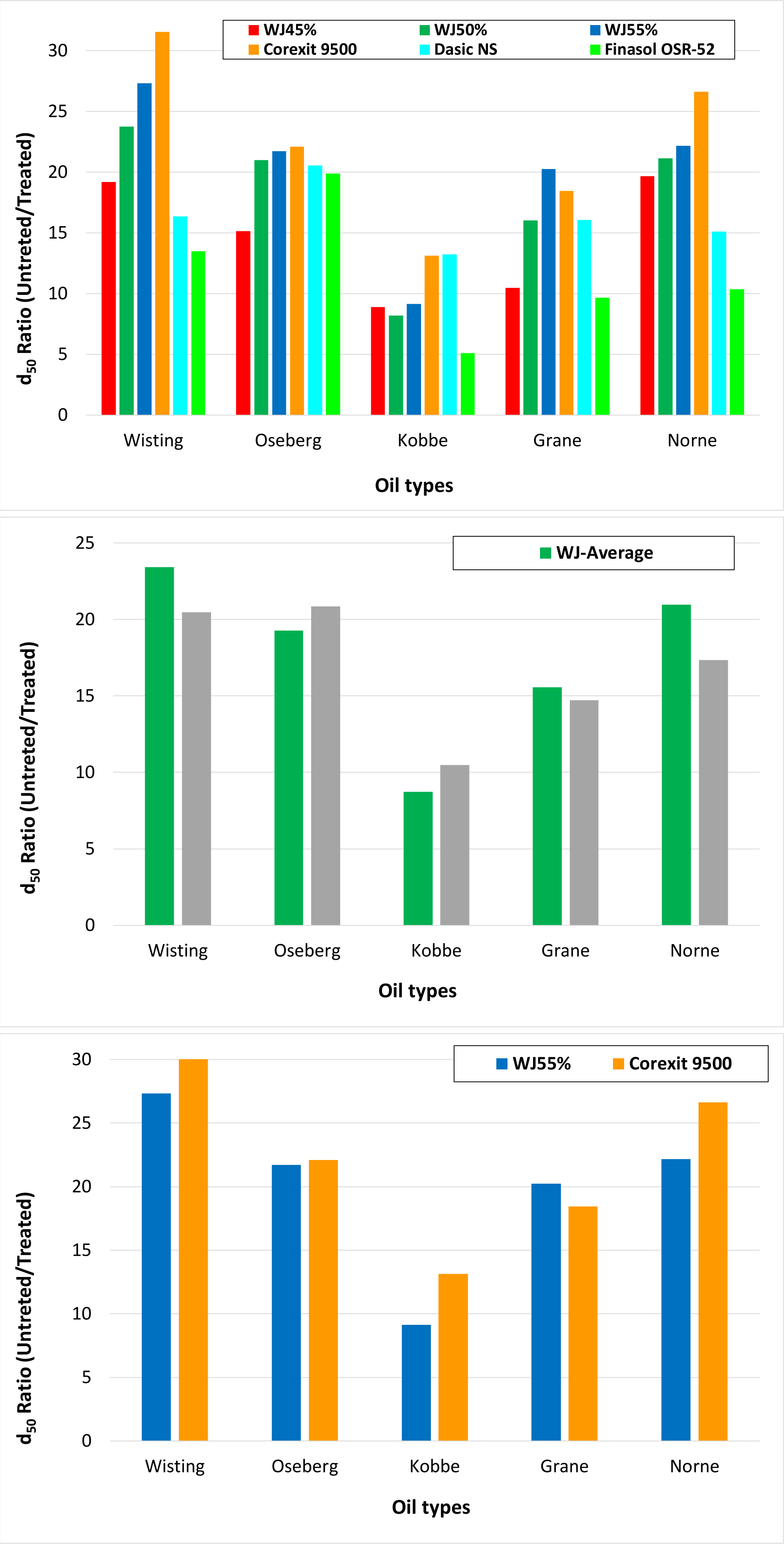
The results presented in Fig. 3.6 show that the ability of SSMD and SSDI to reduce oil droplet sizes is very comparable, at both medium-scale (SINTEF basin) and at large-scale (Ohmsett). This indicates that the two technologies will show comparable effectiveness also in a full-scale scenario. It can also be observed from Fig. 3.6 that the effectiveness (d_{50}-ratio) is larger for the SINTEF medium-scale experiments, likely due to the lower stability of the larger untreated oil droplets used (4110 versus 2750 μm).

4. Summary conclusions

Results from experimental testing of SSMD and SSDI effectiveness with a simulated subsea release of oil performed in a medium scaled basin facility have been presented in this paper. The ratio between the oil release diameter and the water jetting nozzle diameter (8.3) and the water jetting level (45–55 %) are regarded as realistic for a full-scale version of the SSMD technology. The release conditions for the oil creates oil droplet sizes for the untreated oil (multiple millimetres) representative for a subsea blow-out with large release diameters and low release velocities (like DWH-2010). The dispersants were also injected prior to the oil release (simulating an insertion wand) according to the best available technology, with a realistic dosage (1 %) of operative relevant dispersants.

Based on the results presented in the previous sections the following conclusions are drawn:

a) SSMD and SSDI effectiveness have been measured in comparable experiments for five oil types spanning a wide range of oil properties.



A: d_{50}-ratio for all experiments

B: d_{50}-ratio for average options (SSMD/SSDI)

C: d_{50}-ratio for best options (SSMD/SSDI)

Fig. 3.5. Summary of dispersion effectiveness (d_{50}-ratio — Untreated/Treated) for both SSMD (45–55 % WJ) and 1 % SSDI for both the individual- and average effectiveness for the three dispersants.

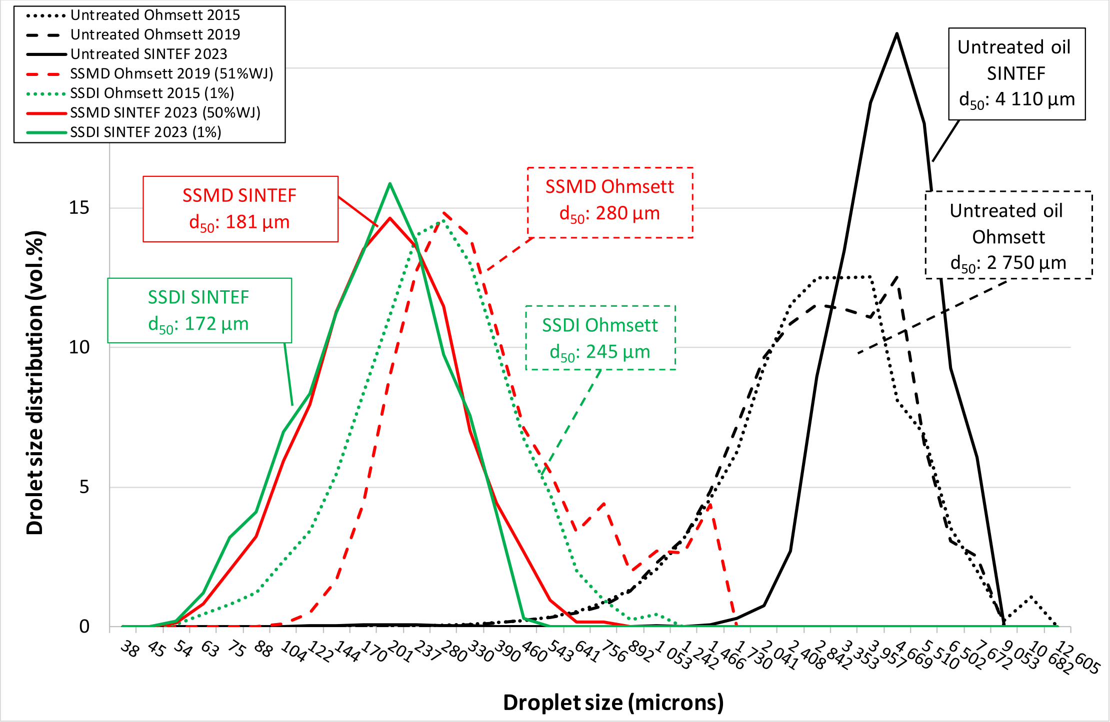


Fig. 3.6. Comparison of SSDI- (1 %-Corexit 9500) and SSMD effectiveness (50–51 % water jetting) presented as reduction in oil droplet sizes compared to untreated oil. Experiments were performed at Ohmsett (see Brandvik et al., 2021a; Brandvik et al., 2023) and as a part of this study. All experiments were performed with Oseberg oil.

b) Measured effectiveness (reduction in oil droplet sizes) for both technologies are generally high but varies significantly within the selection of oils.
c) The effectiveness was reduced for both technologies for the viscous Grane and the light oil or condensate Kobbe.
d) Waxy oils with high pour point could be challenging if the oil temperature during the release becomes too low. In our experiments the additional energy from SSDM seems to give better results than SSDI on the waxy oil.
e) Averaged effectiveness for the two technologies over the five oil types are very similar and the small differences are probably not significant.
f) Selecting the best dispersant for the actual oil type is important to achieve high SSDI effectiveness, since the variation in dispersant effectiveness can be large for some oil types.
g) Comparable effectiveness for SSMD and SSDI is consistent with earlier large-scale testing at Ohmsett for SSDI (2015) and SSMD (2019).

Recommendations:

a) Water jetting introduces additional entrainment of ambient water and influence the orientation of oil and gas plume during the initial phase of the release. This will probably influence plume characteristics, for example diameter, possible trapping height and possible environmental effects on the marine environment. Modelling studies of SSMD and plume behaviour are needed to answer these questions.
b) The SSMD efficiency measured in this study was dependent on the alignment of the water jetting nozzle, the horizontal distance from the water jetting nozzle to the released oil and the vertical distance (or height above) the release nozzle. We recommend relative distances as indicated in Fig. 2.2, but an operationalisation of this technology needs to implement sufficient flexibility so the position of the nozzle can be adjusted to optimise effectiveness with varying release conditions in a full-scale scenario.
c) To bring the technology further and document a technology readiness level (TRL) sufficient to implement SSMD as an operational response method, both design, construction and field testing of a full-scale prototype are needed.

CRediT authorship contribution statement

P. J. Brandvik; Project administration; Conceptualization; Supervision; Investigation; Software; Validation; Visualization; Writing - original draft; Review & editing.

F. Leirvik; Conceptualization; Investigation; Software; Resources; Writing - review & editing.

K.H. Hofstad; Funding acquisition, Validation; Writing - review & editing.

T. McKeever; Funding acquisition, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The first author (Brandvik) has an Adjunct Professor position at the Norwegian University of Science and Technology (NTNU). This is a 20 % position financed by a cooperation between NTNU and a major energy company in Norway (Equinor AS). The program is called Akademia-avtalen. However, this cooperation does not give the industry any influence on candidates holding the adjunct position funded by the program. They are employed by NTNU through an ordinary announcement/evaluation process.

The industry has also no influence on the academic activity or production of the adjunct professors.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115479.

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