

Applicability Assessment of Integrated Heavy-class Remotely Operated Vehicle–Manned Diving Operational Frameworks: A Case Study of the Sewol Ferry Disaster

Woo-Dong Lee,¹ Seongkyeong Jeong,^{1,2} Taeyoon Kim,³
Yeonjoong Kim,⁴ and Myoungsoon Kim^{5*}

¹Department of Ocean Civil Engineering, Gyeongsang National University,
2, Tongyeonghaean-ro, Tongyeong-si, Gyeongsangnam-do 53064, Republic of Korea

²Sea Salvage & Rescue Unit, Republic of Korea Navy,
25, Chungjang-ro, Jinhae-gu, Changwon-si, Gyeongsangnam-do 51686, Republic of Korea

³Department of Fire Protection Engineering, Pukyong National University,
45, Yongso-ro, Nam-gu, Busan 48547, Republic of Korea

⁴Water and Land Research Group, Division for Integrated Water Management, Korea Environment Institute,
370, Sicheong-daero, Sejong-si 30147, Republic of Korea

⁵Institute of Marine Industry, Gyeongsang National University,
2, Tongyeonghaean-ro, Tongyeong-si, Gyeongsangnam-do 53064, Republic of Korea

(Received December 1, 2025; accepted June 15, 2026)

Keywords: integrated ROV–diver operations, underwater search and rescue (USAR), high-current environments, marine disaster response, Sewol ferry disaster

In this study, we quantitatively evaluated the applicability of an integrated operational framework combining a heavy-class remotely operated vehicle (ROV) with manned diving systems, including the surface-supplied diving system (SSDS) and self-contained underwater breathing apparatus (SCUBA), under predicted tidal conditions at the Sewol ferry disaster site. A 31-day tidal-current dataset was analyzed to assess operational durations, phase-based deployment strategies, and personnel requirements. The results showed that integrated ROV–diver operations substantially expanded operational availability compared with standalone diving, increasing deployable time by 26.4% for SSDS and 54.7% for SCUBA. During neap tides, SSDS enabled long-duration deployment, whereas SCUBA maintained operational efficiency through rapid preparation and high mobility. Under spring tide conditions, the limited diving window made the heavy-class ROV the primary platform for search, inspection, and hazard-removal tasks. In this phase-based framework, sensor-derived information from the ROV supports underwater environmental assessment, target detection, hazard identification, and decision-making on the transition between ROV operations and diver deployment. Personnel analysis further showed that actual requirements were substantially lower than arithmetic estimates and represented only 6.6–10.1% of the Sewol response workforce, indicating the feasibility of coordinated ROV–diver missions. These findings provide a quantitative basis for developing standardized procedures and integrated command structures for large-scale underwater search and rescue operations.

*Corresponding author: e-mail: koko0925@gnu.ac.kr
<https://doi.org/10.18494/SAM6185>

1. Introduction

The global demand for marine resource development and offshore infrastructure continues to grow steadily. According to the Organisation for Economic Co-operation and Development,⁽¹⁾ the real value of the global ocean economy nearly doubled between 1995 and 2020 and is projected to expand to 2.5–4 times the 1995 level by 2050. Large-scale offshore industries have expanded rapidly in recent years. This includes oil and gas exploration, offshore wind energy development, and subsea cable installation. As a result, both the scale and complexity of marine operations have increased substantially. Moreover, long-duration activities in offshore and deep-water environments, complex structural installation tasks, and operations under high-pressure and strong current conditions have become more frequent, accompanied by compounded risks including operator fatigue, equipment malfunction, and communication failures.

These changes have inevitably contributed to an increase in the frequency and severity of marine accidents. Recent reports from Det Norske Veritas,⁽²⁾ the Norwegian Maritime Directorate,⁽³⁾ and the Australian Maritime Safety Authority⁽⁴⁾ indicate that marine safety incidents have risen by more than 40% on average over the past decade, while the complexity of offshore structures and intensified work environments have further amplified accident severity. Therefore, enhancing equipment performance alone is insufficient to ensure safe offshore operations. A comprehensive understanding of ocean and underwater environmental conditions—including tidal currents, water depth, and meteorological factors—is also essential.

With advancements in science and engineering, marine disaster response has shifted from traditional manpower-centered systems toward intelligent and automated technologies. Among these technologies, remotely operated vehicle (ROV) systems have gained increasing attention. They are capable of accessing hazardous areas and conducting detailed inspections, which significantly enhances operational safety. However, ROVs remain limited in tasks requiring entry into confined internal spaces or the execution of fine manual operations, for which human divers continue to play an indispensable role. Consequently, continuous technological advancement and operational research on ROV systems are essential for large-scale marine disaster response.

Recent advances in underwater intervention technologies demonstrate rapid improvements in unmanned and diver-support systems. A search-and-rescue ROV capable of 200 m operations with 8 kW thrust and an integrated particle-filter and fast region-based convolutional neural network (R-CNN) object-recognition algorithm was developed to enhance low-visibility and strong current performance.⁽⁵⁾ The EU FP7 TRIDENT project subsequently introduced a survey–intervention architecture that combined an autonomous surface craft with an intervention autonomous underwater vehicle (AUV), demonstrating the feasibility of coordinated control among unmanned platforms.⁽⁶⁾ In New Zealand ports, ROV-based surveys demonstrated performance comparable to that of experienced divers under controlled conditions when supported by AI-based video analytics, underscoring their potential for remote marine inspections.⁽⁷⁾ Moreover, gesture-recognition-based human–robot interaction methods have been proposed to improve cooperative efficiency and reliability between divers and robotic platforms in disaster environments.⁽⁸⁾ More recently, a compact diver-assistance robot designed

for proximity monitoring and AI-based situational assessment was proposed to enhance diver safety and operational efficiency, underscoring the growing importance of intelligent robotic assistance in underwater operations.⁽⁹⁾

Collectively, these studies demonstrate not only substantial advancements in ROV technology but also the expanding potential of integrated operations based on cooperation among unmanned systems and human–robot interaction. Building upon this trend, in the present study, we emphasize the necessity of developing heavy-class ROV–manned diving integrated operational procedures that explicitly reflect the characteristics and roles of each system in marine disaster environments.

The Sewol ferry disaster, which occurred on 16 April 2014 off the coast of the Republic of Korea, revealed the absence of a scientific and organized underwater search and rescue (USAR) framework for large-scale marine disasters. Strong tidal currents, low visibility, and the complex internal structure of the wreck clearly exposed the physical and physiological limitations of manned diving operations. Since the accident, several studies have been aimed at improving diving efficiency and safety. Long-term ocean circulation simulations were conducted to predict the tidal current field at the disaster site and to compute the diveable time (DAT) for various diving systems.⁽¹⁰⁾ By building on these findings, daily self-contained underwater breathing apparatus (SCUBA) diving plans were established,⁽¹¹⁾ and systematic procedures and personnel compositions for surface-supplied diving system (SSDS) operations were subsequently developed.^(12,13) However, in strong-current environments, day-by-day diving management is practically infeasible. To address this limitation, detailed diving procedures, workable times, and personnel deployment plans for both SCUBA and SSDS were proposed on the basis of tidal cycles.⁽¹⁴⁾ Considering the environmental conditions and equipment characteristics at the Sewol site, SCUBA—with its high mobility and rapid deployability—was evaluated as suitable for shallow hull-diving operations, whereas SSDS, owing to its high stability and structured gas-supply system, was assessed as more appropriate for deeper seabed tasks.

During the Sewol response, ROVs were urgently deployed but fulfilled only limited roles because of hardware constraints and the absence of systematic operational standards.⁽¹⁵⁾ This highlighted the need to integrate ROV capabilities into manned diving operations. In response, integrated procedures for compact-class ROV–manned diving operations were proposed,⁽¹⁶⁾ and the applicability of compact-class ROV–SCUBA integration under predicted tidal current conditions at the Sewol site was further examined.⁽¹⁷⁾ More recently, operational strategies for coordinating heavy-class ROVs capable of high-load tasks with manned diving systems have been suggested to support large-scale marine disaster response.⁽¹⁸⁾

In this study, we aim to quantitatively evaluate the applicability of integrated operational procedures linking heavy-class ROVs with manned diving systems, including SCUBA and SSDS, under predicted tidal current conditions at the Sewol ferry disaster site. In this framework, sensor-assisted ROV functions are considered supporting information sources for environmental assessment, hazard identification, and phase transition between ROV operations and diver deployment. On the basis of the predicted tidal conditions, in this study, we systematically analyzed the available operational time for each system, operational strategies by tidal cycle, and personnel compositions required for effective integrated operations.

2. Evaluation Conditions and Methods

In this study, we quantitatively evaluated the integrated operational procedures between a heavy-class ROV and manned diving systems in a marine disaster environment characterized by strong tidal currents. To accomplish this, the actual tidal current characteristics and water depth conditions of the Sewol ferry disaster site were incorporated into the analysis. On the basis of these environmental conditions, the workable time of each system, operational strategies by tidal cycle, and required personnel compositions were systematically examined to assess the operational efficiency and applicability of each system.

2.1 Field conditions

The study area is located approximately 3.1 nautical miles (about 5.7 km) northeast of Byeongpungdo, Jindo County, Jeollanam-do, Republic of Korea, where the Sewol ferry sank. The disaster site, known as the Maenggol Channel, lies between Jindo and Haenam and serves as a major route to Jeju Island, forming an important maritime corridor that connects the Yellow Sea with the South Sea. This channel extends approximately 25 km in length and 2.5–5 km in width and is characterized by a narrow geometry that generates strong tidal currents with highly variable flow directions. Because of these hydrodynamic characteristics, the area has historically been considered difficult to navigate and is still classified as a hazardous maritime zone.

According to the “Sewol Accident Response Support Report” published by the Korea Institute of Ocean Science and Technology,⁽¹⁹⁾ tidal currents in the area fluctuate rapidly. Acoustic Doppler Current Profiler observations conducted since 26 April 2014 recorded maximum current speeds exceeding 2 kn. Additionally, the mean current speed measured during the period from 26 April to 23 August was reported as 1.18 kn. Such strong currents have been identified as major limiting factors for both diver-based operations and ROV deployment.

The hull of the Sewol ferry remained largely intact after sinking and settled approximately 4 m southeast of the sinking point, with the port side resting on the seabed.⁽²⁰⁾ Structural damage occurred when the port aft section impacted the seabed during the sinking process. The seabed depth at the site was approximately 48 m, while the depth at the upper portion of the starboard side was approximately 26 m (see Fig. 1). These seabed characteristics and hull conditions are critical for defining dive zones, determining operational depths for equipment deployment, and establishing ROV approach routes and umbilical management strategies during USAR operations.

2.2 Tidal current environment

The tidal current environment of the study area was characterized using the one-month (31-day) ocean circulation simulation results from 16 April to 16 May 2014.⁽¹⁰⁾ As shown in Fig. 2, the site exhibits a typical semi-diurnal tidal pattern, with two high tides and two low tides occurring daily at an average interval of approximately 12 h and 25 min. Slack water occurred four times per day, during which the current velocity approached nearly zero. These periods were identified as the primary workable windows for diving operations.

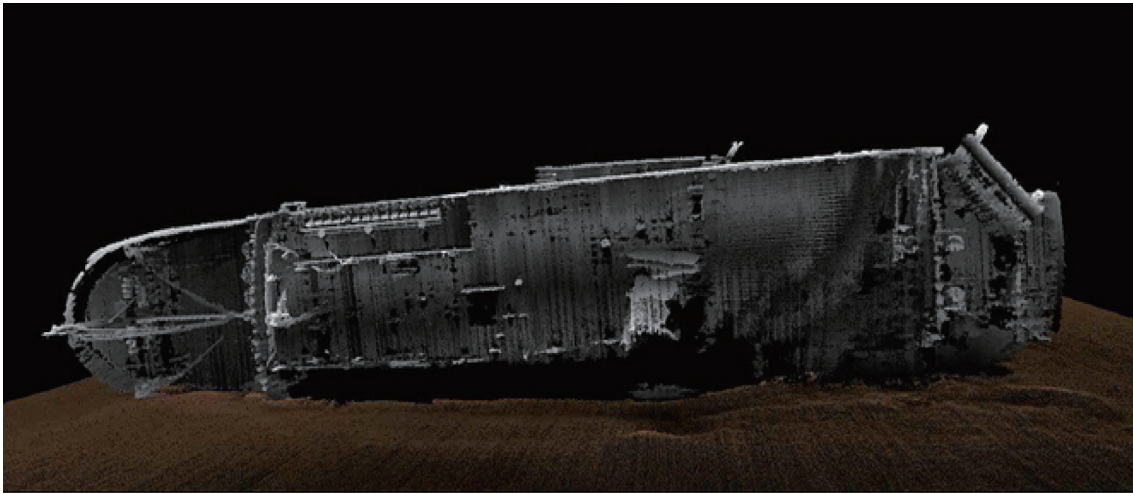


Fig. 1. Schematic illustration of the Sewol ferry wreck position and surrounding seabed topography at the disaster site.⁽¹⁹⁾

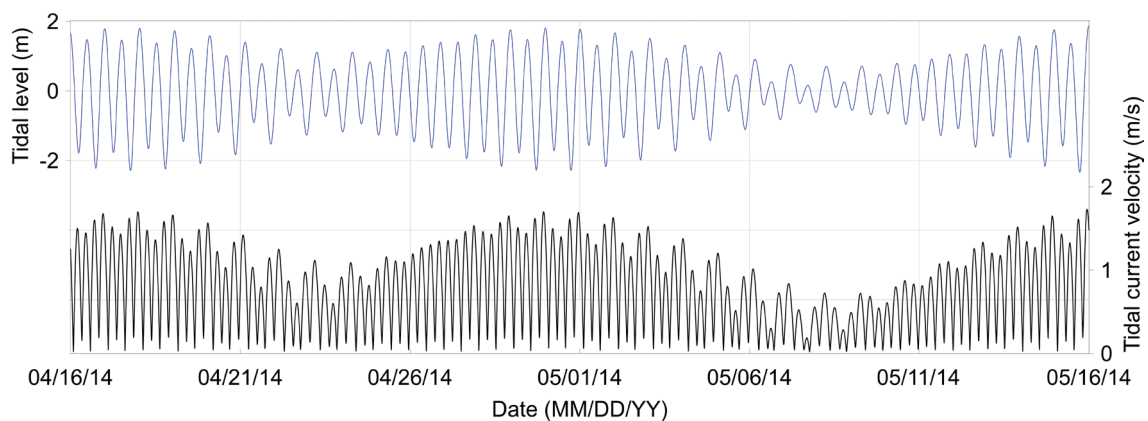


Fig. 2. (Color online) Tidal level and current velocity at Sewol ferry disaster site obtained from numerical simulations.⁽¹⁰⁾

On the basis of these tidal variations, the tidal-induced diving cycle (TIDC) was analyzed. One TIDC had an average duration of approximately 6 h, 12 min, and 30 s, and a total of 120 cycles occurred during the analysis period. Furthermore, the DAT for each manned diving system—SSDS and SCUBA—was estimated by applying the safe operational limit (SOL) current velocities of each diving mode to the TIDC framework.⁽¹⁴⁾

2.3 Characteristics of ROV and manned diving systems

Table 1 provides a comprehensive summary of the key operational characteristics and limiting conditions of the heavy-class ROV, SSDS, and SCUBA systems. These systems exhibit structural and functional differences in terms of their gas or power supply methods, primary

Table 1
Key operational characteristics and limiting conditions for ROV, SSDS, and SCUBA.

Category	Heavy-class ROV	SSDS	SCUBA
Supply system	• Electrical and hydraulic power-supply system	• Surface-supplied diving system	• Self-contained breathing-gas system
Principal applications	• Search and salvage • Inspection • Mapping and survey	• Search and salvage • Inspection • Enclosed space diving	• Initial response • Shallow-water search • Light-duty inspection
Advantages	• No diver risk exposure • Long-duration operations • Minimal depth constraints • Real-time data • Wide range of tools	• Unlimited gas supply • Voice/line-pull communication • Head protection • Fast deployment	• Simple configuration • Rapid deployment • High mobility • Effective for shallow-water tasks
Disadvantages	• High cost and maintenance • Requires skilled operators • Limited by umbilical • Affected by sea states	• Limited mobility • Requires support vessel and infrastructure • Depth and decompression limits	• Limited gas supply • Restricted by NDL • No real-time communication • Navigation risk
SOL	• $V_{SOL}^{ROV} = 2 \text{ kn (1.03 m/s)}$	• $V_{SOL}^{SSDS} = 1.5 \text{ kn (0.77 m/s)}$	• $V_{SOL}^{SCUBA} = 1 \text{ kn (0.51 m/s)}$
Personnel composition (per team)	• 2 pilots • 1 supervisor/assistant	• 2 divers • 1 supervisor • 1 console operator • 1 standby diver • 1 tender • 1 standby tender	• 2 divers • 1 supervisor • 1 tender

operational objectives, advantages and limitations, personnel composition, and critical current velocities.

The heavy-class ROV is a work-class platform designed with an integrated electrical–hydraulic power supply system that ensures stable performance even in deep-water and strong current environments. Its real-time video transmission capability, combined with multiple manipulators and sensors, enables a single platform to perform diverse tasks such as search, salvage, inspection, mapping, and subsea construction support. However, the high-performance configuration inevitably requires substantial maintenance costs and skilled operators. In addition, the size and weight of the launch and recovery system (LARS) and tether management system (TMS) impose mobility constraints and increase operational complexity during deployment and retrieval.

The SSDS supplies breathing gas continuously from the surface, allowing longer working durations and enabling real-time verbal communication. Helmet-based equipment enhances stability and task precision, although it introduces limitations such as reduced mobility, dependence on support vessels and surface infrastructure, and decompression constraints.

SCUBA offers simple configuration, rapid deployment, and high mobility, making it suitable for initial response, shallow-water searches, and light-duty inspection tasks. Nevertheless, SCUBA operations are limited by the available gas volume and the no-decompression limit (NDL), and the absence of real-time communication increases underwater control risks.

The SOL current velocities for each diving system were defined as follows: $V_{SOL}^{ROV} = 2$ kn, determined by the ROV's thrust and umbilical management capability; $V_{SOL}^{SSDS} = 1.5$ kn and $V_{SOL}^{SCUBA} = 1$ kn, following the recommended limits in the U.S. Navy Diving Manual.⁽²¹⁾ These SOL values were applied to the predicted tidal current conditions to compute the DAT for each system.

Personnel compositions and shift cycles for each system were established on the basis of international operational standards and previous studies.^(14,21,22)

- Heavy-class ROV: In accordance with the International Marine Contractors Association (IMCA) operational guideline,⁽²²⁾ each operating team consists of two pilots and one supervisor/assistant (three personnel in total), and a 12-hour shift cycle was applied to maintain operational stability.
- SCUBA: Each team consists of two divers operating as a buddy pair, one tender, and one supervisor (four personnel total). Teams rotate in accordance with the TIDC cycle (6 h, 12 min, and 30 s).
- SSDS: Each team consists of two divers, one supervisor, one console operator, one standby diver, one tender, and one standby tender. The shift interval is identical to that of SCUBA.

2.4 Integrated operational procedures (Phases I–IV)

The tidal-current-based integrated operational procedure for ROV–manned diving consists of four phases, as illustrated in Fig. 3.⁽¹⁶⁾

- Phase I (Standby): Standby condition in which neither SCUBA nor the ROV can be deployed owing to significantly strong tidal currents.
- Phase II (Pre-dive ROV tasks): A pre-dive phase in which only the ROV can operate owing to marginally reduced tidal currents.
- Phase III (Manned diving): A main search and rescue operation phase in which manned diving is feasible owing to the weakest tidal currents.
- Phase IV (Post-dive ROV tasks): A post-dive phase in which only the ROV can operate before tidal currents regain strength.

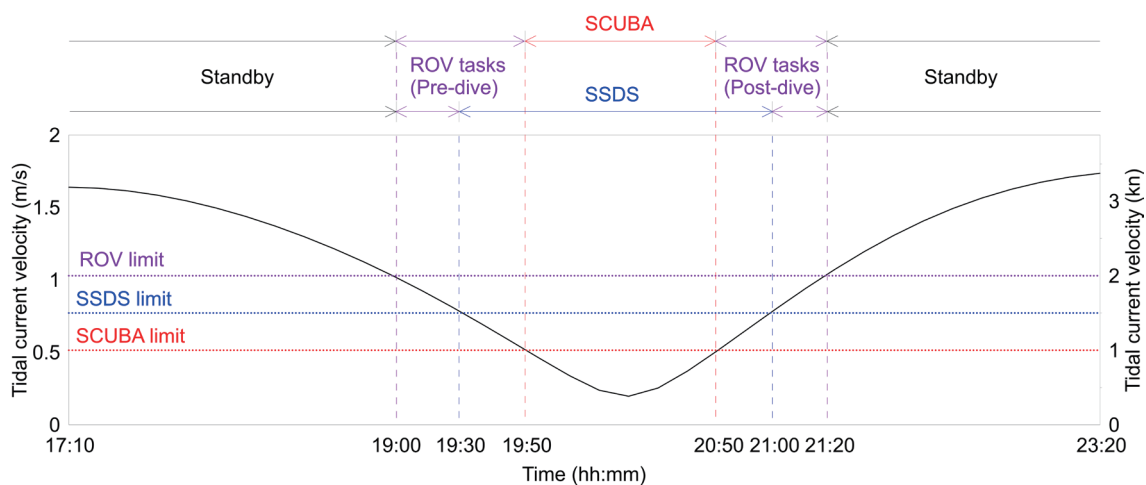


Fig. 3. (Color online) Tidal-current-based operational phases for integrated ROV–manned diving systems.⁽¹⁸⁾

On the basis of this procedure, the operational framework was further expanded to incorporate SSDS and SCUBA operations for heavy-class ROV systems.⁽¹⁸⁾ In the expanded integrated operations, the roles of the ROV during Phase II and Phase IV are defined as follows.

- Phase II (Pre-dive ROV tasks): The ROV performs pre-dive risk mitigation tasks using its high-load operational capability, including cable cutting, detaching entanglements, and removing obstacles prior to diver entry.
- Phase IV (Post-dive ROV tasks): The ROV is redeployed to conduct three-dimensional inspections of structural micro-displacements, cracks, and localized damage, which are difficult for divers to visually confirm, using high-resolution cameras, multibeam sonar, LiDAR, and other precision sensing instruments.

This stepwise integrated operational framework assigns complementary roles to the ROV and manned diving systems in accordance with the tidal cycle, thereby minimizing operational downtime, enhancing diver safety, and improving overall equipment utilization efficiency.

2.5 Conditions for manned diving operations

In this study, the diving procedures and operational criteria defined for each TIDC were adopted directly from the established framework,⁽¹⁴⁾ as illustrated in Fig. 4. The specific diving conditions applied in this study are summarized as follows.

- Diving locations: On the basis of the depth distribution at the Sewol ferry disaster site, hull diving and seabed diving were defined at depths of 26 and 48 m, respectively.
- Diving systems: SCUBA operations were conducted under NDLs, whereas SSDS operations followed air decompression diving procedures.

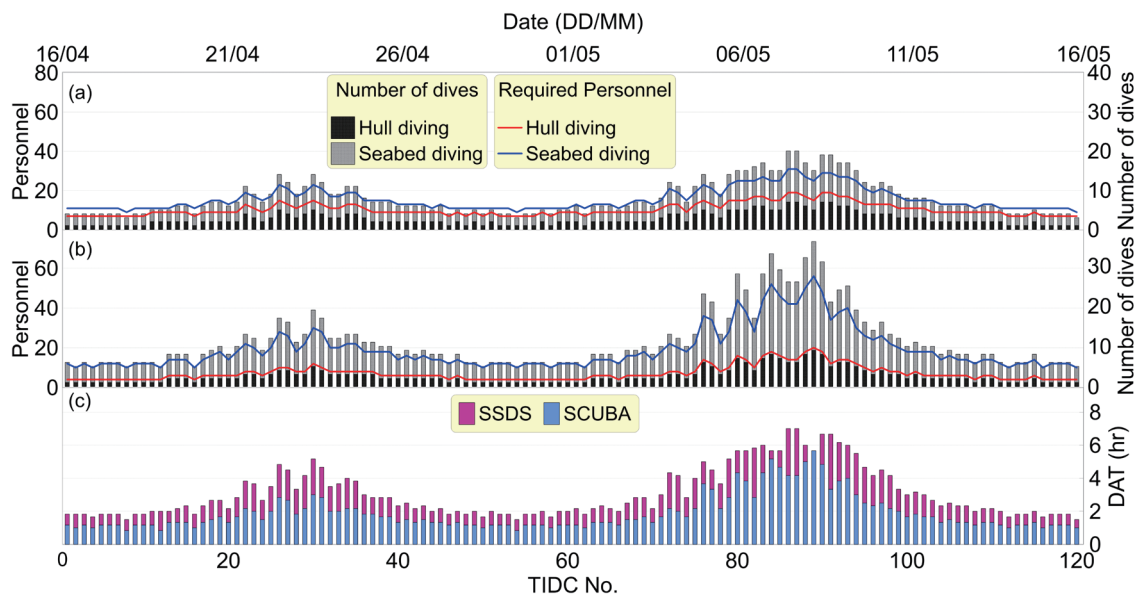


Fig. 4. (Color online) Required number of dives and divers for (a) SSDS and (b) SCUBA based on (c) DAT considering the SOL.

- Diving times: For a single dive, the SCUBA hull dive and seabed dive durations were 35.89 and 12.33 min, whereas the SSDS hull dive and seabed dive durations were 56.89 and 32 min, respectively.

Using these diving conditions, we quantitatively analyzed the number of possible dives within a single TIDC and the corresponding personnel deployment structures for each diving mode under varying tidal current conditions.

3. Quantitative Analysis of Operational Time and Personnel Requirements

3.1 Total operational time

Using the predicted tidal current data for the Sewol ferry disaster site, we quantitatively evaluated the workable time for heavy-class ROV integrated operations over the one-month (31-day) period from 16 April to 16 May 2014. Figure 5 shows the phase-wise distribution of operational time based on the total integrated operation duration of 29990 min for both ROV–SSDS and ROV–SCUBA operations.

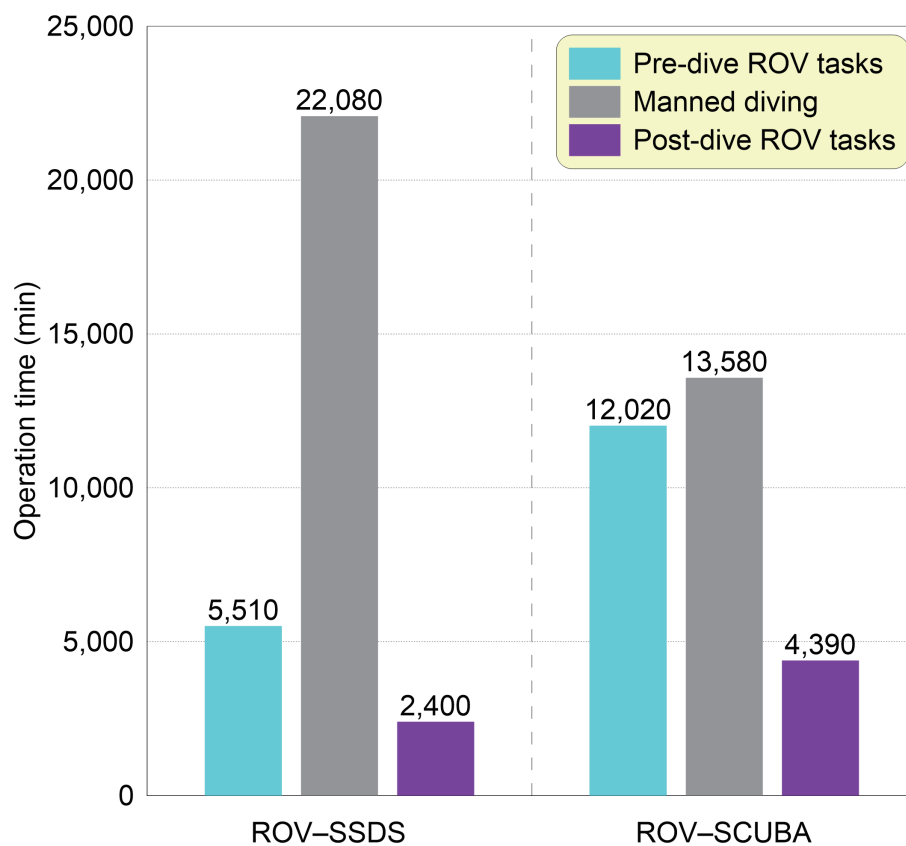


Fig. 5. (Color online) Phase-wise distribution of operational time for integrated operations between the heavy-class ROV and manned diving systems during the 31-day analysis period.

Although both integrated operation configurations share the same total operational time, their phase-wise time distributions exhibit markedly different patterns. In the ROV–SSDS integrated operations, the manned diving phase accounts for approximately 74% of the total, reflecting the system-specific characteristics of SSDS—namely, its SOL velocity (1.5 kn) and its capability for extended underwater working durations. In contrast, the ROV pre-dive and post-dive phases represent 18.4 and 8.0% of the total time, respectively.

For the ROV–SCUBA integrated operations, the proportion of the manned diving phase decreases to 45.3%, whereas the ROV pre-dive and post-dive phases increase to 40.1 and 14.6%, respectively. This shift results from the lower SOL of SCUBA (1 kn) and its restricted working duration imposed by the NDL, thereby limiting manned diving time and expanding the periods during which the ROV can be deployed.

These phase-wise time distributions highlight which phases dominate depending on tidal current intensity and equipment characteristics. This finding underscores the potential to design efficient ROV–manned diving operational strategies. By analyzing phase allocations in relation to predicted tidal currents and equipment-specific critical velocities, practical criteria can be established for task sequencing, equipment role distribution, and optimal scheduling of underwater missions.

3.2 Arithmetic estimation of required personnel

Table 2 provides an arithmetic summary of the personnel required for heavy-class ROV–manned diving integrated operations during the analysis period from 16 April to 16 May 2014.

For the ROV–SSDS integrated operations, the ROV was deployed 102 times during the pre-dive phase and 82 times during the post-dive phase, requiring 306 and 246 personnel, respectively, based on a three-person team structure. During the same period, SSDS manned diving enabled 330 hull dives and 643 seabed dives. With two divers per team, the total number of divers required for hull and seabed dives was calculated as 660 and 1286, respectively. In

Table 2
Arithmetic personnel requirements for heavy-class ROV–manned diving systems.

System	Operational site	Role	Number of operations	Personnel required
ROV	Surface	Pre-dive	102	306
		Post-dive	82	246
	Surface	Surface-support	120	600
SSDS	Hull	Divers	330	660
		Total personnel requirement	$306 + 600 + 660 + 246 = 1812$	
	Seabed	Divers	643	1286
		Total personnel requirement	$306 + 600 + 1286 + 246 = 2438$	
ROV	Surface	Pre-dive	117	351
		Post-dive	82	246
	Surface	Surface-support	120	240
SCUBA	Hull	Divers	310	620
		Total personnel requirement	$351 + 240 + 620 + 246 = 1457$	
	Seabed	Divers	1038	2076
		Total personnel requirement	$351 + 240 + 2076 + 246 = 2913$	

addition, five surface-support personnel were assigned per TIDC, resulting in 600 personnel for the 120 TIDCs in the analysis period. Therefore, the total personnel requirement for SSDS manned diving was 1260 for hull diving and 1886 for seabed diving. When the ROV personnel requirements were added, the total arithmetic personnel requirement increased to 1812 for hull diving and 2438 for seabed diving.

For the ROV–SCUBA integrated operations, the ROV was deployed 117 times during the pre-dive phase and 82 times during the post-dive phase, requiring 351 and 246 personnel, respectively. SCUBA manned diving, based on a two-diver team structure and two surface-support personnel per TIDC, resulted in 310 hull dives (860 personnel) and 1038 seabed dives (2316 personnel). Consequently, the total arithmetic personnel requirement, including the ROV personnel, was 1457 for hull diving and 2913 for seabed diving.

These arithmetic estimates represent theoretical personnel requirements and do not reflect the actual number of personnel deployed. Because shift rotations and repeated deployment of the same personnel are not considered, the results tend to be greater than the practical staffing needs. Nevertheless, these values provide meaningful upper-bound estimates for determining the minimum personnel capacity required under given tidal conditions and equipment operational limits. On the basis of these arithmetic estimations, it is necessary to evaluate how actual personnel availability constrains or modifies integrated operational planning.

3.3 Operational characteristics of integrated systems

3.3.1 Neap tide period

Table 3 summarizes the operational durations and arithmetic personnel requirements for integrated heavy-class ROV–manned diving operations under neap tide conditions, when tidal currents are relatively weak.

For the ROV–SSDS integrated operations, a weak-current window lasting 4650 min was observed across TIDC Nos. 82–94, during which the tidal current did not exceed the ROV's SOL. Within this interval, 130 min (2.8%), 4440 min (95.5%), and 80 min (1.7%) were assigned to Phase II (pre-dive ROV tasks), Phase III (manned diving), and Phase IV (post-dive ROV tasks), respectively. The single pre-dive and post-dive ROV tasks required a total of six ROV operators. During the manned diving phase, 72 hull dives (204 personnel) and 134 seabed dives (328 personnel) were conducted. The resulting arithmetic personnel requirements for the ROV–SSDS integrated operations were as follows.

- Hull diving (210 personnel): 6 ROV operators, 12 supervisors, 48 support personnel, and 144 divers
- Seabed diving (334 personnel): 6 ROV operators, 12 supervisors, 48 support personnel, and 268 divers

For the ROV–SCUBA integrated operations, a stable weak-current duration of 1260 min was present across TIDC Nos. 87–90. Of this period, 110 min (8.7%), 930 min (73.8%), and 220 min (17.5%) were allocated to Phase II, Phase III, and Phase IV, respectively. Two iterations of pre-dive and post-dive ROV tasks required a total of six ROV operators. During the manned diving

Table 3

Operational phases and personnel requirements for integrated heavy-class ROV-manned diving operations under neap tide conditions.

Integrated system	TIDC No.	Phase	Duration		DAT (min)	Number of dives		Required personnel	
			(DD/MM hh:mm)			Hull	Seabed	Hull	Seabed
			Start	End					
ROV-SSDS	82	II	07/05 02:40	07/05 04:50	130	1	1	3	3
	83		07/05 04:50	07/05 10:50	360	6	11	17	27
	84		07/05 10:50	07/05 16:30	340	5	10	15	25
	85		07/05 16:30	07/05 22:10	340	5	10	15	25
	86		07/05 22:10	08/05 05:10	420	7	13	19	31
	87		08/05 05:10	08/05 12:10	420	7	13	19	31
	88	III	08/05 12:10	08/05 18:10	360	6	11	17	27
	89		08/05 18:10	08/05 23:50	340	5	10	15	25
	90		08/05 23:50	09/05 06:30	400	7	12	19	29
	91		09/05 06:30	09/05 13:10	400	7	12	19	29
	92		09/05 13:10	09/05 19:20	370	6	11	17	27
	93		09/05 19:20	10/05 01:20	360	6	11	17	27
	94		10/05 01:20	10/05 06:50	330	5	10	15	25
	94	IV	10/05 06:50	10/05 08:10	80	1	1	3	3
	Total		07/05 02:40	10/05 08:10	4650	74	136	210	334
ROV-SCUBA	87	II	08/05 11:20	08/05 13:10	110	1	1	3	3
	88		08/05 13:10	08/05 18:10	300	8	24	18	50
	89	III	08/05 18:10	08/05 23:50	340	9	27	20	56
	90		08/05 23:50	09/05 04:40	290	8	23	18	48
	90	IV	09/05 04:40	09/05 08:20	220	1	1	3	3
		Total		08/05 11:20	09/05 08:20	1260	27	76	62

phase, 25 hull dives (56 personnel) and 74 seabed dives (154 personnel) were performed. Accordingly, the arithmetic personnel requirements for the ROV-SCUBA integrated operations were as follows.

- Hull diving (62 personnel): 6 ROV operators, 3 supervisors, 3 support personnel, and 50 divers
- Seabed diving (160 personnel): 6 ROV operators, 3 supervisors, 3 support personnel, and 148 divers

Under neap tide conditions, both ROV and manned diving systems can be operated continuously for extended durations, demonstrating the efficiency of concentrated operational strategies during periods of stable tidal currents. Although SCUBA equipment has a lower SOL than SSDS and thus faces challenges in securing long DAT under typical conditions, neap tide operations show that pre-dive ROV time is slightly shorter (0.85 times) than in SSDS-integrated operations, while post-dive ROV time is significantly longer (2.75 times). The combined ROV time for Phase II and Phase IV during SCUBA-integrated operations is approximately 1.6 times longer than in SSDS-integrated operations.

Moreover, the proportion of ROV Phase II and Phase IV tasks out of the total operational duration is 4.52% for SSDS-integrated operations and 26.19% for SCUBA-integrated operations. These results indicate that although SCUBA alone cannot sustain long-duration diving activities, integrating SCUBA with the ROV effectively compensates for its limited dive duration. In

particular, the expanded role of the ROV in pre- and post-dive tasks during SCUBA-integrated operations minimizes diver downtime and enhances mission continuity, suggesting that ROV–SCUBA integration can serve as a highly efficient operational alternative under weak-current conditions.

3.3.2 Spring tide period

Table 4 summarizes the operational durations and arithmetic personnel requirements for integrated heavy-class ROV–manned diving operations during the spring tide period, when tidal currents are the strongest.

For the ROV–SSDS integrated operations, only 140 min of workable time were available in TIDC No. 8, during which the tidal current did not exceed the ROV’s SOL. Within this limited interval, 30 min (21.4%), 90 min (64.3%), and 20 min (14.3%) were assigned to Phase II (pre-dive ROV tasks), Phase III (manned diving), and Phase IV (post-dive ROV tasks), respectively. The pre- and post-dive ROV tasks required a total of six ROV operators. During the manned diving phase, one hull dive (7 personnel) and two seabed dives (9 personnel) were performed. The resulting arithmetic personnel requirements for the ROV–SSDS integrated operations were as follows.

- Hull diving (13 personnel): 6 ROV operators, 1 supervisor, 4 support personnel, and 2 divers
- Seabed diving (15 personnel): 6 ROV operators, 1 supervisor, 4 support personnel, and 4 divers

For the ROV–SCUBA integrated operations under the same TIDC, a total of 140 min of workable time was also secured. Of this, 50 min (35.7%), 50 min (35.7%), and 40 min (28.6%) were assigned to Phase II, Phase III, and Phase IV, respectively. Two iterations of the pre- and post-dive ROV tasks required a total of six ROV operators. During the manned diving phase, one hull dive (4 personnel) and four seabed dives (10 personnel) were performed. Accordingly, the arithmetic personnel requirements were as follows.

- Hull diving (10 personnel): 6 ROV operators, 1 supervisor, 1 support personnel, and 2 divers
- Seabed diving (16 personnel): 6 ROV operators, 1 supervisor, 1 support personnel, and 8 divers

Table 4
Operational phases and personnel requirements for integrated heavy-class ROV–manned diving operations under spring tide conditions.

Integrated system	TIDC No.	Phase	Duration (DD/MM hh:mm)		DAT (min)	Number of dives		Required personnel	
			Start	End		Hull	Seabed	Hull	Seabed
			ROV–SSDS	8		II	17/04 19:20	17/04 19:50	30
III	17/04 19:50	17/04 21:20			90	1	2	7	9
IV	17/04 21:20	17/04 21:40			20	1	1	3	3
Total	17/04 19:20	17/04 21:40			140	3	4	13	15
ROV–SCUBA	8	II	17/04 19:20	17/04 20:10	50	1	1	3	3
		III	17/04 20:10	17/04 21:00	50	1	4	4	10
		IV	17/04 21:00	17/04 21:40	40	1	1	3	3
		Total	17/04 19:20	17/04 21:40	140	3	6	10	16

During the spring tide period, manned diving durations are severely restricted by strong tidal currents. However, when integrated with the ROV, the total operational duration for SSDS increases from 90 min (manned diving alone) to 140 min. This represents a 55.56% increase. For SCUBA, the enhancement is even more pronounced: the total operation time increases from 50 min of manned diving to 140 min, representing an expansion of 180%. These results indicate that even under highly unfavorable tidal conditions, ROV integration can partially compensate for the limited manned diving time. In particular, the significant extension of workable periods under both integrated configurations demonstrates the operational advantage of adopting ROV-supported diving strategies under spring tide conditions with strong tidal currents.

4. Applicability Assessment

4.1 Current-adapted integrated operational strategy

A comparative analysis between the integrated operations examined in this study and the standalone SSDS and SCUBA operations⁽¹⁴⁾ indicates that the integration of a heavy-class ROV with each of the two manned diving systems substantially increases the total workable time. Compared with the standalone modes, the integrated ROV–SSDS and ROV–SCUBA operations provide an additional 7910 min (26.3%) and 16410 min (54.7%) of workable time, respectively. These findings demonstrate that, in marine disaster environments where tidal current variability repeatedly constrains diving durations, the integrated approach offers improved operational continuity, enhanced safety margins, and greater adaptability compared with standalone manned diving. Furthermore, the pronounced temporal disparity between the neap and spring tide periods highlights the importance of developing differentiated operational strategies tailored to the characteristics of individual tidal cycles. Accordingly, the applicability of the integrated approach is proposed in the following manner.

4.1.1 Neap tide period

During the neap tide period, tidal current fluctuations remain relatively small, enabling long-duration, continuous operations, as shown in Table 3. For the heavy-class ROV–SSDS system, a total workable interval of 4650 min was secured across TIDC Nos. 82–94, of which 4440 min (95.48%) were assigned to manned diving. The heavy-class ROV–SCUBA system exhibited a similar tendency, securing 1260 min of workable time across TIDC Nos. 87–90, of which 930 min (73.81%) were used for manned diving.

Such prolonged manned diving durations raise multiple operational concerns, including cumulative diver fatigue, reduced cognitive performance, increased risks during decompression procedures, and a heightened probability of accidents caused by diminished situational awareness.⁽²³⁾ Therefore, even under favorable conditions that allow extended manned diving during the neap tide period, a staggered deployment strategy that accounts for both the physiological limits of divers and the specific nature of assigned tasks (e.g., task complexity, workload intensity) is essential. On the basis of these considerations, in this study, we propose the following integrated operational strategies.

- Mission-based integrated operations: Assign follow-up or secondary mission tasks—such as structural displacement and deformation inspection, removal of remaining underwater obstructions, drifted-debris tracking and monitoring, and site condition updates using video/acoustic data—to the ROV. This approach minimizes the unnecessary redeployment of divers and enhances overall operational efficiency.
- Personnel-based integrated operations: For the fully expanded neap tide intervals, the arithmetic diver requirements were calculated as 49 personnel for SSDS hull diving, 56 personnel for SSDS seabed diving, 48 personnel for SCUBA hull diving, and 74 personnel for SCUBA seabed diving. Repeated deployment of the same personnel across consecutive cycles can significantly elevate fatigue levels and degrade concentration, necessitating careful personnel rotation and workload management.^(24,25) Therefore, after allowing divers to conduct continuous diving for up to one surface-interval cycle, operational shifts should be adjusted to increase the workload share of the ROV, thereby ensuring sufficient rest time for divers.

These neap tide operational strategies achieve practical applicability by reducing diver workload while maintaining both the safety and efficiency of mission execution.

4.1.2 Spring tide period

During the spring tide period, rapidly varying and strong tidal currents significantly restrict manned diving durations, thereby increasing the relative operational contribution of the heavy-class ROV. Within the 140 min of workable time identified for TIDC No. 8, manned diving accounted for 90 min (64.28%) in the ROV–SSDS operations and 50 min (35.71%) in the ROV–SCUBA operations (see Table 4). This reflects a substantial reduction in manned diving compared with the neap tide period, indicating that ROV-centered operations should be emphasized under strong current conditions. Moreover, as the workable time during spring tides is physically limited, more sophisticated operational planning is required to ensure both safety and efficiency, even when using identical equipment configurations. On the basis of spring tide operational characteristics, the following key strategies are proposed.

- Refined planning of manned diving operations: For the ROV–SSDS configuration, the workable manned diving time available during TIDC No. 8 was 90 min. Within a single TIDC, a hull dive requires approximately 56.89 min and a seabed dive requires approximately 32 min, enabling one hull dive and two seabed dives. However, these durations leave remaining times of approximately 33.11 min (hull) and 26 min (seabed). These residual periods should be allocated to pre-dive or post-dive ROV tasks, enabling the concentration of manned diving within the weakest-current interval and assigning remaining periods to ROV operations. This approach ensures both the safety and efficiency of overall operations.
- Objective-specific operational strategy: During the spring tide period, tidal current fluctuations are rapid and unstable, raising operational risks for manned diving. Accordingly, the mission objectives must be clearly delineated. For search-oriented missions, extending the ROV's operational duration can minimize diver exposure to high-risk intervals, whereas for tasks that require confirmed target engagement, short but highly focused manned diving

should be conducted during the brief weakest-current window. Such objective-based strategies help secure diver safety and maximize operational efficiency even under high-current conditions.

Manned diving inherently possesses physiological and physical limitations in strong tidal currents. High-current conditions rapidly increase the risks associated with diver station keeping, visibility degradation, control difficulty, and umbilical safety hazards.^(21,23) Under such circumstances, integrated operations with a heavy-class ROV provide an effective means to maintain continuity, accessibility, and safety in USAR operations.

4.2 Practical personnel requirements

Having established the integrated operational strategies, it is now necessary to assess how realistically available personnel limit or modify the level of continuity that can be maintained in practice. The key consideration in analyzing personnel requirements for integrated operations is the fundamental difference between personnel who are deployed underwater and personnel who remain at the surface. Heavy-class ROV pilots, supervisors, and topside support staff operate under rotational shift systems and are not constrained by diving physiology, such as depth-dependent limitations, underwater exposure time, inert gas accumulation, or decompression obligations. By contrast, manned divers must strictly adhere to dive profiles, inert gas loading, and decompression requirements, all of which directly affect the number of available personnel as well as the feasible rotation cycle, even under identical operational conditions. Consequently, the practical staffing capacity for SCUBA and SSDS operations is inherently more limited than that of ROV teams, particularly under extended or strong-current conditions where diving exposure becomes more restrictive.

In this study, the diving procedures and operational criteria proposed in previous work⁽¹⁴⁾ were applied to compare the arithmetic personnel requirements with the actual required personnel for integrated heavy-class ROV operations under neap tide conditions, where personnel demand is maximized. In this context, the actual required personnel refers to the number of divers who can be redeployed after fully satisfying decompression obligations and surface interval (SI) requirements. Table 5 provides a detailed schedule of descent, bottom time, decompression with ascent, and SI for each access point in manned diving operations.⁽¹⁴⁾

During the neap tide period (TIDC Nos. 82–94), a total of 4650 min of ROV–SSDS integrated operations were feasible, with 180, 4440, and 80 min allocated to Phases II, III, and IV, respectively. Because manned diving accounted for the vast majority of the operational window,

Table 5
Required times for a single dive using SCUBA and SSDS dive systems.

System	Access point	Time (min)			Dive time (min)	Surface Interval (min)
		Descent	Bottom	Decompression with Ascent		
SCUBA	Hull	1.73	31.27	2.89	35.89	636
	Seabed	3.2	3.8	5.33	12.33	375
SSDS	Hull	1.73	38.27	16.89	56.89	741
	Seabed	3.2	11.8	17	32	584

the Actual Required Personnel was estimated on the basis of established rotation schemes and role-specific deployment rules, as follows.

- ROV operators: A three-person team (two pilots and one supervisor/assistant) operates under a 12 h rotational cycle; thus, only six personnel are required for the entire neap tide period.
- Supervisors and topside support staff for SSDS: A five-person team operates per TIDC, and three alternating teams maintain continuous coverage; therefore, 15 personnel are required.
- Divers: Divers follow a buddy-diving configuration (two divers per team). After securing SI and re-entry criteria, the actual number of divers required was 28 for 72 hull dives and 38 for 134 seabed dives.

For the ROV–SCUBA integrated operations during the neap tide period (TIDC Nos. 87–90), a total of 1260 min were available, with 330 min allocated to ROV tasks (Phases II and IV combined) and 930 min to manned diving (Phase III). On the basis of NDL and SI requirements, the Actual Required Personnel was determined as follows.

- ROV operators: Identical operational conditions to SSDS; two deployments require a total of six personnel.
- Supervisors and support staff: Owing to the reduced equipment complexity of SCUBA, only a two-person unit (including the supervisor) is required for each TIDC, and three teams operate in rotation; a total of six personnel are needed.
- Divers: Following the buddy-diving principle, and accounting for SI and repeat-dive limits, 25 hull dives and 74 seabed dives require 36 and 62 divers, respectively.

A clear discrepancy exists between the arithmetic estimates of personnel requirements and the actual personnel required when diving physiology and shift rotation rules are considered. For ROV–SSDS integrated operations, only 23.33% (hull) and 17.66% (seabed) of the arithmetic estimates were actually required. Similarly, for ROV–SCUBA operations, 77.42% (hull) and 44.58% (seabed) of the arithmetic estimates were sufficient. The significantly reduced personnel requirement for SSDS results from its decompression-based repeat-dive capability, which allows efficient reuse of the same divers within a single neap tide cycle. Although SCUBA is limited by NDL constraints, fewer than half of the arithmetic personnel requirements were needed in actual operational terms.

These findings indicate that personnel requirements for USAR must not be derived using simple arithmetic calculations; such estimates would fail to capture the operational conditions and physiological limitations governing real-world deployment. Professional considerations—including diving physiology, decompression procedures, and repeat-dive eligibility—must be incorporated in planning, managing, and supervising manned diving operations. Therefore, personnel estimation and USAR planning in marine disaster response must be performed with direct participation from diving-operations specialists.

4.3 Personnel availability and operational planning

4.3.1 Assessment of personnel availability

To evaluate whether the personnel requirements estimated in this study are realistically attainable, the required personnel numbers were compared with the actual personnel deployed during the Sewol ferry disaster response.⁽¹⁴⁾ The personnel records were obtained from official interagency reports submitted to the Special Investigation Committee on the Sewol Ferry Disaster (SIC-SFD) under the National Assembly of the Republic of Korea.⁽²⁶⁾

During the Sewol response period, the maximum daily personnel deployment occurred on 24 April 2014 with 727 personnel, while the minimum was 620 personnel on 16 May. The average daily deployment was 653 personnel, including both diving teams and surface-support staff. In comparison, the maximum personnel requirement derived from the integrated operational framework in this study—74 personnel for the ROV–SCUBA seabed-dive scenario (including 6 ROV operators, 6 supervisory/support staff, and 62 divers)—is approximately 8.38 to 9.82 times smaller, with an average difference of 8.82-fold. This comparison indicates that the integrated operational framework is fully feasible under real disaster-response manpower levels.

In actual marine disaster response scenarios, operational constraints can arise from equipment availability, interagency coordination, and varying levels of personnel proficiency. Therefore, the following personnel-management measures are proposed to enhance the field applicability of integrated ROV–manned diving operations.

- Establishment of a unified national command-and-control system: Large-scale marine disasters often suffer from fragmented command structures among agencies, leading to confusion and safety risks during early-stage operations. Because no national-level unified command system currently exists in Korea, a centralized control tower capable of coordinating equipment, personnel, and mission assignments is essential.
- Development of a specialization-based personnel management system: In Korea, most diving operations rely heavily on SCUBA systems, while compact-class ROVs are used across various organizations. However, heavy-class ROVs and SSDS capabilities are limited to the Navy's Sea Salvage & Rescue Unit. ROV operations generally require manufacturer-provided training rather than standardized qualifications. A national-level education, certification, and training system is therefore required to secure professional competency and ensure safe, standardized ROV operations.

4.3.2 Operational planning based on available personnel

On the basis of the SIC-SFD records of daily personnel deployment, the personnel requirement for the integrated operational strategies proposed in this study can be sufficiently met under realistic field conditions. Specifically, the diver requirements for heavy-class ROV–SSDS and ROV–SCUBA integrated operations—48–74 personnel for hull and seabed diving—represent only 6.6–10.1% of the actual available personnel during the Sewol response. This indicates that the flexible adjustment of personnel allocation can enable the effective implementation of the integrated operational framework.

For the ROV–SSDS integrated operations, the total personnel requirements were 49 for hull diving and 59 for seabed diving, whereas those for the ROV–SCUBA integrated operations were 48 for hull diving and 74 for seabed diving (see Table 6). When compared with the available manpower during the Sewol operation, even a single diving line (hajeom line) could secure sufficient personnel, and expansion to additional lines would also be feasible. According to the analysis presented previously,⁽¹⁴⁾ four diving lines were used during the Sewol operation; however, on the basis of the manpower requirements calculated in this study, up to eight diving lines could be operated.

These findings demonstrate that when sufficient personnel are available, diverse integrated operational strategies—such as combining SSDS and SCUBA systems, dividing tasks between ROV-based search and diver-based precision work, and applying adaptive task scheduling—can be implemented in practice. In particular, under strong current or low-visibility conditions where manned diving windows are limited, the heavy-class ROV can perform wide-area searches, while divers can be deployed intensively during stable-current periods to optimize both safety and operational efficiency.

In conclusion, assuming personnel availability comparable to that of the Sewol ferry disaster response, the integrated operational strategies proposed in this study are practically applicable. With appropriate expansion of diving lines, optimized diver allocation, and coordinated ROV–diver task sharing, large-scale USAR operations can be executed effectively. This underscores the importance of developing personnel-centered operational frameworks that maximize the synergy between available manpower and technological assets.

4.4 Depth-specific integrated operational strategy

In addition to the heavy-class ROV–manned diving integration framework developed in this study, depth-specific operational strategies were also established by incorporating the severity-level-based classification for ROV–manned diving operations.⁽¹⁸⁾ Figures 6 and 7 further illustrate the TIDC-based and phase-based breakdown of hull and seabed diving durations and corresponding personnel requirements, providing an integrated operational schedule applicable across varying depth conditions.

Table 6
Arithmetic versus actual personnel requirements for integrated heavy-class ROV–manned diving operations under neap tide conditions.

Integrated system	Access point	DAT (min)	Arithmetic personnel requirements				Actual personnel requirements				Ratio (%)
			ROV	Manned diving		Total	ROV	Manned diving		Total	
				Staff	Diver			Staff	Diver		
ROV–SSDS	Hull	4650	6	60	144	210	6	15	28	49	23.33
	Seabed		6	60	268	334	6	15	38	59	17.66
ROV–SCUBA	Hull	1260	6	6	50	62	6	6	36	48	77.42
	Seabed		6	6	154	166	6	6	62	74	44.58

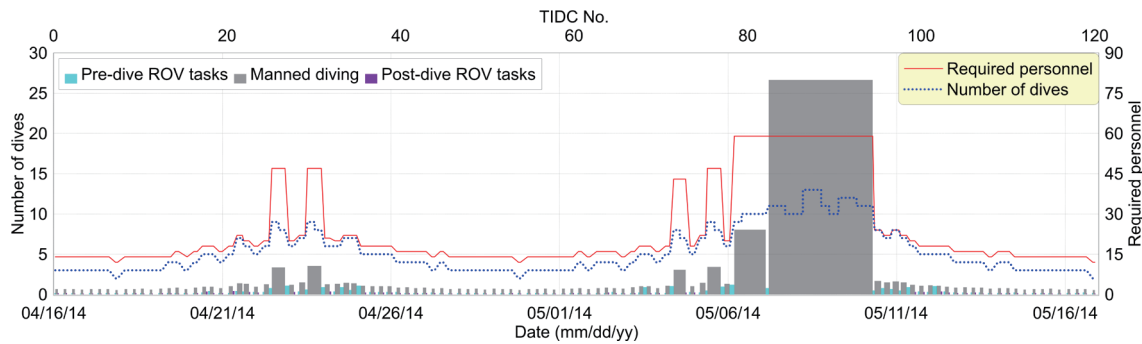


Fig. 6. (Color online) Integrated operational duration and required personnel for seabed diving under the heavy-class ROV-SSDS integrated operation scenario.

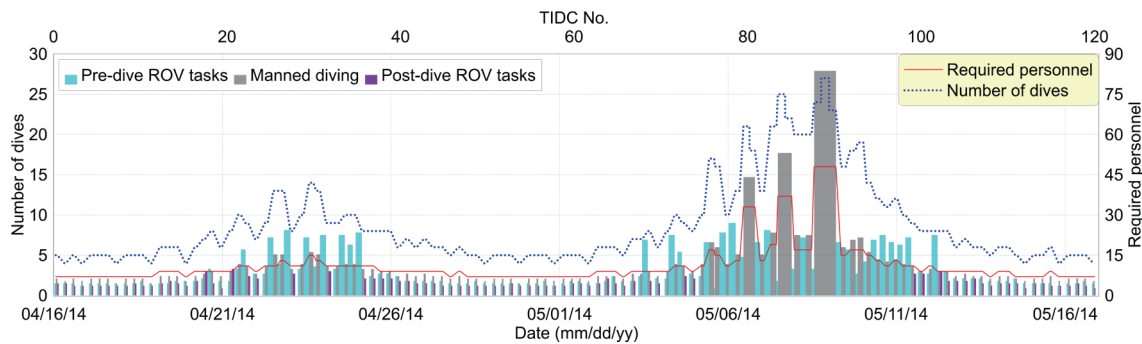


Fig. 7. (Color online) Integrated operational duration and required personnel for hull diving under the heavy-class ROV-SSDS integrated operation scenario.

4.4.1 Seabed diving

Seabed operations involve numerous constraints, including greater depths, limited visibility, rapidly changing currents, and the presence of underwater obstacles. Therefore, diving systems with stable gas supply mechanisms and long-duration operating capability are essential. SSDS offers substantial advantages for deep and prolonged dives because it relies on surface-supplied breathing gas and standardized decompression procedures. Compared with SCUBA, SSDS provides superior endurance and operational stability for long-duration missions.

As shown in Table 6, the Actual Required Personnel for seabed operations was 59 for SSDS and 74 for SCUBA, confirming that SCUBA demands significantly more personnel. This difference arises from the NDL constraints that limit SCUBA repeat-dive capability, whereas SSDS allows decompression-based reentry and therefore achieves higher personnel efficiency.

In terms of equipment, deep-water tasks involving precise manipulation, prolonged exposure, and strong current conditions are best served by heavy-class ROVs. These systems provide highly stable station-keeping via LARS/TMS deployment, high-thrust propulsion, and advanced manipulator capabilities. Such features enable accurate approach and intervention on seabed structures and significantly reduce diver exposure to hazardous environments.

By integrating these findings, the heavy-class ROV–SSDS combination is judged to be the most effective strategy for complex, long-duration seabed missions. When evaluated together with the personnel requirements in Fig. 6, this pairing offers the best balance of operational continuity, precision, and diver safety.

4.4.2 Hull diving

Hull diving generally occurs in shallower waters, where rapid response and maneuverability are more important than prolonged exposure. SCUBA is well suited to these missions owing to its quick preparation time, mobility, and flexibility. It is highly effective for initial response, hull inspection, surface-level search, and rescue operations.

A comparison of dive durations shows that SSDS allows 56.89 min of total dive time, compared with 35.89 min for SCUBA (a ratio of approximately 1.59). However, the difference in effective working time is much smaller: 38.27 min for SSDS versus 31.27 min for SCUBA (approximately 1.22). This reduction in performance gap indicates that SCUBA's rapid deployment compensates for its shorter allowable bottom time, enabling efficient task execution even within limited exposure windows.

Compact-class ROVs are also advantageous in hull-centered missions. Unlike heavy-class ROVs, compact systems do not require LARS or TMS, enabling rapid field deployment and improved maneuverability around hull structures. Their high accessibility and quick repositioning capabilities make them ideal for hull inspection, tracking, and visual search tasks during the early response phase.

As shown in Table 6, the Actual Required Personnel for hull operations was 28 for SSDS and 36 for SCUBA, demonstrating that SCUBA remains operationally practical in terms of personnel demand. Considering the mobility benefits of SCUBA and the rapid deployment capability of compact-class ROVs, the compact-class ROV–SCUBA integrated strategy is the most effective option for initial hull-focused search and assessment missions. Combined with the personnel trends illustrated in Fig. 7, this integrated approach provides a rapid, flexible, and field-ready response framework for hull-level operations.

4.5 Evaluation of applicability of integrated operational plan

The comprehensive operational plans presented in Figs. 6 and 7 serve as essential references for establishing a systematic framework for integrated heavy-class ROV and manned diving operations. These figures provide more than a simple schedule or personnel chart; they consolidate TIDC-based tidal variations, phase-specific (Phase II–IV) operational windows, dive duration, feasible dive frequency, and the number of required divers and ROV operators for both hull and seabed missions.

First, by clearly visualizing the variability of available working time across tidal cycles, the plans enable operators to formulate differentiated strategies under neap and spring tide conditions. This highlights that the decisive factor in determining diver deployment is not merely the total task load but the phase-dependent operational windows shaped by tidal current fluctuations.

Second, the figures serve as critical tools for validating the adequacy of diver and ROV operator allocation. When the required personnel are compared with the actual manpower historically available during large-scale disaster responses, it becomes evident that the integrated operational workforce demands fall well within feasible limits. This confirms that the proposed integrated strategies are not theoretical constructs but instead highly practical and field-ready plans.

Third, the integrated operational plans effectively illustrate the operational strengths associated with different equipment combinations. The heavy-class ROV–SSDS configuration offers high endurance and stability for seabed operations, particularly in deep or strong current environments. SSDS enables long-duration and repeat dives via decompression procedures, while the heavy-class ROV provides precise manipulation and reliable station-keeping, making this combination optimal for sustained seabed-centered tasks. Conversely, the compact-class ROV–SCUBA configuration is highly efficient in shallow-water and hull-focused missions. SCUBA's rapid preparation and mobility, combined with the compact ROV's immediate deployability, provide significant advantages during early-response operations, hull inspections, and short-duration surface searches.

In conclusion, the integrated operational plan is not merely a visual summary but a comprehensive analytical tool that supports (1) structured interpretation of operational feasibility under varying tidal and depth conditions, (2) validation of the suitability of equipment combinations, (3) assessment of the realism of personnel requirements, and (4) development of tactical operational scenarios. These findings collectively demonstrate the practical applicability of ROV–manned diving integrated strategies in real marine disaster response environments.

5. Conclusions

In this study, we quantified the operational durations, personnel requirements, and integrated ROV–manned diving strategies under neap and spring tide conditions. Using the predicted tidal current conditions at the Sewol ferry disaster site from 16 April to 16 May 2014, the applicability of integrated operations comprising a heavy-class ROV and manned diving systems (SSDS and SCUBA) was evaluated. The assessment considered system-specific operational durations, both arithmetic and practical personnel requirements, feasibility based on available manpower, and optimal equipment combinations according to depth. The key findings are summarized as follows.

- 1) Integrated operations significantly extend overall mission duration compared with standalone manned diving. The integration of SSDS with the heavy-class ROV increased total feasible operational time by 7910 min (26.3%) relative to SSDS-only operations, whereas SCUBA–ROV integration increased operational time by 16410 min (54.7%) compared with SCUBA-only operations. These results demonstrate substantial improvement in mission continuity under complex marine-disaster conditions.
- 2) Optimal operational strategies vary between neap and spring tide conditions. During neap tides, the long-duration capability of SSDS and the high mobility of SCUBA enabled extended continuous operations. In contrast, during spring tides, manned diving windows

were sharply reduced, making ROV-centered search, approach, and hazard-removal tasks essential. This confirms that phase-based planning aligned with tidal current cycles is a critical component of integrated operational strategies.

- 3) Arithmetic estimates of personnel requirements considerably overestimated actual needs. When diver redeployment, decompression requirements, and shift rotation were incorporated, the actual personnel required for SSDS-integrated operations amounted to only 23.33% (hull) and 17.66% (seabed) of arithmetic estimates. For SCUBA-integrated operations, only 77.42% (hull) and 44.58% (seabed) of arithmetic estimates were needed. This highlights the inefficiency of simple arithmetic estimations that ignore diving physiology.
- 4) Required staffing levels are well within the manpower historically available during the Sewol disaster response. The peak daily personnel deployment during the incident was 727 personnel. By comparison, the personnel requirements in this study—for example, 48–74 personnel for integrated operations—represent only 6.6–10.1% of the peak available manpower. This confirms that integrated operations are fully achievable in real disaster-response environments and that expansion of diving lines is feasible when needed.
- 5) Depth-dependent equipment selection yields clear advantages. For deep and complex seabed operations, the heavy-class ROV–SSDS combination provides enhanced situational awareness and precise control through sensor-assisted information, thereby improving operational stability, endurance, and efficiency. For shallow-water hull tasks requiring rapid deployment and high mobility, the compact-class ROV–SCUBA configuration is the most practical and operationally flexible.

The comprehensive operational plan developed in this study integrates TIDC-based scheduling, phase-specific operational windows, dive frequency, and personnel requirements, thereby serving as a foundational tool for constructing tactical operational scenarios. The findings can support the development of a national unified USAR command system, standardized SOPs for integrated ROV–manned diving operations, and structured training programs tailored to each diving system. Notably, the enhanced safety, continuity, and adaptability offered by integrated operations under strong currents, poor visibility, and complex disaster conditions underscore their importance as a core operational strategy for future marine disaster response frameworks. In addition, recent advances in AUVs indicate their potential to support wide-area reconnaissance and pre-dive hazard assessment before direct ROV or diver intervention.⁽²⁷⁾ Incorporating AUV-based reconnaissance into the integrated USAR framework can reduce personnel burdens and further enhance the adaptability and robustness of USAR operations.

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (RS-2024-00356327).

References

- 1 Organisation for Economic Co-operation and Development: The Ocean Economy to 2050 (OECD Publishing, Paris, 2025). <https://doi.org/10.1787/a9096fb1-en>
- 2 Det Norske Veritas: Maritime safety trends 2014–2024: Preparing for future risks (DNV Maritime, Høvik, Norway, 2024) <https://www.dnv.com/maritime/publications/maritime-safety-report-2014-2024-download/> (accessed September 2025).
- 3 Norwegian Maritime Directorate: Annual report on commercial vessel incidents 2024 (Norwegian Maritime Directorate, Haugesund, Norway, 2024) <https://safety4sea.com/norway-reports-increase-in-commercial-vessel-incidents/> (accessed September 2025).
- 4 Australian Maritime Safety Authority: Marine incident annual report 2024 (Australian Maritime Safety Authority, Canberra, Australia, 2024) https://www.amsa.gov.au/sites/default/files/marine-incident-annual-report-2024_fn.pdf (accessed September 2025).
- 5 B. Sun, W. Pang, M. Chen, and D. Zhu: *Intell. Robot.* **2** (2022) 355. <https://doi.org/10.20517/ir.2022.23>
- 6 P. J. Sanz, P. Ridaio, G. Oliver, C. Melchiorri, G. Casalino, C. Silvestre, Y. Petillot, and A. Turetta: *IFAC Proc.* **43** (2010) 187–192. <https://doi.org/10.3182/20100906-3-IT-2019.00034>
- 7 L. W. Tait, J. Bulleid, L. P. Rodgers, K. Seaward, L. Olsen, C. Woods, H. Lane, and G. J. Inglis: *Front. Mar. Sci.* **10** (2023) 1102506. <https://doi.org/10.3389/fmars.2023.1102506>
- 8 S. Aldhaheri, F. Renda, and G. De Masi: arXiv:2406.12473 (2024). <https://arxiv.org/abs/2406.12473>
- 9 H. Kang, G. R. Cho, H. Jin, M. G. Kim, J. H. Li, S. Jin, J. Lee, and J. Min: *J. Ocean Eng. Technol.* **39** (2025) 235. <https://doi.org/10.26748/KSOE.2025.005>
- 10 M. Kim, M. Song, J. Park, S. Kim, and W. D. Lee: *J. Coastal Res. Spec. Issue* **116** (2023) 433. <https://doi.org/10.2112/JCR-SI116-088.1>
- 11 M. Kim, S. Kim, T. Kim, Y. Kim, and W. D. Lee: *J. Coastal Disaster Prev.* **12** (2025) 31. <https://doi.org/10.20481/kscdp.2025.12.1.31>
- 12 W. D. Lee, Y. Kim, T. Kim, and M. Kim: *J. Korean Soc. Coastal Ocean Eng.* **37** (2025) 38. <https://doi.org/10.9765/KSCOE.2025.37.2.38>
- 13 W. D. Lee, Y. Kim, T. Kim, and M. Kim: *J. Korean Soc. Coastal Ocean Eng.* **37** (2025) 50. <https://doi.org/10.9765/KSCOE.2025.37.2.50>
- 14 M. Kim, K. Cheon, Y. Kim, T. Kim, and W. D. Lee: *Sustainability* **17** (2025) 11073. <https://doi.org/10.3390/su172411073>
- 15 D. J. Choi: Robots Deployed for the Sewol Ferry Disaster: The Future of Disaster Science and Technology, HelloDD (2014) <https://www.hellodd.com/news/articleView.html?idxno=48567> (accessed September 2025).
- 16 M. Kim, M. Song, K. Cheon, T. Kim, and W. D. Lee: *J. Ocean Eng. Technol.* **39** (2025) 467. <https://doi.org/10.26748/KSOE.2025.027>
- 17 M. Kim, M. Song, S. Jeong, J. Park, and W. D. Lee: *J. Korean Soc. Saf.* **40** (2025) 108. <https://doi.org/10.14346/JKOSOS.2025.40.6.108>
- 18 M. Kim, S. Jeong, J. Park, S. Kim, and W. D. Lee: *Sens. Mater.* **38** (2026) 3391. <https://doi.org/10.18494/SAM6186>
- 19 Korea Institute of Ocean Science and Technology: Results of the site investigation for the technical review of Sewol ferry hull disposal (Presentation material) (KIOST, Busan, Korea, 2015) <https://archive.416sewolfamily.org/items/show/26154> (accessed October 2025).
- 20 Korea Coast Guard: Report on the sinking of the Sewol ferry (Special Investigation Committee on the Sewol Ferry Disaster, Seoul, Korea, 2014) <https://agri.na.go.kr/emmit/bbs/BCMT2075/view.do?nttId=3004215> (accessed October 2025).
- 21 U.S. Navy: U.S. Navy diving manual, Rev. 7 (Naval Sea Systems Command, Washington, DC, USA, 2016) https://www.navsea.navy.mil/Portals/103/Documents/SUPSALV/Diving/US%20DIVING%20MANUAL_REV7.pdf (accessed October 2025).
- 22 International Marine Contractors Association: The safe and efficient operation of remotely operated vehicles, IMCA R 004 Rev. 6 (IMCA, London, UK, 2024) <https://www.imca-int.com/resources/technical-library/document/60d8d35a-c55b-ee11-8def-6045bdd2c0c0/> (accessed November 2025).
- 23 International Marine Contractors Association: International code of practice for offshore diving, IMCA D014 Rev. 3.3 (IMCA, London, UK, 2025) <https://www.imca-int.com/resources/technical-library/document/134b165f-c55b-ee11-8def-6045bdd2c9bc/> (accessed November 2025).
- 24 International Marine Contractors Association: Mobile/Portable/Daughtercraft surface supplied systems, IMCA D 015 Rev. 1 (IMCA, London, UK, 2015) <https://www.imca-int.com/resources/technical-library/document/124b165f-c55b-ee11-8def-6045bdd2c9bc/> (accessed November 2025).

- 25 International Marine Contractors Association: Requirements for IMCA-approved Diver Medic training courses, IMCA D 20 Rev. 1.3 (IMCA, London, UK, 2024) <https://www.imca-int.com/resources/technical-library/document/cf5ac45a-c55b-ee11-8def-6045bdd2c3b2/> (accessed November 2025).
- 26 Sewol Investigation Committee – Special Fact-Finding Division: Sewol Ferry Disaster Investigation Records Archive. Korea Center for Investigative Journalism (Newstapa) (2014) <https://sewol-fact.newstapa.org/archive> (accessed November 2025).
- 27 H. S. Jin, H. Kang, M.-G. Kim, M.-J. Lee, and J.-H. Li: J. Ocean Eng. Technol. **38** (2024) 187. <https://doi.org/10.26748/KSOE.2024.057>

About the Authors



Woo-Dong Lee received his Ph.D. degree in coastal and ocean engineering from Nagoya University, Japan, in 2012. From 2012 to 2017, he worked as a research fellow at the Institute of Marine Industry, Gyeongsang National University, Republic of Korea. Since 2017, he has been a professor in the Department of Ocean Civil Engineering at Gyeongsang National University. His research interests include numerical modeling, hydraulic experiments, coastal hazard assessment, marine disasters, and diving engineering. (wdlee@gnu.ac.kr)



Seongkyeong Jeong received his B.S. degree in underwater technology from Korea Maritime and Ocean University, Republic of Korea, in 2012. He has served as a professional diver and ROV supervisor in the Sea Salvage and Rescue Unit of the Republic of Korea Navy since 2005. He is currently studying for his master's degree in the Department of Ocean Civil Engineering at Gyeongsang National University. His research interests include ROV operations and diving management. (krsk13@gmail.com)



Taeyoon Kim received his Ph.D. degrees in coastal engineering and civil engineering from Pusan National University, Republic of Korea, in 2016 and 2021, respectively. Since 2024, he has been an assistant professor with the Department of Fire Protection Engineering at Pukyong National University, Republic of Korea. His research interests include the application of artificial intelligence to urban disaster prevention and mitigation. (taeyun.kim@pknu.ac.kr)



Yeonjoong Kim received his Ph.D. degree in hydraulic engineering from Kyoto University, Japan, in 2013. From 2013 to 2019, he was a researcher at CTI Engineering International Co., Ltd. From 2019 to 2022, he was a research professor at Inje University, Republic of Korea. Since 2022, he has been a research fellow at the Korea Environment Institute. His research interests are in coastal engineering, estuarine and coastal management, and compound coastal disasters. (anyseason@kei.re.kr)



Myounghoon Kim received his Ph.D. degree in hydraulic engineering from Gyeongsang National University, Republic of Korea, in 2024. From 2005 to 2025, he served as a professional diver in the Sea Salvage and Rescue Unit of the Republic of Korea Navy. He is currently a research professor at the Institute of Marine Industry, Gyeongsang National University. His research interests include marine accident response, diving operations, subsea safety, diving technology, and underwater search and rescue. (koko0925@gnu.ac.kr)