Sensors and Materials, Vol. 38, No. 6 (2026) 3391–3412
MYU Tokyo

S & M 4509

Formulation of Integrated Heavy-class Remotely Operated Vehicle–Manned Diving Procedures for Underwater Operations in Large-scale Marine Disasters

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

Keywords: underwater search and rescue, remotely operated vehicle, manned diving, integrated underwater operational procedure, marine disaster response

In this study, we propose an integrated operational procedure combining a heavy-class remotely operated vehicle (ROV) with manned diving to improve the efficiency and safety of underwater search and rescue (USAR) operations in large-scale marine disasters. The procedure was developed by considering tidal-current variations and the safe operational limits of ROV, surface-supplied diving system (SSDS), and self-contained underwater breathing apparatus (SCUBA) operations. Using a spring tide window with strong current conditions, we analyzed the operational time allocation for integrated ROV–SSDS and ROV–SCUBA operations. The results showed that ROV–SSDS integration allowed a longer manned-diving window, whereas ROV–SCUBA integration required a greater proportion of pre- and post-dive ROV tasks because of the more restrictive current limit of SCUBA. In the proposed procedure, ROV-mounted sensor technologies, including sonar, depth sensors, and video systems, support situational awareness, target localization, environmental monitoring, and safety verification during integrated USAR operations. In addition, a classification framework was established by considering accident severity, support vessel requirements, manpower composition, and operational depth to support the selection of ROV-alone, manned-diving-alone, or integrated operations. These findings provide a basis for developing standardized operational guidelines for diving systems in marine disaster response.

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https://doi.org/10.18494/SAM6186

1. Introduction

Large-scale marine disasters can occur unpredictably owing to the complex interaction of environmental, human, and systemic factors. In the Republic of Korea, a series of catastrophic maritime accidents, including the Seohae ferry sinking in 1993, the Cheonan naval vessel incident in 2010, and the Sewol ferry disaster in 2014, have resulted in substantial loss of life. These events revealed structural weaknesses in the national disaster response framework and underscored the urgent need for fundamental improvements in marine safety management. In particular, the inefficiency of underwater search and rescue (USAR) operations during post-accident recovery highlighted the necessity of establishing standardized and systematic management for diving personnel and underwater equipment.

Following the Sewol ferry disaster, the Korean government reinforced its institutional framework by revising key maritime safety laws, including the Ship Safety Act,(1) the Shipping Act,(2) and the Ship Safety Management Act.(3) These revisions introduced measures such as the ship operation manager certification system and the mandatory installation of voyage data recorders. However, according to the Ministry of Oceans and Fisheries (MOF) of the Republic of Korea,(4) the number of maritime accidents in 2024 reached 3255, an increase of 5.3% from the previous year. During the same period, the number of fatalities and missing persons rose sharply by 74.5%. These figures indicate that the legislative and institutional reinforcement alone is insufficient to fundamentally reduce maritime disaster casualties, emphasizing the need to improve the operational efficiency of USAR in the post-accident phase.

Although diving operations play a crucial role in the final stage of disaster response, Korea's current standards, including the Standards for Hyperbaric Work(5) and the Occupational Safety and Health Standards,(6) remain less comprehensive in terms of operational procedures and safety management than international guidelines established by the International Marine Contractors Association (IMCA) and the International Organization for Standardization (ISO). As a result, Korean researchers have adopted numerical modeling approaches to address key issues such as decompression safety, work efficiency, and tidal current prediction. For example, the variable permeability model (VPM)(7,8) has been applied to develop dive simulation methodologies, which were later extended to air diving(9) and nitrox diving(10) to improve decompression safety. Coupled analyses integrating computational fluid dynamics with the VPM(11) have also enabled the quantitative evaluation of wave-induced effects on diver decompression. Furthermore, available dive durations have been estimated on the basis of tidal current predictions,(12) and daily dive planning procedures for self-contained underwater breathing apparatus (SCUBA)(13) and operational management procedures for the surface-supplied diving system (SSDS)(14,15) have been proposed. These studies contributed to the standardization of dive planning across various diving modes; however, systematic analyses of integrated operational procedures between remotely operated vehicles (ROVs) and manned diving systems remain limited.

More recently, integrated operational strategies combining compact-class ROVs with manned diving have been proposed,(16,17) demonstrating the feasibility of cooperative operations. However, compact-class ROVs exhibit inherent limitations in payload capacity, thrust capability, and operational depth, making them unsuitable for large-scale underwater operations conducted under strong hydrodynamic conditions or in deep-water environments. Therefore, heavy-class ROVs with high-thrust propulsion, precise control capability, and sensor-assisted operational functions are required to overcome these operational limitations. These sensor-assisted functions not only support ROV attitude control but also provide information for underwater environmental scanning and seafloor exploration.

Despite these technical advantages, the current framework for large-scale marine disaster response lacks both a clearly defined operational procedure for heavy-class ROVs and an integrated operation strategy incorporating manned diving. Establishing standardized operational procedures has thus become an urgent necessity. Accordingly, in this study, we aim to develop integrated operational procedures for heavy-class ROVs and manned diving systems based on international standards set forth by IMCA(18) and ISO.(19) Furthermore, we propose a safe and efficient USAR operational procedure through phase-based mission division that reflects tidal current characteristics and the safe operational limit (SOL) for each system.

2. Overview of ROV and Manned Diving Systems

2.1 ROV system configuration

ROVs are classified into various types according to their operational purposes, onboard equipment, and environmental conditions. Representative classification frameworks were established by IMCA(18) and ISO.(19) IMCA categorizes ROVs into six classes based on mission objectives and functional characteristics. Classes I and II are defined as portable ROVs primarily used for observation and light intervention tasks, corresponding to the compact class. Classes III and IV are defined as non-portable ROVs belonging to the medium/heavy class, designed to perform mid- to large-scale subsea operations. Class V refers to experimental ROVs designed for research and technology verification, typically featuring non-standard configurations and large-scale structures. Class VI represents autonomous underwater vehicles that operate independently without tethers and are used for autonomous exploration and monitoring missions. Conversely, ISO provides a classification system subdivided according to the equipment configuration and intervention mode, such as manipulator-based, tool carrier, and dual-line systems (see Table 1).

The heavy-class ROV examined in this study is a ship-based system that requires an integrated operational framework comprising a launch and recovery system (LARS) and a tether management system (TMS). Although this type of ROV has limited mobility and emergency responsiveness, it provides excellent precision and stability owing to its high-power thrusters, dual manipulators, and multi-sensor modules. A typical configuration of a heavy-class ROV system is illustrated in Fig. 1, consisting of the control room, LARS, TMS, and the ROV itself.

The operational workforce varies depending on the size and purpose of the ROV. Generally, compact-class ROVs require at least two operators, whereas heavy-class ROVs require three or more personnel. The typical crew includes a pilot, a technician, a supervisor responsible for overall operation management, and dedicated personnel for LARS and TMS. For extended operations, a shift-based system is essential to prevent fatigue accumulation and ensure operational safety.

Table 1
Comparison of ROV classification standards.

Standard	IMCA[18]	ISO[19]
Classification perspective	• Defines six classes (I–VI) based on mission objectives and functional characteristics	• Defines intervention modes based on equipment configuration and functional combination
Representative categories	• Class I: Pure observation (camera, lights, sonar only) • Class II: Observation with sensors/light intervention • Class III: Work-class (heavy intervention, manipulators) • Class IV: Towed or bottom-crawling vehicles • Class V: Prototype/development type • Class VI: Autonomous underwater vehicles/untethered underwater vehicles (autonomous systems)	• Manipulator-based intervention (direct robotic arm tasks) • Manipulator-held tool intervention (tool grasp and use) • Tool deployment unit intervention (precision docking system) • Dual downline intervention (ROV tether + separate lift line) • Tool skid intervention (modular skid-mounted tool systems)
Main focus	• Which class of ROV is suitable for a given mission	• Which intervention method should be applied for specific operations
Primary application	• Used for equipment selection, personnel training, and qualification standards	• Used for mission-specific system configuration and operational planning

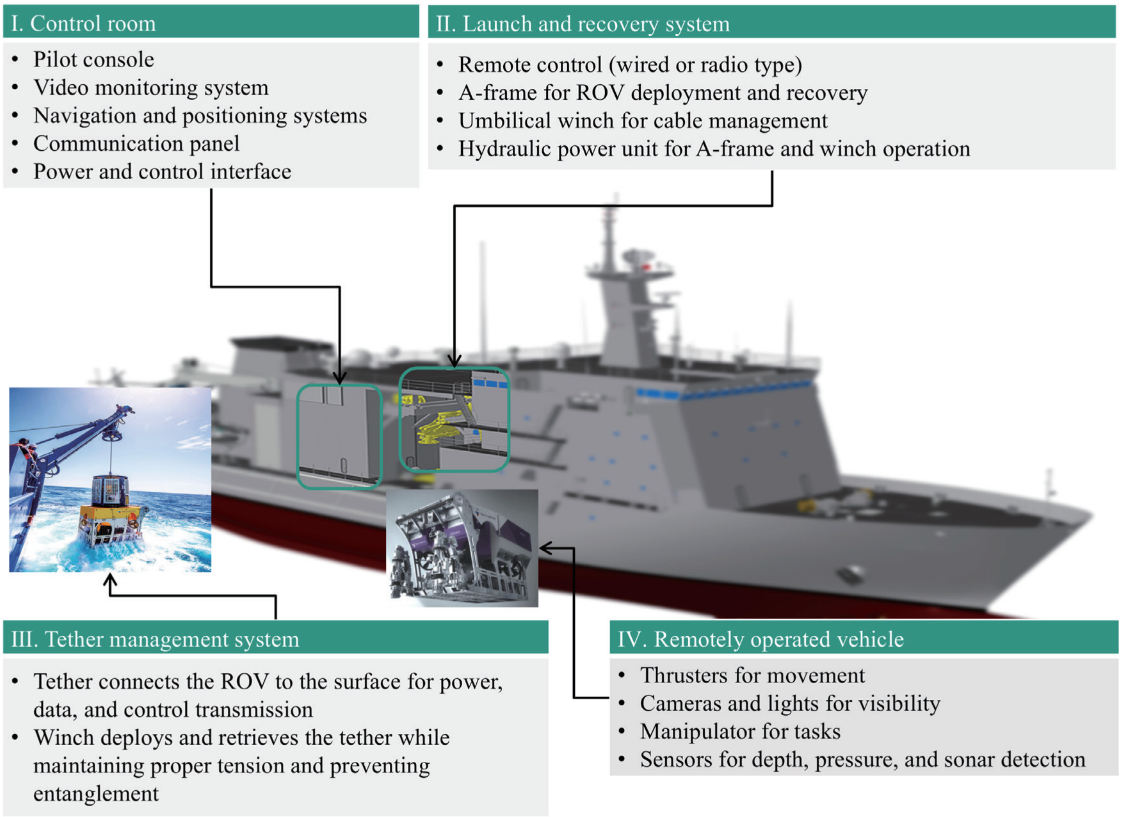


Fig. 1. (Color online) System configuration of a heavy-class ROV.[20–22]

2.2 Heavy-class ROV system

2.2.1 Selected ROV

The TechnipFMC ROV system has been operated by the Republic of Korea Navy for deep-sea search and recovery missions. Notably, during the 2016 Lynx helicopter crash in the East Sea, the heavy-duty ROV installed on the Tongyeong vessel successfully recovered three missing personnel and parts of the helicopter fuselage from a depth of approximately 1030 m.(23) In 2024, during the sinking of the fishing vessel Geumseong-ho near Biyangdo, Jeju, the ROV mounted on the Cheonghaejin vessel recovered a missing crew member from a depth of approximately 90 m.(24) These cases demonstrate the high reliability and operational suitability of the TechnipFMC ROV system in practical marine disaster response and deep-sea operations.

On the basis of the technical foundation of the Heavy Duty (HD)-class ROV, TechnipFMC developed and launched the GEMINI ROV in 2020, with its performance specifications shown in Table 2. Compared with the HD-class system, the GEMINI ROV features enhanced automation and station-keeping capabilities, with a SOL (V_{SOL}^{ROV}) of 1.02 m/s (2 kn), enabling stable operation under strong tidal conditions. The system supports both TMS and free-fly operation modes, and its modular control system and lightweight frame structure allow for versatile applications such as drilling assistance, subsea construction, oceanographic surveys, salvage operations, and military missions.(21)

Accordingly, in this study, we selected the TechnipFMC GEMINI ROV as the representative heavy-class ROV system and established integrated operational procedures for coordinated operations with manned diving systems.

2.2.2 Limitations of heavy-class ROV

Heavy-class ROVs are unmanned underwater systems capable of performing missions at depths of 3000 to 4000 m, beyond the physiological limits of human divers, and can operate

Table 2
Key specifications of GEMINI ROV.(21)

Category	Specification	Category	Specification
Working depth	• 3000–4000 m	Thrusters	• 7 × Sub-atlantic 4207
Payload/lift	• 80 kg/3500 kg	Thrust (F/A/L–V)	• 1200 kgf/1000 kgf
Sensors	• Depth sensor (Valeport) • Heading sensor (iXblue Nano) • Doppler velocity log (1200 kHz)	Manipulators	• Dual 6-DOF manipulators (4000 m rated, automatic tool exchange)
Power/pumps	• 250 hp HPU with 150 hp ISOL-8 pump (50 gpm @ 5000 psi)	Video system	• Ethernet-based 1920 × 1080 @ 60 fps
Size ($L \times W \times H$)/Weight	• 3.7 × 2.4 × 2.2 m^3/6340 kg	Operational capability	• Up to 28 days of continuous deployment

without temporal constraints. Equipped with high-power thrusters and hydraulic propulsion systems, they maintain stable performance even under strong current conditions. In addition, high-resolution video systems and advanced sonar sensors enable effective target detection and object identification in low-visibility environments. These characteristics provide a higher operational efficiency than manned diving systems under diverse marine environmental conditions, including variations in current velocity, wave height, visibility, and water temperature.

However, several technical and operational limitations are associated with heavy-class ROVs. First, there are limitations in fine manipulation capability. Although manipulator technology has advanced significantly, it cannot fully replicate the delicate manual dexterity of human divers. This limitation constrains the ability of ROVs to perform fine or intricate tasks such as working within confined or complex structures or conducting delicate cutting and fastening operations.

Second, constraints exist regarding safety and operational efficiency. Heavy-class ROVs employ high-voltage electrical and high-pressure hydraulic systems, making them unsuitable for direct human rescue missions because electrical leakage or hydraulic hazards may pose safety risks when divers are nearby. In addition, their large body size decreases maneuverability and limits their ability to enter narrow or confined structures. Moreover, their reliance on dedicated support vessels and a large operational workforce reduces overall efficiency during on-site operations.

In conclusion, heavy-class ROVs are the most suitable unmanned platforms for deep-sea and long-duration search and recovery operations; however, they remain constrained by limited precision manipulation and unsuitability for direct human rescue, reflecting their inherent characteristics as remotely operated underwater systems.

2.3 Manned diving systems

2.3.1 SCUBA diving

The SCUBA diving system is a self-contained diving system in which the diver independently carries all equipment and breathing gas required for underwater operations. Because it does not rely on external gas supply systems or surface support infrastructure, the system is characterized by simplicity, mobility, and rapid deployability, allowing efficient operation under various underwater conditions.

The SCUBA diving system is primarily employed for shallow-water tasks such as rescue activities, surface-layer searches, underwater photography, and seabed mapping or topographic surveys, which are typically short in duration and limited in range. Moreover, SCUBA diving can be conducted safely and efficiently when the current velocity does not exceed a specified threshold. According to the U.S. Navy,(25) the SOL (V_{SOL}^{SCUBA}) is 0.51 m/s (1.0 kn). When this threshold is exceeded, the diver's propulsive efficiency decreases sharply, resulting in increased physical fatigue and a higher risk of disorientation, thereby limiting the feasibility of mission execution.

Figure 2 illustrates the basic configuration of the SCUBA diving system with the following components:

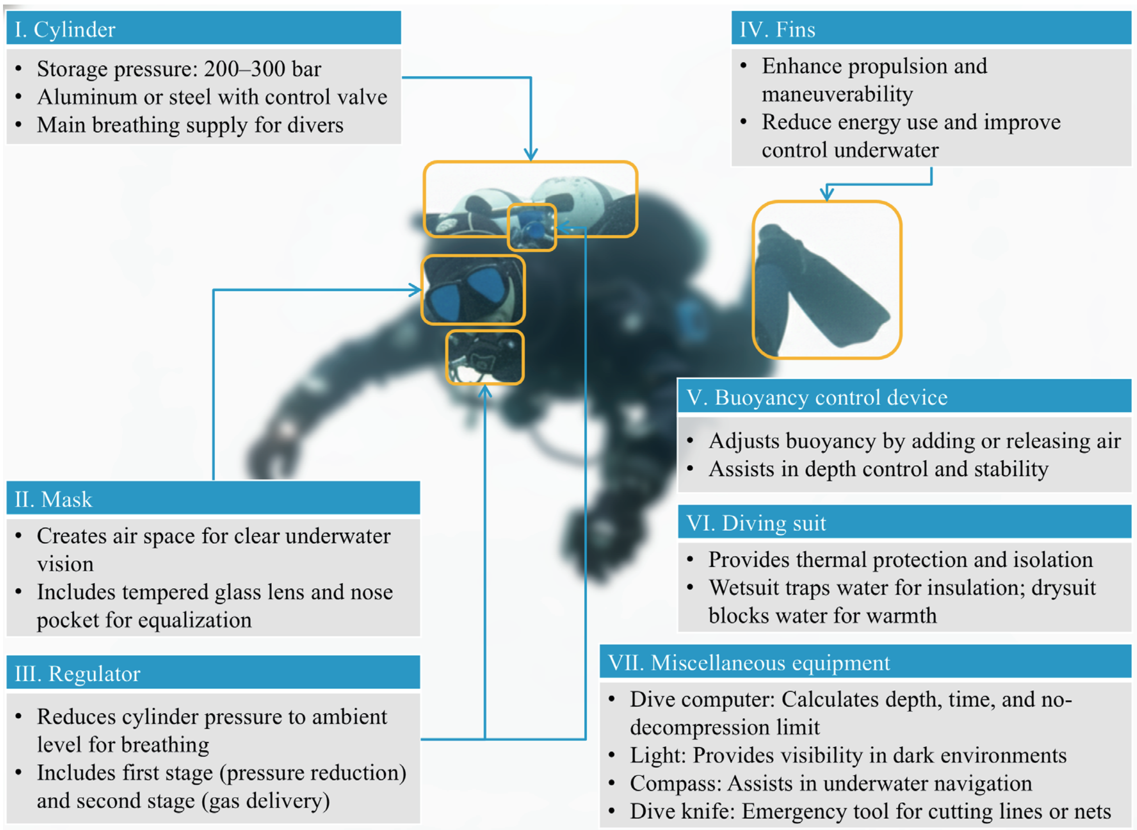
- cylinder: storage of compressed air or mixed gas carried directly by the diver;
- regulator: reduction in high pressure from the cylinder to an ambient pressure suitable for breathing;
- buoyancy control device: maintenance of neutral buoyancy for stable posture and depth control underwater;
- diving suit and accessories: provision of thermal protection and task support using a mask, fins, dive computer, and compass.

The operational procedure of SCUBA diving is generally divided into the following stages:

- pre-dive inspection: checking the cylinder pressure, regulator function, buoyancy control device, and diving suit condition, and confirming the dive plan and signaling procedures;
- entry and descent: entering the water and descending at a controlled rate while verifying equipment functionality;
- mission execution: conducting assigned tasks such as search activities, documentation, and structural inspection;
- ascent and recovery: controlling ascent speed, conducting decompression stops if necessary, and surfacing safely.

2.3.2 Limitations of SCUBA diving

The SCUBA system allows divers to operate independently by carrying personal cylinders, providing high mobility, simplicity, and rapid deployability. However, this system has several structural and operational limitations, as described below.



I. Cylinder
- Storage pressure: 200–300 bar
- Aluminum or steel with control valve
- Main breathing supply for divers

IV. Fins
- Enhance propulsion and maneuverability
- Reduce energy use and improve control underwater

V. Buoyancy control device
- Adjusts buoyancy by adding or releasing air
- Assists in depth control and stability

II. Mask
- Creates air space for clear underwater vision
- Includes tempered glass lens and nose pocket for equalization

VI. Diving suit
- Provides thermal protection and isolation
- Wetsuit traps water for insulation; drysuit blocks water for warmth

III. Regulator
- Reduces cylinder pressure to ambient level for breathing
- Includes first stage (pressure reduction) and second stage (gas delivery)

VII. Miscellaneous equipment
- Dive computer: Calculates depth, time, and no-decompression limit
- Light: Provides visibility in dark environments
- Compass: Assists in underwater navigation
- Dive knife: Emergency tool for cutting lines or nets

Fig. 2. (Color online) System configuration of the SCUBA system.

First, there are limitations associated with the duration of breathing gas supply. The diver's underwater stay time is determined by the capacity of the carried cylinder, and under strong current conditions or during intensive tasks such as cutting and fastening, the diver's breathing rate increases sharply, leading to rapid gas consumption. In addition, the permissible working duration is restricted by the no-decompression limit, which decreases as depth increases, resulting in a significant reduction in operational efficiency at depths greater than 30 m.

Second, limitations exist in communication and safety during ascent and return-to-surface operations. Most SCUBA systems are not equipped with real-time communication networks, making command, control, and coordination between divers or with surface personnel difficult. Moreover, because the system lacks a physical tether or umbilical line, divers face an increased risk of disorientation or failure to return under low-visibility conditions. The absence of external monitoring and support may also delay emergency response in critical situations.

Overall, SCUBA diving is unsuitable for deep or long-duration missions but remains one of the most mobile and flexible diving methods for initial response operations, surface-layer searches, and short-term detailed inspections under moderate environmental conditions.

2.3.3 SSDS diving

The SSDS provides divers with a continuous supply of breathing gas from the surface, enabling stable and prolonged underwater operations. Unlike the self-contained SCUBA system, the SSDS is connected to an external gas source, allowing continuous gas supply, underwater communication, real-time monitoring, and operational control, thereby ensuring suitability for complex and high-risk underwater tasks.

The SSDS can be operated safely and efficiently when current velocities remain below a specified threshold. According to the U.S. Navy,(25) the SOL (V_{SOL}^{SSDS}) is 0.77 m/s (1.5 kn). When this limit is exceeded, it becomes difficult for the diver to maintain a stable position, and increased tension on the umbilical line poses significant safety risks, thereby restricting deployment.

Figure 3 illustrates the typical configuration and gas flow of an SSDS installed on a dive support vessel. Atmospheric air is compressed by a high-pressure compressor and transferred to high-pressure storage cylinders. The gas is then regulated through a distribution panel and supplied to the diver via the umbilical or diving bell. Depending on the operational environment, additional components such as a low-pressure compressor, volume tank, and emergency gas supply may be integrated into the system. These components are arranged and operated according to diving depth and mission duration.(26)

The standard operational procedure of SSDS diving is generally divided into four phases:

- pre-dive inspection: verification of the functionality and safety of the gas supply line, diving helmet, communication system, power system, and decompression chamber;
- deployment phase: deployment of the diver via a diving bell or stage under the supervision of the diving supervisor, with the real-time monitoring of gas pressure and voice communication by the console operator;
- mission phase: execution of underwater tasks such as cutting, recovery, and installation;
- recovery and decompression phase: completion of ascent and decompression procedures and, when required, additional decompression inside the chamber.

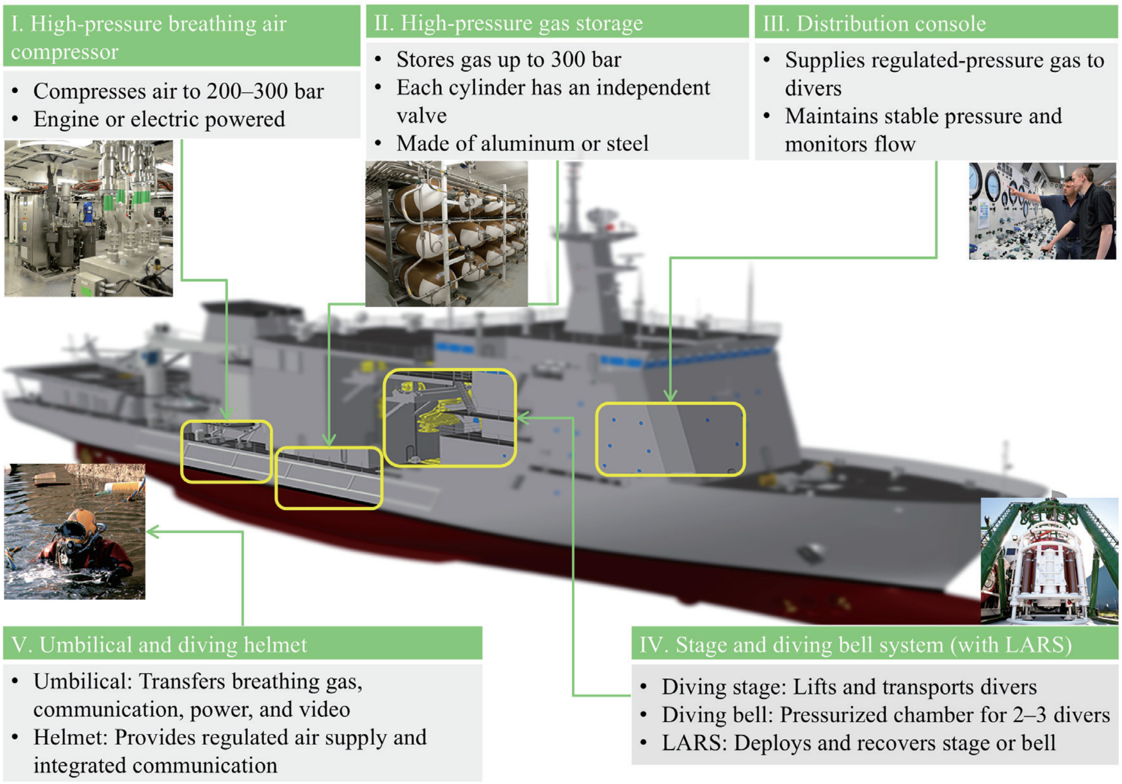


Fig. 3. (Color online) System configuration of the SSDS.(20,26)

This structured procedure ensures diver safety and unified operational control during underwater tasks, providing a reliable framework for long-duration missions such as marine construction, salvage, and emergency response operations.

2.3.4 Limitations of the SSDS

The SSDS delivers breathing gas continuously from an external supply source, thereby ensuring high stability and operational efficiency during extended underwater operations. However, this system has several structural and environmental limitations.

First, increased hydrodynamic resistance occurs owing to the large equipment volume and tension on the umbilical line. As diving depth increases, the tension acting on the umbilical line also rises, and when the current velocity exceeds the SOL, it becomes difficult for the diver to maintain a stable position. This increases the risk of equipment damage and safety hazards, thereby limiting SSDS deployment under strong current conditions.

Second, the system exhibits strong dependence on large-scale equipment and specialized personnel. The SSDS requires complex surface installations such as compressors, decompression chambers, and distribution panels, as well as skilled operators. The deployment and recovery of equipment require significant time, which consequently leads to high maintenance and operational costs.

Overall, although the SSDS is well suited for deep and long-duration missions, it remains limited in terms of mobility and rapid deployability and is therefore less efficient for time-sensitive or high-mobility underwater operations.

3. Integrated Operational Strategy

3.1 Operational time analysis based on tidal current conditions

The configurations, operational procedures, and SOL of the heavy-class ROV and manned diving systems indicate the independent operational characteristics and performance boundaries of each system. These distinctions suggest that a complementary division of roles can be established depending on tidal current intensity, water depth, and task type. Accordingly, a four-phase integrated operational procedure linking compact-class ROVs with manned diving systems was established(16) on the basis of tidal current variations within a tidal cycle.

- 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): pre-dive phase in which the ROV alone can be deployed owing to marginally reduced tidal currents
- Phase III (manned diving): main USAR phase in which manned diving is feasible owing to the weakest tidal currents
- Phase IV (post-dive ROV tasks): post-dive phase in which the ROV alone can be deployed before tidal currents regain strength

Figure 4 shows the predicted tidal current profiles at the Sewol ferry sinking site, as reported in a previous study.(12) During the spring tide on May 16, 2016, coordinated operation between the ROV and manned diving systems enabled a total operational duration of approximately 140 min. In this case, when integrated with the SSDS, the operational phases were divided into 30 min for pre-dive ROV tasks, 90 min for manned diving, and 20 min for post-dive ROV tasks.

When integrated with the SCUBA system, which has a lower SOL, the available operational time was 50 min for pre-dive ROV tasks, 60 min for manned diving, and 30 min for post-dive ROV tasks. Compared with the SSDS, this indicates that ROV operational time increases, whereas manned diving time decreases because of the more restrictive current limit of SCUBA (Table 3).

These results demonstrate that the operational duration of each system varies significantly depending on tidal current intensity, emphasizing that phase-specific task allocation and the optimization of operational time based on tidal cycles are essential for efficient mission execution. Therefore, the integrated operational strategy proposed in this study does not simply compare system limits but presents a systematic procedure designed to sequentially and complementarily deploy the heavy-class ROV and manned diving systems according to tidal current variations, thereby maximizing operational efficiency and safety in complex marine environments.

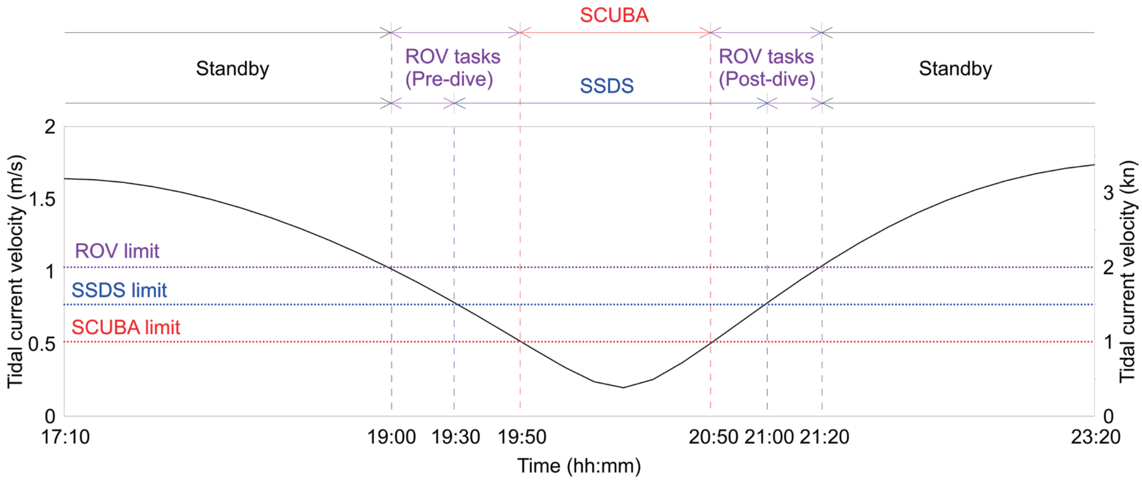


Fig. 4. (Color online) Integrated ROV–manned diving operational strategy based on predicted tidal current conditions at the Sewol ferry disaster site.(16)

Table 3
Comparison of operational durations under spring tide conditions (May 16, 2016).

Integrated system	Entry time, exit time, and duration (hh:mm–hh:mm/min)			Total time (min)
	Pre-dive ROV tasks	Manned diving	Post-dive ROV tasks	
With SCUBA	19:00–19:50/50	19:50–20:50/60	20:50–21:20/30	140
With SSDS	19:00–19:30/30	19:30–21:00/90	21:00–21:20/20	140

3.2 Mission phases of integrated operations

The integrated operational procedure proposed in this study aims to enhance overall safety and efficiency by classifying the operational windows of each system according to tidal current cycles and systematically assigning tasks to each phase. In particular, ROVs (heavy-class and compact-class) and manned diving systems exhibit complementary functionalities. Through phase-based cooperative operations between these systems, the operational success rate of underwater missions in large-scale marine disaster environments can be maximized.

3.2.1 ROV missions

The heavy-class ROV configured in this study and the compact-class ROV presented in a previous study(16) demonstrate distinct operational characteristics within the integrated operational procedure.

Both ROV systems follow a three-phase operational sequence comprising standby, pre-dive, and post-dive ROV tasks according to the tidal current cycle. The common mission profiles for each phase are as follows.

- Standby: This phase corresponds to periods of strong currents or unstable working conditions during which ROV deployment is not feasible. It serves as the stage for equipment inspection and preparation. Primary tasks include checking the functionality of both the ROV and the manned diving equipment, verifying the stability of communication and power-supply systems, providing crew rest, and establishing subsequent operational plans.

- Pre-dive ROV tasks: Conducted as tidal currents gradually weaken, this phase involves the early deployment of the ROV to perform area surveys, target identification, and hazard removal. The video footage and environmental data collected during this stage are used to determine the optimal timing for diver deployment (SSDS or SCUBA) and to validate operational safety.
- Post-dive ROV tasks: After manned diving operations are completed, the ROV is deployed again to conduct post-task verification, assess structural conditions, and identify unsearched areas. These tasks ensure operational completeness and enhance data reliability. The acquired video records also serve as baseline information for subsequent analysis and recovery processes.

The compact-class ROV is a lightweight system optimized for rapid deployment, capable of operating from small vessels or within confined spaces. It does not require complex power supply systems or extensive logistical support, enabling immediate deployment within a short time. Owing to its high maneuverability and compact body, the compact-class ROV provides excellent operational efficiency during pre- and post-dive ROV tasks.

- Pre-dive ROV tasks: The compact-class ROV can be deployed immediately as the current weakens, allowing the detailed inspection of narrow structures and debris gaps. This capability enables early reconnaissance and hazard identification before diver entry, improving operational safety and situational awareness.
- Post-dive ROV tasks: Owing to its lightweight structure and simple recovery mechanism, the system can be quickly retrieved and redeployed by a small team, facilitating repeated inspections or short-interval resurveys.

In contrast, the heavy-class ROV is a high-performance work-class system designed for deep-sea operations and precision intervention. Its high-thrust propulsion and precision control systems allow stable positioning under fluctuating currents or external disturbances. Mission-specific tasks that can be performed exclusively by the heavy-class ROV are as follows.

- Pre-dive ROV tasks: The heavy-class ROV can perform heavy-load operations such as cable cutting, the detachment of structural connections, valve manipulation, and obstacle removal, effectively eliminating hazards prior to diver deployment.
- Post-dive ROV tasks: Using multiple sensors and high-resolution imaging systems, the heavy-class ROV can detect subtle displacement or structural damage that is difficult to observe visually. These capabilities enhance post-dive safety verification and structural integrity assessment.

In summary, the compact-class ROV is optimized for rapid response and high-mobility inspection in confined environments, demonstrating superior performance in pre-dive reconnaissance and hazard detection before manned diver entry. In contrast, the heavy-class ROV, with its precision control and high-load handling capabilities, is better suited for pre- and post-dive inspection, recovery, and precision intervention tasks.

3.2.2 Manned diving missions

The manned diving systems proposed in this study are operated in coordination with the ROV systems according to tidal cycles and offshore environmental conditions. Depending on the equipment configuration and operational objectives, they are categorized into SCUBA and SSDS. Both systems are integrated with the pre- and post-dive ROV tasks, performing missions that require direct human intervention such as precision manipulation, close-structure access, and survivor rescue operations that are difficult for ROVs to accomplish independently. The main characteristics of the manned diving phase for each system are described below.

The SCUBA diving system features a simple equipment configuration and rapid deployment procedures, making it suitable for initial response and shallow-water exploration immediately after a marine disaster. During the SCUBA diving phase, divers are directly deployed underwater to perform key missions such as rescuing survivors, inspecting external hull structures, recording video footage, and installing markers. Because of its high mobility and ease of deployment, the SCUBA system enables immediate response and on-site reconnaissance in the early stages of an incident.

However, SCUBA diving is limited by short bottom time, depth restrictions, and the absence of real-time communication capability. Therefore, it is unsuitable for long-duration or deep-water operations and is more appropriately utilized as a supplementary system for initial response and short-term search missions. Subsequent operations should transition to SSDS or ROV systems on the basis of the exploration results and marker information obtained during the SCUBA phase, enabling more precise and continuous underwater activities.

The SSDS serves as the primary diving system for marine disaster response operations that require long working durations and complex manipulative tasks, offering high precision and safety. During the SSDS phase, divers directly perform essential missions such as cutting, fastening, lifting, and securing operations that demand fine control. The SSDS provides a stable and continuous gas supply, whereas real-time voice communication enables supervisory command and control, ensuring efficient performance even in complex and high-risk underwater environments.

The SSDS provides high precision and safety during heavy-object recovery, entry into confined or complex structures, and underwater installation or maintenance tasks that are difficult for ROVs to perform independently. It serves as the central platform for long-term and complex underwater operations in coordination with ROV search and verification stages and is therefore proposed as the core manned diving system for USAR during large-scale marine disaster response.

4. Discussion

4.1 Sequential operation procedure

Figure 5 illustrates the conventional sequential operation procedure for ROVs and manned diving systems commonly applied at marine disaster sites. This procedure follows a vertically structured sequence in which each mission is performed independently within separate time frames, indicating that ROV and manned diving operations are conducted successively rather than simultaneously. The overall process consists of several stages, beginning with personnel and equipment mobilization, followed by pre-dive planning, site arrival and initial assessment, ROV deployment and subsea survey, task coordination between ROV and diving teams, manned diving operations, and finally mission termination and post-mission evaluation. The details of each stage are as follows.

- Mobilization and pre-dive planning: Personnel and equipment are mobilized, and fundamental data such as weather, tidal current, depth, and visibility at the accident site are collected. This stage establishes the overall direction of the mission plan and forms the basis for strategies for ROV and diver deployment.
- Arrival on site, setup, and initial assessment: Upon arrival, the team sets up equipment, connects power and communication systems, and conducts real-time measurements of weather and current conditions. The collected data are used to determine the appropriate timing for ROV deployment and the suitability of diver access zones.
- ROV deployment and subsea survey: The ROV is deployed first to conduct visual and sensor-based examinations of seabed topography, target locations, and obstacle distribution. This step is essential for ensuring diver safety. The gathered data are used to refine dive plans and define or restrict diving areas.
- Task handover and operational coordination: In this stage, information exchange and mission transfer between the ROV and diving teams are carried out in preparation for diving

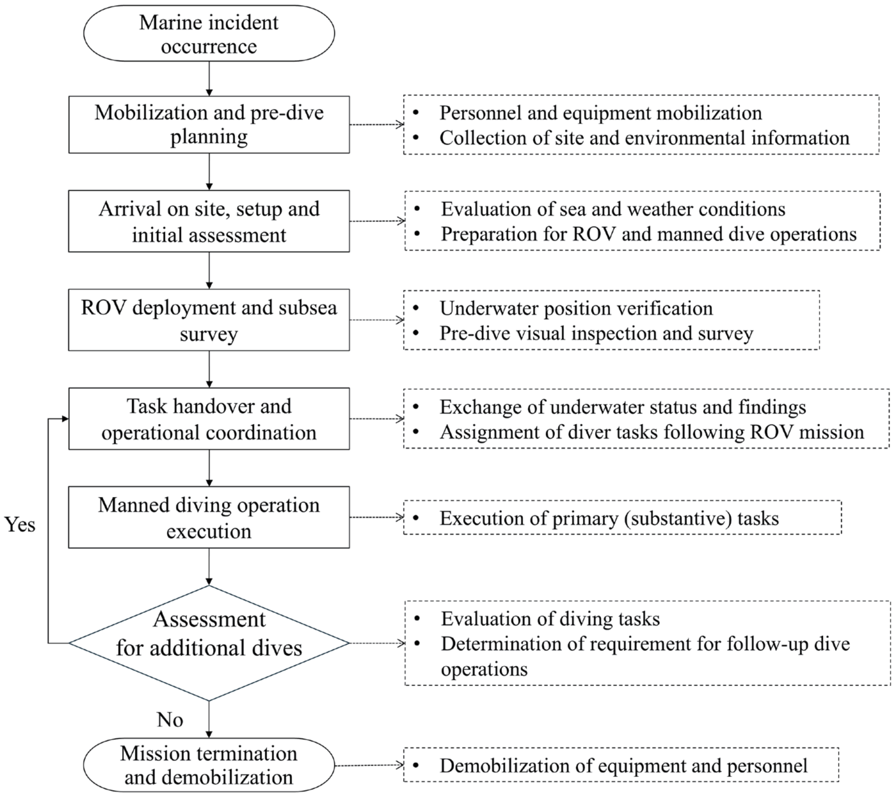


Fig. 5. Flowchart of the sequential operational procedure for non-integrated ROV and manned diving operations.

operations. It serves as the final coordination phase in the sequential framework, ensuring that all findings from ROV exploration are effectively transferred before the manned operation begins.

- Manned diving operation execution: SCUBA or SSDS divers are deployed to perform key missions such as rescue of survivors, marker installation, structure access, and fastening. This phase involves the highest level of risk and requires advanced professional skills. Divers rely on ROV-provided data to identify target positions accurately and adapt to environmental changes during the operation.
- Assessment for additional dives: After mission completion, the team evaluates mission success, underwater visibility, current velocity, equipment condition, and diver fatigue to determine whether additional dives are necessary.
- Mission termination and demobilization: Equipment retrieval, personnel withdrawal, data organization, and result reporting are conducted. The collected data serve as critical references for accident analysis, structural assessment, and post-recovery planning.

This sequential operation framework offers advantages in organizational simplicity, the clarity of management, and efficient personnel utilization. In particular, when target search or environmental investigation is prioritized over survivor rescue operations, many missions can be completed through ROV-alone deployment, providing high practical efficiency. However, this vertically structured approach limits the ability to combine the complementary strengths of the ROV and manned diving. For example, if manned diving is conducted outside the optimal current range or during strong tidal flow, the risk of accidents increases. Conversely, if the ROV is deployed during weak-current periods, the ideal operational window for manned diving may be missed, resulting in reduced efficiency. Therefore, to address these limitations, it is necessary to establish an improved operational framework that incorporates tidal current cycles and enables coordinated task scheduling between ROVs and divers.

4.2 Integrated operation procedure

In this study, we propose an integrated operation procedure between the ROV and manned diving systems for marine disaster response, as illustrated in Fig. 6. This procedure classifies the operational availability of each system on the basis of the SOL of each system and provides a framework in which their respective missions are coordinated concurrently. It addresses the environmental adaptability limitations of the vertically structured sequential operation shown in Fig. 5 and enables the ROV and manned diving systems to perform complementary tasks throughout tidal current cycles.

The mobilization and pre-dive planning stage and the arrival on site, setup, and initial assessment stage are identical to those of the sequential operation. During the system activation stage, the integrated operational framework becomes active. This includes system checks for both the ROV and manned diving units, the setup of power and communication systems, crew rotation planning, and the detailed coordination of tasks. This stage functions not only as a pre-operational inspection but also as a preparation phase that allows the real-time adjustment of operational sequences based on SOL assessments.

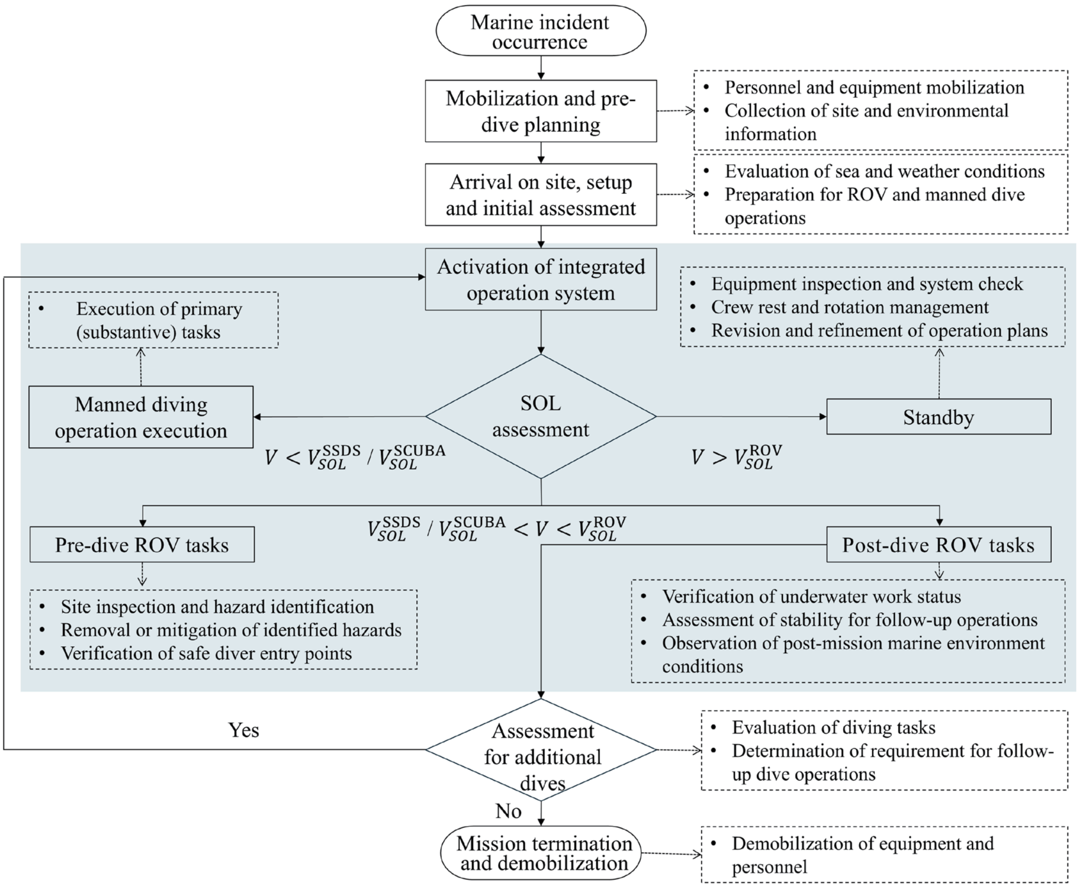


Fig. 6. (Color online) Flowchart of the integrated operational procedure for heavy-class ROV and manned diving systems structured by current velocity thresholds.

The core of the integrated operation is the SOL assessment stage, in which the primary operating system is determined according to the SOL of each system. The procedure varies according to current velocity conditions as follows.

- $V > V_{SOL}^{ROV}$: represents a period when no equipment can be deployed, corresponding to Phase I (standby). During this phase, equipment inspection, personnel rest, and the adjustment of operational plans are conducted.
- V_{SOL}^{SSDS} or $V_{SOL}^{SCUBA} < V < V_{SOL}^{ROV}$: represents conditions suitable for pre-dive ROV tasks, during which the ROV performs safety assessments, obstacle removal, and the verification of diver entry points. During post-dive ROV tasks, the ROV is redeployed to validate the results of manned diving operations and to reassess structural deformation or unsearched areas using video, acoustic, and sensor data.
- V_{SOL}^{SSDS} or $V_{SOL}^{SCUBA} > V$: represents conditions suitable for manned diving operations, during which divers conduct precision tasks such as rescue of survivors, marker installation, cutting, and fastening based on information provided by the ROV.

Subsequently, during the assessment for additional dives stage, current velocity conditions relative to the SOL of each system and mission outcomes are reviewed comprehensively to determine the necessity for further diving operations. If additional dives are deemed unnecessary, the process transitions to the mission termination and demobilization stage, during which equipment retrieval, personnel withdrawal, data storage, and result reporting are completed.

This integrated operation procedure ensures operational continuity between the ROV and manned diving phases and minimizes efficiency fluctuations caused by tidal current cycles. Compared with the conventional vertically structured operation, it provides improved operational efficiency and safety by clearly defining the timing and roles of each system. In particular, it reduces unnecessary standby periods under strong current conditions and maximizes diver safety during stable-current intervals, thereby enhancing the overall performance of USAR operations in dynamic marine environments.

4.3 Classification of diving operation modes

In marine disaster response, selecting an appropriate diving operation mode is essential to ensure both operational efficiency and diver safety. In this study, we propose an integrated operation framework that combines the ROV and manned diving systems, taking into account current velocity conditions and equipment characteristics. However, in actual field operations, multiple environmental factors such as weather, sea state, current velocity variation, visibility, and equipment availability interact simultaneously, requiring flexible and situational judgment.

Accordingly, in this study, we present a set of criteria for determining suitable diving operation modes, as summarized in Table 4. The table shows the applicability of three operational modes: manned-diving-alone, ROV-alone, and integrated ROV–manned diving operations. This assessment considers accident severity level, the type of support vessel, personnel requirements, and operational depth.

The classification of marine disaster severity follows the casualty investigation code of the International Maritime Organization,(27) which defines the categories as follows.

- Very serious marine casualty (VSMC): incidents involving total loss of a vessel, loss of life, or severe environmental damage
- Serious casualty (SC): incidents less severe than VSMC but involving major damage caused by fire, explosion, grounding, collision, or structural failure, requiring towing or external assistance

Table 4
Proposed classification and criteria for ROV and manned diving operations in marine disaster response.

Operation method	Manned diving	ROV	Severity levels	Support vessel	Manpower standards	Maximum depth (m)
Stand-alone	SCUBA	—	MI	SV	≥4	≤40
Stand-alone	SSDS	—	SC	DSV	≥7	≤100
Stand-alone	—	Compact-class	MI	SV	≥2	≤2000
Stand-alone	—	Heavy-class	VSMC	DSV	≥3	≤4000
Integrated	SCUBA	Compact-class	SC	SV	≥6	≤40
Integrated	SSDS	Compact-class	VSMC	DSV	≥9	≤100
Integrated	SCUBA	Heavy-class	VSMC	DSV	≥7	≤40
Integrated	SSDS	Heavy-class	VSMC	DSV	≥10	≤100

- Marine incident (MI): events that may pose potential risks of injury, loss, or damage to persons, vessels, marine structures, or the environment

On the basis of this classification, the nature and risk level of diving missions are defined, and the corresponding operation mode must be supported by an appropriate type of support vessel. In this study, the classification of support vessels follows the standards of MOF,(4) as described below.

- Small vessel (SV): vessel less than 12 m in length, typically used for SCUBA diving or compact-class ROV operations
- Dive support vessel (DSV): specialized vessel equipped with systems such as LARS and a diving bell, which serves as a primary platform for SSDS and heavy-class ROV operations

The minimum personnel requirements for manned diving and ROV operations are derived from U.S. Navy(25) and IMCA(18) standards, excluding standby personnel or vessel operation crews. The maximum operational depths presented in Table 4 were specified by considering the technical capabilities and safe operating ranges of the respective systems.

4.4 Diving system operation by severity levels

Table 4 presents a classification framework that distinguishes three operational modes: manned-diving-alone, ROV-alone, and integrated ROV–manned diving operations. Severity levels are the primary determinant when selecting the appropriate operation mode.

VSMC requires a comprehensive national-level response system and operational conditions that support the deployment of a heavy-class ROV and DSV. At this level, it is essential to secure sufficient manned diving and ROV crews, as well as rotation personnel and additional support staff, to sustain long-duration underwater operations.

SC requires a stable operating environment centered on the SSDS and DSV. Continuous underwater communication and a reliable breathing gas supply are necessary to ensure both efficiency and safety during rescue missions.

MI prioritizes rapid response and life-saving operations. Accordingly, SCUBA and compact-class ROVs are employed because of their high mobility and rapid deployability. This combination is well suited for short-duration tasks in the early response phase, such as external hull inspection, locating missing persons, and installing markers.

Manned-diving-alone operations may be implemented immediately under emergency conditions when the water depth is shallow and visibility and sea state are favorable during daylight. If ROV deployment would delay the response, the manager may prioritize manned diving to maintain operational efficiency. Under MI conditions, life-saving is the highest priority, and SCUBA is typically the primary mode. Under SC conditions, the SSDS is used within its safe depth range and provides a more stable and systematic operational environment than SCUBA. The SSDS also offers higher precision and safety for tasks that are difficult for the ROV, such as detailed rescue, missing person recovery, underwater cutting, and reinforcement work.

Under ROV-alone operations, tasks are conducted exclusively by the ROV. The compact-class ROV is commonly used to locate and recover voyage data recorders from vessels or flight recorders from aircraft after crew evacuation. The heavy-class ROV is suitable for deep-water missions beyond manned diving limits, including body recovery, lifting heavy objects, and complex fastening tasks.

By considering severity levels, underwater mission characteristics, and equipment performance, an appropriate operation mode can be selected. For this framework to function effectively, the organization must ensure sufficient equipment capability, adequate manpower, and support vessel availability. In this context, Table 4 provides essential reference information for the control tower during marine disaster response and supports the development of future operational manuals and standardized diving operation guidelines.

5. Conclusions

In this study, we proposed an integrated operational strategy that combines a heavy-class ROV with manned diving systems to enhance the efficiency and safety of USAR operations during large-scale marine disasters. Building on the coordinated operational procedure for compact-class ROV and SCUBA operations developed in a previous study,(16) we established a detailed operational sequence and coordination strategy for integrated heavy-class ROV and manned diving operations. The key findings are summarized as follows.

1) The analysis of each diving system's configuration and operational characteristics showed that the heavy-class ROV and SSDS provided stable operational performance but exhibited limited maneuverability. In contrast, SCUBA offered high mobility and accessibility in underwater environments but was constrained by short operation duration and safety limitations. This comparative analysis clearly identified the operational boundaries of each system and revealed their complementary potential.
2) Under strong current conditions during the spring tide, which allowed a total underwater working time of 140 min, the integrated operation of the heavy-class ROV and SSDS allocated 90 min (64.3%) to manned diving, 30 min (21.4%) to pre-dive ROV operations, and 20 min (14.3%) to post-dive ROV operations, demonstrating a higher proportion of manned diving activity. In contrast, when integrated with SCUBA, manned diving accounted for 60 min (42.9%), whereas ROV pre- and post-dive operations accounted for 50 min (35.7%) and 30 min (21.4%), respectively, indicating a larger share of ROV-based operations.
3) To improve upon the conventional sequential operation procedures commonly applied at marine disaster sites, we proposed a decision-making framework based on the SOL assessment. This framework determines the deployment and retrieval timing of both the ROV and manned diving systems, minimizes unnecessary standby periods, enhances diver safety, and optimizes overall underwater work efficiency.
4) A classification system for selecting appropriate diving operation modes was established by comprehensively considering severity levels, support vessel type, personnel composition, and operational depth. This classification framework provides scientific criteria for determining whether ROV-alone, manned-diving-alone, or integrated operations should be applied and serves as essential reference information to support prompt decision-making by control authorities during marine disaster response.

Given the current lack of clear guidelines and procedures for integrated ROV–manned diving operations, the results of this study are expected to serve as a foundational reference for establishing standardized operational guidelines for diving systems in marine disaster response. Future work will focus on quantitatively validating the operational effectiveness of the proposed heavy-class ROV and manned diving integration strategy. In addition, recent advancements in compact diver-assistance robots designed for proximity monitoring and AI-based situational assessment(28) highlight the potential for enhancing safety and supporting decision-making during integrated operations. Furthermore, the expanding capabilities of autonomous underwater vehicles, supported by advanced sensor technologies, may provide a useful basis for wide-area reconnaissance and pre-dive hazard assessment, thereby reducing personnel workload and improving the flexibility and robustness of USAR missions.(29) Integrating these autonomous platforms into the broader USAR framework will be a key direction for future research.

Acknowledgments

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

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