Investigating and evaluating liquefaction of pipes buried in seabed

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ABSTRACT: One of the most momentous phenomena in geotechnical engineering and marine structures is seabed instability caused by exceeding pore water pressure due to wave. Also by increasing application of pipes buried in seabed, examining these pipes efficiency possesses a specific importance as earthquake occurrence. Pipelines vulnerability to earthquake and its resulting liquefaction has been observed in many previous quakes and there are exhaustive reports in this regard. Liquefaction occurrence is one of the main reasons of buried pipes damages within earthquake. So in this paper in addition to vast studies, it has been tried to identify and evaluate buried pipes liquefaction using achieved experiences of similar researches in other parts of the world, and propose their stabilizing solutions by declaring effective parameters of pipe’s function versus liquefaction.

Keywords: liquefaction, seabed, pipes, stabilizing, earthquake.

INTRODUCTION

In case of earthquake, saturated loose sandy soils become compressed due to consequent vibrations of quake, and soil compression results in increasing pore water pressure of soil particles. The soil liquefies when pore water pressure equals excess soil pressure. Due to equalization of total soil stress and pore water pressure of soil element, effective stress becomes zero, and because shear strength of sandy soils is proportional to effective stress regarding zero coherence, adhesion stress becomes zero, too. Losing shear strength of soil resulted from increasing pore water stress is typically called liquefaction. Liquefaction can cause great deformations in structures by means of lateral expansion, flow failure, loss of load bearing, settlement, and floating. Resultant liquefaction of wave in sandy bed divides into two categories according to increasing pores pressure. In first category, gradual increase of pressure takes place in saturated granular bed due to periodical shear stresses caused by earthquake. These stresses lead to gradual excess of pore pressure and liquefaction which are representative of residual liquefaction. Second category is immediate liquefaction because of differences in pore pressure excess in various points which are along with mass compression in unsaturated bed. In a few last decades, there have been achieved great improvements about understanding and perception, and also executing notion of bed liquefaction in addition to encountering its risks [1]. Liquefaction depends on minute particles structures, shear module G, coefficient of permeability K, weaker marginal layers in soil bed [2].

Literature review

Casagrande (1936) was the first researcher who paid attention to loose and saturated sands’ tendency for shrinkage under effect of sequent loading in drained conditions, and he observed that it results in increasing pore water pressure in undrained conditions. Seed et al. in addition to approve of Casagrande’s observations, presented a series of experimental relations in their studies on saturated sand behavior under effect of sequent loads in order to dynamic analysis of liquefaction in which shear module of soil and attenuation ratio were dependent on strain level in soil (Seed & Idriss, 1967). Fin and Lee (1975) suggested an analyzing process of effective stress which was able to model influences of increasing pore water pressure on shear stiffness of soil mass. In 1986, Sandhu solved differential equations correlated to deformation and pore pressure via Finite Element Method (FEM) which
were proposed by Biot in 1941. Ghaboussi employed this method to analyze liquefaction of granulated soils but he could not model increasing pore water pressure in saturated sands, because the formulation was based on elastic presumption of soil structure. Later, Ghaboussi and Dikman successfully predicted increase of pore water pressure in saturated sandy masses under sequent loading via an elasto-plastic behavioral model in 1978. Using Ghaboussi’s experiences, Zienliewicz et al. (1978 & 1980) provided a multi-purpose computerized program to solve soil mechanics problems and particularly to analyze liquefaction [3]. Zhou C. Y. et al. (2011) and Zhou X. L. et al. (2011) presented the results from an experimental study of soil behavior around a pipeline that was either half buried or resting on the seabed in different types of soils subject to regular wave and wave plus current actions [4,5].

After lots of destructions and damaged resulted from liquefaction within Niigata and Alaska earthquake in 1964, matters related to liquefaction were drawn to attention in geotechnical and civil engineering societies. Afterwards, many efforts were made to study around base mechanism and different aspects of the phenomenon and their relations to one another (Ishihara, 1993). The matter of soil liquefaction became subject of many researches, and advice and standards were suggested in respect of explaining liquefaction based on field and laboratory data [6].

DISCUSSION AND INVESTIGATION

Buried life lines and pipes

Submarine pipelines have been widely used for transportation of oil and gas in marine engineering. During last few decades, the problem of seabed stability has been of great concern to coastal engineers and researchers, due to the needs of the developments along the coastal zone. However, such a problem has not been fully understood because of the complicated behavior of soil and wave. The resulting loss of soil strength may have catastrophic consequences, such as large horizontal displacements of pipelines on the seabed, floating up of buried pipelines, tilting of caissons, and shear failure of breakwater slopes. Wave action causes soil displacement and creates stresses in soil-pipe interface. Increasing pore water pressure in pipe area results in instability of soil around pipe, and finally it will lead to liquefaction.

Subject of soil liquefaction and pipeline floatation has a great importance in practical applications. Two substantial factors here are applied force on pipe and the other, pore water pressure oscillations around pipe. Applied force on pipe will cause turbulence in soil around pipe, and pore pressure will oscillate by each wave current on pipe. As a result, pore water pressure enhances around pipe area, and thus effective shear strength of soil structure will reduce. Composite effect of soil turbulence due to applied force and pore water pressure oscillations will bring about liquefying soil around pipe, and pipeline floating up as a result [7]. Fig. 1 describes schematically the effective stress transmitted by soil particles and excess pore pressure before and during liquefaction: \( \sigma' \) denotes the effective stress; \( u \)=excess pore pressure; \( b_h \)=bulk density of soil; \( b_{li} \)=bulk density of liquefied soil; \( p_w \)=density of water; \( p_p \)=average density of pipe; \( g \)=gravity acceleration; \( D \)=pipe diameter; \( A \)=pipe area; \( A_w \)=pipe area exposed to water; and \( A_{li} \)=pipe area exposed to liquefied soil. Before liquefaction, the effective stress transmitted by soil particles at the free field equates to the submerged weight of soil multiplied by the depth, since no excess pore pressure is present. The effective stress beneath a pipe is higher due to the additional submerged weight of the pipe. During liquefaction, the excess pore pressure in the free field increases to a value of submerged soil weight multiplied by the depth, which in turn reduces the effective stress to zero.

![Figure 1. Effective stress of soil and excess pore pressure at free field and beneath a pipe; (a) before liquefaction; (b) during liquefaction [8]](image-url)
**Damages and failures caused by earthquake and liquefactions**

One of the main reasons of buried piped failures within earthquake is liquefaction occurrence [9]. Great movements of the earth can be derived from phenomena like fault, landslide, and soil liquefaction. Furthermore, researches after earthquake have indicated that most of seismic damages in oil and gas continuous steel buried pipelines are done by constant earth displacement, and just a few of these damages are resulted from waves' propagation phenomenon. Constant earth displacement is exerted to pipeline in a quasi-static way and it does not have an extreme intensity, essentially; but may cause a serious damage to pipeline, though. Such damages are reported in a great number of earthquakes. For example, it can be referred to earthquakes including San Fernando 1971, Kobe 1995, Niigata and Alaska 1964, and Chi Chi, Taiwan 1999. In Iran, numerous cases of occurrence of liquefaction phenomenon and its catastrophic effects on arterial lines have been reported that Manjil earthquake can be mentioned among them [10].

**Proposed Models**

Various models have been proposed in order to analyze buried pipes under effect of liquefaction. Wang and Yeh suggested a beam-column model for buried pipelines to analyze buried pipes under effect of liquefaction phenomenon via separating two liquefied and non-liquefied areas. It is supposed in this model that the soil around liquefied environment loses its whole shear strength and behaves as a viscous liquid [11]. Nishio examined resultant dynamic strains of soil liquefaction in buried pipeline. His results show that severe strains are produced in pipe under conditions of liquefaction in some part of soil. Moreover, strains decrease significantly by considering slippage between soil and pipe [12]. Hamada et al. accomplished similar studies via considering great displacements of earth resultant of liquefaction effect of Chubu-Nihoukai earthquake in 1983 [13]. In fact, shear strength between soil and pipe intensively reduces in liquefied sand. Wang Guoxin et al. investigated seismic response of buried pipe during soil liquefaction phenomenon by waves propagating through different axial and lateral directions. They assumed effective soil stress and floating effect in their model and utilized a spring system of soil and pipe for stimulation [14]. Fu-lu proposed two static approaches to examine matter of liquefaction and its influence on buried pipeline. In first approach, it is assumed that straight pipeline transforms under effect of sandy soil liquefaction, and the theory of beam on elastic bed was used to formulate the problem. In this modeling, pipe bending stiffness, soil reaction modulus, pipeline weight per unit length in regard to floating effect were considered. In second modeling approach, a point on pipe curvature is assumed as an inflection point in which second derivative of displacement is zero, and it can be considered as a simply supported beam based on his belief, and various points displacements can be obtained by solving it [15]. Yamamoto et al. [16] and Madsen [17] conducted an examination by assuming soil as an elastic and porous environment and compressibility of pore water. Madsen suggested analytical results of pore pressure distribution around a buried pipe [18]. Jeng and Cheng proposed an FDM (Finite Difference Method) model in curvilinear coordinate system to investigate bed response to wave loading around a buried pipe [19]. Biot’s dynamic equations were used by Mei and Foda to study resultant local stresses of waves in a pipe placed on the bed [20].

Jeng and their co-workers have developed a series of a closed-form analytical solution for the soil response in a porous seabed subject to wave loading, including infinite seabed and finite seabed. These solutions have been used for the prediction of the wave-induced seabed instability such as liquefaction and shear failure[21].

In other research A failure mechanism of pipelines on liquefied seabeds is analyzed. An analytical model to predict the pipelines sinking depth is proposed, and the comparison with measurements shows that the analysis is consistent with observed behavior. Three possible ways are identified to stop the pipe from sinking: 1 the pressure gradient of excess pore pressure or density of liquefied soil around the pipe; 2 the stable layer that propagates upwards; and 3 the impermeable base or nonliquefied soil. They are verified with experimental results and also with a proposed analytical solution for the propagation velocity of a stable layer [22].

**Influences of resulting liquefaction of earthquake on buried pipes**

Bavanpoori et al. conducted a numerical study on buried pipes under effect of liquefaction using ABAQUS software. They declared that liquefying force can cause buried pipe floating exiting pipe from transmission network and consequent probable damages as a result, and liquefying force can result in pipeline distortion in particular cases according to soil profile conditions. Also by enhancing excess pore water pressure, floating force exerted to buried pipe increases, so that various ways of reducing excess pore water pressure is suggested to prevent from this force increase; drain piles can be mentioned in this regard. Furthermore, reducing level of underground water leads to pore water pressure decreasing and decline of floating force applied to pipe and also effective stress enhancement in soil. In fact, declining level of underground water reduces buried pipe damages during liquefaction [23]. According to figure 3 and 4, floating force of soil liquefaction enhances by increasing excess pore water.
pressure ratio, so that perception of this matter is interpretable in accordance with liquefaction mechanism. Also as observed in this figure, strain enhances initially by increasing ratio of excess pore water pressure, but finally it reaches a maximum value and then, we observe a decline in strain by increasing excess pore water pressure ratio.

Figure 2. Comparison between experimental observation and theoretical prediction for the embedment of floating pipe on liquefied soil at different pipe specific gravity

Figure 3. Relation between excess pore water pressure ratio and floating force

Figure 4. Relation between excess pore water pressure and strain
Resultant liquefaction of wave current around submarine pipes

Xiang et al. investigated and evaluated wave and wave-induced seabed response of around submarine pipeline on sea bottom. Achieved results are shown in the figure 5. With the proposed numerical model, the effects of wave, current and seabed characteristics, such as Poisson's ratio, Young's modulus, degree of saturation, and pipeline buried depth on the wave-induced seabed response are examined. The numerical results demonstrate significant effects of anisotropic soil behavior on seabed liquefaction [22].

![Figure 5](image)

Figure 5. Liquefaction depth for various parameters (a) wave steepness (H/L=0.05, 0.07, and 0.08); (b) pipeline buried depth (e=2, 4, and 6 m); and (c) permeability (k_z=0.01, 0.001, and 0.0001 m/s).

The maximum liquefaction depth z_L increases as seabed permeability k_z decreases. The maximum liquefaction depth z_L decreases as the degree of saturation increases. The values of z_L commonly reduce rapidly when the degree of saturation S_r approaches 1.0. It is found that no liquefaction occurs in a seabed with permeability k_z= 0.01 m/s and k_z=0.001 m/s when the degree of saturation S_r=1.0 in the example presented in Figure 6. It is also found that liquefaction always occurs in a seabed with permeability k_z<0.0001 m/s. It indicates the seabed with higher permeability may be more hard liquefaction than the seabed with lower permeability [24].

![Figure 6](image)

Figure 6. The maximum liquefaction depth z_L versus the degree of saturation S_r for various permeability k_z.
In a research, wave-induced liquefaction of seabed around buried pipes was investigated via 2D numerical Finite Element Method. An experimental model was used in order to achieve function of excess pore pressure generation. Based on present model, excess pore water pressure in pipe bottom enhances extremely in proportion to free level of seabed, and so the pipe bottom will be a critical point to start liquefaction. Maeno et al. (1999) report the results of an experimental study where the effect of a progressive wave is simulated by an oscillating water table. As the pore-water pressure oscillates, a model pipeline buried in the soil floats to the surface of the soil, apparently due to the uplift force on the pipeline induced by the oscillating water table. Further, the paper presents a stability analysis for the floatation of the pipeline in which the pressure and the soil shear stresses are calculated by the numerical model of Magda (1997). It may be noted that, in the study of Maeno et al. (1999), the degree of saturation plays a significant role; even a slight reduction in the degree of saturation a reduction from the value of unity may lead to the so-called momentary liquefaction Sakai et al. (1992), or to a considerable uplift on the pipe Maeno et al. (1999) [25].

Following figure shows proportion of pore water pressure to depth in seabed and far from the pipe with various shear modulus of soil. As seen in the figure below, pore water pressure ratio declines by depth increase. This proportion increases in same elevation points by shear modulus enhancement. For example, pore water pressure ratio will be less than 1.0 in all points when shear modulus of soil has equaled 10 MPa, and so liquefaction will take place in no points.

Achieved results indicate that pore water pressure ratio declines by increasing depth in seabed, while this matter happens inversely around pipe pore water pressure ratio increases from top of the pipe toward pipe bottom. This phenomenon will mean that beginning of liquefaction around pipe will start beneath pipe contrary to seabed, and so pipe bottom will be a critical point for pipe stability. In addition, excess pore water pressure ratio will have a significant increase in proportion to its leveled points in seabed and far from the pipe [26]. Moreover, influence of soil parameters on liquefaction potential such as fluid type inside the pipe was investigated in another research. Summary of results obtained from the analysis demonstrated that liquefaction potential decreases by enhancing deformation modulus; and liquefaction area and depth of bed including oil pipe is more than gas pipe. Also liquefaction potential declines significantly by slight enhancement of permeability module, and liquefaction potential increases by enhancing Poisson ratio [27].

**Necessary arrangements to decrease liquefaction potential [28]**

In this part, in order to better perception of the issue approaches and control process of liquefaction in seabed within artificial islands are mentioned. According to increasing growth of constructing artificial islands, existence of problems such as liquefaction during earthquake is one of the challenges in these isles developments. In addition to laboratory studies, seismic examinations and also experiments including STP and CPT are accomplished to determine soil characteristics, thickness and area of layers, and substance changes of seabed soil in such projects. After determining distance of sea bottom to bedrock, if sea bottom sediments do not have enough
bearing capacity and also thickness of sediments to bedrock is slight, sea bed bearing capacity will be improved using precast concrete piles and striking them into sediments. In contrary, in circumstances that sediment thickness is major and pile construction is not possible, other methods including cement mortar injection and constructing drain wells and also extending island foundation would be employed in order to force distribution on larger area and decreasing applied stresses as a result [29].

**Encountering liquefaction**

Special arrangements are employed to reduce liquefaction potential in artificial isles before and after constructing islands that include various technics and methods of improvement such as drain well, vibrating compression, and graded lateral rocks. Vibrating compression and constructing graded lateral rocks are methods for improvement of soil used in islands, and they are done after constructing actions of isle’s main framework. Drain wells are executed in determined distances in seabed and include a column of sand which has high permeability to conduct and depreciate pore water. Pore water pressure increases extremely during earthquake that leads to reduction of effective stress and liquefaction as a result. In this case, drain wells installation results in on time depletion and depreciation of excess pore pressure and reduction of liquefaction potential [30, 31]. Comparison between results of improved and unimproved soil has been shown in the figure below.

![Figure 8. Liquefaction strengths at improved and unimproved sites](image)

Another solution for reducing liquefaction potential is using vibrating compression method. Vibrating compression is a process in which sand particles get floated and it results in rearrangement of sand particles in a more compressed state. Soil particles become more compressed by more penetration of vibrator inside the soil because of incorporating vibration effect and water jet, and so this issue results in considerable reduction of liquefaction potential [29]. Also executing graded lateral rocks based on a particular pattern and arrangement in which particles size increases gradually from bottom to surface, causes decline of liquefaction potential. Tsuoshi Honda et al. proved that liquefaction damages can be decreased using pile [32]. Amirali Mostafavi Moghadam et al. via employing displacement reducer panels (DRPs) in caisson quay walls tried to install some kind of seismic fuse behind the wall using geofoam elastic and create DRPs behind quay walls [33].

**CONCLUSION**

According to importance of vital arteries, particularly buried pipes in seabed, and considering that one of the main reasons of buried pipes is liquefaction phenomenon, achieved results are explained below:

Seabed pipes stability under effect of pipe density is subjected to liquefaction regarding surrounding environment. This matter has been investigated in many researches. Also seabed can be liquefied by effect of dynamic forces necessary for pipe instability.

Pore water pressure ratio declines by increasing depth in seabed, while this matter happens inversely around pipe and pore water pressure ratio increases from top of the pipe toward pipe bottom.

Liquefaction depth decreases by enhancing permeability coefficient for a soil with a determined
compression, and amount of liquefaction always equals zero for a specific permeability coefficient bigger than 1.0. Using gravel drainage is proposed in order to encounter liquefaction based on depreciation of pore water pressure. Applied floating force on buried pipe increases by enhancing excess pore water pressure, so that various ways can be suggested to prevent this force from enhancement including constructing drain pipes.

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