Review

Features of Earthquake-Induced Seabed Liquefaction and Mitigation Strategies of Novel Marine Structures

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Abstract: With the accelerated development of marine engineering, a growing number of marine structures are being constructed (e.g., seabed pipelines, drilling platforms, oil platforms, wind turbines). However, seismic field investigations over recent decades have shown that many marine structures were damaged or destroyed due to liquefaction. Seismic liquefaction in marine engineering can have huge financial repercussions as well as a devastating effect on the marine environment, which merits our great attention. As the effects of seawater and the gas component in the seabed layers are not negligible, the seabed soil layers are more prone to liquefaction than onshore soil layers, and the liquefied area may be larger than when liquefaction occurs on land. To mitigate the impact of liquefaction events on marine engineering structures, some novel liquefaction-resistant marine structures have been proposed in recent years. This paper reviews the features of earthquake-induced liquefaction and the mitigation strategies for marine structures to meet the future requirements of marine engineering.

Keywords: marine engineering; seismic liquefaction; novel liquefaction-resistant structures; mitigation strategies

1. Introduction

An increasing number of structures are being constructed in offshore areas; these include wharfs, cross-sea bridges, seabed tunnels, wind turbines and oil platforms. An important challenge of our times is to develop eco-friendly and renewable energy sources in marine areas [1,2]. Thus, offshore engineering has greatly developed in various countries and the pace of marine resource development is gradually accelerating [3]. The United Nations pointed out that the 21st century is the century of the oceans.

However, marine geohazards occur frequently because of the complex and harsh marine environment [4,5]. Under cyclic loading, such as storms, sea ices, waves and earthquakes, the strength and stiffness of marine soft clay will decrease and liquefaction may occur [6]. Seabed liquefaction can lead to catastrophic consequences, such as the creation of a submarine slope, pile foundation instability, flotation of buried pipelines, and overturning of wind turbines [7–9]. For example, Christian et al. reported a flotation accident on a 3.05-m diameter steel pipeline in Lake Ontario in 1974, which was induced by seabed liquefaction [10]. In 2010, huge waves caused liquefaction of the seabed soil in some areas of the Yellow River Delta in China, and an offshore platform capsized, causing two deaths and economic losses of 5.92 million RMB [11]. In the 2011 Tohoku Earthquake, Kamisu and Hiyama wind farms located 300 kilometers away from the epicenter survived without major damage because the wind turbine system (~3 s) is designed to have a dominant period of ~3 s, which is considerably different from

that of the seismic motions at the farm sites (0.07–1.0 s). However, one wind turbine with a monopile foundation tilted due to the seismic seabed liquefaction [12]. These liquefaction-induced accidents had huge financial impacts and severely affected the environment. Due to the serious consequences, researchers have made great efforts in the studies of seabed liquefaction induced by various types of excitation. For instance, Jia and Ye carried out systematic wave flume experiments and numerical simulation works respectively, which well explained the hydrodynamic behaviors (liquefaction and re-suspension) of marine deposits under the sea wave loads [13,14]. Sui et al. considered distribution gradient terms of soil properties and analyzed liquefaction of an inhomogeneous seabed caused by waves [15]. Huang et al. comprehensively reviewed the mechanisms of wave-induced liquefaction and relevant remedial measures [16]. Additionally, in some high-altitude areas, ice-induced vibration needs to be considered, which may also cause liquefaction around marine structures [17,18]. The duration of wave and ice loads is much longer than that of earthquakes. However, earthquakes can produce more energy in a short time compared to waves or ice sheets, so marine structures located in the earthquake zone will be at great risk due to seismic liquefaction. Unfortunately, most earthquakes occur on the seafloor, especially in offshore areas [19]. In Japan, a large earthquake occurs off the coast every three to four years on average, with potential to cause severe damage to marine structures [20]. Therefore, it is important to understand the effect of seismic seabed liquefaction on marine engineering structures.

Significant advances have been made in the study of onshore seismic liquefaction and anti-liquefaction measures [21,22]. However, the ocean environment is more complicated than the onshore one. Earthquake-induced seabed liquefaction has some unique features. For example, the dynamic response of the seawater during an earthquake event can also cause liquefaction in the seabed [23]. Furthermore, the biggest feature and most important development trend which ocean engineering faces is moving from shallow to deep sea. In marine engineering, especially in the abyssal environment, reinforcing the seabed soil skeleton or improving the pore water to prevent liquefaction are not always applicable because of the difficulty and cost. In recent years, scientists have been extensively studying earthquake-induced seabed liquefaction and damage mitigation related to the design of new marine structures. For example, Groot et al. systematically summarized the physical principles of various triggering mechanisms for liquefaction affecting ocean construction [8]. Esfeh et al. used an advanced liquefaction model with FLAC3D and successfully analyzed the liquefaction effect on floating structures [24]. Through dynamic centrifugal tests, Yu et al. studied the dynamic behaviors of different types of foundation (mono-pile and gravity) under seismic loadings that caused liquefaction [25]. Wang et al. presented a comprehensive review of research on mainstream wind turbine foundations and new suction bucket foundations based on both experimental and numerical methods [26].

However, the characteristics of marine seismic liquefaction and the latest marine structures proposed for reducing liquefaction damage have not been reviewed systematically. This article summarizes previous studies and outlines specific issues of seismic liquefaction in marine engineering. Moreover, perspectives on novel liquefaction-resistant marine structures are presented to help cope with the future trends and challenges of ocean engineering. This paper can help readers understand the problems of marine engineers in designing liquefaction-resistant marine structures, and provide useful guidelines on the subject.

2. Seismic Field Investigations in Marine Engineering

A large number of earthquakes occur in highly populated coastal areas such as the Pacific Rim earthquake zone and the Mediterranean earthquake zone. Therefore, earthquake damage investigations such as the seismic survey of the Grand Banks submarine landslide were conducted as early as 1929 [27]. In 1964, after the Alaska earthquake, investigations on seabed liquefaction and submarine landslides were also carried out [28,29]. Due to the difficulties of underwater surveying, there are a limited number of seismic damage investigations on the sea floor compared with those on land. However, from the existing cases, we can still conclude that earthquake-induced seabed liquefaction has caused serious damage to marine engineering structures in the past. Recently, there has been growing

interest in seismic field investigations in marine engineering. Sumer et al. summarized seismic liquefaction around ocean engineering structures in Japan and Turkey [20]. Kardogan et al. reported on historical cases of earthquake-induced liquefaction of pile-support wharf structures [30]. This article supplements these studies and summarizes earthquake-induced liquefaction field investigations in marine engineering (Table 1) to provide readers with a systematic understanding of historical cases over the last three decades.

**Table 1.** Major historical cases of seismic liquefaction in marine engineering.

Date	Earthquakes	Magnitude	Details	References
17 October 1989	1989 Loma Prieta Earthquake	6.9	Monterey Bay Aquarium Research Institute's pier subsided approximately 30 cm led by liquefaction, evidence of seabed liquefaction extending seaward over 600 m, a large number of pipelines failed, some fuel tanks tilted at the dock	[30,31]
17 January 1995	1995 Hyogoken-nanbu Earthquake	7.2	All 240 berths in Kobe Port suffered at least some damages, quay walls moved laterally seaward	[32]
17 August 1999/12 November 1999	1999 Kocaeli, earthquake/Duzce earthquake	7.4/7.1	Almost all the backfill and sheet-piled structures were liquefied behind dock walls, some structures were displaced seaward, seabed settled and some marine structures collapsed	[20,33]
26 January 2001	2001 Bhuj Earthquake	7.7	Dams built on alluavia badly damaged, intake tower titled induced by liquefaction, differential settlement and lateral spreading occurred	[34]
26 December 2004	2004 Great Sumatra Earthquake	9.0+	Liquefaction-induced coastal structures and embankment failures occurred	[35]
12 January 2010	2010 Haiti Earthquake	7.0	A piece of coastal land disappeared, large delta area liquefied	[36]
27 February 2010	2010 Chile Earthquake	8.8	Liquefied zone covered an area with a length of almost 1000km in the north-south direction, several piles-supported facilities were damaged because of liquefaction-induced lateral spreading, some tanks at gas facility titled	[37,38]
11 March 2011	2011 off the Pacific coast of Tohoku Earthquake	9.0	Liquefaction occurred in the river delta area, offshore ground failed, uplift of pipelines and fuel tanks occurred, sand boiled on quay wall, dike collapsed for liquefaction at the bottom, a wind turbine tilted	[39]
4 September 2010 (start on)	2010–2011 Canterbury Earthquake Sequence (CES)	7.1 (mainshock)	Severe seismic liquefaction damage to infrastructures happened, recurrent and large-area liquefaction in offshore area	[40,41]
6 February 2012	2012 Negros Earthquake	6.7	Columns titled and spans of bridge dismembered, induced by liquefaction, large area settlement of coastal roadbed	[42]
14 November 2016	2016 Kaikōura Earthquake	7.8	Gravel and sand ejected near the entrance to the harbor, the pier settled below the surface of water, foundation connection failed and wharves damaged	[43,44]
28 September 2018	2018 Indonesia Sulawesi Earthquake	7.5	Extensive liquefaction happened in offshore areas, floatation of pipelines was observed, a piece of coastal land disappeared, devastating tsunami took place caused by liquefaction	[45]

## 3. Features of Earthquake-Induced Seabed Liquefaction

Both submarine seismic liquefaction and onshore seismic liquefaction can be explained using the principle of effective stress. However, the amount of seismic damage in marine areas indicates that seabed seismic liquefaction has many characteristics that differ from those of onshore seismic liquefaction.

3.1. Marine Deposits Layer

Based on extensive soil liquefaction cases, particle size distribution curve boundaries for the possibility of liquefaction can be drawn, as shown in Figure 1 [20]. Generally, if the curve of the seabed soil samples falls within the range defined by the two blue boundaries, it is necessary for us to consider the risks of soil liquefaction in engineering design. Well-sorted aeolian sands are widespread in offshore areas, which is inclined to liquefaction easily [46]. For example, the offshore areas of China are mainly layered soils composed of sand, silt and clay (as shown in Figure 2) [47,48], and the submarine soil layers in the North Sea of Europe are dominated by sands [49].
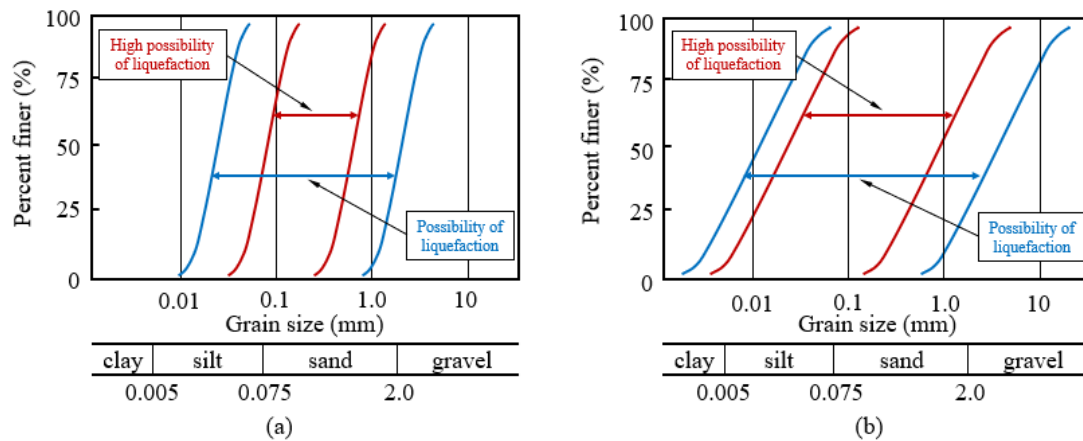
Figure 1. Grain size distribution curve boundaries for the possibility of liquefaction: (**a**) soil with low coefficient of uniformity; (**b**) soil with high coefficient of uniformity (modified from [20]).
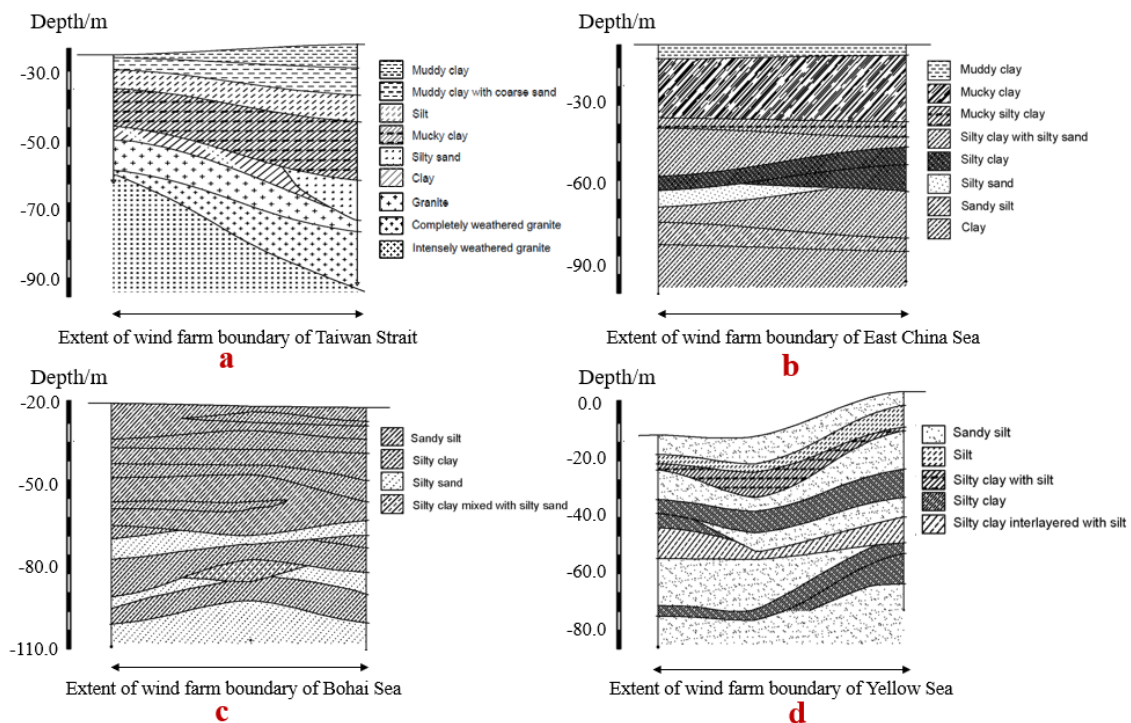
Figure 2. Typical ground profiles in Chinese waters: (**a**) Taiwan Strait; (**b**) East China Sea; (**c**) Bohai Sea; (**d**) Yellow Sea (modified from [48]).

In addition, another important feature of the marine deposits layer is the presence of calcareous sands. It worth noting that calcareous sands are widely distributed in the South China Sea, the Gulf

of Mexico, the coasts of Australia, etc. Calcareous sands may have higher resistance to liquefaction than siliceous sands [50]; however, they are also at a great risk of liquefaction [51]. The liquefaction mechanisms of calcareous sands are not very clear yet due to their unique structural characteristics, such as crushability, high content of angular particles and mineralogy surface roughness [52]. Studies on the seismic liquefaction behavior of calcareous sands are of great significance in marine engineering and need to be further carried out.

3.2. Influence of Sea Water

When analyzing seismic earthquake forces in marine areas, it is necessary to consider the increase in pore-water pressure on the seabed caused by earthquake-induced water waves acting in offshore areas. Thus, the external excitation that triggers the liquefaction of the soil is not only seismic action but also wave action. Waves can cause two types of seafloor liquefaction: instantaneous liquefaction and residual liquefaction [16].

Moreover, after the seafloor is liquefied, the soil is liable to form mud flows due to the action of waves and seawater; the suspended flow can diffuse over a long distance, which results in lateral spread over a larger area compared with land liquefaction. When liquefaction occurs in soil layers below the seabed surface, the pore-water pressure dissipates much more slowly than on land, and the strength recovery is slower [53].

3.3. Influence of Submarine Gas Composition

Gas is always present in gas-charged sediments which are widespread in marine or offshore environments [54]. Under normal conditions, methane is the dominant gas component [55]. As there are many differences between the behavior of unsaturated soils and typical saturated soils under seismic loading [56], it is necessary to clarify and summarize the differences in their liquefaction characteristics.

Firstly, seismic cyclic loading is likely to cause the discharge of shallow seabed gas, which will accelerate the increase in pore pressure and make liquefaction more likely to occur [53]. Moreover, research suggests that small amount of tiny gas bubbles suppress the accumulation of soil pore-water pressure, but may increase the instantaneous liquefaction risk under waves or vertical seismic motion [57]. Figure 3 shows the change in pore pressure with depth for saturated and unsaturated soils. If the soil contains some air or gas, the pore pressure will dissipate very rapidly with depth. In unsaturated soil, the pore pressure gradient can be extremely large, especially near the seabed surface, which means considerable lift can be generated during the passage of a wave trough [58].
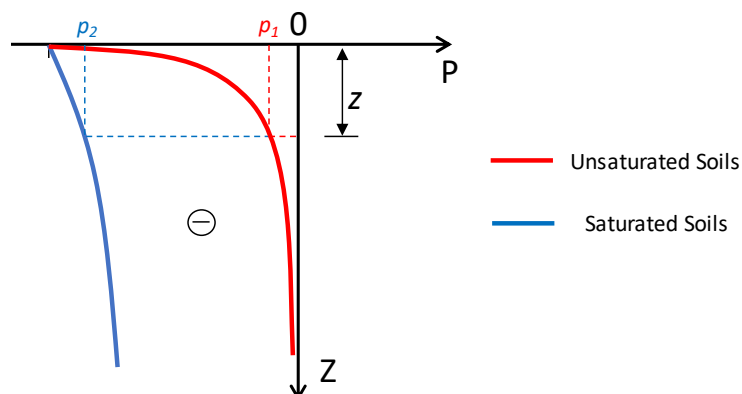
Figure 3. Typical pore pressure distributions in saturated and unsaturated soils during the passage of a wave trough (modified from [58]).

Additionally, natural gas hydrates are widely distributed in marine sediments. Under standard conditions, 1 unit volume of hydrate can release about 164 units of methane [59]. When a large amount of gas migrates upward, it may be trapped under the low-permeability soil layer, which can reduce

the effective stress to zero and cause potential instability [60]. An earthquake can trigger dissociation of a large amount of gas hydrate. Moreover, Xu et al. studied the shear behavior of dissociated gas hydrate in undrained conditions using DEM and found that the dissociation of gas hydrate produced significant excess pore pressure and volume expansion, and occasionally static liquefaction [61].

In conclusion, under the influence of sea water and trapped gas, seabed soil layers are more prone to liquefaction than onshore soil layers, and the liquefied area may be larger.

4. Seismic Liquefaction Mitigation Strategies of Novel Marine Structures

4.1. Conventional Liquefaction-Resistance Measures

Generally, for seabed liquefiable foundation soils, it is imperative to lower the risks of liquefaction. Measures to reduce liquefaction damage can be summarized into three categories [16]: (i) reinforcement of seabed soil; (ii) improvement of pore water; and (iii) improvement of structures. In the design stages, the advantages and disadvantages of various remedial measures are compared, and the most suitable and economical method is selected. Sometimes, a combination of two or more countermeasures leads to better results.

4.2. Liquefaction-Resistance Measures of New Marine Structures

In recent years, novel liquefaction-resistant marine structures to prevent liquefaction have been widely researched. This is because traditional measures are difficult and costly to take on the ocean floor. It is worth noting that marine structures are divided into two types in this paper: (1) non-supported structures, such as submarine pipelines and cables; and (2) foundation-supported structures, such as wind turbines, drilling platforms and oil platforms.

4.2.1. Non-Supported Structures

This section provides a brief introduction to pipelines. Submarine pipelines are an important part of the marine oil and gas extraction system, and are currently the most convenient and economical tool for transporting oil and gas. Seismic liquefaction is one of the main causes of damage to submarine pipelines, mostly through the following two failure modes: (1) due to the difference in soil gravity between the pipe and the liquefied seabed, the pipe will rise or sink; (2) seabed sliding causes lateral movement of the pipe. In conventional mitigation measures, the pipelines are buried deeper; however, it is difficult to do so in a marine environment. Ren et al. proposed a new measure for liquefaction damage prevention by reinforcing pipelines with wing plates, and verified the feasibility through shaking-table tests [62]. Yang proposed a simple portal frame to limit the displacement of pipelines. Compared with general anchoring reinforcements, the portal frame allows a certain upward displacement of the pipeline, which greatly reduces the stress of the pipeline and improves the safety when liquefaction occurs [63].

4.2.2. Foundation-Supported Structures

As listed in Table 1, many marine facilities experienced strong earthquakes and were damaged to a certain extent. Among various foundation-supported structures (offshore drilling platforms, oil platforms, wind turbines, cross-sea bridges, etc.), offshore wind turbines are gradually becoming the focus of attention. This is mainly because of the trend of developing clean and eco-friendly energies. Wind energy as a representative has aroused great research interest. Europe is a pioneer of offshore wind turbine (OWT) construction [64]. A 2019 report on European offshore wind turbines showed that OWTs are moving towards the deeper sea (Figure 4). As OWTs are deployed in deeper water, the OWT foundations are being modified, as shown in Figure 5.

Meanwhile, the wind turbine is a slender structure, which has a larger length/width ratio compared to other marine structures, so it is very sensitive to lateral loads [65]. Under the combined effect of winds, waves, and possible seismic loads, the structure–soil interaction will become quite complicated. The soils around the foundations of wind turbines may be greatly disturbed and have a great potential of liquefaction. Thus, in this section, we take the wind turbine as a typical marine structure and highlight research on new foundation structures of liquefaction resistance as applied to it.
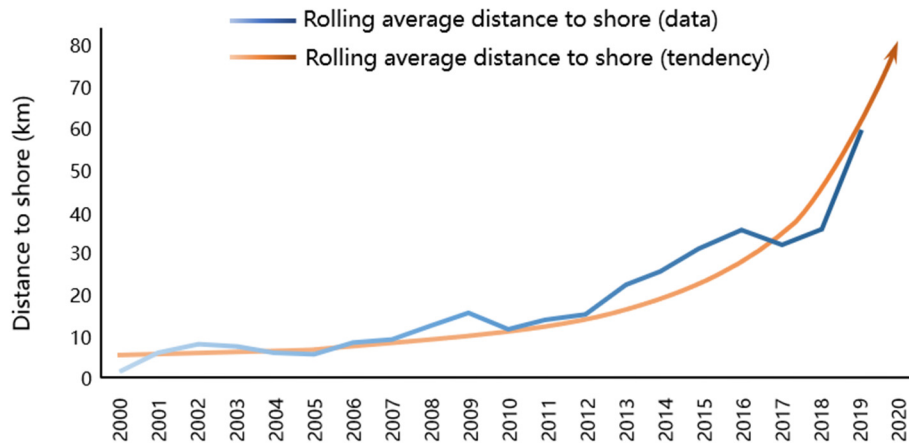
**Figure 4.** Average distance to shore of offshore wind turbine (OWTs) in Europe (modified from [66]).
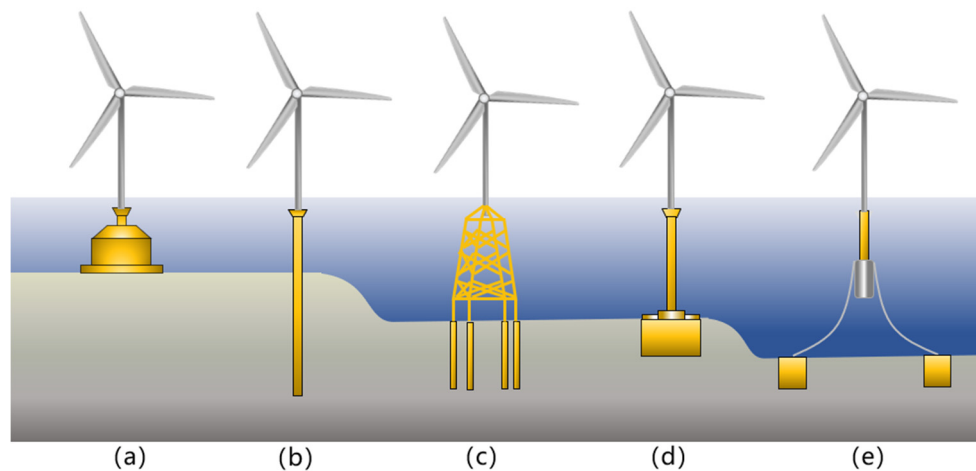
Figure 5. Major foundation types used in OWT design: (**a**) gravity foundation; (**b**) mono-pile; (**c**) jacket foundation piles; (**d**) suction bucket (mono-pod); (**e**) floating wind turbine with anchors (modified from [67]).

At present, there are five main types of foundation structure for OWTs: gravity, monopile, jacket, suction bucket and floating foundation. Many researchers have studied the damage-mitigation performance of the above foundation forms, mainly by numerical methods and dynamic centrifuge experiments. To meet the various marine engineering challenges in the future and improve the liquefaction-resistant performance of the foundations, many innovative structure improvements have been proposed (Table 2).

Table 2. Main OWT foundation types and novel liquefaction-resistant structure improvements (based on [2,26,68–71]).

Foundation Type	Application Scape	Descriptions	Novel Anti-Liquefaction Structure Improvements
Gravity	Shallow water (0~10 m)	Simple structure, long construction period and low cost, compaction effect on soil body	Cross-shaped structure [72]
Monopile	Shallow water (0~30 m)	Industrialization, large disturbance to soil, high cost, scour effect, poor resistance to liquefaction	Hybrid monopile foundation [73,74], tripod foundation [75]
Jacket	Intermediate water (10~50 m)	Applicable to various geological conditions, difficult installation and high cost	—
Suction Bucket	Intermediate water (5~60 m)	Fast construction, reusable, most applicable for soft clay, low cost, good resistance to liquefaction	Umbrella suction anchor foundation [64,68], large-scale prestressed concrete bucket foundation [76,77], tripod suction bucket foundations [78], modified suction caisson with external skirt [79,80], modified suction buckets with honeycomb compartment [81]
Floating	Deep water (>50 m)	Flexible installation, unstable foundation and a little high cost	Anchor piles and suction anchors [24]

The monopile foundation is the main type of OWT foundation currently in use. A new adaptation is the multi-pile foundation (to some extent, the jacket foundation can also be classified as a multi-pile foundation). Hao et al. carried out dynamic centrifugal model tests on the tripod foundation and found that it has better resistance to liquefaction than the common monopile one [75]. Wang et al. proposed a new hybrid monopile foundation, also based on centrifugal tests, and found that the mixed foundation has smaller lateral displacement and enhanced liquefaction resistance than ordinary monopile foundations [73,74]. General views of these two alternatives are illustrated in Figure 6. In fact, the concept of a hybrid monopile can be used to strengthen existing structures.
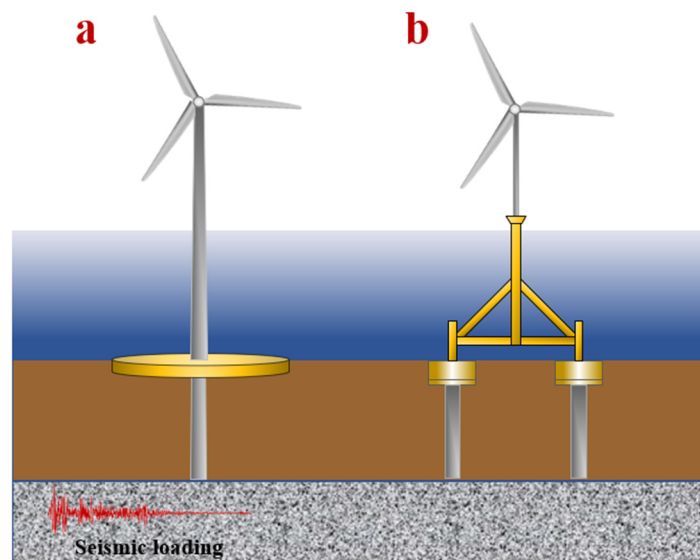

Figure 6. New structures of monopile foundation to increase liquefaction resistance: (**a**). hybrid monopile; (**b**). tripod foundation (based on [74,75]).

New anti-liquefaction jacket foundations have not been proposed in published articles to our knowledge. However, Ju et al. used the finite element method to analyze the seismic response of NREL 5-MW jacket-type OWT under combined loads (earthquakes, waves and winds), and found that the first-mode tuned mass dampers are necessary, which can effectively reduce the vibration induced by combined loads when liquefaction occurred [82].

As shown in Table 2, the suction bucket foundation is a hot topic currently. Many modifications of the suction bucket foundation have been proposed and implemented, such as the large-scale prestressed concrete bucket foundation, with certain success in real engineering by mitigating liquefaction damage (details in Section 4.2.3). Many other new liquefaction resistant structures are still in the research stage of model testing and numerical calculations; these include suction buckets with honeycomb compartments, a modified suction caisson with an external skirt, an umbrella suction anchor foundation, and so on (Figure 7). Experiments by Wang et al. showed that the honeycomb-compartment bucket can reduce soil settlement by about 50% according to experimental data [81]. Li et al. found that the external skirt provides the modified suction caisson with a higher lateral capacity [79,80]. Liu et al. studied a new umbrella suction anchor foundation with anchor branches that closely fit the seafloor; this system improves the anti-overturning ability of the master cylinder and the anti-scouring ability of the surrounding seabed soil [64,68]. Compared with conventional foundations, these new structures show good liquefaction-resistance performance, and have broad application prospects in practical marine engineering.
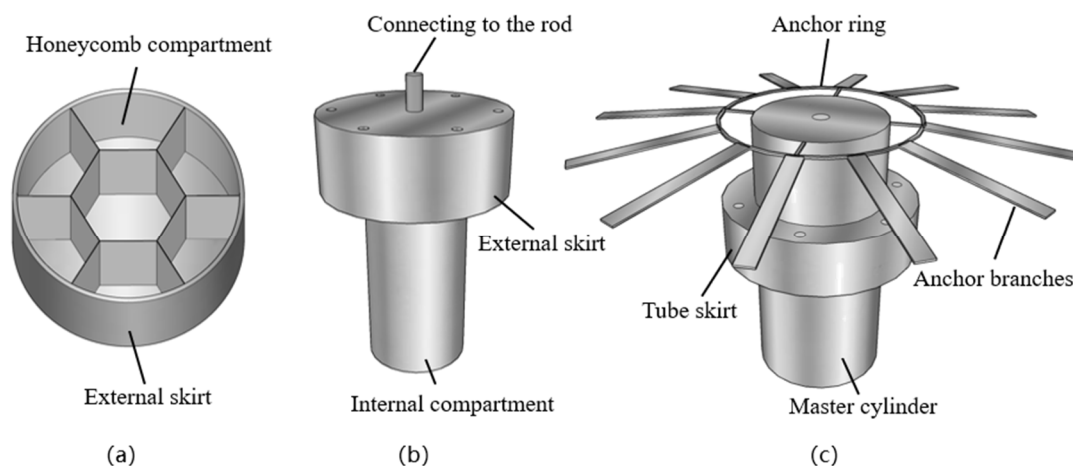
Figure 7. New structures of suction bucket foundations with increased liquefaction resistance: (**a**) modified suction buckets with honeycomb compartment; (**b**) modified suction caisson with external skirt; (**c**) umbrella suction anchor foundation (based on [64,79,81]).

With the development of marine engineering, gravity foundations have been gradually phased out because they can only be used in shallow waters and cannot meet future demands. In contrast, floating foundations are suitable for deep-sea environments. It is foreseeable that research on floating foundations will increase in the coming years, and new liquefaction-resistant structures of floating foundations may be developed and applied in the field, which will become the next research hotspot.

4.2.3. An Example on Site

In this section, we enter a concrete example in reference to the field of wind turbines (large-scale prestressed concrete bucket foundation in Qidong Sea), in order to make readers understand the issues discussed in this article more clearly.

Qidong Sea is located in Jiangsu Province, China, near the border between the East China Sea and the Yellow Sea. In October 2010, the first large-scale prestressed concrete bucket foundation (diameter 30 m, buried depth 7 m) was constructed in this area. As shown in Figure 2, the ground

conditions China's four major marine areas are soft and layered. In this wind farm, the geological survey showed that the soil properties from 0 to 33.5 m below the seabed are mainly silty sand and sandy silt, and the soil properties change into dense silty fine sand with the buried depth greater than 33.5 m [83]. These soils are liable to liquefy under strong seismic motion. Therefore, the effect of soil liquefaction needs to be considered in the design process of the wind turbines.

According to the detailed geological surveys and the seismic fortification intensity of this site (7 degrees), Zhang et al. used the ADINA program to analyze the liquefaction-resistance ability of soils below and inside this foundation and showed improvements due to the overburden pressure of the foundation and the constraint effect of the skirt [76,77]. They found that the concrete bucket foundation could still work after soil liquefaction. However, they only added the design ultimate wind loads to the structure, and the dynamic effects of seismic waves combined with the winds were not considered.

Many other new structures have not been constructed in real engineering, but some related research works are also based on site geological conditions. For example, the model tests of modified suction buckets with honeycomb compartment were also carried out in Jiangsu Province [84], and the umbrella suction anchor foundation has been designed for the Yellow River Delta area in the future [64].

In addition, although there are no actual engineering cases of new measures, many scholars have studied earthquake-induced liquefaction in Taiwan, Mexico and other sites. Kuo et al. focused on Changbin offshore wind farm in Taiwan Strait, and evaluated the liquefaction potential based on the typical ground profile of this site [85]. Mardfekri et al. proposed a probabilistic framework to evaluate the vulnerability of wind turbines in the Gulf of Mexico [86]. Martín del Campo et al. used numerical methods to analyze a wind turbine in Mexico under combined loads of earthquakes and winds, and made the fragility analysis [87].

In the above research, we can see that there are not many examples of new liquefaction-resistant structures that have been built. Works of this topic are still dominated by model tests and numerical simulations. The advanced numerical models are generally consistent with the results of the dynamic centrifugal tests. Numerical calculation has the advantages of being efficient and low cost while being able to evaluate many parameters and provide insight into the entire process of liquefaction-induced failure of structures. However, in view of the complexity of the marine environment, pore-pressure models and soil-structure interactions need to be further studied. Thus, numerical analysis of seismic seabed liquefaction will still be a focus of future research.

5. Conclusions

The features of onshore seismic liquefaction are quite different from seabed liquefaction, which is more complicated and requires great attention and extensive research. In addition, mitigation strategies of novel marine foundation structures were reviewed considering their resistance of liquefaction. Based on the reviewed studies, the following conclusions can be drawn.

(1) This article summarizes seismic liquefaction field investigations in marine engineering to provide a systematic understanding of the historical cases published over recent decades. These cases show that seismic-induced liquefaction has a huge impact on marine structures and should be taken into account when designing in the future.

(2) Seabed seismic liquefaction has different characteristics to those seen in land seismic liquefaction. The effect of seawater and trapped or escaping gas on seismic liquefaction is not negligible; seabed soil layers are more prone to liquefaction than onshore soil layers, and the liquefied area may be larger than on land.

(3) Many novel improvements of foundation structures that reduce liquefaction damage in marine engineering have been proposed in recent years; these include the hybrid monopile foundation, umbrella suction anchor foundation, and anchor piles with suction for floating foundations, etc. Experimental and numerical analyses show that these new marine structures have better

liquefaction-resistance performance than traditional structures and need to be further promoted in engineering design.

(4) Having the advantages of low cost, fast construction and reusability, the suction bucket modification used in OWTs is the most widely studied concept nowadays. However, the monopile is the main foundation type for OWTs in current use. The hybrid monopile concept can be used to strengthen existing monopile structures to increase their liquefaction resistance. In addition, it is foreseeable that the research on floating foundations is likely to expand in the coming years, and new liquefaction-resistant structures with floating foundations may become the next research hotspot.

(5) Many other marine structures have been designed while taking into account seismic liquefaction. However, the prevention of submarine seismic liquefaction damage is still facing many difficulties and challenges. Thus, we should give priority to marine geological disaster prevention in project site selection and design to minimize the damage caused by seismic liquefaction around marine structures.

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