Recent Developments on Wave-Induced Liquefaction of Marine Seabed

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Abstract

Due to cyclic loading of water waves, the seabed soil may undergo a process called liquefaction where pore pressure counterbalances the effective stresses in the soil and disables the load bearing capacity leading to devastating consequences for coastal and offshore structures. This phenomenon has drawn much attention in the last four decades. Especially within the recent years, by different researchers including the authors of this paper, important advancements have been made in the direction of not only understanding the physics associated with liquefaction but also making *quantitative* assessments of wave-induced liquefaction risk and its consequences on such structures. The objectives of this paper are two folds: (1) To present a brief review of those most up-to-date approaches and techniques, (2) To point out some of the practical problems yet to be tackled.

Keywords: *Waves, marine structures, instantaneous liquefaction, residual liquefaction, marine hydro-geomechanics.*

1 Introduction

Wave-induced liquefaction of seabed, a phenomenon with catastrophic consequences, has been extensively studied over the past decades through analytical, numerical and experimental means. Even though there have been several studies conducted to understand the dynamic response and instability of seabed under waves, there are relatively limited amount of studies conducted thus far to understand the soil failures associated with foundations lying inside or on the seabed. Yet, it has not been clearly defined what measures or actions to take to prevent these failures nor do any national or international design manuals exist identifying these measures explicitly. Furthermore, the need for proper design of marine structures is expected to grow rapidly in the future due to the climate change which increases the magnitude and frequency of strong storms observed globally. From this sense, one of the most important threats to the marine infrastructure comes out to be the instability of seabed and seabed-structure systems (Figure 1) under wave-induced cyclic and impact loads. Not only the geotechnical aspects but also coastal and marine hydrodynamics play a significant role in the initiation of these instabilities. To address these issues of marine civil engineering, a new interdisciplinary sub-branch is emerging which can be named as *marine hydro-geomechanics* (Sumer, 2014a).

Unfortunately, as is the case in other problems of coastal hydrodynamics and geomechanics, the processes governing wave-induced liquefaction in marine environment are dynamic, nonlinear, and hence quite complex. During the past decades, an important progress has been made towards the understanding of these processes and their impact on the stability of marine infrastructure. A thorough review of the subject can be found in Sumer (2014b). However, there still remains a significant need for further studies to understand the underlying mechanics, formulate models, and develop tools for the response and instability of some very important seabed-structure systems. In this paper, the developments made in recent years to satisfy this need are briefly summarized. Authors intend to present the outcomes of the most recent research on the topic that they have been involved, as well as other key studies conducted prior to theirs and contemporarily. The paper primarily focuses on two aspects of wave-induced liquefaction studies: (1) instantaneous liquefaction and (2) residual liquefaction.

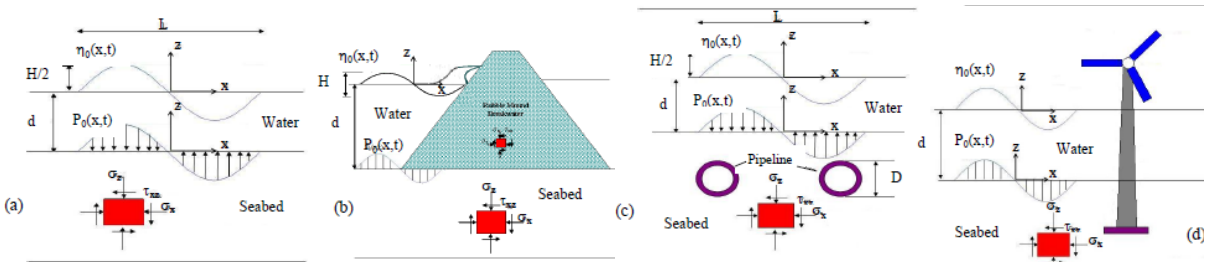

Figure 1. Marine hydro-geomechanics problems: a) Free field, b) Coastal protection structure c) Buried pipeline, d) Seabed-monopile interaction supporting a wind turbine

2 Mechanism of Liquefaction

Liquefaction is the process where the overburden stress of the soil is balanced by the pore pressure and, as a result, soil acts like a liquid mixture of grains and water. Such a soil would have no bearing capacity and stability of structures resting on/in it would have a risk of failure. Waves as well as earthquakes can cause the liquefaction of marine soils. The latter is out of the scope of the present study. There are two major mechanisms of wave-induced liquefaction: the oscillatory mechanism (*momentary/instantaneous liquefaction*) and the residual mechanism (*residual/progressive liquefaction*). The former is driven by the oscillatory component of pore pressure and occurs mostly near the seabed surface where the pore water may contain very small amount of gas in the voids whereas the latter is caused by the build-up of pore pressure due to wave-induced irreversible cyclic shear deformations. The recent developments on *instantaneous liquefaction* are mostly achieved by analytical and numerical methods whereas laboratory physical models supported by analytical results are commonly used to study the *residual liquefaction* and its consequences.

2.1 Instantaneous Liquefaction

In case of nearly saturated sediments, with some amount of gas present in the pore spaces, under certain conditions the wave-induced stresses may lead to the case where the effective mean stress reduces significantly and becomes zero signifying a state called "*instantaneous liquefaction*". This is possible even when the soil solids are considered to remain linear isotropic elastic. When a wave trough is passing over the seabed it will generate a negative pressure in excess of hydrostatic pressure. If there is gas content (i.e. air bubbles) in between the soil grains, the pressure will quickly be dissipated by the voids and an upward directed pressure gradient (seepage flow) will be generated. As a rule of thumb, whatever the wave conditions may be, instantaneous liquefaction will not be expected to occur if there is no gas content in the soil. Zen and Yamazaki (1990) suggested a criterion for soil liquefaction under the influence of a two-dimensional progressive wave introducing "excess pore pressure" which induces downward (under wave crest) or upward (under wave trough) flows of the pore fluid within the soil. The wave-induced liquefaction occurs when the submerged weight of soil skeleton is less than the upward seepage force exerted on it. This criterion was further extended for a more general stress state by Tsai (1995). The criterion of instantaneous liquefaction implying a state of *zero mean effective normal stress* for a free field case (i.e. no structure) can be expressed as:

$$-\frac{1}{3}\gamma' z\left(1+2K_0\right)+\frac{1}{3}\left(\sigma_x'+\sigma_y'+\sigma_z'\right)=0 \tag{1}$$

where K_0 is the coefficient of lateral earth pressure at rest and the second term is the mean effective stress induced by the wave on the sea floor. Assumption of elasticity leads to, $K_0 = \nu/1-\nu$ with ν, the Poisson's ratio. If we write $\sigma_y' = \nu\left(\sigma_x' + \sigma_z'\right)$ for plane strain stress state, relation (1) is rewritten as,

$$\frac{1}{3}\left[-\gamma' z\left(1+2K_0\right)+\left(1+\nu\right)\left(\sigma_x'+\sigma_z'\right)\right]=0 \tag{2}$$

For a mean general stress field, one must include the mean effective stress increase due to the weight of a structure (e.g. breakwater) as suggested by Ulker et al. (2010), $\Delta\sigma'_{m0}$, and modify equation (2) as,

$$\frac{1}{3}\left[-\gamma' z\left(1+2K_0\right)+\left(1+\nu\right)\left(\sigma_x'+\sigma_z'\right)\right]+\Delta\sigma'_{m0}=0 \tag{3}$$

It should be observed that the above criterion for instantaneous liquefaction is the most fundamental and appropriate one for the coupled flow and deformation analysis. It should also be noted that the other criteria available in the literature were developed within the context of one-dimensional or decoupled analyses.

2.2 Residual Liquefaction

Under progressive wave action, seabed soil undergoes cyclic shear deformations which rearrange the soil grains at the expense of pore volume. As the pore volume reduces, the pore-water is pressurized and forced out of the intergranular space, leading to pore-pressure buildup. If the built-up pressure is not dissipated fast enough, the pore-water pressure may reach levels exceeding the initial mean normal effective stress. As a result, soil skeleton vanishes and soil acts like a liquid leading to the liquefaction state. This process is called the *residual liquefaction* (Sumer and Fredsoe, 2002). Figure 2 shows an example for the pore pressure buildup under wave action. The criterion for residual liquefaction in terms of pore pressure buildup is as follows (Sumer et al., 2012):

$$\overline{p}\geq\frac{1}{3}\left[\gamma' z\left(1+2K_0\right)\right] \tag{3}$$

Here the right-hand side of the equation is the initial mean normal effective stress and the left is the excess pore-water pressure. In Figure 2, the initial mean effective stress is marked and it can be seen that the soil is liquefied at the 14^{th} wave cycle (i.e. after 15sec). Once the soil is liquefied, pore pressure attains to a maximum value and stays at that level until it is dissipated (Sumer et al., 2006 for details of the process). During this time, the soil stays in liquefied state, a serious threat for the marine structures. Research showed that the essential ingredients of residual liquefaction are: (1) granular soil with relatively lower permeability, (2) a loose state of soil and (3) high waves to cause high shear deformations. In addition to wave generated shear deformations, there are also cases reported where the wave driven *shaking* of the structure also contributes to the pore pressure buildup (Sumer, 2014b). Among the cases of failures in marine engineering related to wave-induced liquefaction, residual liquefaction is more commonly encountered compared to instantaneous liquefaction.

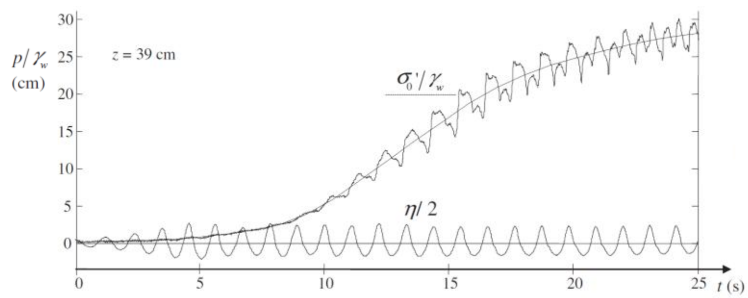

Figure 2. Pore-water pressure buildup in a wave flume (Kirca, 2013). η is the wave profile. Soil is silt with d_{50}=0.07 mm, soil layer thickness is 40 cm, wave characteristics are H=7.7 cm, T=1.09 s and h=30 cm

3 State-of-the-Art

3.1 Earlier Studies

In the last decades, progress has been made towards understanding the instabilities, liquefaction in particular, under wave action. Rahman et al. (1977) analyzed the wave-induced pore pressures under a gravity structure with a decoupled analysis. Mynett and Mei (1982) developed a solution for the wave-induced stresses in saturated seabed under a caisson. Response of underlying seabed has later been considered (Mase et al., 1994).

Instability due to liquefaction in seabed has been one of the significant causes of failure of such structures (Maeno and Nago, 1988; de Groot et al., 2006a, b). Sakakiyama et al. (1991) developed a porous body model to study surface displacements in and near a composite breakwater. Jeng et al. (2001), Kudella et al. (2006) and Lara et al. (2008) are other studies that focused on analytical evaluation of wave-induced seabed response and instability around a coastal structure. Earlier studies on such structures were largely empirical in nature and ignored the effects of internal wave-induced flow and stresses as well as the dynamic soil behavior. Later, these were considered with varying degrees of accuracy (Oumeraci and Partensky, 1990; Losada et al. 2008).

Wave-induced pore pressure buildup and resulted liquefaction has also been studied experimentally. Sumer et al.'s (1999) study was one of the pioneer works of wave flume liquefaction tests. They concentrated on residual liquefaction of seabed and floating/sinking of pipelines in the liquefied seabed. Later, the sequence of processes in the marine seabed that leads to residual liquefaction was demonstrated in detail by some benchmark wave flume tests (Sumer et al., 2006). Sumer and Fredsoe (2002) developed a practical method to assess the pore pressure buildup and liquefaction potential of marine seabed, based on the solution of Hsu and Jeng (1994).

3.2 Recent Studies

In the last five years, the wave-induced liquefaction of seabed under progressive, standing and breaking waves have been studied through various means extensively by researchers including the authors of this paper. These recent studies are presented below in this section.

3.2.1 Analytical and Numerical Studies on Wave-Induced Instantaneous Liquefaction

The wave-induced instantaneous liquefaction, considering a single soil layer in the domain, was recently studied by Ulker et al. (2010, 2012). Ulker et al. (2009) presented a set of generalized analytical solutions for response of a saturated porous seabed under plane strain condition including all the inertias in the equations. The results are presented in terms of pore pressure and stress distributions within the seabed. For typical values of wave period and seabed permeability, the regions of applicability of the three formulations are identified and plotted in parametric spaces. Ulker et al. (2010) investigated the standing wave-induced dynamic response and instability of seabed around a caisson breakwater. A seabed-rubble-caisson breakwater system is modeled using finite elements. The dynamic response of the porous seabed-rubble foundation is assumed to be governed by the Biot's coupled equations of flow and deformation. In the paper also the instantaneous liquefaction in the seabed is identified as the regions with zero mean effective stress. Liquefaction depths in the rubble and the seabed are also evaluated. *Fully dynamic* (FD) analysis yielded larger areas of liquefaction along the seabed compared to *quasi-static* (QS) form. As the permeability of seabed increases, liquefied zones decrease in size. Seabed with larger degree of saturation reduces the liquefied areas, which reaches a *no liquefaction state* for fully saturated case. Ulker et al. (2012) studied the breaking wave-induced liquefaction around a caisson breakwater. Breaking waves were found to cause liquefaction in the system. This was studied for two values of seabed permeability. Zero contours indicating the liquefied areas were obtained at a time instant when they reached maximum in size in the analyses. It was found that as the permeability increases, FD form yielded slightly more liquefied areas in the seabed. Instantaneous liquefaction initiates from the rubble surface at the front toe of the breakwater and moves deep into the rubble exceeding toward the seabed layer. Ulker (2012) developed 1-D analytical and numerical solutions for the dynamic response of a two-layer seabed. The instability of the porous soil because of wave loading is investigated in terms of instantaneous liquefaction. Finite element numerical results are verified with their analytical counterparts, which are also developed therein. Then, the problem of a two-layer soil under waves both in an open domain and in front of a vertical wall is studied in terms of response variations and instantaneous liquefaction. The results indicate that the two-layer response is significantly different from that of a conventional single-layer approach. In this study, for the first time a fully dynamic analytical solution has been derived for multi-layer situation and its liquefaction behavior has been investigated. Most recently the analytical solutions derived by Ulker (2012) were extended to two dimensions by Ulker (2014) and the dynamic response of a number of soil layers is obtained. The results were validated against analytical solutions.

3.2.2 Experimental and Analytical Studies on Wave-Induced Residual Liquefaction

As mentioned above, there are only a few practical and well-established methods for estimation of residual liquefaction potential. One of them, the method proposed by Sumer and Fredsoe (2002) has recently been validated against a wave flume dataset by Sumer et al. (2012) where a numerical case and remarks on practical application were included as to how the method can be implemented by a designer. Standing waves, seen commonly in the vicinity of many coastal and offshore structures can also induce liquefaction. Residual liquefaction beneath a standing wave is studied by Kirca et al. (2012a, 2013) through wave flume experiments.

Here liquefaction under standing waves has significant differences compared to progressive wave case along with some similarities. It is shown that pore pressure buildup starts beneath the nodal section first and then the process spreads towards antinodes by a diffusion mechanism controlled by the coefficient of consolidation of the soil. Nevertheless, number of waves causing liquefaction at the nodes equals to that for progressive waves for the same wave height. Hence, the liquefaction potential assessment method for progressive waves can also be used for standing waves as a first approximation, provided that the height of the superposed wave is taken as the representative wave height (Kirca et al., 2013). In marine engineering, it is quite likely to encounter clayey seabed. There had been different views among the researchers regarding the effect of clay content on liquefaction, particularly for wave-induced case. Some had suggested that clayey soil was liquefaction resistant whereas others argued the opposite. To enlighten this point, Kirca et al. (2012b, 2014) performed wave flume experiments where influence of clay content on wave induced liquefaction was monitored. They tested pure silt and pure sand versus different percentages of silt-clay and sand-clay mixtures. The results showed that up to a certain amount of clay liquefaction susceptibility increased with the clay content. Beyond this limit, however, the liquefaction resistance increased greatly, an opposite behavior. The aforementioned limit was presumably clay-specific (observed to be roughly 30% for that particular case). According to Kirca et al. (2014): (1) For relatively small percentage of clay, the permeability of the soil is decreased which expedited the pore pressure buildup and consecutively liquefaction (permeability-dominated behavior). (2) When the clay amount is raised over a limit, the clay matrix encapsulates the grains such that no considerable shear strain can occur (plasticity-dominated behavior). For clayey silt or sand, standard liquefaction potential assessment methods can be used provided that the soil parameters are defined properly. As discussed above, objects resting on (or in) seabed sink into seabed if the specific weight of the object is larger than the liquefied soil. Likewise, the object resting on seabed will float to the surface if it is lighter than the liquefied soil. Sumer et al. (1999) and Teh et al. (2006) are two of the few studies that dealt with this, particularly for pipelines. Recently, Kirca (2013) studied the sinking of irregular shaped heavy blocks (i.e. armor blocks, sea mines, anchors or sinkers, etc.) in terms of wave-induced liquefaction. Results indicated that the shape of the block is of minor (or no) importance from the dynamics of sinking standpoint. Based on their experimental data and the earlier studies, Kirca (2013) suggested a procedure that explains how to assess the sinking damage (ultimate sinking depth) of an object in the case of residual liquefaction. A broader discussion of the subject is given Sumer (2014b).

4 Closure and Future Works

In this paper, the recent developments of wave-induced liquefaction, particularly the studies in which the present authors are involved, are presented. Especially in the last five years, analytical methods were developed to evaluate the seabed response to wave loading and instantaneous liquefaction potential. These methods were extended to multi-layer and to 2D fully dynamic case. Also, numerical methods were utilized to assess the response of marine structure foundations to breaking and non-breaking waves. On the other hand, experimental facilities have been effectively used to describe the residual liquefaction under progressive/standing waves, to validate semi-analytical tools for residual liquefaction and to find answers to practical problems associated with residual liquefaction such as the sinking damage of structures in liquefied soil and effect of clay content on liquefaction potential. Although there have been improvements in this field, there are still remaining problems and unanswered questions yet to be dealt with. There is still a need for a generic and validated poro-elastoplastic soil model that accounts for the dynamic seabed response and instability. Furthermore, the mechanical behavior of the liquefied soil is not yet sufficiently understood requiring more experimental and theoretical studies. Another point is the liquefaction risk around coastal protection structures and new generation marine structures, such as a monopile, jacket or a bucket foundation of a wind turbine. If not liquefaction, stability of such structures may also be endangered by accumulation of irreversible strains due to cyclic shearing. Large impact forces caused by wave slamming against these structures may also cause further deformation of the seabed underneath.

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