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A Review of Key Issues in the Resilience of Marine Geotechnical Engineering

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ABSTRACT: This article systematically reviews the key issues and development trends in the research of marine geotechnical engineering resilience. Firstly, it elaborates on the concept of resilience and its core significance in resisting marine disasters, ensuring engineering safety, and facilitating rapid recovery. It focuses on analyzing the challenges in engineering stability, dynamic loads, and multi-field coupling effects in complex geological environments (such as marine soft soil, coral sand, and energy soil), as well as extreme climate disaster prevention. It also discusses the progress of frontier technologies such as surveying techniques, new foundation structures, and intelligent monitoring. By combining application scenarios such as deep-sea resource development, offshore wind power, and island reef engineering, it points out that interdisciplinary integration and green sustainable development are important directions for the future. It emphasizes that through technological innovation and system integration, the adaptability and resilience of marine engineering can be enhanced to support the safe development and sustainable utilization of marine resources.

KEYWORDS: Marine geotechnical engineering; Resilience; Multi-field coupling; Geological disaster prevention and control; Intelligent technology.

I. INTRODUCTION

Marine geotechnical engineering mainly involves geological and civil engineering activities conducted in marine environments. The marine environment has unique conditions such as water depth, tidal variations, wave impact, salt corrosion, and seawater pressure, which pose significant challenges to the design and construction of geotechnical engineering. Therefore, in marine geotechnical engineering, special exploration methods, material selection, structural design, construction techniques, and monitoring measures need to be adopted to ensure the safety and stability of the project. With the development of the global economy and the increasing demand for marine resources by humans, the importance of marine geotechnical engineering has become increasingly prominent. Currently, fields such as offshore oil and gas extraction, offshore wind farm construction, underwater tunnel excavation, and cross-sea bridge construction all rely on the support of marine geotechnical engineering technology. At the 13th National Conference on Soil Mechanics and Geotechnical Engineering held in Tianjin, China, a consensus was proposed: Future geotechnical engineering should possess the qualities of "resilience, greenness, intelligence, and humanity." At the same time, the "resilience" of geotechnical engineering was elaborated: "Geotechnical engineering is closely related to people's livelihood and is almost everywhere in construction projects. Breaking the traditional safety concept, establishing a new safety concept for geotechnical engineering, enhancing the resilience of geotechnical engineering to resist natural disasters or severe disasters caused by human factors and maintain its functions to the greatest extent, as well as restoring its functions as soon as possible after a disaster, are important qualities of geotechnical engineering to support resilient urban and social construction." Resilient marine geotechnical engineering refers to the engineering adaptability and recovery ability in the face of extreme climates, geological disasters, and complex marine environments.

This article aims to systematically review and summarize the key issues of resilience research in marine geotechnical engineering. First, it will explain the core connotation and urgent necessity of the resilience concept in marine geotechnical engineering. Then, it will focus on several core scientific issues and technical challenges that constrain the resilience of the project, including the stability of complex marine soft soil and special soils (coral sand, energy soil) under dynamic loads, the coupling mechanism of multiple disasters such as waves, ocean currents, and earthquakes,

and the prevention and control of seabed erosion and geological disasters in extreme climate conditions. Next, it will review the emerging cutting-edge technologies for enhancing resilience, such as intelligent surveying equipment, new adaptive foundations, and disaster warning systems based on multi-source monitoring and artificial intelligence. Finally, through the analysis of typical engineering applications such as offshore wind power, deep-sea mining, and island construction, it will envision the technical trends for building a more resilient marine engineering system through interdisciplinary integration and green sustainable development paths in the future. This article hopes to provide a comprehensive perspective on resilience construction for researchers and engineers in the field of marine geotechnical engineering, and jointly promote the development of marine infrastructure towards a safer, smarter, and more sustainable future.

II. KEY ISSUES OF RESILIENCE IN MARINE GEOTECHNICAL ENGINEERING

2.1 Engineering Stability in Complex Geological Environments

The undrained shear strength of marine soft soil is one of the important parameters for the design of horizontal load-bearing foundations. Under the action of waves, earthquakes, and cyclic loading of the foundation, marine soft soil will accumulate excess pore water pressure, resulting in the weakening of the dynamic strength and dynamic modulus of the soft soil, and subsequently causing deformation, failure, or even destruction of the building (structure). Li Gaoyi et al. [1] analyzed the seismic response of marine soft soil pile foundations in single-pile structures by establishing a mathematical model of pile foundations in marine soft soil and a finite element numerical simulation model. Island reef projects require a large amount of construction materials, but transporting construction materials from the land is very labor-intensive, resource-intensive, and financially costly. Therefore, it is inevitable to adopt coral sand as the construction material for island reef foundations based on local conditions. The special formation of coral sand has resulted in its mechanical properties being different from those of terrestrial sands, and this difference is closely related to the structural characteristics of coral sand. Gan Yidong et al. [2] conducted a series of triaxial consolidated undrained shear tests on saturated coral sand and obtained the stress-strain relationship, pore pressure-strain, and shear strength parameters of coral sand corresponding to the grading effect.

Marine energy soil refers to marine sedimentary soil containing methane hydrates, mainly distributed at the bottom of the ocean. During the extraction process, the decomposition of combustible ice can lead to the weakening of the rock and soil parameters of marine sedimentary soil, affecting the engineering safety. Kong Liang et al. [3-6] conducted indoor experiments, constitutive models, and numerical simulations around the mechanical properties of typical mud-sand type energy soil in the typical hydrate formation area in the northern part of the South China Sea. The research results revealed the mechanical response mechanism of energy soil during hydrate extraction and the evolution law of engineering geological risks, which not only deepened the scientific understanding of the mechanical behavior of deep-sea energy soil but also had important reference value for promoting the commercial trial production process of marine methane hydrate.

2.2 Dynamic Loads and Multi-field Coupling Effects

Wang Liyan et al. [7] proposed the use of grid cages, which are inexpensive, easy to construct, have strong corrosion resistance, and have low maintenance costs, for coastal wave erosion protection. They also utilized numerical simulation and analyzed the protective effects of the presence or absence of grid cages and three different cross-sectional shapes of grid cages on coastal erosion. Ou Xiaoduo et al. [8] based on numerical simulation combined with actual engineering, studied the mechanical properties and deformation laws of steel sheet pile cofferdams under the influence of tidal forces, providing guidance and corresponding remedial methods for the design and construction of similar steel sheet pile cofferdam projects.

Coral sand liquefaction is the main cause of the destruction of various buildings and structures on islands and reefs. Wu Qi et al. [9] conducted vibration table model tests to test and analyze the dynamic responses of coral sand foundations and building group pile foundations under the dynamic interaction of pile-soil-structure, and explored the different dynamic response characteristics of the site under different seismic motion intensities, providing certain seismic design basis for the construction of pile foundations on coral islands and reefs in the South China Sea.

2.3 Prevention of Extreme Climate and Disasters

Oceanic disasters such as storm surges, waves, sea ice, and red tides severely restrict the economic and social development of coastal areas and pose a threat to the lives and property of the people. Offshore engineering faces the risks of erosion and foundation liquefaction caused by rising sea levels and intensified storm surges, while deep-sea energy development needs to address the seepage-mechanical coupling issues triggered by the decomposition of methane hydrates. A large number of scholars currently adopt a combined approach of multi-scale experiments (such as centrifugal model tests and water tank simulations) and numerical simulations (CFD-DEM coupling analysis) to construct disaster evolution models, combined with in-situ monitoring data; at the same time, by developing new protective materials (such as self-repairing concrete) and intelligent monitoring systems (based on fiber optic sensing and InSAR technology), a disaster prevention and control system from the offshore to the deep-sea is established.

2.4 Intelligent and Digital Technologies

The internal environment of the ocean is complex, and the problems in offshore geotechnical engineering often involve multi-field coupling issues such as flow, solid, and chemical. Therefore, numerical simulation technology is difficult, especially the complex multi-physical field coupling behaviors related to heat transfer, multiphase seepage, reservoir deformation, hydrate phase change, and sediment transport in the methane hydrate exploitation reservoir, which affect and control the production evolution laws and risk changes during the development process, and have a direct impact on the safe and efficient development of methane hydrates. Therefore, in-depth understanding of the basic logic of multi-field coupling in the complex ocean environment and achieving precise simulation and analysis of multi-field coupling is an important fundamental scientific issue faced by marine geotechnical engineering research [10].

In the research on seabed geological environment monitoring technology, although good progress has been made and a large amount of monitoring data has been obtained, there are relatively few data management and analysis databases, with a narrow range of disaster types, and few databases focusing on seabed geological disasters have been developed and applied. Moreover, the database functions only stop at compiling historical monitoring data, without real-time data access, storage, and visualization display, making it difficult to meet the needs of disaster monitoring and early warning.

III. FRONTIER TECHNOLOGIES AND ENGINEERING APPLICATIONS

3.1 Frontier Technologies

3.1.1 Surveying Techniques

The traditional geophysical survey techniques include:

- Seismic exploration method: By emitting seismic waves and recording the signals reflected back to the ground, to detect the positions, thicknesses and physical-mechanical properties of different layers underground. It is suitable for the investigation of deep seabed sedimentary strata.
- Drilling and sampling method: Using drilling equipment to conduct seabed drilling and collect sediment samples at different depths, and conducting laboratory tests to obtain their physical-mechanical parameters.
- Sonar detection method: Utilizing sonar equipment to emit and receive ultrasonic waves, to determine the seabed topography, shallow geological structures and obstacles, etc.
- Geoelectric method: Based on the changes in the observed geoelectric fields on the surface or in the well, to infer the distribution characteristics of underground media.

Among these, regarding the drilling and sampling method, since the drilling equipment is prone to be disturbed by the marine environment, which can change the original state of the seabed soil. In recent years, China has applied a type of wave compensation drilling equipment, mainly using hydraulic technology or counterweight weights to improve the stability of the drill string, which can effectively reduce the impact of environmental interference factors on the drilling results [11]. In terms of in-situ testing, Professor Randolph from the University of Western Australia developed a new type of full-flow penetration testing technology based on marine static probing. The full-flow penetration testing technique changes the shape of the probe and the position of the pore water pressure ring, which can accurately obtain the parameters of marine soft soil. This method has the characteristics of low disturbance, fast time, and flexible operation, and is currently a new technology for soft soil survey and also an important research direction for marine survey in the future [12]. In recent years, the free-fall penetration instrument (FFP) has attracted attention due to its ability to provide rapid and economically efficient strength analysis of seabed sediments. It can be

used to monitor the relative density and friction angle in sandy nearshore environments and estimate the consolidation coefficient of fine-grained nearshore and estuarine sediments [13].

3.1.2 New Foundation Design

The suction piles and bucket-shaped foundations, as innovative deep-water foundation forms in marine engineering, have demonstrated significant technical advantages in offshore wind power and marine platform construction. Their working principle is based on negative pressure penetration technology - by pumping out the water inside the foundation to create an internal pressure difference, the structure penetrates the seabed, and ultimately relies on the interaction between soil and structure to provide bearing capacity. In complex marine environments, these foundations have three core advantages: (1) Excellent resistance to horizontal loads, with the wide diameter ratio design effectively resisting overturning moments caused by typhoons and ocean currents; (2) Adaptive installation characteristics, achieving millimeter-level penetration accuracy through precise control of suction pressure, particularly suitable for uneven seabed geological conditions; (3) Economic performance throughout the entire life cycle, reducing steel usage by 30% compared to traditional pile foundations and allowing for recycling and reuse. Recent studies have shown that using soil-water-structure coupling numerical models (such as the CEL method) and centrifuge tests can optimize their dynamic responses under multi-load conditions such as waves, ocean currents, and earthquakes, and the intelligent foundation system based on optical fiber monitoring further enhances its stability warning capability during the service period. These technical characteristics make them the preferred solution for current deep-sea engineering foundations.

Future efforts should focus on solving scientific problems such as deep-water high-pressure sealing, prediction of soil weakening under long-term cyclic loads, and improvement of the accuracy of multi-physics field coupling simulations. By establishing an international joint test platform (such as the EU PRIMaRE program), sharing extreme environment test data, and accelerating technological iteration. In the next 5-10 years, these two types of foundations are expected to become the "standard configuration" for deep-sea energy development, driving the advancement of marine engineering towards intelligence and green development.

3.1.3 Technological Innovation in Inspection

High-resolution dynamic measurement technology can be applied in the inspection of offshore platform pile foundations. Fan Zixia [14] et al. mentioned the full-process monitoring of large-diameter steel piles of China's offshore platforms during dynamic measurement and the repeated driving test, which changed the situation where there was no effective monitoring of the driving process and verification of design calculations.

In addition to single-pile bearing capacity testing, due to the harsh and variable marine environment, especially in offshore wind farm areas, extreme sea conditions such as strong winds, large waves, and rapid tides cause significant damage to the underwater structure of single piles; the high salinity of seawater in the underwater area, the attachment of marine organisms, etc., create a very harsh corrosive environment; some geological disasters, geological changes, and water dynamic effects lead to partial exposure and suspension of the pile foundation base and connection cables, and the suspended pipelines bear internal forces, external water pressure, and vibration, which may cause fatigue damage to the structure and suspended cables; at the same time, the single-pile foundation structure has large flexibility and small stiffness, which will increase the dynamic displacement and natural vibration period of the pile foundation, and resonate with the waves in the ocean, increasing the possibility of structural damage. Therefore, regular external inspections of offshore wind pile foundations and cables, checking the exposure and suspension of the cables, and investigating and monitoring the seabed topography around the pile foundation are extremely crucial. However, the traditional diving method for inspection is limited to a depth of 50 meters or less, while the underwater robot inspection method is not affected by the depth of the operation or the duration of the operation, and is safer. Currently, underwater robot inspection of offshore wind foundation water areas in China is still in the experimental and exploration stage, and most related technologies and methods are borrowed from marine oil and gas engineering and foreign wind power inspection projects, but the costs of marine engineering and foreign detection equipment, technologies, and operation vessels are high. Domestic experts and practitioners have made technical references and method improvements based on the characteristics of our wind farms, gradually forming a low-cost, high-efficiency underwater structure inspection technology suitable for our country [15].

3.2 Engineering Applications

3.2.1 Research on Key Equipment for Deep-sea Resource Development

The development of deep-sea resources and energy exploration is witnessing significant technological breakthroughs. The domestically developed "Weiqi" intelligent drilling system of China has demonstrated outstanding performance in the pilot production of natural gas hydrates in the South China Sea. Its innovative adaptive drilling control system can adjust the drilling pressure and speed in real time, successfully overcoming the drilling challenges in deep-sea soft-hard interlayers and the easy decomposition of natural gas hydrates.

In the field of deep-sea mining, the "KaiTao Er" 4000-meter multi-metal crust mining vehicle has achieved efficient and environmentally friendly mining under the complex seabed terrain of the Western Pacific through an integrated system of intelligent recognition - precise collection - hydraulic transportation. Regarding the special mechanical behavior of energy soil, China has established a multi-field coupling test platform for seepage, mechanics, and chemistry, and developed a THMC (heat-water-fuel-chemistry) constitutive model considering the phase change of hydrates, providing theoretical support for the safe development of deep-sea resources. In the future, key breakthroughs will be made in deep-sea in-situ testing, intelligent mining robot cluster operations, and dynamic monitoring of the ecological environment during the mining process, building a "exploration-mining-environment protection" full-chain technology system, and promoting the sustainable development of deep-sea resources.

3.2.2 Island Reef Construction

In the filling stage of island reef construction, coral reef rock and soil need to be processed. The research on the engineering characteristics of coral sand and rock soil has significant importance for national strategic interests. Due to the biochemical effects during sedimentation and the influence of the marine hydrodynamic environment, coral sand has a high porosity and contains internal pores, has a high particle density, is prone to fracture under pressure, has irregular particle shapes, uneven particle size distribution, and is prone to cementation, so its physical and mechanical properties are significantly different from ordinary quartz sand. The special engineering mechanical properties of coral sand make the construction of pile foundation in coral sand strata face many difficult problems, such as the difficulty in obtaining in-situ test data due to the island reef environment restrictions, the low resistance at the pile side and pile end caused by particle fragmentation, and the difficulty in calculating and designing pile foundations due to the alternation of loose layers and cemented layers [16]. To address the problem of coral sand pile foundation treatment, it may be necessary to develop more types of pile foundations in coral sand strata, fully considering the influence of the high compressibility of coral sand on the settlement of pile ends and the compaction effect of soil between piles.

3.2.3 Foundation Treatment for Port Engineering

At present, there are many common foundation treatment methods in port engineering. When choosing a foundation treatment method, factors such as soil conditions and loading methods, building types and adaptability to deformation, construction conditions, material sources, groundwater conditions, and treatment costs should be considered. After comparing multiple schemes, the method can be selected. When necessary, multiple foundation treatment methods can be combined [17].

3.2.4 Foundation Engineering of Offshore Wind Farms

In recent years, offshore wind energy, as a clean, green, and renewable energy source, has broad prospects for development. Large-diameter single-pile foundations are widely used in offshore wind power projects due to their large bearing capacity, good bending resistance, and relatively lower cost. In China and Europe, they account for 65% and 74% of offshore wind power foundation construction, respectively. The pile foundation of offshore wind power not only needs to withstand the permanent loads acting on the wind turbine structure over a long period and the live loads acting on it during service, but also needs to withstand more complex environmental loads such as wind loads, wave loads, current loads, and sea ice loads.

At present, offshore wind power foundations include pile-type foundation structures, gravity-type foundation structures, and floating-type foundation structures. Among them, pile-type foundations are divided into single piles, multi-piles, jacket-type, and tripod-type. The pile-type foundation is a fixed foundation structure that can be widely applied to various different seabed soils and has the characteristics of simple process and low cost. From a future development perspective, offshore wind power remains the mainstream. However, as the resources in the near sea

become increasingly saturated, the wind energy resources in the deep sea are more abundant, with more stable wind speeds and certain development prospects. However, as the water depth increases, the size and cost of the wind power foundation structures will rise sharply. Therefore, pile foundations will be difficult to be applied in the construction of the deep sea. In recent years, floating technology has gradually been verified by the downstream industry and is expected to be applied on a small scale in the construction of wind turbines in the deep sea.

3.2.5 Marine Fishery Base Construction

The "wind-fish integration" model is an important development direction for the pile foundation construction of marine fisheries in recent years. The integration of marine fisheries and offshore wind power mainly utilizes the underwater pile foundations of offshore wind power devices as mooring components, breeding platforms, etc., and provides green energy required for breeding production management. Around the wind turbines, fish farming cages and artificial reefs are built to form a "comprehensive marine fishery", which can fully utilize marine space and maximize the benefits of marine fisheries and offshore wind power industries, optimize the layout of marine fisheries and offshore wind power industries, and construct a "sea-based granary + blue energy" new model, achieving simultaneous and efficient production of clean energy and safe aquatic products. By using the offshore wind power pile foundations as the foundation of the breeding platform, not only can the resource utilization efficiency be improved, but also the dual goals of ecological restoration and fishery enhancement can be achieved. For example, the Lufeng Houhu project in Xuan'ou, Guangdong Province is the first pile frame-type "wind-fish integration" marine fishery project deployed in an area without shelter from typhoons. Its anti-wind-wave capacity reaches level 17, demonstrating the advanced and feasible nature of this model.

3.2.6 Coastal Engineering

In coastal engineering, breakwaters serve the functions of resisting wind and waves to create a favorable water environment within the port, and blocking sediment to reduce erosion. Due to their deep placement in the sea and the thick soft soil layer, as well as the complex foundation conditions, during the construction process of breakwaters, the foundation often experiences uneven settlement, rapid settlement rate, and large horizontal displacement. Moreover, the excessively fast loading rate not only poses a threat to the safety and stability of the embankment during the construction process, but also weakens the strength of the foundation soil. Therefore, the safety assessment and inspection of the stability of breakwaters are particularly important.

IV. TECHNOLOGICAL DEVELOPMENT TRENDS

4.1 Interdisciplinary Integration

Traditional foundation reinforcement mainly employs physical or chemical methods such as mechanical vibration compaction, geotextiles, or cement/epoxy resin curing. These methods are severely limited in marine applications and have drawbacks such as high costs, poor construction environment, and pollution of the marine environment. The mineralization effect of the microbial-induced calcium carbonate precipitation technology (MICP technology) can fill the pores and bond particles together, achieving the effect of reducing liquefaction and improving the physical and mechanical properties of the soil. To better apply microbial reinforcement technology to marine sandy soil engineering, scholars have conducted some related research based on the properties of marine sandy soil and the actual depositional environment.

Machine learning has inherent advantages in processing images, time series, and big data, so it can bring new thinking and methods for solving problems in traditional geological field research. Therefore, it is very important to summarize, summarize, and discuss the application value and prospects of machine learning in marine engineering geology. For example, using machine learning to assess the susceptibility of submarine landslides can help ensure the safety of marine resource development and utilization [18].

4.2 Green Sustainable Development

This section explores technological advancements in resource utilization and environmental protection, such as reducing construction waste and lowering energy consumption, in order to achieve coordinated development between marine engineering and ecology. In terms of resource utilization and environmental protection, suction piles and bucket foundation technologies are evolving towards green construction and eco-friendly approaches. By optimizing designs to reduce steel usage (such as using topological optimization structures) and developing low-carbon concrete materials,

the carbon footprint can be reduced by over 30%; replacing traditional piling with static penetration technology can reduce the impact of construction noise on marine life and avoid disturbing seabed sediments; developing recyclable foundations and modular disassembly technologies enables the recycling of foundation structures, reducing marine engineering waste; combining biocompatible anti-corrosion coatings and artificial reef designs promotes the natural restoration of the marine ecosystem around the foundation. In the future, it is necessary to further develop digital construction management systems to precisely control material usage and energy consumption, and optimize environmental performance through life cycle assessment (LCA), ultimately achieving a new model of "low disturbance - low emissions - high efficiency" for marine engineering construction, and promoting the sustainable development of industries such as offshore wind power and the marine environment.

V. CONCLUSION

The research on the resilience of marine geotechnical engineering not only ensures the safety of energy development and reduces disaster losses, but also promotes high-end equipment manufacturing, scientific research innovation and economic development, and has significant economic and social value. The improvement of this system will provide important support for energy security, the maintenance of maritime rights and interests, and sustainable development. The future development of marine geotechnical engineering resilience can be summarized as the following points:

- Build a national-level multi-source data platform to enhance the precise identification ability of geological disasters. Integrate marine geological and environmental data from multiple periods and types, establish a unified national data set, and support high-resolution seabed morphology and geological disaster mapping. Focus on compiling geological disaster distribution maps for new energy development zones and adjacent sea areas, clearly defining the locations, scopes and hazard levels of landslides, turbidity currents, etc., to provide scientific basis for risk prevention and control.
- Break through deep-water observation and exploration technologies, and build a core equipment system. Develop long-term seabed monitoring networks (such as seismometers, hydrodynamic floats, optical fiber sensing, etc.), reveal the triggering mechanisms of geological disasters caused by internal and external forces. Accelerate the research on deep-water operation-level AUVs, high-precision sonar systems and in-situ testing equipment (such as drilling, static probing), and develop a three-dimensional visualization platform to dynamically display seabed topography, stratum structure and disaster characteristics, supporting disaster risk assessment and decision-making.
- Focus on breakthroughs, that is, for key blocks of new energy development, focus on conducting research on hazardous landslides, gravity flows and bottom current erosion and other disasters. At the same time, systematically study the geological processes and sedimentary results of marine landslides, gravity flows and bottom current erosion, which also helps to study the deep-water sedimentary environment and climate environmental changes such as sea surface variations.

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