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Estimation of a Mechanical Recovery System's Oil Recovery Capacity by Considering Boom Loss

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Abstract

Ability to estimate the recovery capacity of countermeasures is vital in establishing a rational response solution for oil spills at sea. This requires estimation of how much of oil can be collected and determination of the rational quantities and operating conditions of the response equipment. In this study, estimation of marine oil spill recovery capacity using skimmer was numerically calculated considering the weathering process of spilled oil, marine environment, and efficiency of skimmer over time. Also, a constant loss rate model and a variable loss rate model were developed to estimate the recovery capacity of a mechanical recovery system, considering the escape of oil past containment booms. The latter model could calculate the speed at which oil loss began to occur and the volume of oil lost. As an case for applying the constant loss rate model, WuYiSan oil spill accident happened on January 31, 2014 was selected as benchmarking test. A comparative analysis on the recovery capacity using the nameplate capacity, Effective Daily Recovery Capacity(EDRC), and the developed model was carried out. Sensitivity studies were performed to analyze the significance of oil loss of the variable loss rate model, and a case study was performed to calculate changes in recovery capacity with respect to adjusting variables. The developed model was able to estimate the best operating situation, thereby optimizing the recovery capacity, for different response times and environmental conditions.

KEY WORDS: Oil spill; Weathering process; Recovery efficiency; Skimmer; recovery capacity; Throughput efficiency; Tow speed; First loss speed; Critical loss speed; Oil loss rate

붐 유실을 고려한 기계적 회수 시스템의 기름 회수 능력 산정

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Abstract

기름 유출사고에 대비하기 위한 회수 능력 산정은 해상에서 기름 유출 사고에 대한 합리적인 대응 방안을 수립하는데 있어서 중요하다. 이는 포집 가능한 기름의 양을 추정하고 합리적인 동원 장비의 수량과 운전 조건을 제시할 수 있어야 한다. 본 연구에서는 유출유의 거동특성, 해양환경 조건과 장비의 효율이 반영된 기계적 회수 시스템의 회수능력을 시간 경과에 따라 수치 해석적으로 계산할 수 있는 모델을 개발하였다. 개발된 모델은 오일 붐으로부터 기름이 유실되는 것을 고려한 일정 유실율 모델과 변동 유실율 모델로 구분된다. 후자의 모델은 기름 유실이 발생하기 시작하는 속도와 유실된 기름의 양을 계산한다. 일정 유실율 모델을 적용하기 위한 사례로, 2014년 1월 31일에 발생한 우이산호 유류오염사고에 적용하여 유회수기의 회수 능력을 추정하였다. 유회수기 명목용량을 이용한 회수량, 유효기름 회수용량(EDRC)을 이용한 회수량, 그리고 회수능력 추정 모델을 이용하여 계산된 회수량 추정 결과를 비교하였다. 변동 유실율 모델의 기름 유실을 분석하기 위해 민감도 연구가 수행되었으며, 사례 연구는 변수 조정과 관련하여 회수 능력의 변화를 계산하기 위해 수행되었다. 개발된 모델은 합리적인 운전 조건을 평가하여 다양한 대응 시간 및 환경 조건에 대해 회수 능력을 최적화하는 결과를 보였다.

KEY WORDS: Oil spill 유류 유출; Weathering process 풍화 과정; Recovery efficiency 회수 효율; Skimmer 유회수기; Recovery capacity 회수 능력; Throughput efficiency 처리 효율; Tow speed 예인 속도; First loss speed 초기 유실 속도; Critical loss speed 임계 유실 속도; Oil loss rate 기름 유실율

Chapter 1 Introduction

1.1 Purpose of Recovery Capacity Estimation using Skimmer

Large and small oil spills due to ship accidents are frequent all over the world including Korea. Oil spills can damage marine ecosystems and sensitive resources and generate enormous amounts of damage (Chun et al., 2018). The cost of environmental and economic impact of Deepwater Horizon oil spill recorded as a major disaster was estimated to be about $36.9 billion to BP(British Petroleum), the environment and the US gulf coast economy (Smith et al., 2011). For both large and small oil spills, it is important to establish an effective response strategy for the cleanup operation, ensuring that the oil is quickly recovered from the affected area. In the case of oil spill accidents, various control techniques and equipment are mobilized to carry out the control work in the accident area. Among the Various response technologies, with the most common option being mechanical recovery using a skimmer and oil boom. This mechanical recovery does not cause any secondary pollution and minimizes environmental damage from pollution accidents, compared to other response methods (Castro et al., 2010).

The objective of the response strategy is not only to maximize the recovery of the spilled oil, but also to minimize the number of skimmers that need to be mobilized, i.e., to ensure that the response is proportional to the scale of the spill. Response contingency planning should also focus on the appropriateness of the mechanical cleanup and the response capability of mechanical recovery for the countermeasure (Nordvik, 1995; Ventikos et al., 2004).

The purpose of recovery capacity estimation is not to predict the exact recovery volume in the given environmental conditions, but to ascertain that the oil recovery volume depends on various factors present at sea and to reflect these factors when establishing response strategies (ASTM, 2010).

1.2 A Method for Estimating a Rational Recovery Capacity

A rational response to oil spill accidents involves estimating the recovery capacity of the response equipment, considering the characteristics of both the oil and the marine environmental conditions. To estimate the recovery capacity, it is necessary to be able to predict changes in the performance of the response equipment for oil cleanup, considering various factors that can change in actual accidents, such as film thickness, weathering processes, and equipment specifications (Gregory et al., 1999).

When the oil is spilled on the sea, the characteristics of the oil change due to characteristics of the oil, such as specific gravity and tie point, and marine environmental conditions such as wind speed, wave height, and temperature. This is the weathering process of the spilled oil (Fingas, 2012). When the characteristics of the spilled oil change, the recovery efficiency of the skimmer to recover it also changes (Fingas, 2004). Therefore, it is necessary to understand the weathering process of oil in case of oil spill accident because the response strategy such as quantity of response equipment to be mobilized is also changed. Therefore, when establishing the response strategy in the actual accident, not only the weathering process such as evaporation, emulsification and natural dispersion of the spilled oil but also the recovery efficiency of the skimmer according to the change of the oil characteristics should be reflected.

Numerical models for simulating the weathering process of spilled oil have been developed continuously (Sebastiao & Soares, 1995; Lehr et al., 2002; Genwest, 2012; Berry et al., 2012; Spaulding, 2017). In particular, ADIOS2 (Automated Data Inquiry for Oil Spills) is based on a model of weathering processes such as natural dispersion, evaporation, and oil painting, Calculate the change (Lehr et al., 2002; Dale, 2011). This model is useful predict the oil characteristic change and remaining oil on the sea surface.

Several previous studies have focused on the recovery capacity estimation of skimmers (USCG, 1997; Allen, A. A., 2012; ASTM, 2010; Dale, 2011). The effective daily recovery capacity (EDRC) is a planning method that estimates the required daily oil recovery capacity for the skimmer to respond to a given spill. The EDRC is calculated by considering the total nameplate capacity of skimmer, its operating time, and its mobilization efficiency. Performance change due to variations in oil properties and characteristics of the recovery equipment is only described with the mechanical efficiency, which is a constant (0.2) in EDRC. The advantage of EDRC is that it can quickly estimate the capacity of the skimmer required for mobilization because of its relatively simple estimation method. It can also be used to regulate the regional preparedness capacity, with the aim of ensuring adequate response resources in the case of an oil spill (USCG, 1997). However, EDRC is not suitable to be applied uniformly to all accidents, because it assumes a constant mechanical efficiency. In Korea, EDRC method is used to estimate target of recovery capability considering the skimmer nameplate capacity, working time, mechanical efficiency, and mobilization ratio according to the response days in the calculation of oil spill recovery target (KCG, 2011).

Unlike EDRC, other recovery capacity estimation models have been developed based on the encounter rate. ASTM F1780-97 provides a calculation procedure for evaluating clean-up equipment (ASTM, 2010). This methodology provides guidelines for estimating recovery effectiveness against the target spill, considering the oil slick's condition and the recovery system's parameters, based on the encounter rate. However, its ability to examine changes in the oil slick and clean-up equipment is limited, as the recovery efficiency is assumed to be constant per day, as are the oil slick thickness and the emulsification factor.

Furthermore, the estimated recovery system potential (ERSP) calculator was developed as a planning tool for estimating the mechanical recovery capacity of the recovery system, based on the encounter rate (Allen, 2012). Similarly, the response options calculator (ROC) estimates the recovery capacity based on the encounter rate, in combination with calculating the weathering process, oil property changes, and oil thickness, using a defined time step (Dale, 2011). This provides additional options for estimating the dispersant application and the burning of oil, in addition to the performance of the mechanical recovery. It is advantageous to consider the recovery efficiency of skimmer with respect to viscosity and wind speed, based on hourly changes in the oil's parameters. Although the efficiency of both the boom and the skimmer are important components of the capacity estimation, the ROC assumes boom efficiency to be constant values.

In this study, a model that can numerically calculate the recovery capacity of the skimmer recovery system reflecting the behavior characteristics of the oil, the marine environmental conditions and the efficiency of the equipment over time have developed. It was developed based on a detailed model of the ROC weathering process algorithm (Galt, 2014).

1.3 The Necessity of Consideration of Oil Loss in Oil Recovery Capacity Estimation Model

The encounter rate-based recovery capacity estimation models, including ASTM F1780-97 and ROC, are strongly correlated with the speed at which the oil slick is collected into the oil boom. In other words, the potential capacity of the recovery system increases with the speed at which the oil slick is collected. However, when oil slicks are accumulated above a certain speed, the collected oil may be lost as it escapes the oil boom, which decreases not only the performance of the oil boom (ITOPF, 2011) but also the recovery capacity. This is one of the most important factors in estimating the recovery capacity, but few studies have connected the loss of oil from the boom with recovery system.

In this study, two models were developed to estimate the recovery capacity while considering the loss of oil from the boom, in an effort to propose how oil loss should be reflected in models based on the encounter rate. One model featured a constant loss rate model, while the other had a variable loss rate. The speed at which the oil loss begins to occur and the volume of oil lost were quantified by empirical correlation, and the calculation procedure of the proposed models was designed to indicate the collection performance of the boom. Several sensitivity studies were then carried out to analyze the significance of the oil loss in the mechanical recovery system. In addition, a case study was carried out to calculate how the recovery capacity varied with adjusting variables and to emphasize the difference between two models. This allowed analysis of how the adjustment of tow speed and size of boom in the models affected their recovery capacity.

Chapter 2 Recovery Capacity Estimation using Skimmer

2.1 Numerical Analysis Method

2.1.1 Modelling of Weathering Process

The spreading of oil spills at sea is mainly determined by spill volume, viscosity and environmental conditions. The spreading of oil proceeds with gravity-inertia spreading, gravity-viscous spreading, and surface tension-viscous spreading over time (Fay, 1971). Low viscous oil spreads relatively faster than high viscous oil. As spreading progresses, environmental conditions become more important than oil characteristics (Hoult, 1972). In this study, spreading area and thickness of the oil film were calculated as shown in eq. (1), considering the dominant spreading time-scale of oil spill due to gravity-viscous force equilibrium according to the results of Fay (1971).

$$t = \frac{V}{A(1-Y)} * C_1 * C_2 \tag{1}$$

eq. (1) takes into account both the increase in the film thickness of the emulsion and the behavior of the oil droplet. C_1 is a coefficient considering the vertical behavior of the oil droplets produced by breakage of the waves, which takes account of the addition of refloating oil droplets to the area of the oil film. C_2 is a coefficient considering the area change due to the windrow of the surface layer of floating oil. The coefficients are defined by the characteristics of the oil and the environmental conditions and are applied with reference to the study of Galt and Overstreet (2009).

The evaporation rate per hour was calculated using the pseudo-component evaporation method of Jones (1997), which is calculated as shown in eq. (2).

$$\frac{dV_e}{dt} = \frac{A^* K_i^* P_i^* V_i}{R^* T^* \sum_{j=1}^{n_c} \frac{V_j}{\overline{V_j}}} \tag{2}$$

Mass transfer coefficient K_i is determined by the components of wind speed and oil. The oil is composed of several hydrocarbon components, and the vapor pressure P_i is dependent on the hydrocarbon component of the oil.

Oil spilled on the sea changes in size of oil droplets according to currents and goes through natural dispersion process. The magnitude of dispersion is largely determined by the characteristic of the oil and the sea state. It is the fastest when viscosity is low where breaking waves are present. The entrainment rate of the oil droplet by natural dispersion is calculated as shown in eq. (3) through the results of Delvigne and Sweeny (1988) and Lehr et al. (2002).

$$Q_e = C_0 D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \tag{3}$$

Where C_0 is the dissipation constant of oil, which is presented as a function of oil viscosity.

When oil is present in water, it absorbs water and forms an emulsion with increased viscosity and density. The ratio of the emulsion is determined by the type of hydrocarbon compound, wind speed and wave height (Eley, 1988). In this study, water content (Y) is calculated by emulsification of oil over time through eq. (4) with the previous study (Eley, 1988; Lehr et al.).

$$Y = \frac{S_c d_w}{6 + S_c d_w} \tag{4}$$

The interfacial area between oil and water (S_c) is affected by wave energy and is obtained as a function of wind speed (Lehr et al., 2002).

As described above, the weathering process, which progresses over time, changes the physical properties of the oil. eq. (5) is a correlation for viscosity changes of oil depending on the weathering process and environmental conditions (Mackay, 1982).

$$\nu = \nu_0 (\exp^{C_{temp}(\frac{1}{T} - \frac{1}{T_0})} * \exp^{C_{evap}F} * \exp^{(\frac{2.5 * Y}{1 - C_{emul} * Y})}) \tag{5}$$

The viscosity increase due to eq. (5) is due to the reference viscosity(ν_0), seawater temperature(T), and evaporation(F) and water contents(Y) according to the weathering process. The temperature constants (C_{temp}) and the evaporation constants (C_{evap}) are the property values calculated by Mackay (1982) oil behavior test. The emulsion constant (C_{emul}) is expressed as a constant with increasing oil droplet size of the emulsion (Lehr et al., 2002). As shown in eq. (5), the viscosity increase is calculated by considering not only the evaporation and emulsification by the weathering process but also the marine environmental conditions. The increase in viscosity can affect the efficiency of the response equipment, which will be discussed in the section 2.1.3.

In this study, the weathering process which influences the characteristics of the oil is modeled and calculated over time. Based on this, the accident scenario was set up to analyze the recovery capability of the skimmer.

2.1.2 Recovery Capacity Estimation Model

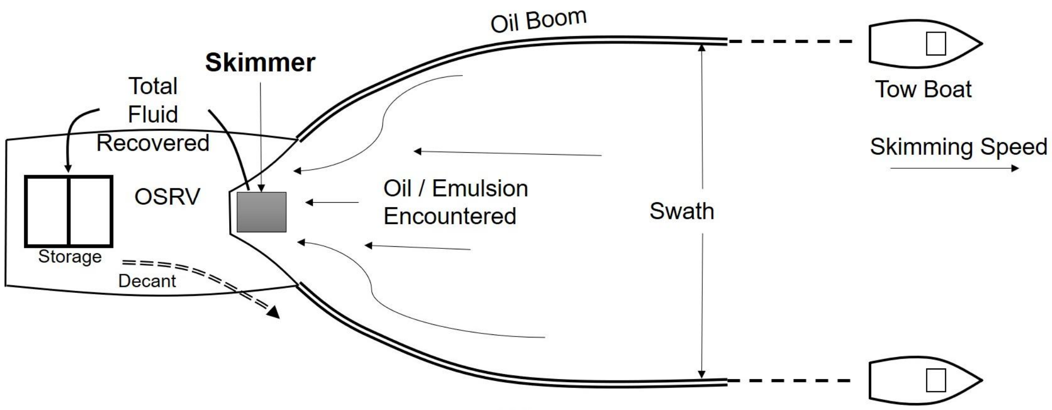


Fig. 1 Schematic of mechanical recovery system through the OSRV (Oil Spill Response Vessel) (Kim et al., 2018).

Fig. 1 shows a mechanical recovery system using a skimmer. The recovery system includes an oil boom for collecting floating oil, a skimmer on an OSRV, a storage tank for storage recovered waste oil accompanied with seawater and a decanting facility (ASTM, 2010).

The Encounter Rate (ER) at which the oil slick enters the oil boom is given by eq. (6).

$$ER = W \times v \times t \tag{6}$$

here, W is sweep width(swath), v is tow speed and t is oil slick thickness calculated in eq. (1). In this study, it was assumed that the tow speed was 0.75 knot considering that the oil was not lost out of the oil boom and the appropriate speed at which it could be collected was between 0.5 knots and 1 knot(ITOPF, 2011). Also, considering the maximum width of the sweeping arm installed on the side of the response ship to collect the oil spilled, the swath is assumed to be 17 m (KCG, 2015a). The thickness of the oil slick was calculated from eq. (1) considering spreading over time.

The oil/emulsion recovery rate (*ERR*) recovered by the skimmer except for the accompanying seawater is given by eq. (7).

$$ERR = TFRR \times RE = ER \times TE \tag{7}$$

here, *TFRR* is total fluid recovery rate, *RE* is recovery efficiency and *TE* is throughput efficiency.

The oil recovery rate (*ORR*), excluding the water contained in the emulsion recovered through the skimmer, is defined as eq.(8).

$$ORR = ERR \times (1 - Y) \tag{8}$$

In eq. (8), water contents(*Y*) is a value indicating the water content of the emulsion which is calculated over time through the weathering process in eq.(4).

Recovery efficiency (*RE*) and throughput efficiency (*TE*) are defined as follows.

$$RE(\%) = \frac{Volume\ of\ Oil/Emulsion\ Recovered}{Volume\ of\ Total\ Fluid\ Recovered} \times 100 \tag{9}$$

$$TE(\%) = \frac{Volume\ of\ Oil/Emulsion\ Recovered}{Volume\ of\ Oil/Emulsion\ Encountered} \times 100 \tag{10}$$

Recovery efficiency, as defined in eq. (9), represents the amount of oil/emulsion, excluding seawater, from the total volume recovered through the skimmer(ASTM, 2016a). This depends on marine environmental conditions, oil properties, and the type of skimmer. According to the magnitude of recovery efficiency, the amount of seawater recovered is determined. The volume of recovered oil/emulsion for encountered the oil/emulsion volume can be quantified to the throughput efficiency as shown in eq. (10) (ASTM, 2016a). The throughput efficiency depends on the current of the accident area and the tow speed of the response vessel, is assumed to be 75 % in this study.

The nameplate recovery rate is defined as the maximum capacity of the skimmer that can be recovered under ideal conditions, such as calm sea conditions and sufficiently thick oil film (ASTM, 2016b). In this study, it was assumed that the total recovery rate (*TFRR*) would be equal to the nameplate recovery rate if the calculated *TFRR* exceeded the nameplate recovery rate.

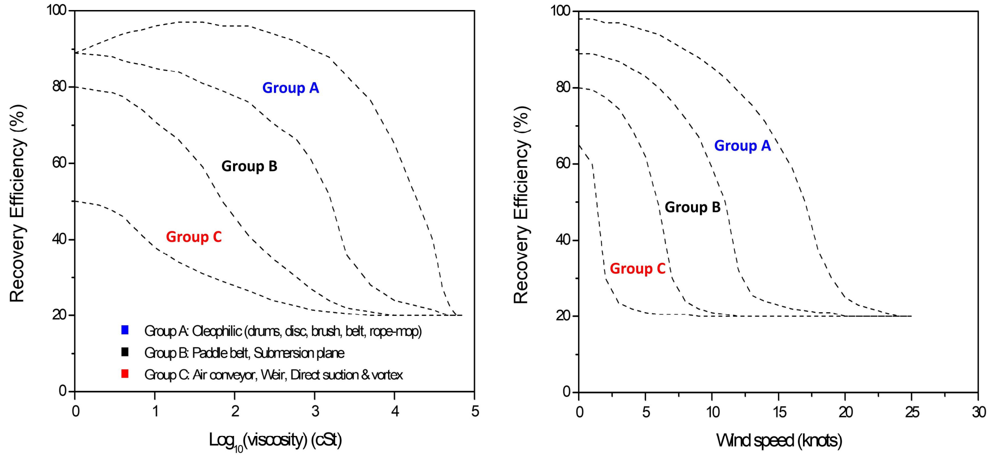
The oil collected through the skimmer is stored in the waste oil storage tank. when it is full, it is necessary to unload it by shore or storage barge. Therefore, it is assumed that the waste oil storage capacity is set differently according to the specifications of the mobilized response vessel by the accident, and the total time for transferring and unloading to the coast of each recovery system is assumed to be 1 hour.

2.1.3 Recovery Efficiency of Skimmer

For the purpose of this study, the recovery efficiency of the skimmer was analyzed in order to quantify the recovery performance of the skimmer. As defined in eq. (9), the recovery efficiency is a value considering only the amount of recovered oil/emulsion, excluding seawater, from the total amount recovered through the skimmer. For example, assuming that a total recovery of 100 kl is recovered through a skimmer with 45 % recovery efficiency, the amount of oil/emulsion recovered is 45 kl and the volume of seawater is 55 kl. Therefore, the meaning of high recovery efficiency is that when the same amount of fluid is recovered through the skimmer, the amount of recovered water is low.

In this study, the change of the recovery efficiency of the skimmer due to the increase of the viscosity of the spilled oil and the marine environmental conditions is reflected to estimate the recovery capacity. The skimmer is divided into several types according to the mechanical characteristics and the recovery principle, and has different recovery efficiency (Schulze, 1998). In Korea, there are diverse types of skimmer and most are oleophilic skimmer (KCG, 2017).

Fig. 2 (a) and (b) show the change in the recovery efficiency of the skimmer according to viscosity and wind speed, respectively (Genwest, 2012). Fig. 2 (a), the recovery efficiency decreases as the viscosity of the oil increases. As the wind speed increases (Fig. 2 (b)), the recovery efficiency decreases and the effects of mechanical recovery operation drastically decreases when wind speeds exceeds about 20 knots or more. In this study, the recovery efficiency of group A was applied (KCG, 2015b) considering the fact that all the skimmer mobilized by time lag in the WuYiSan accident scenario is oleophilic skimmer.



(*a*) (*b*)

Fig. 2 Recovery efficiency according to oil viscosity (a) and wind speed (b) (Kim et al., 2018).

2.1.4 Calculation Condition

Table 1. Oil spill accident scenario of WuYiSan case

Oil spill time	2014. 1. 31. 10:00
Recovery period	2014. 1. 31. 11:00~2014. 2. 4. 14:00
Spill volume	926.3~1025.3 ㎘
Spilled oil (amount)	Crude Oil (559,9 ㎘) Naphtha (334.4 ㎘) Oily mixture (32~131 ㎘)
Wind speed	8~10 m/s

In this study, the oil pollution accident of WuYiSan in Yeosu was applied on January 31, 2014 as an example to estimate the recovery capacity of the recovery system using the skimmer. Table. 1 shows the oil spill time, recovery period, spill volume and the wind speed at the actual accident. The accident vessel collided with the Pipeline at Yeosu GS Caltex Crude Oil 2 Pier (KCG, 2015b). Oil such as crude oil and naphtha leaked into the sea at the same time. The spilled oil volume is 559.9 kl of crude oil, 334.4 kl of naphtha and 32 ~ 131 kl oily mixture (KCG, 2015b). The response have focused on mechanical recovery through skimmer considering that accidental areas are ecologically and environmentally sensitive (KCG, 2015b). Therefore, the WuYiSan accident is regarded as an appropriate example for comparative analysis of recovery performance through mechanical recovery system.

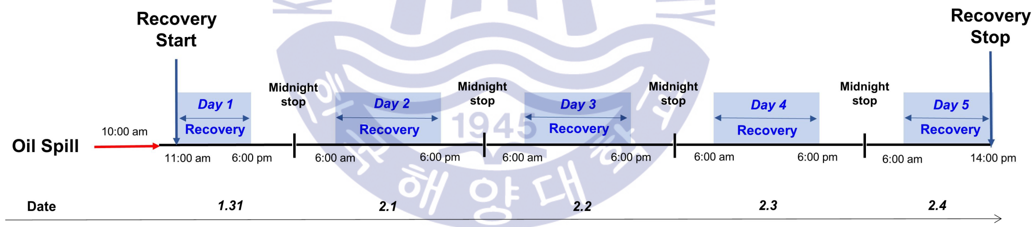


Fig. 3 Timetable of WuYiSan oil spill accident scenario (Kim et al., 2018).

The accident scenarios are shown in Fig. 3. The oil was leaked from the sea at 10:00 on January 31, and clean-up operation was carried out at 11:00 am. It was decided that the marine control was ended at 14:00 on February 4. The oil was discharged at once and the weathering and oil properties of the remaining oil were calculated assuming that the oil was present for 100 hours until the end of the mechanical recovery.

Table 2. Calculation conditions of WuYiSan oil spill accident scenario.

Calculation conditions		Input value
Spilled oil remaining time		100 h
Recovery time		51 h
Initial spill volume		894.3 ㎘ (Crude Oil (559.9 ㎘), Naphtha (334.4 ㎘))
Crude oil type	case 1	Forties Blend Crude oil (API 40.5)
	case 2	Basrah Light (API 33.7)
Number of skimmers		34
Wind speed		8 m/s
Sea water temperature		7 ℃

The mobilization time and number of response vessel was calculated according to the timetable of actual accident (KCG, 2015b). From 6:00 pm to 6:00 am, it was assumed that recovery work was impossible due to obstruction of sight due to sunset. In order to analyze the recovery, it is assumed that only the offshore oil is collected except the coast. In addition, only the recovered amount through the skimmer was calculated except the dispersant and the sorbent.

Table 2 shows the conditions for the weathering process of the spilled oil and the calculation of the response scenarios, reflecting the actual accident conditions (Table 1). The volume of spilled oil was 559.9 kl of crude oil and 334.4 kl of naphtha according to the actual accident information. However, the oily mixture is not known for the accurate characterization of the oil, and is relatively small compared to the amount of crude oil and naphtha discharged. So it is excluded from the calculation of weathering and recovery performance. Therefore, the total amount of crude oil and naphtha discharged was calculated as 894.3 kl.

In the actual accident, the oil pipeline of GS Caltex was destroyed and the crude oil was leaked. However, There was a lack of specific information on the oil type. Therefore, considering the loaded crude oil at ship and predicted crude oil as leaked oil type (KCG, 2015b), it was classified as Forties blend crude oil and Basrah light. The results of the weathering and recovery performance calculations for the types of spilled oil are shown in Table 2. The total number of skimmer mobilized in the accident during the 5 days is 34 unit, including the Tongyoung, Busan and Changwon as well as the control equipment of accident area at Yeosu. The recovery performance of the each skimmer was calculated by taking into consideration the specifications of 34 units and the storage tank capacity by reference (KCG, 2017). The wind speed was set at 8 m/s, and the temperature was set at 7 ℃ using the data of Korea Hydrographic and Oceanographic Agency (KHOA) in 2014 for the sea environment.

2.2 Result of Recovery Capacity Estimation: Comparative Analysis of WuYiSan Oil Spill Case

2.2.1 Characteristics Analysis of Oil Spill according to Weathering

When the oil spills at the sea, some of the oil is removed from the sea surface by evaporation and natural dispersion. The evaporation volume of crude oil and naphtha until the end of spilled oil remaining time was calculated through eq. (2). The naphtha was highly volatile and most of it evaporated within one hour of spill, and all of it evaporated within 2 hours.

This means that about 37 % of the total spilled oil, which corresponds to the evaporation volume of naphtha, can be excluded from oil spill response. Forties Blend is characterized by low specific gravity and low viscosity and is evaporated to about 127.2 kl within the first hour of spill. It is about 15 % of total spilled of volume. Basrah Light is crude oil with a higher specific gravity than Forties Blend and evaporates to about 92.3 kl within 1 hour.

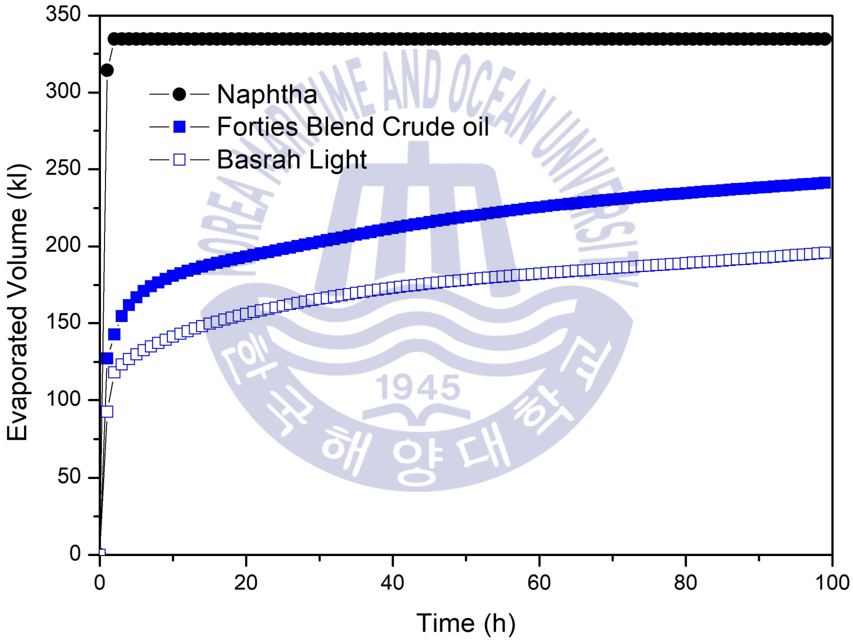


Fig. 4 Evaporated volume of spilled oil over time (Kim et al., 2018).

As the relatively volatile components of the initial hydrocarbon components rapidly evaporate, Fig. 4 shows a sudden change in the slope. Especially, in the case of Forties Blend, the spread area is widened due to the characteristics of light oil having a low viscosity and a high initial spread ratio. This rapid evaporation and spreading can change the characteristics of the spilled oil and affect the overall recovery system. Forties Blend evaporates rapidly in the first hour and evaporates at a final rate of 241.6 kl by 100 hours. Basrah Light has a final evaporation of 185.6 kl, which is about 76 % of the Forties Blend.

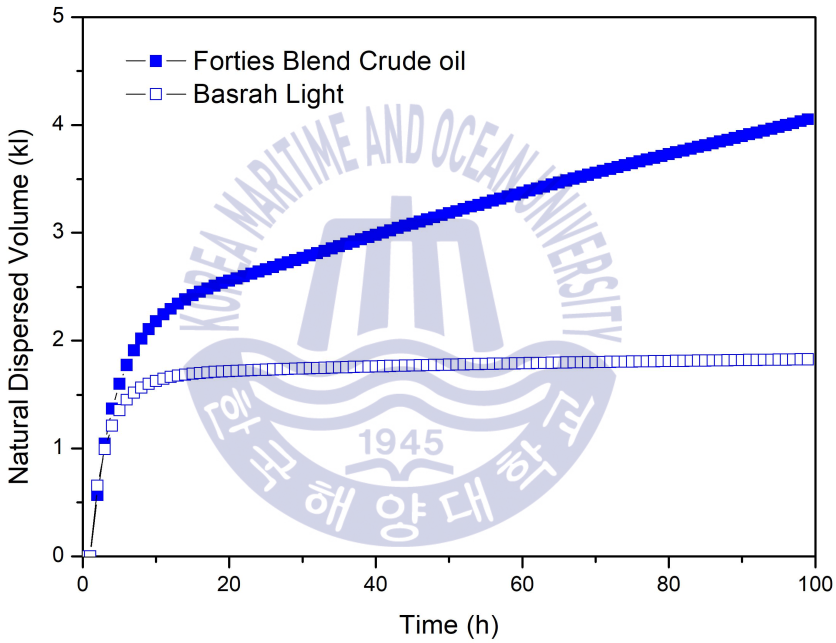


Fig. 5 Naturally dispersed volume of spilled oil over time (Kim et al., 2018).

The volume of natural dispersion of oil is calculated and shown in Fig. 5. The calculated results represent the natural dispersion of the two crude oils calculated by eq. (3). The Naphtha is not included in the calculation because the total amount has evaporated initially. The volume of natural dispersion is influenced by the marine energy with the oil characteristics and the wind speed. Forties Blend and Basrah Light are finally dispersed 4.1 ㎘ and 1.7 kl respectively according to the wind speed of 8 m/s. Within 10 hours of the initial accident, the amount of natural dispersion per unit time tends to be large. However, the viscosity of the oil increases gradually due to the influence of evaporation and emulsification over time. The natural dispersions of the two crude oils calculated are less than 1 % of the total spilled oil and smaller than the evaporation.

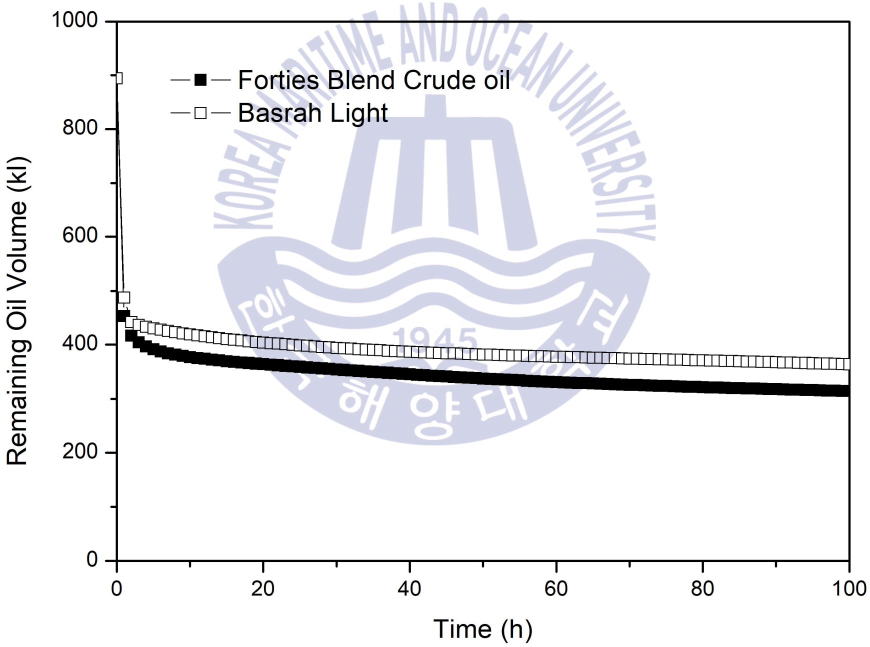


Fig. 6 Remaining oil volume of spilled oil over time (Kim et al., 2018).

Fig. 6 shows the remaining volume of spilled oil excluding the volume of evaporation and natural dispersion over time. Based on the evaporation volume, natural dispersion volume and Fig. 6, the remaining oil volume of

Forties Blend and Basrah Light are about 35 % and 41 % of total volume, respectively. This means the percentage of oil that needs to clean-up at sea from the perspective of response plan. In the case of the WuYiSan accident, it is necessary to estimate the response resources that can clean-up with the spilled oil of 314.2 ㎘ or 374.2 kl, which corresponds to 35 % or 41 %.

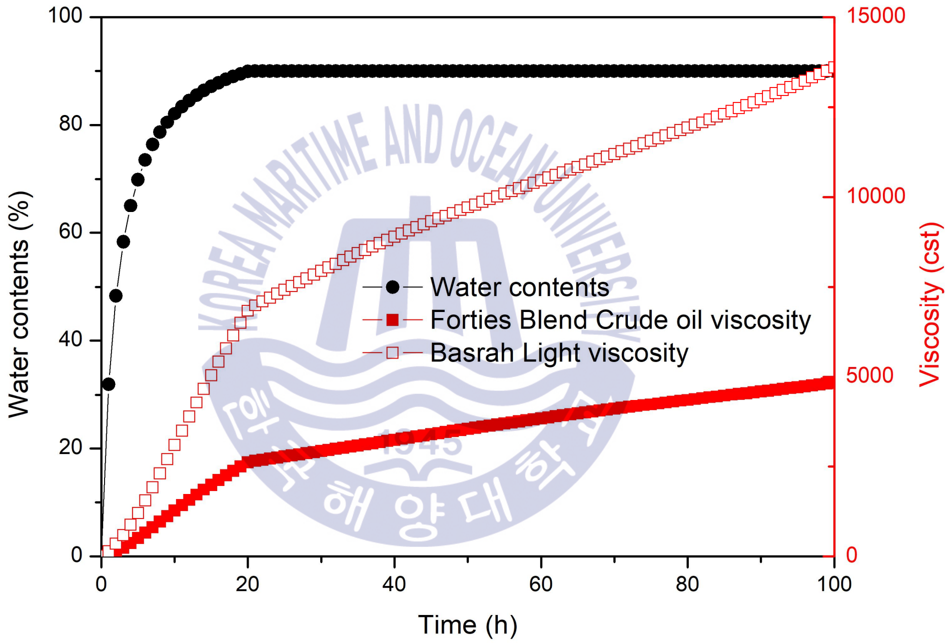


Fig. 7 Changes of water contents and viscosity of spilled oil over time (Kim et al., 2018).

The water content of the oil due to the emulsification is shown in Fig. 7. The water content of Forties Blend and Basrah Light was calculated the same. This is because the eq. (4) according to water contents is a function of wind speed, and both oil type have the same wind speed conditions. The oil forms an emulsion that absorbs water, which accelerates the viscosity increase of the spilled oil. At the beginning, the viscosity of oil tends to increase sharply. These results are due to the rapid initial evaporation and the increase in emulsion. The viscosity of Forties blends increase about 3000 cst within 20 hours as the water contents increases. After the water content of the oil reaches up to 90 %, the water contents does not proceed any more and the slope of the viscosity decreases. After 20 hours, it increases up to about 5000 cst by the end of spilled oil remaining time mainly due to evaporation. Basrah Light behaves similar to Forties Blend and increases its viscosity to a maximum of about 13,500 cst. The viscosity increase of the spilled oil due to the evaporation and emulsification may decrease the efficiency of the recovery operation, which affects the reduction of the recovery efficiency mentioned in the section 2.2.2.

2.2.2 Recovery Efficiency and Recovered Amount of Skimmer

Fig. 8 shows the range of change in the recovery efficiency of the skimmer due to the change in viscosity (see Fig. 2 (a)) with weathering after the accident. As the viscosity of Forties Blend increases to about 5000 cst for 100 hours, the recovery efficiency tends to decrease. At the early 20 h of the accident, the recovery efficiency by viscosity is as high as 81 ~ 96 %. As the recovery efficiency gradually decreases, the minimum and maximum ranges tends to increase. When the viscosity of the spilled oil rises to the maximum, the recovery efficiency ranges from 30 to 75 %. For Basrah Light, the recovery efficiency ranges from 20 to 59 % when the viscosity increases to 13,500 cSt. The range of recovery efficiency by wind speed (see Fig. 2 (b)) is 21 to 58 %. This means that the recovery efficiency by wind is lower than the recovery efficiency by viscosity, but the range of recovery efficiency by wind does not change over time according to constant wind speed (8 m/s) in accident scenarios. Therefore, only the recovery efficiency by viscosity was considered in order to consider the decrease of the recovery efficiency over time in the calculation of the recovery capacity of the skimmer of this study. Fig. 8 shows that the change in the properties of the oil over time can reduce the efficiency of the mechanical recovery operation through the skimmer, thereby reducing the recovery capacity. Also, if the wind speed varies with time rather than a constant wind speed, the recovery capacity reflecting the recovery efficiency change of the skimmer can be estimated according to the collection time. Therefore, for rational response strategies, such performance changes should be fully considered.

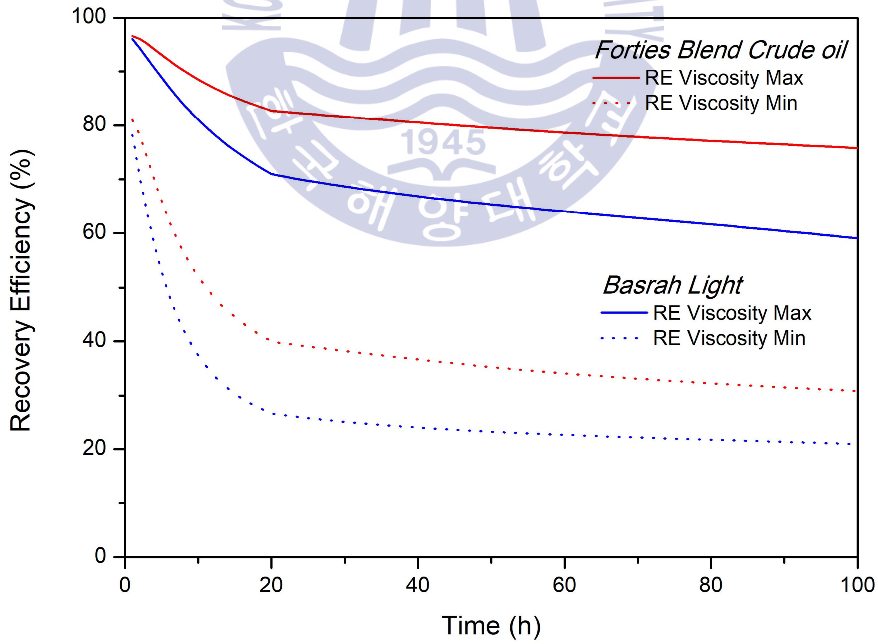


Fig. 8 Skimmer recovery efficiency variation due to viscosity change (Kim et al., 2018).

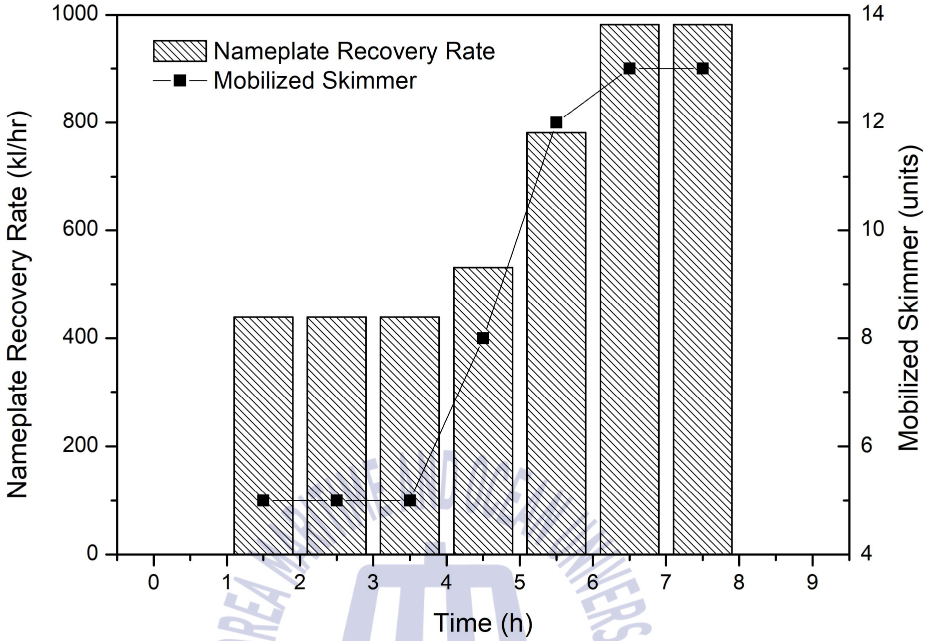
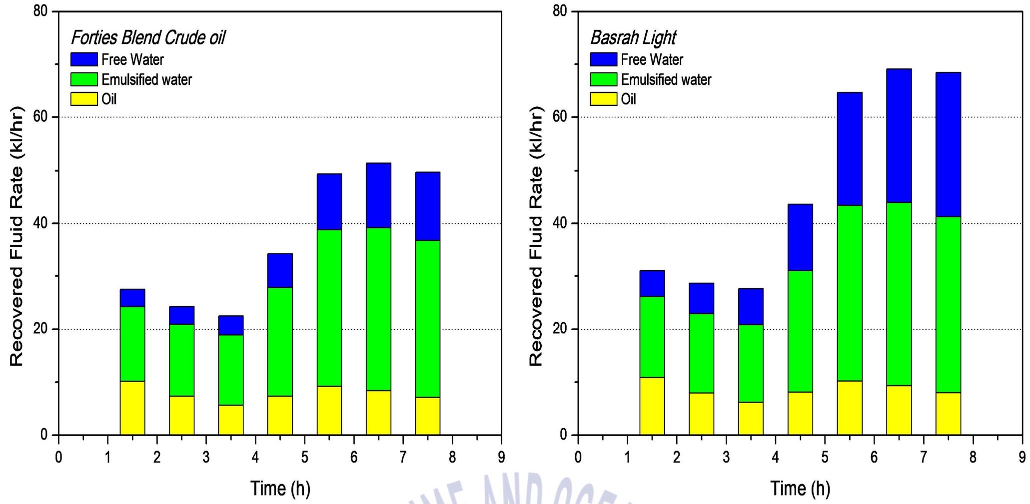


Fig. 9 The number of mobilized skimmers and nameplate recovery rate over time in 1st day (Kim et al., 2018).

The recovered volume of skimmer was calculated over time and compared with actual collection results. The quantity and the capacity of skimmer were different according to the situation time. Fig. 9 represents the nameplate recovery rate and quantity of the skimmer during the first day of the accident. As the emergency response was carried out after 1 hour of the accident, the five skimmer recovered. After that, 3, 4, and 1 skimmer were additionally mobilized after 4, 5, and 6 hours of accidents, respectively. A total of 13 skimmer were mobilized on the first day of the accident. nameplate capacity also increased with the quantity of skimmer.



(*a*) (*b*)

Fig. 10 Amount of recovered oil, emulsion water and free water according to Forties Blend Crude oil(a) and Basrah Light(b) using mobilized skimmers over time in 1st day (Kim et al., 2018).

The results of recovered fluid rate of the skimmer mobilized for the first day are shown in Fig. 10. The results show that the oil/emulsion recovery rate (*ERR*), seawater recovery rate, and oil recovery rate (ORR) are calculated from the mobilized skimmer by time lag, which is attributed to eq. (7) and (8). The oil recovery rate is the recovery of pure oil, excluding the emulsified water contained in the oil/emulsion recovered by the skimmer. The calculated recovery does not reflect the oil attached to the shore since it is assumed that only oil present at offshore is recovered. The calculation result of Fig. 10 indicates the recovery result through skimmer from 1 hour after the oil spill at 10:00 on the day of the accident to 8 hours after the end of the first day of recovery. The results of Forties Blend (Fig. 10 (a)) and

Basrah Light (Fig. 10 (b)) are different for the two calculated oil type. When Forties Blend is recovered as shown in Fig. 10 (a), the five skimmer mobilized at the beginning of the accident have a recovery capacity of 27.5 kl/hr including free water. Thereafter, the total recovery capacity tends to decrease until 4 hours before the skimmer is further mobilized. The fresh spilled oil after spillage may be suitable for recovery due to the thick oil film, but over time, mechanical recovery is limited by the spreading of spill oil and subsequent reduction in film thickness. This results in a decrease in the encounter rate of oil per skimmer over time. After 5 hours, it is affected by the film thickness decrease, but the total recovery rate is increased because the skimmer is additionally mobilized. When the type of spilled oil is basrah light (Fig. 10 (b)), the skimmer has a recovery capacity of 30.9 kl/hr including sea water at the beginning of the accident. Because Basrah Light has a relatively higher specific gravity and viscosity than Forties Blend, the film thickness calculated by eq. (1) is relatively thick. Therefore, even when the same sweeping width and towing speed are applied, the amount of recovered oil/emulsion and seawater is higher than that of Forties Blend because it has higher encounters than Forties Blend.

The ratio of recovered oil/emulsion among the total recoveries of Forties Blend during the first hour of recovery is 88 % (Fig. 10 (a)). And 79 % at the end of the first day of collection, with a tendency to decrease with time. This is explained from the calculated results that the recovery efficiency decreases with time and thus the ratio of oil/emulsion recovered through the skimmer decreases. However, Fig. 8 shows that the range of recovery efficiency due to the viscosity shows a result Basrah Light lower than Forties Blend. As a result, as shown in Fig. 10 (b), the total recovery of Basrah Light of 1 day was 28 % higher than that of Forties Blend, but the ratio of oil/emulsion recovered was 68 % lower than Forties Blend. These results indicate that the capacity of the skimmer varies depending on the type of oil, so it is necessary to estimate the response capacity considering the characteristics of the oil spill. Also, considering the result that the ratio of seawater recovered in the low recovery efficiency range is large, it is necessary to estimate the capacity of the waste oil storage tank considering the recovery capacity range according to the oil type.

Table 3. Calculation result of recovered volume of oil, emulsion and free water, number of mobilized skimmers and nameplate rate according to recovery time

Recovery time (days)	Recovered oil/emulsion (㎘)		Recovered oil (㎘)		Recovered free water (㎘)		Number of skimmers (accumulation) (unit)	Mobilized skimmer nameplate rate (accumulation) (㎘/hr)	Actual recovered amount (㎘) (KCG, 2015b)
	case1	case2	case1	case2	case1	case2			
1	206.6	229.4	55.6	61.0	52.5	103.7	13	981	302.8
2	232.8	262.3	23.5	26.2	179.7	438.7	14	1,181	N/A
3	170.9	196.1	17.3	19.6	155.0	397.1	30	3,045	N/A
4	95.3	111.0	9.6	11.1	97.0	254.8	34	3,445	N/A
5	33.8	39.7	3.4	4.0	37.6	101.5	34	3,445	N/A
Sum	739.3	838.6	109.5	121.9	521.8	1295.7	34	3,445	811.6

* note: case 1 and 2 refer to Forties Blend Crude oil and Basrah Light, respectively, listed in Table 2

Recovered oil/emulsion, recovered oil and recovered free water, skimmer cumulative quantity, nameplate capacity and actual recovered amount through skimmer by accident date are shown in Table 3. The amount of oil recovered represents the amount of pure oil only, excluding the emulsified water contained in the oil/emulsion. In addition, the recovery of seawater is the recovery of seawater accompanying the change in recovery efficiency, independent of the moisture content in the oil/emulsion. The oil/emulsion recoveries of case 1 (Forties blend crude oil) and case 2 (Basrah Light) were 206.6 kl and 229.4 kl on the first day of the accident, respectively. Also, the recovery of oil excluding emulsified water was 55.6 kl 61.0 kl . As the operation time increases on the second day of the accident, the recovery of oil/emulsion increases but then decreases with time. This is due to the reduction of the overall efficiency of the skimmer, which results in a decrease in the amount of recovery even though the skimmer is additionally used. Decrease in recovery efficiency results in increased seawater among the total fluid recovered. The recovery of seawater increases by the second day of accident as the skimmer mobilization quantity increases. However, after second days of recovery, the oil/emulsion and the recovery of sea water are reduced due to the overall decrease in skimmer recovery performance as well as the decrease in film thickness.

In case of the actual accident shown in Table 3, the waste oil recovered from the sea is 302.8 kl on the first day of the accident and the final recovery result is 811.6 kl. The total recoveries of oil/emulsion calculated from the scenarios were 206.6 kl (case 1) and 229.4 kl (case 2) on the first day of the accident, and 739.3 kl (case 1) and 838.6 kl (case 2) were total recovered. Actual recovery and calculated recovery show similar results. These results imply that if the detailed information such as the field operation and the skill of the worker in the actual accident is input in the recovery capacity estimation model, it is expected that it can be used effectively in the decision making when calculating the recovery capacity.

From the calculation results, it can be seen that the largest amount of waste oil was recovered in the first day and the second day of the accident, in which the initial recovery work was performed. In addition, the results of recovered volume versus mobilization skimmer show the importance of the first action extremely. It can be considered that relatively large amounts of oil/emulsion can be recovered even at a relatively small amount of resources at the beginning of the accident when the mechanical recovery system is used in the recovery work. This indicates that mechanical recovery by skimmer can be effectively applied at the beginning of the accident. Therefore, in order to maximize the effect of mechanical recovery at the initial action of the accident, a sufficient amount of waste oil storage tank or barge should be secured, and a pump capable of discharging the accompanied free water in order to reserve additional waste oil storage space.

When the mechanical recovery system using skimmer was applied in consideration of the weathering effect and the characteristics of the spilled oil in the case of WuYiSan accident, the volumetric change of the spilled oil in case 2 is shown in Fig. 11. The total amount of evaporation of the spilled oil during the simulation time was 59 %, and a considerable part of it evaporated. In 41 % of the remaining oil, 121.9 kl was recovered by 34 skimmer mobilized up to 5 days. The final remaining oil, excluding evaporation and mechanical recovery, is 250.5 kl. These results indicate that about 13.6 % of the spilled oil can be recovered by the mobilized 34 skimmer. This is 48.6 % of remaining oil, excluding evaporation. When the above results were applied to the decision making for the calculation of response resources, it can be considered to use the sorbent or chemical dispersant for the 51.4 % of remaining oil.

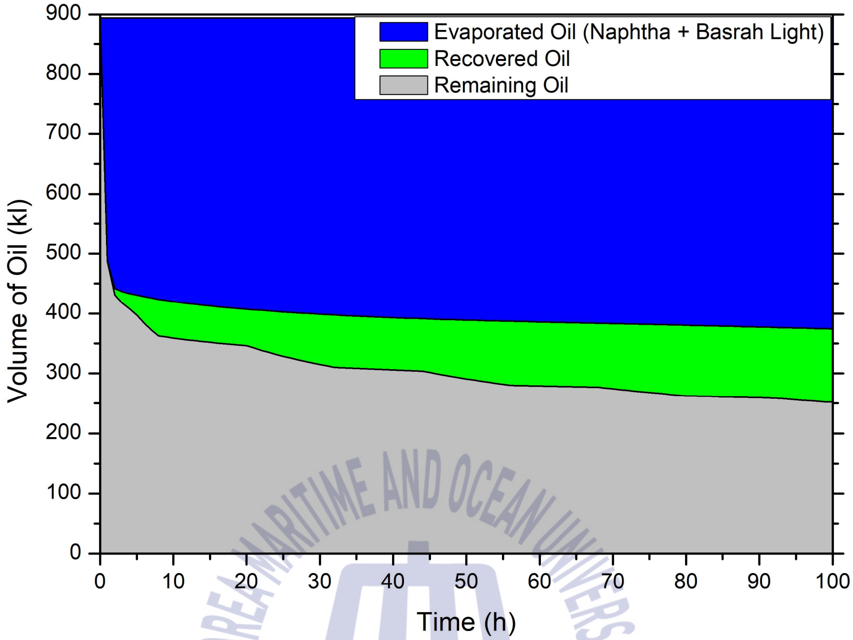


Fig. 11 Mass balance of spilled oil reflecting skimming and weathering of case 2 (Kim et al., 2018).

2.2.3 Comparative Analysis of Estimation of Recovery Capacity by Using Skimmer

The results of the oil/emulsion recovery, the nameplate capacity, and the effective daily recovery capacity (EDRC) calculated in this study are shown in Fig. 12. The nameplate capacity, EDRC, and the calculation results of this study were applied for a total of 51 hours during the 5 days and the same operation time (see Fig. 3) depending on the timetable. The nameplate capacity and the amount of recovery by EDRC tend to increase with the increase of the number of skimmer. The recovery capacity decreases as the daily operation time decreases from 12 hours to 8 hours on the 5th day. The recoveries from the mobilized skimmer nameplate capacity tend to overestimate when compared with the calculated recoveries. In addition, It is also overestimated to compared with actual recoveries of 302.8 kl and final recoveries of 811.6 kl shown in Table 3. This is due to the accumulation of the skimmer mobilized according to the date of recovery in Table 3, resulting in an increase in the total nameplate capacity. The efficiency coefficient (0.2) is applied to the EDRC estimation method, which is relatively small compared to the recovery of the nameplate capacity. However, the recovery of EDRC tends to depend on the nameplate capacity of the mobilization skimmer. Therefore, as with the nameplate capacity, it shows an overestimation result to compared with the actual result. In this study, the recovery capacity of two types of oil, which are expected to spilled oil, is the closest to the actual amount of the first day. This is a result of reflecting the decrease of the recovery performance due to the spreading and the viscosity increase of the spilled oil.

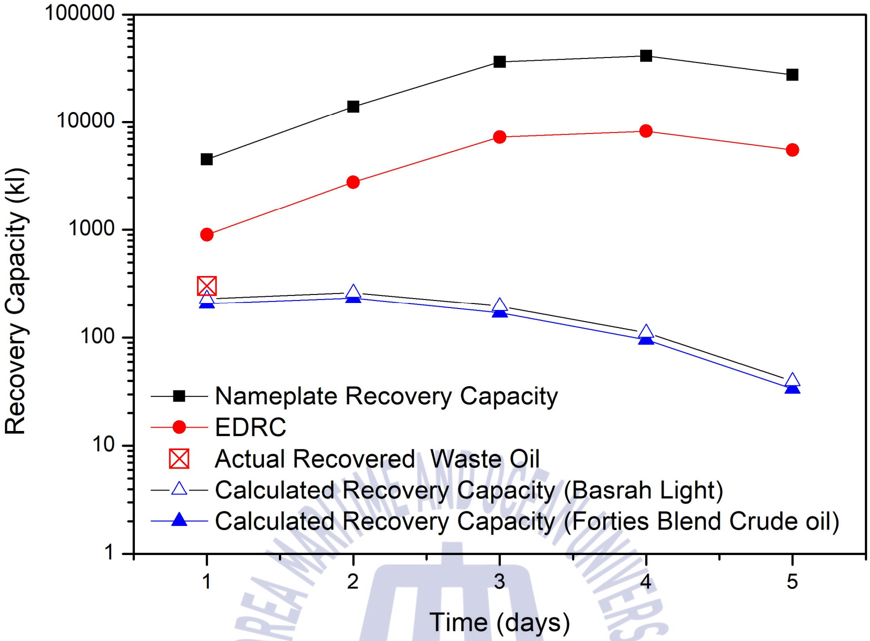


Fig. 12 Comparison of recovery capacity (nameplate, EDRC and calculation of present study) (Kim et al., 2018).

Nameplate capacity is an important consideration used as an indicator for estimating response resources. However, it is estimated when the oil film is sufficiently thick and environmentally ideal. Fig. 12 shows that the nameplate capacity does not reflect the weathering effect of the oil and the recovery performance of each skimmer in the actual accident environment. Therefore, there is a limit to the index for the effective recovery estimation.

Chapter 3 Estimation of a Mechanical Recovery System's Oil Recovery Capacity by Considering Boom Loss

3.1 Quantification of Oil Boom Loss

Oil booms are used to prevent the spread of the oil slick remaining on the sea surface. However, oil loss can occur through various modes, depending on environmental conditions such as currents, wave, and wind, and on oil properties such as oil density and viscosity. Equipment specifications, such as the freeboard and draft of the oil boom, can also influence oil loss (ITOPF, 2011). *TE* is defined as the containment efficiency of the oil boom, considering the loss of encountered oil. The occurrence of oil loss from the boom can be calculated using the loss speed. ASTM (2012) defines three loss speeds; first loss speed, gross loss speed, and critical loss speed.

The first loss speed (U_{1st}) is defined as the lowest speed at which the oil starts to escape, during which oil droplets are continuously lost as they pass below the bottom of the boom (ASTM, 2012). If the oil boom is towed at a high speed, or moored in a fast current, turbulence is generated around the captured oil. At this time, droplets of the captured oil can become separated and lost. As defined by ASTM (2012), gross loss speed (U_{Gross}) is defined as the speed at which massive oil, rather than droplets, is continuously lost. Once the tow speed (U_{Tow}) exceeds U_{1st}, the oil loss volume increases in proportion to the difference between U_{1st} and U_{Tow}. The critical loss speed (U_{Crit}) is the speed at which the oil cannot be captured due to high waves or fast currents such as splash-over, submergence, or planning (ASTM, 2012). U_{Crit} is dependent on the buoyancy, roll response, and heave response of the boom (Amini, 2007). In this study, the loss rate of oil was quantified using the difference between U_{1st} and U_{Tow}.

TE, as defined in eq. (10), correlated with the encountered and lost volumes of oil of the boom. An empirical correlation of U_{1st}, U_{Crit}, and loss rate was modified to quantify *TE* in terms of loss speed and loss rate. In this study, U_{1st} was defined as the minimum speed at which the oil loss is initiated in the encountered oil, and U_{Crit} was defined as the maximum speed at which the oil is fully lost. The loss rate determines the *TE* of U_{Tow} that operates between U_{1st} and U_{Crit}. In this study, the unit of loss speed was expressed in m/s. The tow speed was expressed in knots (m/s), taking into account the conventional operating speed unit.

3.1.1 Modification of Throughput Efficiency

Though *TE* is a key factor in estimating the recovery potential, the models of previous studies (Dale, 2011) and the constant loss rate model in this study, assign it a constant value (usually 0.75). In addition, previous studies used a constant *TE* regardless of the type of oil and the severity of the marine environment. Therefore, there is a need for more studies that consider the variation of *TE* according to accidental and environmental conditions.

To overcome this problem, a modified definition for *TE* was adopted in the variable loss rate model in this study. This new model accounts for oil loss, i.e., the performance of the boom, as shown in eq. (11).

$$TE(\%) = \frac{ER - Oil\,Loss\,Rate}{ER} \times 100 \tag{11}$$

Though the constant loss rate model used a constant *TE* value, the variable loss rate model was able to simulate variations in *TE* through time. The revised *TE* in eq. (11) can be calculated by considering both the oil loss speed and oil loss volume. In this study, *ERR* was regarded as a concept of collecting performance rather than recovery performance. Oil loss occurs once the tow speed exceeds oil loss speed. When the tow speed is lower than the oil loss speed, the *TE* is 1, since there is no loss rate. In this case, the recovery system can recover all of the encountered oil. If the tow speed exceeds the oil loss speed, *TE* returns values of between 0 and 1, depending on the loss rate.

Ohmsett(Oil Spill Research and Renewable Energy Test Facility) is the official testing laboratory for full-scale oil spill equipment, testing the performance of mechanical, electrical, and chemical systems in a variety of realistic sea environments. In this study, empirical correlation was suggested using data accumulated from 1975 to 2000 in Ohmsett and CCG (Canadian Coast Guard) to correct *TE*.

3.1.2 First Loss Speed

The entrainment failure of the oil boom can occur at relatively low speeds compared to other modes of oil loss. It is one of the most sensitive phenomena that can limit the containment capability of oil boom (Brown et al., 1996; Goodman, R. H., 1997; ITOPF, 2011; Oebius, 1999). Wicks (1969) conducted a study on the three different oil loss regions (headwave, intermediate, and near-boom), and observed that oil droplets are separated from the headwave by high water velocities. They found that this phenomenon was affected by the Weber number (*We*), which is expressed as the balance of the inertia force and surface shear. Agrawal and Hale (1974) found through an experimental study that the critical We value at which entrainment occurs in the headwave region is 28.2, twice the value presented by Wicks (1969). With respect to the effect of the Kelvin-Helmholtz wave, which is formed by instability at the oil-water interface, several studies have observed the formation of oil droplets by breaking waves (Leibovich, 1976; Milgram and Houtent, 1978). Leibovich (1976) expressed the region at which entrainment occurs, as displayed in eq. (12):

$$U_{KH} = (2\frac{\rho_w + \rho_o}{\rho_w \rho_o}\sqrt{\sigma g(\rho_w - \rho_o)})^{1/2} \tag{12}$$

where U_{KH} is the Kelvin-Helmholtz threshold instability velocity, ρ_w is the water density, ρ_o is the oil density, g is gravitational acceleration, and σ is the oil-water surface tension.

Lee and Kang (1997) proposed an empirical equation related to the threshold speed at which oil entrainment occurs, based on U_{KH} and the oil density. Amini and Schleiss (2009) modified the constant value of the empirical equation presented by Lee and Kang (1997) by considering the initial failure velocity in the presence of wave steepness, as shown in eq. (13):

$$\frac{U_{1st}}{\sqrt{gD}} = 1.98\frac{U_{KH}}{\sqrt{gD}} + 0.08\sqrt{\triangle} - \frac{5}{3\sqrt{gD}}s \tag{13}$$

where U_{1st} is the first loss speed, D is the oil boom draft, $\triangle$ is the oil density relative with water, and s is the wave steepness. U_{KH} is derived from eq. (12).

The effects of wave steepness on the first loss speed were experimentally tested by Ohmsett and Canadian Coast Guard. This test data was then evaluated by adjusting wave height and wave length in a subsequent study (Schulze, 2001). The majority of the data were classified according to their wave steepness, at values of 0, 0.021, and 0.065. This wave steepness(s)

represents the ratio of wave height and wave length, as shown in Fig. 13.

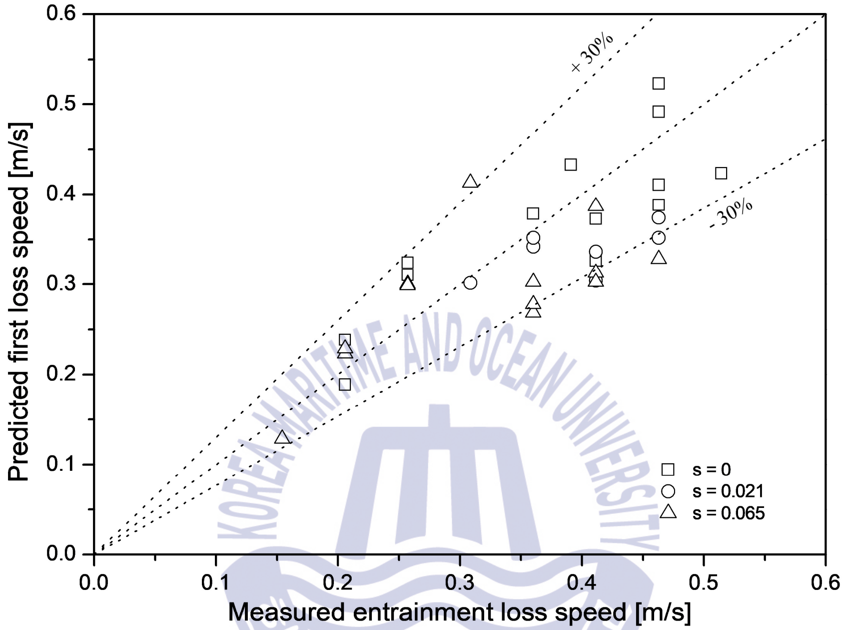


Fig. 13 Comparison of predicted first loss speed to measured entrainment loss speed, based on eq. (13) and the measured entrainment loss speed of Schulze (2001) (Kim et al., under review).

3.1.3 Critical Loss Speed

U_{Crit} is the loss speed at which the oil can no longer be collected normally, because of the instability of the oil boom. Previous studies (Potter.S, 2003) have evaluated the effect of waves and the B/W ratio on the performance of the oil boom. The *B/W* is the ratio of the buoyancy and weight of the oil boom. Schulze (2001) summarized experimental data on the planning, submergence, and splash-over loss speed of the boom. In this present study, the critical loss speed was proposed as a function of the wave steepness and B/W ratio in order to quantify it, as shown in Fig. 14. U_{Crit} approaches U_{1st} in poor conditions with high wave steepness, indicating that critical losses can occur immediately. The decrease in U_{Crit} is noticeable at B/W ratios of <10.

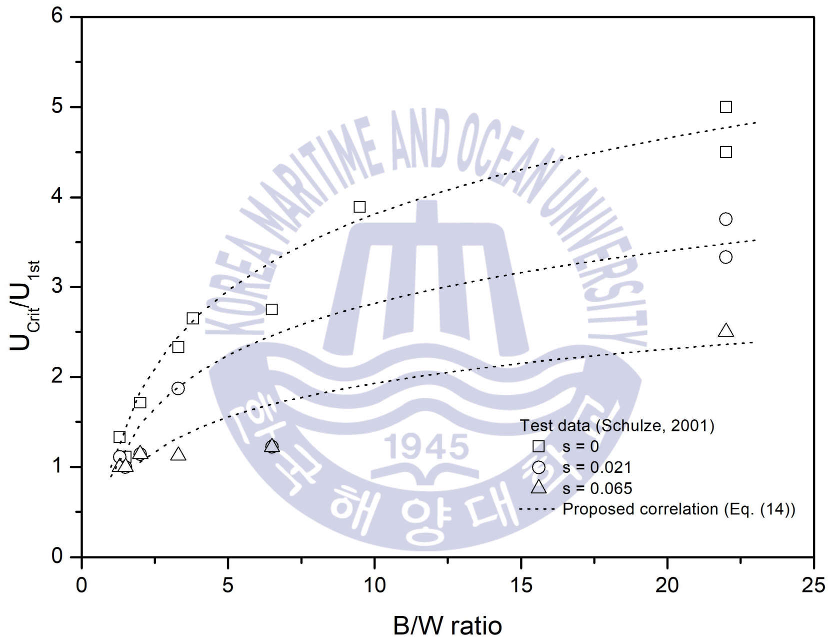


Fig. 14 Critical loss speed according to B/W ratio and wave steepness (Kim et al., under review).

The critical loss speed for an oil boom with flexible skirt depends on whether it is classified as a curtain or an inflatable type. Booms with flexible skirts tend to have high B/W ratios making them suitable for use during roll and heave motions on the sea surface (Amini, 2007). In this study, the ratio of U_{Crit} to U_{1st} is correlated as a function of the B/W ratio, as shown in eq. (14):

$$\frac{U_{crit}}{U_{1st}} = (1.22 - \sqrt{7s})\ln(B/W) + (1 - 5s) \tag{14}$$

3.1.4 Loss Rate

In order to quantify the performance of the oil boom, it is crucial to know not only when oil loss occurs, but also the volume of oil being lost. The former is related to the loss speed and the latter is related to the loss rate. The loss rate of the oil captured in the boom increases proportionally to the difference between the tow speed and the loss speed. The majority of previous studies that have estimated the loss rate used empirical forms obtained by correlation between laboratory data and field data (Agrawal and Hale, 1974; Amini et al., 2008; Fannelop, 1983; Lindenmuth et al., 1970). The empirical loss rate equation of Lindenmuth et al. (1970) and Agrawal and Hale (1974) was described in terms of dimensionless numbers. The study of Fannelop (1983) was carried out just for one type of test oil, and therefore, it is not sufficient to estimate the loss rates of various oil types. Amini et al. (2008) proposed a loss rate model according to the draft of the oil boom, volume of the captured oil, and oil loss speed, developing an empirical equation at low viscosity.

Schulze (2001) summarized experiments on the oil boom loss rate carried out by Ohmsett and Canadian Coast Guard. These experiments exhibited loss rates in excess of 0.1 knots (0.051 m/s) and 0.3 knots (0.154 m/s) at the first loss speed. Among the variables of the experimental conditions, the oil boom draft and the preload oil volume, which represents the volume of oil captured by the oil boom in the test tank, were the key factors influencing the oil loss rate. The loss rate data from Schulze (2001) and the loss rate model presented by Amini et al. (2008) are shown in Fig. 15. These results show that the loss rate can be correlated with the draft and preload oil volume regardless of the oil boom type. Furthermore, it can be seen that the loss rate is proportional to the preload oil volume and I_U, which describes the difference between U_{1st} and U_{Tow}, while the draft is inversely proportional to the loss rate.

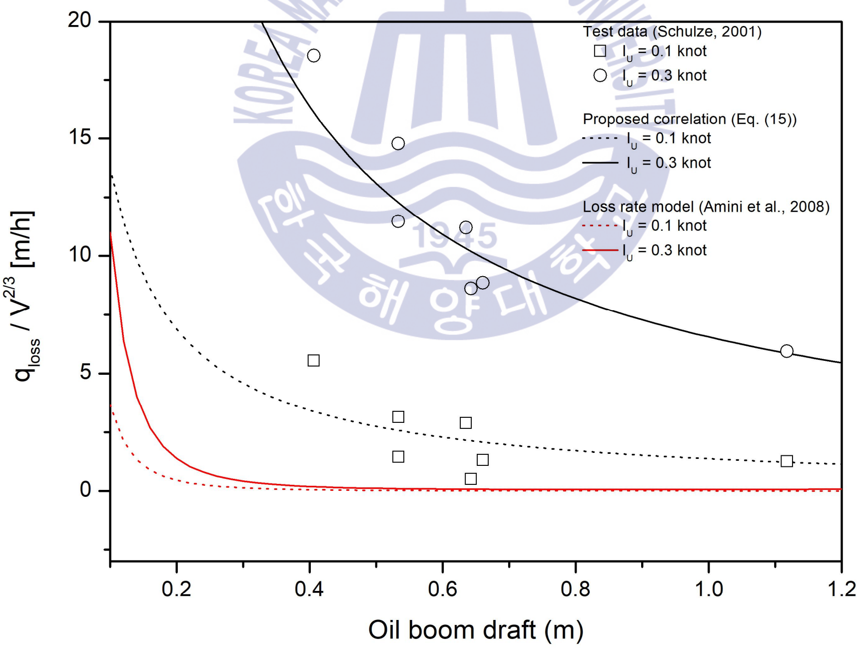


Fig. 15 Loss rate per preload volume ($q_{loss}/V^{2/3}$) according to the draft of the oil boom and the difference between the tow speed and the first loss speed (Kim et al., under review).

Amini et al. (2008) represented their loss rate model as a function of both the boom draft and the oil volume. However, their model is only applicable for low-draft booms, because the prototype boom in their experiment had drafts of 0.1 and 0.2 m. Therefore, as shown in Fig. 15, their loss rate converges towards zero for drafts larger than 0.4 m. In contrast, the draft in the test data reported by Schulze (2001) was larger than 0.4 m, which corresponds to the draft size of most practical oil booms. The data of Schulze (2001) is therefore not directly compatible with the empirical equation proposed by Amini et al. (2008).

Despite the insufficient volume of test data, it is worthwhile to suggest an empirical correlation for the performance of an oil boom. In this study, the loss rate was therefore proposed to be an exponential function of I_U. Furthermore, a correlation between the preload volume and the draft was proposed based on the test data of Schulze (2001). In this study, the empirical correlation is expressed as shown in eq. (15); this is only applicable for booms with a draft higher than 0.4 m. In calculating the recovery capacity, the preload oil volume (*V*) in eq. (15) is regarded as the volume of oil encountered per unit time (*ER*). The loss rate is then reflected by *TE*, which represents the oil boom efficiency of the recovery system.

$$q_{loss} = \frac{0.63\,V^{\frac{2}{3}}}{D} exp(15.17 I_U) \tag{15}$$

Here, q_{loss} is the oil loss rate in m^3/h and *V* is the preload oil volume in m^3/h.

3.2 Revised Recovery Capacity Estimation Model by Considering Variable Loss rate

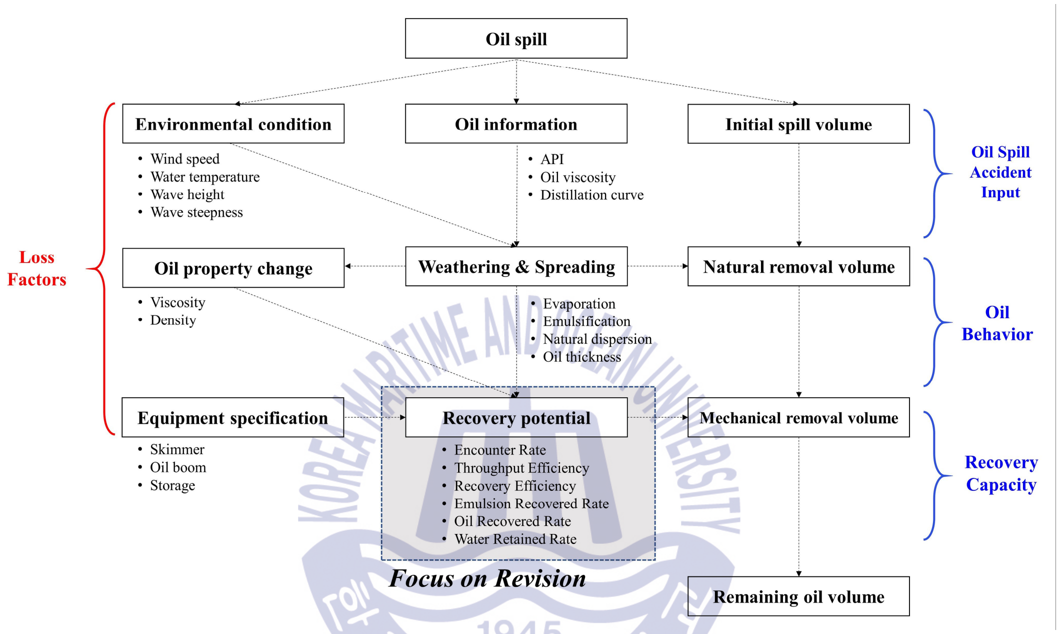


Fig. 16 Schematic of the model for estimating the recovery capacity (variable loss rate model) (Kim et al., under review).

Fig. 16 shows an outline of the revised recovery capacity estimation model (herein the “variable loss rate model“). The variable loss rate model consists of three parts: the oil spill accident input, calculation of the oil’s behavior, and calculation of the recovery capacity. The oil spill accident input involves setting the input values for the environmental conditions, oil information, and initial spill volume. The weathering and oil thickness change are then calculated, accompanied with the physical and chemical behavior of the oil. The equipment specifications and the oil behavior are both critical factors in estimating the recovery capacity. The recovery system removes the oil mechanically from the sea surface; therefore, the remaining oil volume can be estimated by considering the interaction of mechanical and natural removal processes.

In this calculation process, focus was given to improving the recovery capacity. the loss factors were regarded to be factors representing the marine environment, oil, and equipment.

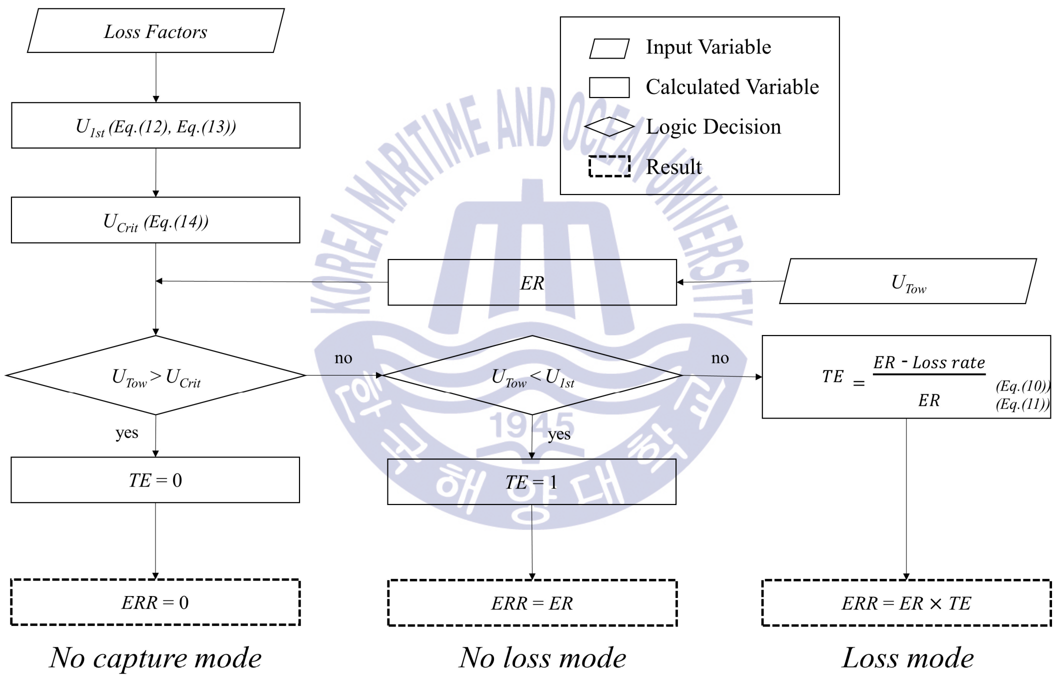


Fig. 17 Calculation procedure for quantifying boom loss (Kim et al., under review).

The detailed procedure for calculating *ERR*, using the developed correlations for the loss speed and the loss rate, is illustrated in Fig. 17. *ER* can be calculated for a given value of U_{Tow}. Furthermore, U_{1st} and U_{Crit} can be calculated using the developed correlations in terms of s, ρ_o, *D*, and *B/W*. *ERR* can be estimated by calculating *TE* based on the aforementioned loss speeds. U_{1st} and U_{crit} are the criteria for determining the occurrence of oil loss. If U_{Tow} exceeds U_{crit}, the oil boom cannot normally capture the oil; this is defined as the "no capture mode." In this condition, *TE* is zero regardless of the loss rate, because the captured oil is completely lost. If U_{Tow} is lower than U_{1st}, then none of the encountered oil is lost, termed the "no loss mode." The "loss mode" refers to instances, where U_{Tow} lies between U_{1st} and U_{Crit}. Depending on the loss rate, *TE* varies from 0 to 1, as expressed in eq. (11). The obtained *TE* is then an estimate of how much of the captured oil is lost. This calculation process of *TE* and *ERR* is performed every hour. By accumulating the calculated *ERR*, the total volume of the oil collected is obtained, which determine the total recovery capacity.

3.3 Results of the Sensitivity Study

Sensitivity studies were carried out by varying some of the factors for the model developed in Section 3.2. The boom loss is dependent on the oil density, wave steepness, tow speed, draft, B/W ratio, etc. First, the relationships among the oil density, wave steepness, and tow speed were studied. Fig. 18 show changes in U_{1st} and U_{Crit} according to changes in oil density (API) and wave steepness, for a U_{Tow} of 0.5-1 knots (0.257-0.514 m/s).

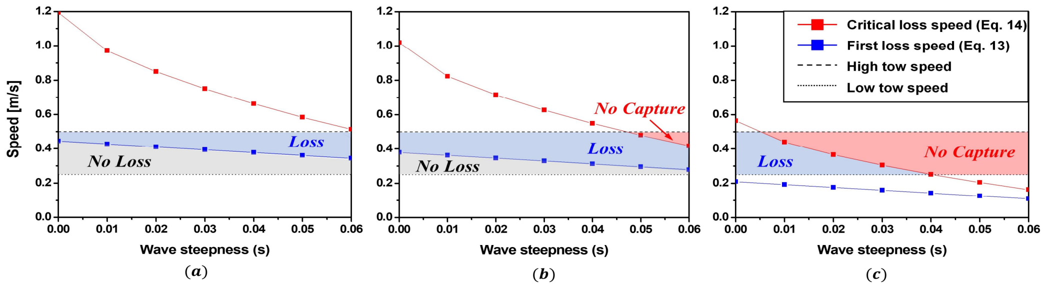


Fig. 18 Effects of wave steepness and tow speed on oil boom loss for API 48 (a), API 28 (b) and API 15 (c) oil (B/W ratio = 4, boom draft = 0.6 m) (Kim et al., under review).

The smaller oil densities correspond to higher U_{1st} and U_{Crit} values. The extent of the oil loss zone also varies according to wave steepness. When the API is 48 (a) and 28 (b), U_{1st} is consistently higher than the lowest U_{Tow} value (0.257 m/s), implying that no loss range in the tow speed exists for these oil densities. Therefore, when the tow speed is kept low, all encountered oil could theoretically be collected regardless of wave steepness. In contrast, heavy oil with an API of 15 (c) has a very low U_{1st} across all wave steepness values. Its U_{1st} is approximately a half of oil with an API of 48. Hence, the API 15 oil is continuously lost across the illustrated range of tow speeds.

At higher operating tow speeds than U_{Crit}, there is a large “no capture zone“ for the API 15 oil, in which the oil is fully lost. The higher API oils tend to have smaller “no capture zones,“ which results from the fact that U_{Crit} is proportional to API. When the tow speed is kept as constant, the high API oils can be recovered even during sea conditions with high wave steepness values. In other words, since no oil loss occurs within the range not exceeding U_{1st}, it is possible to operate in unfavorable environmental conditions by maintaining low tow speeds. When considered from the viewpoint of recovery capacity estimation, this means that a relatively high tow speed can be applied for low API oil. For this reason, the applicable range of tow speed appears to be closely related to the oil density and to weathering processes.

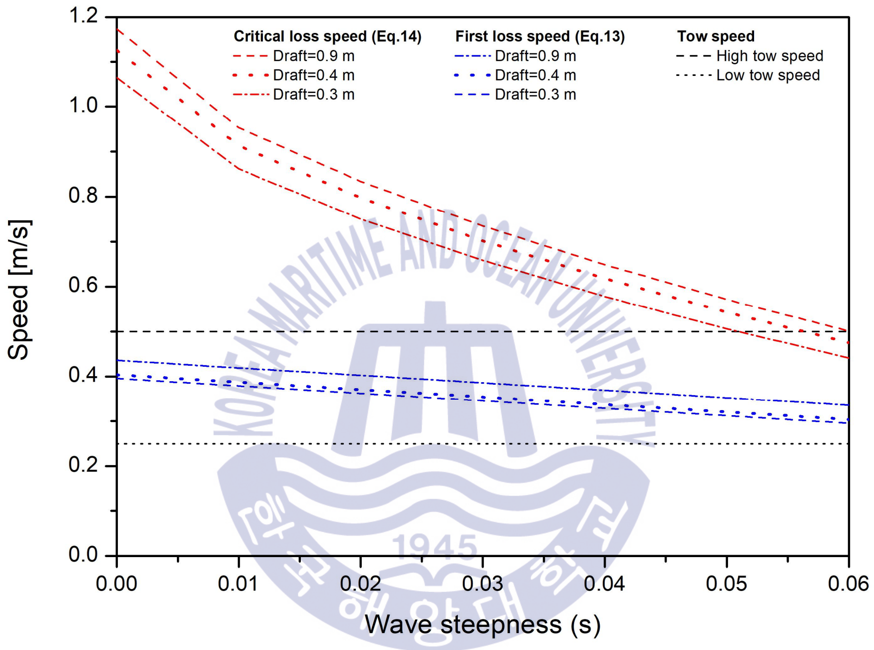


Fig. 19 Effects of draft, wave steepness, and tow speed on oil boom loss (B/W Ratio = 4, API = 37) (Kim et al., under review).

The relationships between the draft, wave steepness, and tow speed were also studied. The draft size was selected based on the Korean oil boom classification standard (KOEM, 2015). In Korea, oil booms are categorized into three groups based on the location of their application. The typical draft sizes of the three groups are 0.3, 0.4, and 0.9 m. Fig. 19 shows that U_{1st} and U_{Crit} both increase with increasing draft size, and with decreasing wave steepness.

This means that a lower draft can be operated at a higher tow speed, compared to higher draft boom. In a similar way to the analysis of the results in Fig. 18, the result of these draft sizes can be related to the tow speed range to distinguish the areas of loss.

A comparison of Fig. 18 to Fig. 19 reveals oil density and draft size have different effects on the loss speed. The calculated loss speed variations due to changing draft size showed a narrower change, compared to those of oil density. This result implies that oil density is a more important factor in determining the loss speed than the size of the draft of the boom.

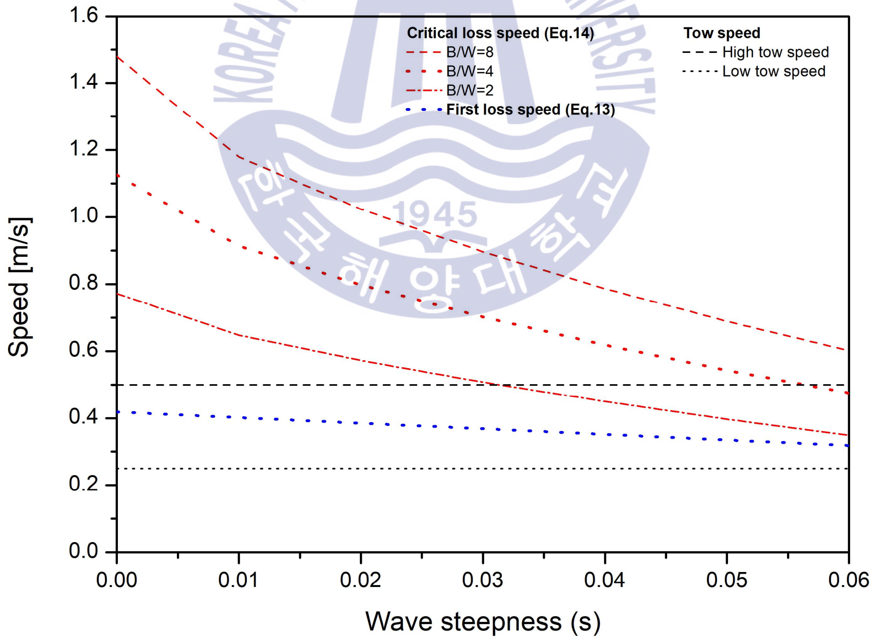


Fig. 20 Effects of B/W ratio, wave steepness, and tow speed on oil boom loss (boom draft = 0.6 m, API = 37) (Kim et al., under review).

Studying the relationships between the B/W ratio, wave steepness, and tow speed (Fig. 20) reveals that the loss speed changed with changes in the B/W ratio. Since the boom draft and API were kept as constants, the first loss speed changed only in response to the wave steepness. The B/W ratio was determined based on the application area proposed by ASTM F1523 (ASTM, 2013). High B/W ratios were linked to higher gradients in the change in loss speed with respect to wave steepness. The B/W ratio determined the size of the no capture region. Furthermore, as the wave steepness increased to values >0.06, U_{Crit} decreased and converged towards U_{1st}.

These sensitivity studies show that the oil density, wave steepness, tow speed, draft, and B/W ratio are key factors in determining oil loss from the boom. They determine the ranges of U_{1st} and U_{Crit}, and the size of the loss region. The key loss factors can be categorized into two groups. The tow speed, which determines the *ER* of the recovery system, and the B/W ratio and draft, which together represent the specifications of the oil boom, can be grouped as adjustable factors. These can be controlled by response operators, to account for the environmental conditions and the properties of the spilled oil. In contrast, oil density and wave steepness can be defined as nonadjustable factors, because they are the given conditions of the accident. In other words, once information on the spilled oil and environmental conditions has been obtained, the response personnel can control only the adjustable factors. The potential capacity of the recovery system can be calculated by selecting the appropriate combination of recovery equipment and then adjusting the operable speed accordingly.

Based on the results of Fig. 19, the oil boom draft appears to have had a relatively small effect on U_{1st}, implying that it is limited in its ability to adjust the response conditions in various accident environments. However, the loss rate can be changed effectively by varying the oil boom draft. An oil boom with a high draft has would have a relatively small loss rate, even if the tow speed were to exceed the first loss speed. As a result, the decrease in the rate of *TE* is small. Therefore, the oil boom draft should be considered to be a key factor. Furthermore, based on the results displayed in Fig. 20, a higher B/W ratio appears to be the best approach to poor marine conditions. Therefore, the B/W ratio should be considered as a factor that can determine the equipment's response, dependent on the marine conditions of the accident in question.

The results of the sensitivity testing in this study highlight that the adjustable factors should be carefully controlled in order to maximize the response strategy. These findings could be utilized in the future development of preparedness strategies, by also considering the nonadjustable factors.

3.4 Results of The Case Study

3.4.1 Spill Scenario of Case Study Calculation

A case study was carried out using the developed variable loss rate-based recovery capacity estimation model. The accident scenario was established by considering the national contingency response plan of Korea. The purpose of the case study was to suggest a relevant adjustable range for the variables that can influence the recovery capacity. The calculation conditions of the spill scenario are summarized in Table 4. It was assumed that the oil spill occurred at 07:00 in Busan, Republic of Korea, and that the mechanical clean-up had a duration off three days. The initial spill volume, consisting of Iranian heavy crude oil, was 500 m3. The weathering and spreading of the oil were calculated every hour. The recovery system started to operate 2 h after the oil spill occurred, and the clean-up was performed for 33 h in total out of the three-day period, as it can only be performed during daylight hours. To calculate recovery capacity, the equipment of the recovery system, including the skimmer and oil boom, was chosen from the World Catalog of Oil Spill Response Products (Poter, 2017). The operating conditions were based on the specifications of the equipment and the normal tow speed (Oebius, 1999). Since this study deals mainly considers the loss of oil from the boom, the offloading time and decanting of storage were not considered.

Table 4. Spill scenario of case study calculation conditions.

Category	Variables	Value		
Simulation time	Calculation time	72 h		
	Recovery time	33 h		
	Calculation unit time	1 h		
Spilled oil	Initial spill volume	500 m3 (Batch spill)		
	Oil type	Iranian heavy (API 30)		
Recovery system	Skimmer model (Nameplate capacity)	Lamor LWS (140 m3/h)		
	Boom type	Boom A	Boom B	Boom C
	Boom model	ACME CONTRACTOR BOOM (Curtain, internal foam)	LAMOR HDB 1300 (Curtain, pressure inflatable)	DESMI RO-BOOM 2000(Curtain, pressure inflatable)
	Draft	0.3 m	0.66 m	1.1 m
	B/W ratio	6.2	9	13
Operating condition	Swath	100m (Boom length/3)		
	Tow speed	0.5 knot (0.257 m/s)		

The case study featured three cases with different wave steepness values and wind speeds: regular, calm, and harbor chop. The calm and harbor chop environmental conditions were selected from data taken from the ocean observatory buoy of Port of Busan, hosted by the Korea Hydrographic and Oceanographic Agency (KHOA), as shown in Table 4. The variations in wave steepness and wind speed are shown in Fig. 21 and Fig. 22, in association with the nonadjustable variables. For the three cases, each with different environmental conditions, we calculated the collecting potential using the variable loss rate-based recovery capacity estimation model developed in this study.

Table 5. Environmental conditions with different wind speeds and wave steepness values.

Case	Environmental condition	Wave steepness (period)	Wind speed [m/s] (period)
Case 1	Regular (average)	0.01 (constant)	5 m/s (constant)
Case 2	Calm	Fig. 21 (2017.07.21.07-2017.07.24.06)	Fig. 22 (2017.07.21.07-2017.07.24.06)
Case 3	Harbor chop	Fig. 21 (2017.01.14.07-2017.01.17.06)	Fig. 22 (2017.01.14.07-2017.01.17.06)

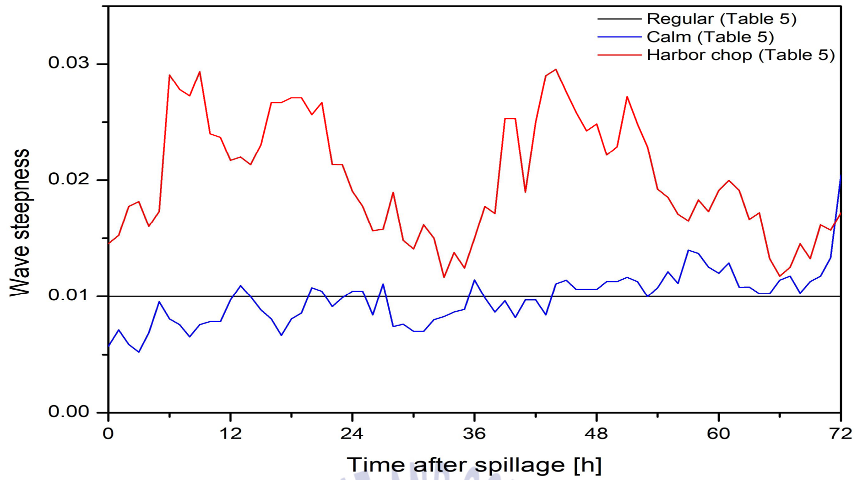


Fig. 21 Wave steepness variation of three environmental cases with time (Kim et al., under review).

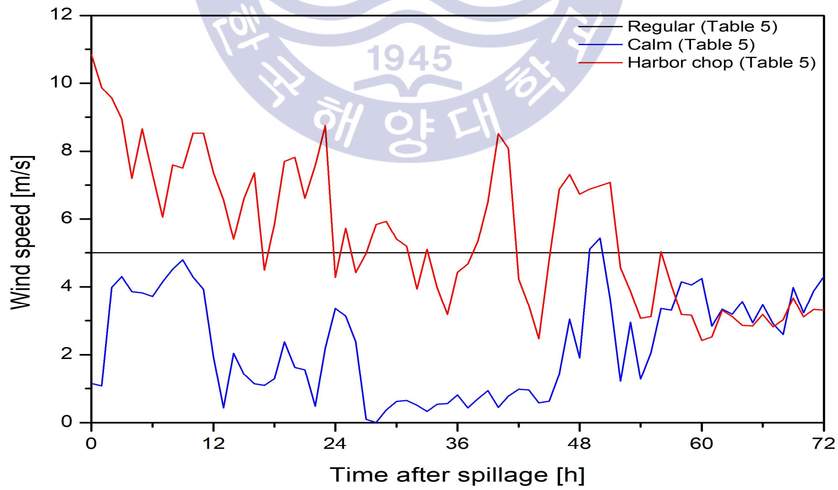


Fig. 22 Wind speed variation of three environmental cases with time (Kim et al., under review).

3.4.2 Results for Tow Speed Adjustment

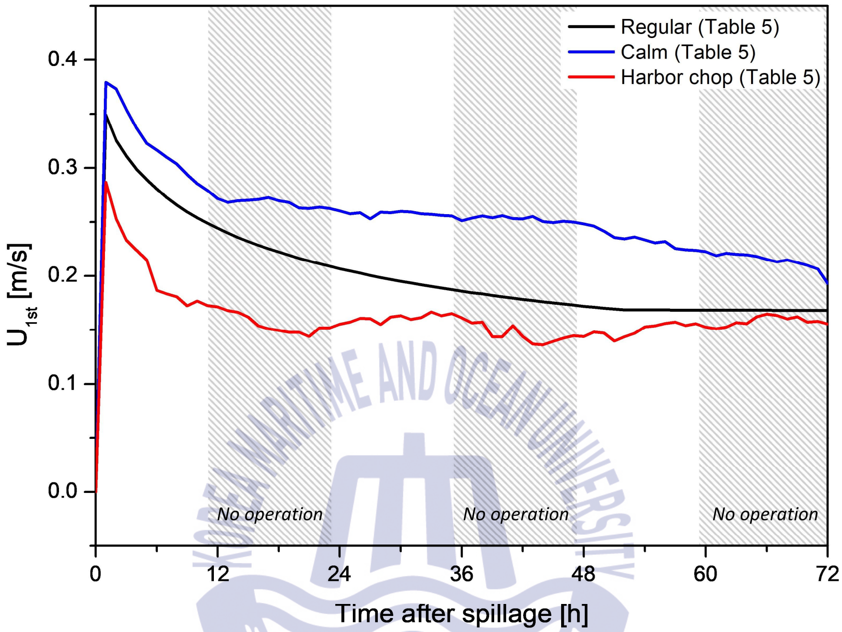


Fig. 23 First loss speed of boom B (Table 4) with spilled time: regular, calm and harbor chop case (Table 5) (Kim et al., under review).

Fig. 23 shows changes in U_{1st} over time for each of the three cases. All three cases were calculated under the same equipment conditions (boom B in Table 4). Despite the fact that the type of oil and specification of boom were both constant, U_{1st} differed increasing time since the spillage. This occurred because the density changes differed due to weathering and variations in wave steepness. While U_{1st} oscillated over time in the cases of calm conditions and harbor chop, during the regular case it instead showed a monotonic decrease, accompanied by increasing density. The calculated results of U_{1st} on the first day show that the high tow speed recovery operation can be applied without any loss of oil.

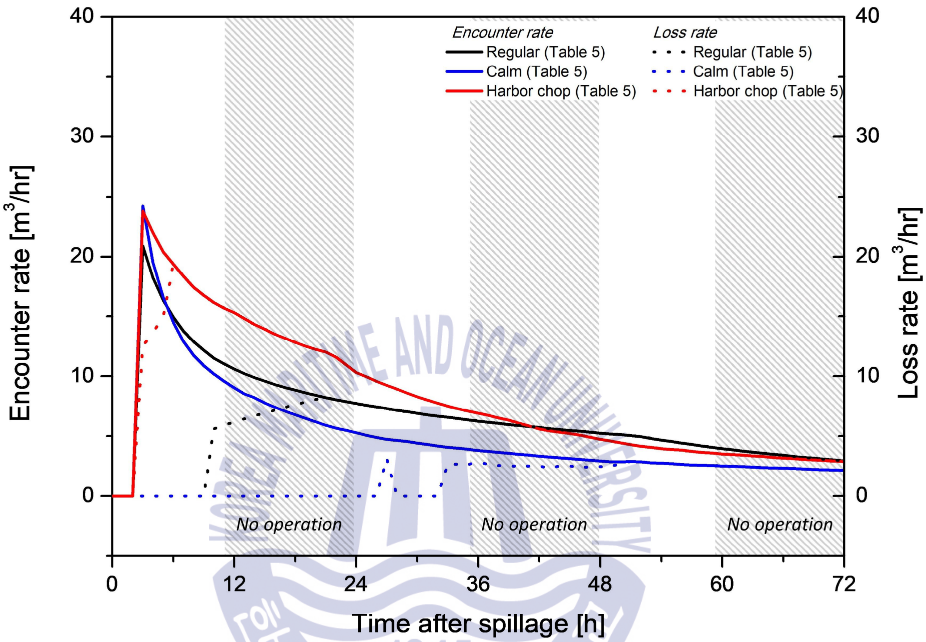


Fig. 24 Encounter rate and loss rate for constant tow speed (0.5 knot) applying boom B (Table 4) over spilled time: Regular, calm, and harbor chop case (Table 5) (Kim et al., under review).

The encounter rate and loss rate, which reflect the difference between U_{Tow} (0.5 knots, constant) and U_{1st} are shown in Fig. 24. During the initial response time, each case had a high encounter rate because of the spreading of the oil slick was limited. For the harbor chop case in particular, the emulsion percentage was high due to weathering form the high wind speeds. Emulsion makes the oil slick thicker, resulting in a higher encounter rate than the regular and calm cases. However, oil loss began to occur from the first day for the harbor chop case, unlike the calm case, and it eventually became equal to the encounter rate. This indicates how much oil is influenced by the constant U_{Tow}, and can be used to determine how to adjust U_{Tow} in response to different environmental conditions.

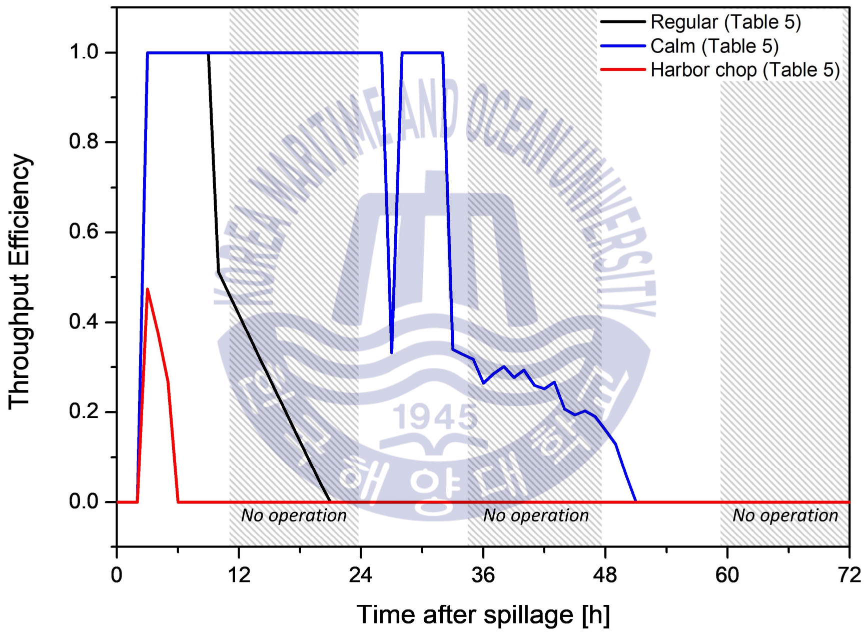


Fig. 25 Throughput efficiency for constant tow speed (0.5 knot) applying boom B (Table 4) over spilled time: Regular, calm and harbor chop case (Table 5) (Kim et al., under review).

The *TE* in Fig. 25 is a comprehensive value that includes a prior result of U_{1st}, the encounter rate, and the loss rate. In addition, over time the *TE* showed when the loss of oil began, and indicated how much oil was escaping from the encountered oil. The *TE* was ~0.5 early on in the harbor chop case, before rapidly decreasing to zero. This implies that there were only a few hours on the first day where operation at a 0.5 knots (0.257 m/s) tow speed was feasible. In the calm case, *TE* remained at 1 until early in the second day, but then suddenly decreased, which was related to the loss rate that time. However, on the third day, the volume of oil encountered was much less than on the first and second days for all of the cases. These smaller encounter volumes mean that the volume of recoverable oil was also small by this point. Therefore, from the quantitative perspective of recovery capacity, care should be taken when interpreting the influence of *TE* over time.

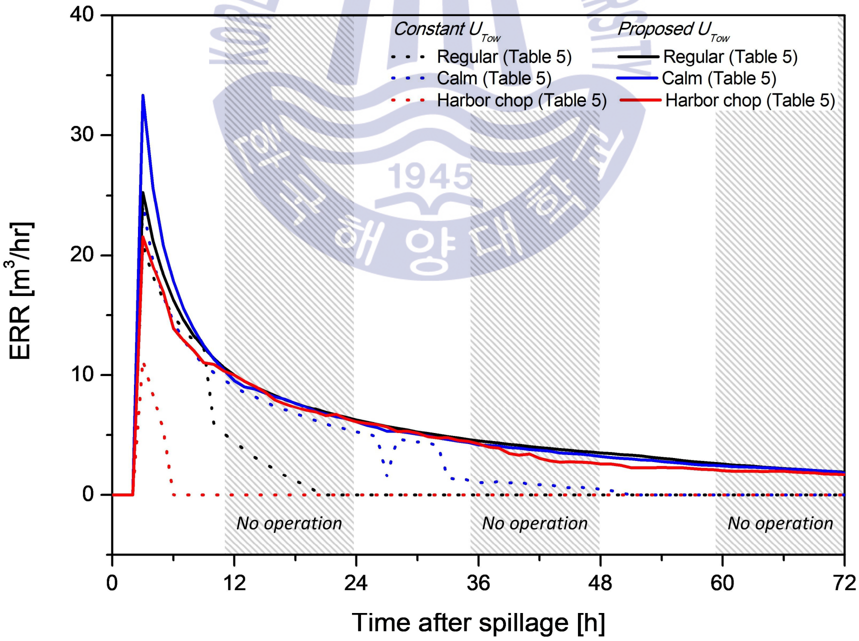


Fig. 26 *ERR* for a constant tow speed (0.5 knot) and proposed tow speed (U_{1st}) applying boom B (Table 4) over spilled time: Regular, calm, and harbor chop case (Table 5) (Kim et al., under review).

As shown in Fig. 26, the *ERR* for a constant tow speed (0.5 knots; 0.257 m/s) and the proposed tow speed, U_{Tow}, correspond to the calculated U_{1st} values. In other words, *ERR* varied when the recovery system was being towed at the first critical speed. *ERR* was proportional to *TE* for constant U_{Tow}. The model estimated that *ERR* decreased continuously over time. For the case of the proposed U_{Tow}, U_{1st} was applied by considering the maximum speed without oil loss, and *TE* was kept as 1. The *ERR* in the proposed U_{Tow} case was expected to be at its highest in the calm case during the first day. However, there was almost no difference in *ERR* across all of the cases during the second to third days, because the oil slick thickness was accompanied by a high *ER*, due to the emulsification of the regular and harbor chop case.

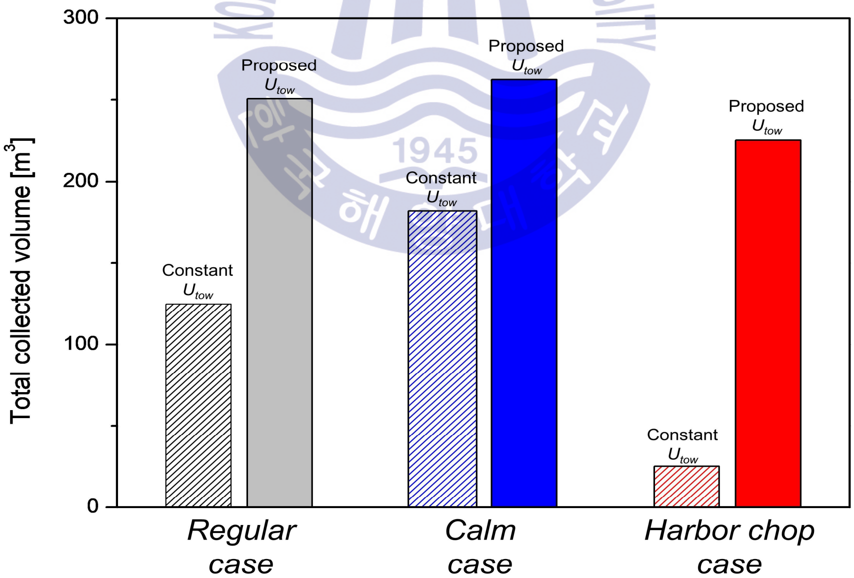
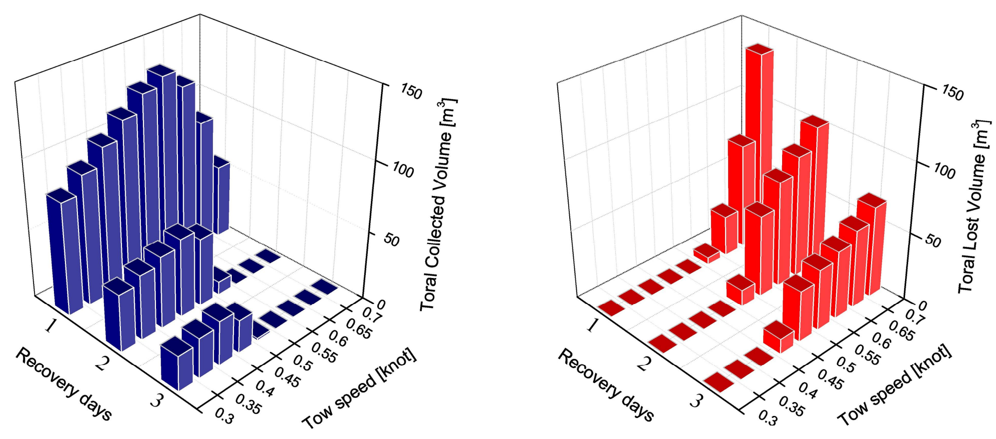


Fig. 27 Total collected volume comparison with constant tow speed (0.5 knot) and proposed tow speed (U_{1st}) applying boom B (Table 4) for 3 days: Regular, calm, and harbor chop case (Table 5) (Kim et al., under review).

A comparison of the total collected volume of oil across the three days between the constant tow speed (0.5 knot) cases and proposed tow speed (U_{1st}) case is shown in Fig. 27. The total collected volume is the cumulative value of the *ERR*, and it is the collecting potential considering *TE*. At a constant value of U_{Tow}, the value was lower in the harbor chop case because the volume of oil lost was highest during these severe environmental conditions (Fig. 24). The difference in total collected volumes between the constant and proposed U_{Tow} cases is evident in the harbor chop case; it represents the accumulated results of the calculated *ERR* values between the constant and proposed U_{Tow} values shown in Fig. 26.

Adjusting the U_{Tow} by calculating U_{1st} is meaningful for estimating the recovery capacity because the environmental conditions dynamically change with respect to time and the location of the spill. While a constant U_{Tow} implies the adoption of a uniform operating speed, applying the proposed U_{Tow} allows for the adjustment of the operating speed so as to minimize the occurrence of oil loss. Even in relatively poor marine environmental conditions, it was possible to obtain the best recovery capacity for oil collection, providing that U_{1st} was recognized as the maximum speed without oil loss.

In conclusion, this result suggests that the developed variable loss rate-based recovery capacity estimation model can be used to determine the most appropriate range for U_{Tow}. The fact that the potential can be presented as a range rather than a specific value is a significant advantage. The model could also be developed to include additional options, allowing it to present the a potential range besides the method of Gregory et al. (1999) for swath expansion to MES (maximum effective swath), considering the permissible nameplate of the skimmer.



(*a*) (*b*)

Fig. 28 Total collected volume(a) and total lost volume(b) depending on constant tow speed applying boom B (Table 4) for recovery days in calm case (Table 5) (Kim et al., under review).

Fig. 28 displays the total collected and lost volumes of oil when using boom B during the calm case, with a tow speed of 0.3-0.7 knots. Three main conclusions can be drawn from the results of this case study. First, performance was greatest on the first day. Fresh, relatively unweathered oil is critical for the recovery system to operate; therefore, U_{Tow} needed to be controlled to reduce oil loss, especially for the first day. Second, there was a value for U_{Tow} that represented the maximum recovery capacity within the response time. This was 0.55 knots on the first day, which then decreased by 0.05 knots. This implies that U_{Tow} should be determined specifically for each day. Third, a U_{Tow} of 0.55 knots led to the best performance estimate on the first day even though there was oil loss during this time (Fig. 28 (b)). It is suggested that the best performance can be obtained with a fast U_{Tow} even though this may result in oil loss.

3.4.3 Results for Equipment Adjustment

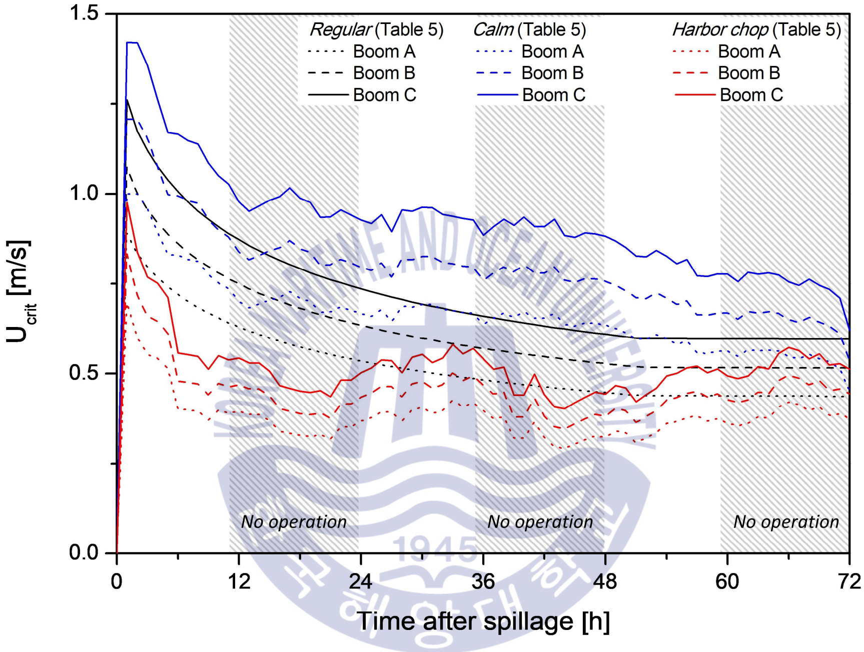


Fig. 29 Critical loss speed with different boom type at constant tow speed (0.5 knot) over spilled time: Regular, calm, and harbor chop case (Table 5) (Kim et al., under review).

The B/W ratio does not determine the volume of the recovery capacity, but is rather an estimate of whether the equipment can be used for the given environmental conditions. For the three boom models (Table 4), Fig. 29 shows variations in U_{Crit} over time for the three different environmental cases. U_{Crit} was more dynamic than U_{1st} over time, which should provide enough of a margin to utilize the boom. Assuming that the margin of U_{Tow} was 1 knots (0.514 m/s) in the harbor chop case, all three booms plotted in zones where U_{Crit} decreased below that speed. Considering the maximum *B/W* was 13 for boom C, the size of this boom would need to be increased to overcome the available U_{Tow}. Even in the harbor chop case, the change in the range of U_{Crit} when moving from boom A to boom C was narrower than that in the calm case. This implies that adjusting the boom *B/W* to avoid critical loss has a limited effect in severe environmental conditions, compared to that in calm conditions. Therefore, before calculating the volume of the recovery capacity, countermeasures should be considered to achieve a desirable *B/W* by estimating U_{Crit} in advance, particularly for poor environmental conditions.

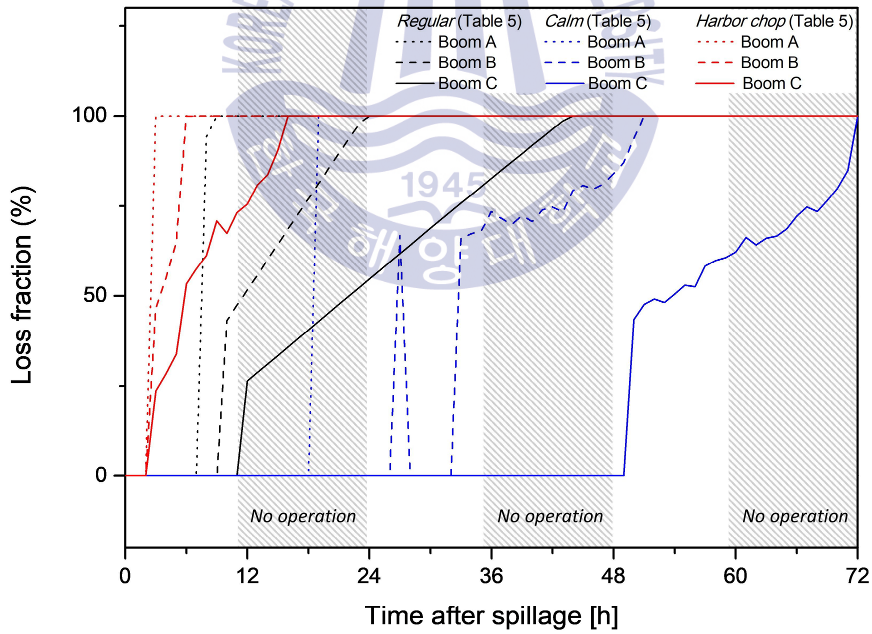


Fig. 30 loss fraction with different boom type at constant tow speed (0.5 knot) over spilled time: Regular, calm, and harbor chop case (Table 5) (Kim et al., under review).

As discussed in the sensitivity study (Section 3), the draft is an adjustable factor that can affect the volume of oil being loss. Fig. 30 describes the percentage of encountered oil being lost at a constant tow speed (0.5 knot) for the three different boom types. The differences in oil loss over time noticeably varied according to the draft size. Boom C showed the slowest oil loss across all environmental conditions, due to its higher draft. This enlargement of the boom size eventually hindered the oil loss. The larger-sized booms could not completely prevent oil loss for the harbor chop case; boom A was rendered useless in this case.

From the perspective of the clean-up operation, the importance of the boom size appears to vary dependent on the environmental conditions. In calm cases, enlarging the draft size may be important for loss-free operation. In the regular case, it is useful to be able to predict, because the loss fraction decreases linearly with the draft size. In harbor chop case, the size of the boom is only significant in the first day, with respect to limiting the loss of oil. However, the recovery capacity on the first day may be very important because of the thickness of oil slick during the first day. It may therefore be most useful to adjust the size of the boom on the first day.

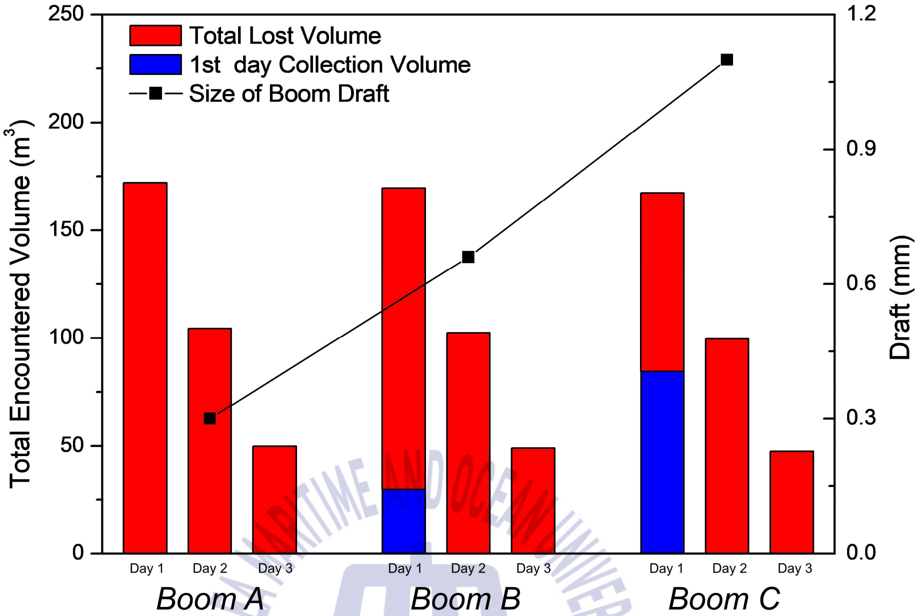


Fig. 31 Comparison of total collected and lost oil volumes at a constant tow speed (0.5 knots) in the harbor chop case (Table 5) over 3 days, for booms A, B, and C (Table 4) (Kim et al., under review).

Fig. 31 shows that for the harbor chop case, changing the boom had a noticeable result on the first day collection volume. While boom A (0.3 m draft) lost all of the oil encountered, enlarging the draft size gradually improved the collected volume. The collected volumes of booms B and C on the first day are shown in Fig. 30.

Adjusting both U_{Tow} and the size of the draft can contribute to a potential improvement. In poor environmental conditions, such as the harbor chop case, U_{Tow} can be adjusted to increase the volume of potential, as shown in Fig. 27. However, it is difficult to adjust U_{Tow} throughout the operating time; therefore, enlarging the boom size can also be an effective option. In calm environmental conditions, however, it is better to adjust U_{Tow} rather than adjusting the size of the draft.

3.4 Discussion for The Model Considering Oil Loss

Comparing the constant loss rate model with the variable loss rate model, based on case 2 (Fig. 32 and Fig. 33), reveals that the total volume of oil collected and the effective time of collection varied according to U_{Tow} during the total recovery time. The time at which *TE* became zero should be excluded from the total effective collecting time. Both the constant and variable loss rate models showed an increase in the encountered volume in proportion to increasing U_{Tow}. The variable loss rate model (Fig. 32) also showed no loss below 0.4 knots; *TE* remained constant (at a value of 1) meaning it was possible to recover all of the encountered oil. Although oil loss did occur at a U_{Tow} of 0.45 knots, volume of oil collected was high, and the effective collecting time did not decrease. At higher U_{Tow} values, the volume of oil lost increased constantly, and the effective collecting time decreased. This result indicates that it is better to apply the U_{Tow} corresponding to the maximum potential, unless there is no specific requirement of U_{Tow}. In contrast, the constant loss rate model (Fig. 33) adopted a constant *TE* of 0.75. Therefore, the total collected volume of oil increased in proportion to the increasing *ER*. furthermore, a constant ratio of the volume of oil lost was generated across all U_{Tow} cases.

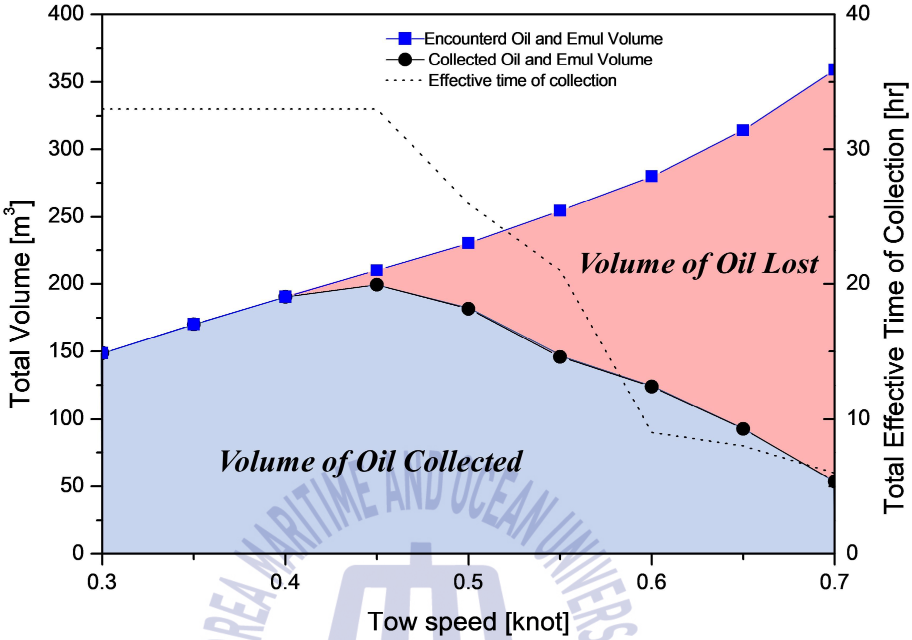


Fig. 32 Comparison of total volume of oil collected and effective time of collection using variable loss rate model with constant tow speed (calculation result by case 2 in Table 5) (Kim et al., under review).

The variable loss rate model represents an improvement in that the response operator can estimate what tow speed is best for a given scenario, and can estimate how much oil will be lost. Although there was no significant difference in the volume of oil collected at low U_{Tow}, the constant loss rate model may have overestimated the recovery capacity at high U_{Tow} values. In the case of the variable loss rate model developed in this study, however, the U_{Tow} of the recovery system was not arbitrarily applied by user, the appropriate range of U_{Tow} can instead be determined by considering the oil loss. Therefore, it can more reliably estimate the recovery capacity and effective collecting time, and can be used to determine an appropriate U_{Tow}

based on *TE*.

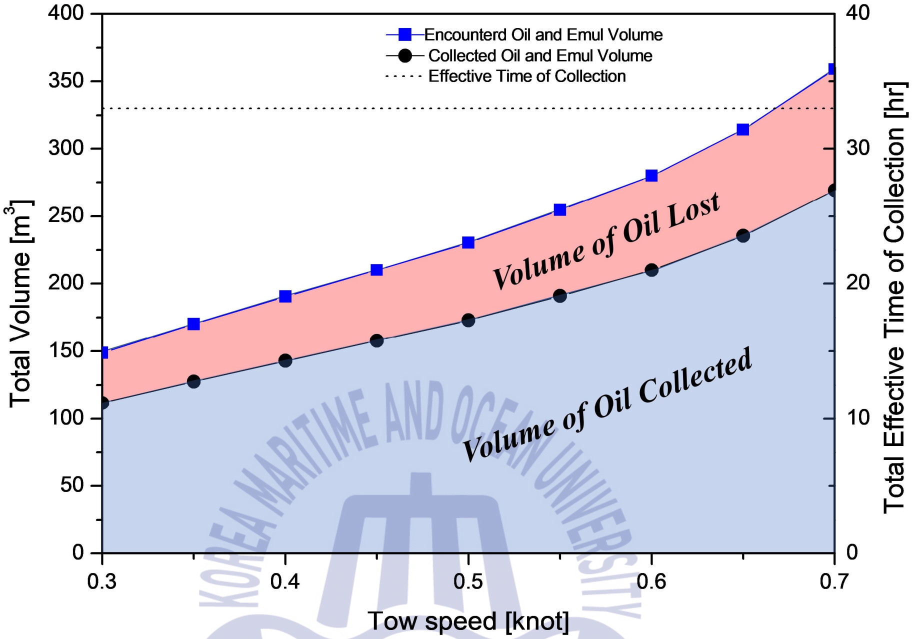


Fig. 33 Comparison of total volume of oil collected and effective time of collection using constant loss rate model with constant tow speed (calculation result by case 2 in Table 5) (Kim et al., under review).

Chapter 4 Conclusion

4.1 Recovery Capacity Estimation using Skimmer

Numerical study was carried out to estimate the recovery capacity of skimmer reflecting the increase of viscosity of spilled oil due to weathering process and the change of recovery efficiency of skimmer with marine environmental conditions. For the comparative analysis of the results, calculation was carried out for the case of WuYiSan oil pollution, which occurred at Yeosu GS Caltex in 2014. The results of this study are as follows.

1) The recovery capacity of skimmer reflecting the characteristics of spilled oil, marine environmental conditions and equipment efficiency was numerically calculated over time. The amount of recovery is calculated based on the encounter rate of the recovery system including the skimmer. This reflects the change in the recovery efficiency of skimmer depending on oil thickness, viscosity change and wind speed.

2) When WuYiSan accident case was analyzed using the recovery estimation model, most of the spilled oil was evaporated at early stage. Natural dispersion amount was very small compared with evaporation amount. As a result, it was analyzed that remaining oil after the oil spill of 100 hours was 36 ~ 42 % of the initial volume of spilled oil. In terms of the response strategy, accurate understanding of the volume of remaining oil can be used as an effective option for estimating the amount of response resource mobilization.

3) The recovery efficiency of skimmer is affected by increasing viscosity due to weathering and marine environmental conditions. As a result of the calculation of WuYiSan accident scenario, 34 skimmer mobilized for 5 days showed that about 12.2 ~ 13.6 % of the spilled oil was recovered. This is 48.6

~ 51.0 % of the remaining oil excluding evaporation and natural dispersion. From these results, it is expected that the timing and quantity of skimmer, and the volume of recovered oil from skimmer can be estimated. This could be used to establish an efficient response strategy.

4) When the recovery capacity using the skimmer nameplate capacity, the EDRC, and the recovery estimation model are compared, the recovered oil volume calculated by the recovery estimation model of this study is the most similar to the actual recovered results. The recovery capacity using nameplate capacity and EDRC tend to overestimate than the actual result. Therefore, in order to estimate a reasonable amount of skimmer mobilization, the change of the weathering process and the recovery efficiency of skimmer should be considered in detail.

5) In the case of the skimmer recovery capacity estimation model used in this study, it is assumed that oil is recovered based on the oil encounter rate and the oil recovery is calculated according to recovery efficiency and throughput efficiency. In this calculation method, there is a limit in considering the skill of the operator and the efficiency change due to the operating conditions in the field. Therefore, in order to effectively utilize the recovery capacity estimation model, it is necessary to further establish the efficiency change by considering operational field and conditions in the future and the marine environment conditions in which the recovery equipment is limited. It will be possible to develop a more reliable recovery capacity estimation model.

4.2 Estimation of a Mechanical Recovery System's Oil Recovery Capacity by Considering Boom Loss

To make a reliable decision on the response strategy for a given oil spill, it is necessary to know how the recovery capacity is affected by various factors that may influence marine oil spill accidents. This knowledge could then be used to propose rational response equipment and determine its operating conditions. This study therefore focused on improving the estimation of the recovery capacity. In this study, two models were developed to estimate the recovery capacity by considering the loss of oil from the boom- a constant loss rate model and a variable loss rate model. The speed at which the oil loss began to occur and the volume of oil lost were both quantified by empirical correlations, following which sensitivity studies were performed to analyze the significance of the oil loss in the mechanical recovery system. In addition, a case study was carried out to calculate how the recovery capacity may vary in response to adjustments in the variables, and to study the differences between the two models. The conclusions of this study are as follows.

First, the throughput efficiency, which represents the effectiveness of the boom, was modified. To quantify the throughput efficiency, the empirical correlation was devised between loss speed and volume in the variable loss rate model, deriving the first loss speed, critical loss speed, and loss rate. The relationship between the tow speed and the loss speed in the calculation procedure can be treated as a threshold for the occurrence of oil loss. The potential of collecting oil into boom can then be estimated. In conclusion, the developed model was able to estimate not only when oil loss may occur, but also how much oil can be lost.

Second, the variables affecting loss speed and volume were classified as either adjustable and nonadjustable factors, as a result of the sensitivity study. The nonadjustable factors, such as oil density and the environmental conditions (including wave steepness) are determined by oil spill accident conditions. The tow speed, and the draft and B/W ratio of the boom, are adjustable factors. To achieve an effective response to minimize loss, these adjustable variables can be optimized using the developed variable loss rate model. One of the sensitivity study results showed that the critical speed variation range from B/W ratio control was 6.3 and 4.3 times higher than that of draft control in calm and harbor chop conditions, respectively.

Third, different environmental conditions alter the effectiveness of the recovery system. It is possible to find out which factors are dominant to enhance the potential for each particular environmental case. The best tow speed and specifications for the boom, which together yield the maximum potential, can be derived for different times and environmental conditions using the developed model. One of the case study results showed that the collected oil volume can be increased by about nine times in severe conditions by adjusting the tow speed. Also, enlarging the size of the draft from 0.6 to 1.1 m meant that an estimated 2.7 times more oil could be collected in severe conditions. The results of the variable loss rate model developed in this study could contribute to predicting whether the enlarging the boom size or controlling the tow speed is better for a given set of environmental conditions.

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Nomenclatures

A = area of spilled oil

B/W = oil boom B/W ratio

C_0 = constant of oil dissipation

C_1 = coefficient due to oil droplet horizontal mitigation

C_2 = windrow coefficient

C_{temp} = temperature constant

C_{evap} = constant of component change due to evaporation,

C_{emul} = impact from droplet size constant

D = the oil boom draft

D_{ba} = dissipation of wave energy per unit surface area

d_o = oil droplet size

d_w = average water droplet diameter

F = fraction of evaporation

F_{wc} = fraction of breaking waves per unit time

K_i = mass transfer coefficient

P_i = partial pressure of each component

q_{loss} = the oil loss rate

Q_e = oil entrainment rate

R = gas constant

s = the wave steepness

S_c = interfacial area of oil and water

S_{cov} = fraction of sea surface covered by oil

T = water temperature

T_0 = oil reference temperature

t = oil thickness

U_{KH} = the Kelvin-Helmholtz threshold instability velocity

U_{1st} = first loss speed

U_{crit} = critical loss speed

V = volume of remaining oil

$\frac{dV_e}{dt}$ = evaporation rate of total moles

V_i = evaporation moles of each component

V_j = evaporation volume of each component

$\overline{V_j}$ = molar volume

ν = oil viscosity

ν_0 = oil reference viscosity,

Y = water contents

ρ_w = the water density

ρ_o = the oil density

σ = the oil-water surface tension

$\triangle$ = the oil density relative with water

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