Numerical modeling of liquefaction potential in fill material of geosynthetic cellular system (GCS) subjected to wave loads

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ABSTRACT: Constructing coastal structures against wave action is one of the common and necessary works in port construction and shoreline stabilization. Construction cost and environmental impact are the important factors in the design and construction of the shoreline protective structures. The idea of Geosynthetic Cellular Systems (GCS) has been made considering the mentioned factors. Basic parts of the GCS are Geosynthetics (usually Geotextile) as container, frame for modification of the shape of the container, and fill material which may be the dredged materials. The stability of this type of breakwater is related to the weight of filler materials. On the other hand, because of the low density of the dredged materials and also saturation pf fill materials below water level, the probability of liquefaction under cyclic wave loading is possible. To assess the probability of liquefaction, physical models of this type of system with different geometrical characteristics (cube, rectangular cube and pyramid) with a variety of filler materials (sand and silt) have been done. In this study, the comparison between the results of the physical model described above and the numerical modeling results of finite difference method are presented. The results show that there is a good agreement between physical and numerical modeling which indicates the ability of the numerical methods in prediction of liquefaction potential of these type of coastal protection structures. Then the effect of the soil parameters, the geometry of the structure and wave characterizations is investigated by numerical parametric studies.

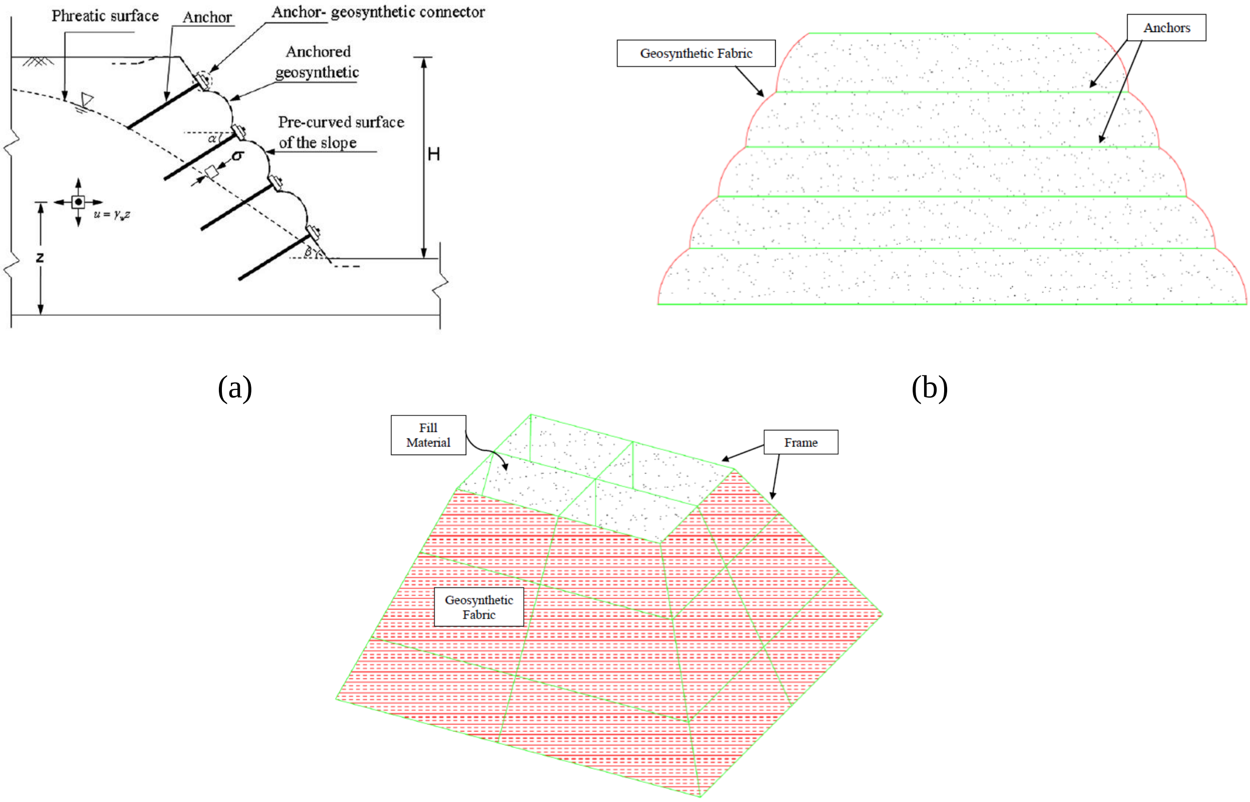
Keywords: Geosynthetic Cellular Systems (GCS), Coastal Protection, Wave induced Liquefaction, Numerical Modeling

1 INTRODUCTION

The background of Geosynthetic Cellular System (GCS) is related to anchored geosynthetic system (AGS) stabilization method (Figure1.a) but with extensive modifications (Hossein Ghiassian, Gray, & Hryciw, 1997). In AGS method, a geosynthetic is draped over the face of a slope and tensioned through steel rods or nails that are driven into the underlying soil mass. The developed tension and curvature of the geosynthetic combine to compress the soil and increase the confining or normal stresses on potential failure surfaces.

Experience has shown that tensile forces in the anchors decrease due to creep and stress relaxation in the soil as well as in the geosynthetic; therefore, they have to be re-stretched after the time (Vitton, 1991). In applications such as levees where the AGS method is applied to both sides of the levee, the required tensile force in the anchors is achieved by using one set of anchors connecting the two sides. The pullout resistance of the anchors is not a factor in this case because the two sides interact through anchors that span across the slope, as shown conceptually in Figure 1.b (Ghiassian H., 2009).

An interesting variation of this idea would be to construct GCS-type coastal structures (Figure1.c) by replacing the rock fill with dredged material. Such a system could be economical in situations where the required rock fill materials are either unavailable or very costly and dredged materials are readily available. GCS is composed of three main components: soil, geosynthetic and a frame. The geosynthetic acts as a shell to transfer lateral soil and external loads to the frame elements, as well as a filter to keep granular particles inside the GCS while allowing water to drain. The frame is usually built similarly to other structural frames. The frame act like anchors that connecting at two sides. After the frame is built, geosynthetic is placed around the interior of the frame and connected to the frame. The frame is then transferred to the desired offshore location and allowed to sink. After the frame is positioned on the sea bottom, it is back-filled with either on shore materials or dredged soils.



(a) (b)

(c)

Figure 1: (a) Anchored geosynthetic system – AGS (b) Conceptual application of AGS to a levee or embankment with horizontal anchors (c) Schematic representation of a GCS structure

According to this new idea, some experimental and numerical modeling are carried out. The summery are listed in table below:

Table 1. Summary of experimental and numerical studies on Geosynthetic Cellular System (GCS)

Row	Description	References
1	Internal stability considerations and the results of some laboratory experiments on small cylindrical models filled with water and sand	Ghiassian & Holtz (2009)
2	The behavior of GCS is compared with theoretical predictions, and a method called "Simple Method"	Ghiassian H (2009)
3	The behavior of GCS cylindrical samples by sand was analytically and experimentally studied using horizontal and vertical reinforcing elements under reinforced and unreinforced conditions	Ghiassian et al. (2013)
4	Laboratory study of geosynthetic cellular system (GCS) models under wave action in flume	H Ghiassian, Jalili, Rahmani & Madani (2013)

Considering the idea of GCS for use in coastal structures construction, knowledge of the wave-induced instabilities in this system is important. One of the most important effects of wave on the GCS could be the liquefaction of fill material. Also in order to evaluate the influence of various components in this structure, the horizontal wave forces are acting on the models and external stability of model under wave action should be considered. Soil liquefaction is generally defined as the state of the soil where the effective stress completely vanishes causing the soil-water mixture to behave like a liquid because the shear strength of soil becomes zero as a result of residual pore water pressure (u_e) reaching the initial effective stress (s'_{v0}). If the effective stress is only reduced without completely vanishing, the term "partial liquefaction" is often used (De Groot et al., 2006).

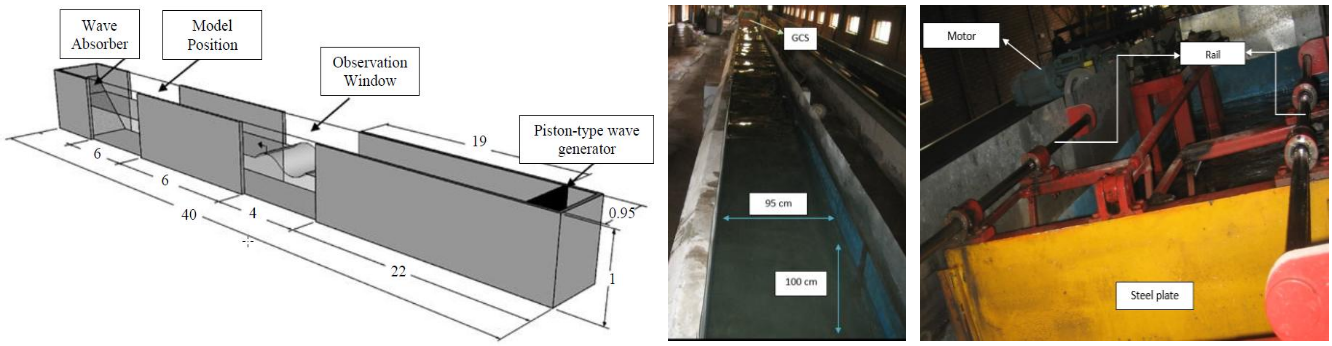
The use of dredged material by hydraulic fill of GCS structure is one of the advantages of this system, but by this method the loose hydraulic filled material could have the liquefaction potential, so this phenomenon is evaluated by experimental and numerical study by using finite element software (Cundall, 2014) and using parametric study in this article.

2 EXPERIMENTAL STUDY

In this section, the experimental modeling of GCS is described and some important result are mentioned. For evaluating the liquefaction of GCS induce to wave load,16 tests with 3 different shapes (square, trapezoidal, and rectangular) by 2 types of dredged material (Firouzkooh 161 Sand and Silt) that subjected to different wave load conditions in wave flume have been done.

2.1 *Experimental setup*

Figure 2 shows the setups of the experimental wave flume (40 m (L) ×1 m (H) ×0.95 m (W)). It is equipped with a piston-type wave generator on one end and models installed on the other end. Behind the models a 1:3 wave absorber slope exist in order to dissipate the overtopped wave energy.



(a) (b) (c)

Figure 2. (a) Experimental flume setups (unit: m) (b) Wave flume (c) Wave generator

2.2 *Dimensions of models*

To evaluate the response of GCS structures under wave attack, three section geometries include square, trapezoidal and rectangular have been studied. The square cross section model is 0.95m height and 1.0m width (perpendicular to channel). The bottom and top length of trapezoidal section model is 1.5m and 0.5m respectively and has height and width similar to the square section model. The rectangular section model has 0.6 m height, 0.95 width and length equal to 0.3 m. The frame of models has been designed using the Simple Method and constructed using steel profiles (Figure 3). The frame build from steel St.37 with two cross sections. Main parts of frame (outer side elements) are constructed by L shaped section (30x30x3 mm) and the interior steel element are constructed by belt section (20x3 mm).

a b c

Figure 3. Frame of GCS models studied in wave channel, (a) Square section, (b) Trapezoidal section, and (c) Rectangular section

2.3 *Properties of material*

2.3.1 *Geosynthetic (Geotextile)*

A nonwoven type geotextile is used to construct the fabric of GCS models. The required strength properties of the geosynthetic have been calculated by Simple Method calculation and hydraulic properties designed using recommendations in (FHWA-HI-95-038, 1995), considering both retention and clogging criteria. These properties are presented in Table 2. In order to satisfy the hydraulic requirements of fabric for silty fill materials, a layer of paper filter was installed between fill material and fabric.

Table 2. Properties of the geotextile.

Material	Thick-ness(mm)	Opening size average (μm) O90	Tensile strength (kN/m) (at 5% strain)	Static puncture Resistance (kN)	Permeability (l/m^{2}s)
Non-woven geotextile	1.7	100	13.5	2.1	100

2.3.2 *Soil*

GCS models are filled with two types of materials including Firouzkooh 161 Sand and Silt materials. The physical and mechanical properties of fill material are summarized in Table 3. The water sedimentation method has been used in order to fill the models to have uniformity of density in throughout the height of the models (Ishihara, 1996). This method of filling results loose fills, which will susceptible for liquefaction.

Table 3. Physical and mechanical properties of fill material.

Fill Material	Classification	d10 (mm)	(F.C) (%)	Uniformity Coefficient (Cu)	Curvature Coefficient (Cc)	$\gamma_{d(max)}$ (gr/cm^3)	$\gamma_{d(min)}$ (gr/cm^3)
Firouzkooh 161 Sand	SP	0.18	0.3	2.1	1.1	1.62	1.35
Silt	ML	---	---	---	---	1.6	---

2.4 *Instrumentation*

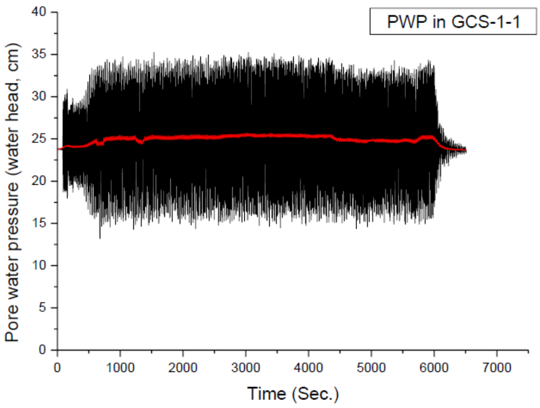
For the measuring the wave pressure on the models, pressure gauges along the sea-side face were deployed. Figure 5 shows their locations, and the pressure gauges were labeled respectively as HP-1 to HP-4 (or HP-5) from toe to top along the face of models. In the fill material of each GCS models eight measuring devices are installed include: Six Pore Water Pressure (PWP) transducers for the measurement of pore water pressure and two Soil Pressure (SP) transducers for the measurement of total stresses. The membrane of the PWP transducers is separated from the soil by a screen filter, and the middle volume in between is filled with water and for the SP transducer this filter in removed. In order to evaluate the wave characteristics, the water-surface elevation was measured using a conventional capacitance wave gauge that installed in front of the model. In order to record the external instabilities (if occurred), a visual observation was made by using a camera that was installed perpendicular to model in glass window position. The video recordings were then reviewed to control the lateral movement as a result of sliding or overturning.

2.5 *Experimental results*

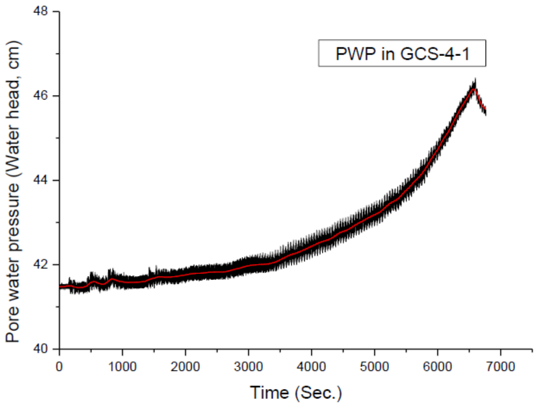
2.5.1 *Pore water pressure*

For all three sections, the evaluation of pore water pressure variations shows that there is close correlation between residual pore water pressure and grain size of fill materials, which will be addressed in Figure 5. The residual pore water pressure recorded at the different locations in models during tests show three stages where (1) the generation of pore water pressure dominates the dissipation; (2) a quasi-equilibrium occurs between generation and dissipation of the pore water pressure; and (3) residual pore water pressure exclusively dissipates. The first stage starts with beginning the wave generation in tests, and the third stage starts just at the end of the tests when no wave action was applied to models.

The duration and amount of the pore water pressure which occurred in stage two depended on the drainage characteristics of fill materials. For models filled by sand material, which have larger permeability and drainage, this stage occurred in lower residual pore water pressure and in models filled by silty material, because of smaller permeability and drainage characterization of fill material, equilibrium between generation and dissipation of pore water pressure occurred in higher residual pore water pressure.



(a)



(b)

Figure 4. (a) Variation of pore water pressure in center of GCS-1-1 at level 410 mm (b) Variation of pore water pressure in center of GCS-4-1 at level 240 mm – PWP: Pore Water Pressure

2.5.2 *Liquefaction potential of fill materials*

The effect of wave loads on pore pressure generation and on r_u variation For two different types of fill materials, and three model geometries are addressed below.

- Fill material with lower permeability leads to weak drainage condition, and higher residual pore water pressure. In models filled by silty material the equilibrium between generation and dissipation of wave induced pore water pressure occurs in larger amount of residual pore water pressure. In models filled by sand material, the variation of pore water pressure has similarity to wave height variation in the vicinity of model and the amount of wave induced residual pore water pressure was negligible specially in cubic and trapezoidal section models.
- Model geometry affects the wave load on model and also initial effective stresses in fill materials.
- Residual liquefaction in means of zero effective stress has been occurred in rectangular section model filled by silty material.
- In whole tests, dissipation of wave induced residual pore water pressure results in settlement after test, but only in liquefied model the amount of this settlement was so large that approximately 10% vertical strain has been occurred. In other models which filled by silty material, larger settlement has been occurred in compare to models filled by sand material, because of larger wave-induced residual pore water pressure in silty fill materials.

3 NUMERICAL MODELING

3.1 *Introduction*

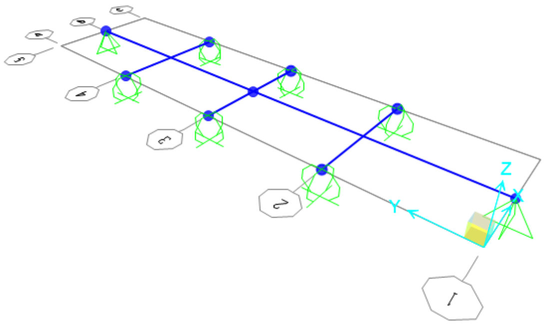
For construction steps of experiment modeling at first the frame are located in flume wave, after that the geotextile are attached into the interior face of the frame. Sedimentation method (Ishihara, 1996) is use for construction of filling material in frame.

3.2 *GCS numerical model*

According to construction steps, that are mention in section before following assumption has been done in 2D numerical modeling:

- For 2D numerical modeling the frame elements are model by link beam that located in the horizontal interior and main parts of frame element at two sides (Figure 5). The axial stiffness of beam calculated by SAP2000 (CSI, n.d.) By effect of all membrane stiffness of all connection point of frame elements.

(a)



(b)

Figure 5. (a) Experimental Model of cubic model (b) modeling mention part in SAP2000 for calculating the axial stiffness element in Flac 2D

- Mohr-coulomb model has been used for soil modeling in static condition based on properties described in pervious section and Finn model has been used for liquefaction evaluating of the soil.
- Wave loads are applying with interpolating between the vertical levels of pressure gauges. It is important that calculation in dynamic cases (wave load), need many time, for that reason only same part of loading time is considered.
- All physical modeling steps are mentioned in numerical modeling steps. Steps 1 to 5 are for construction and static loading of each side of GCS and in steps 6, the wave loads are applying and the liquefaction will be checked.

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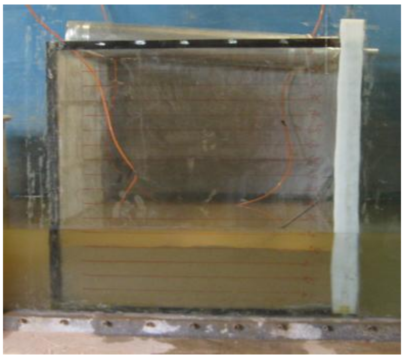

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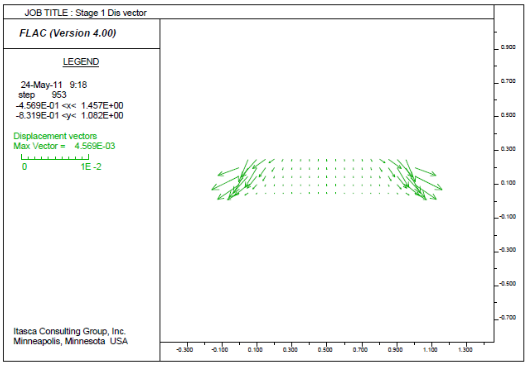

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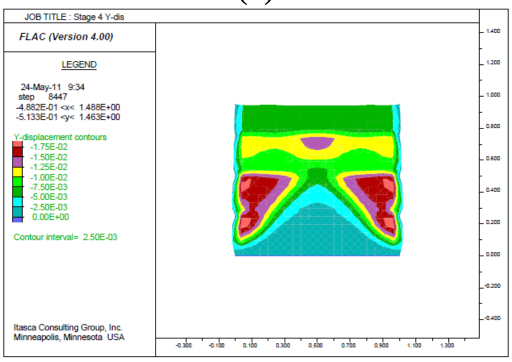

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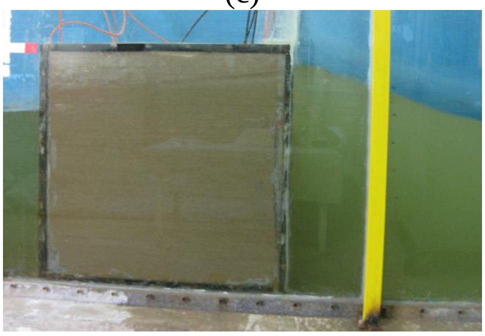

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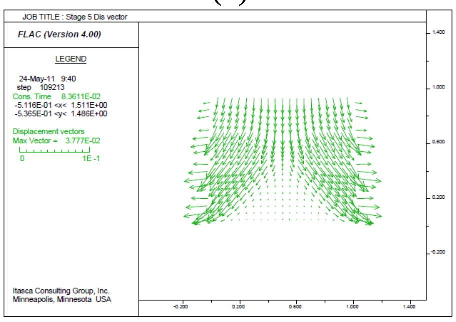


(f)

Figure 6. (a,b) Construction sequences (c,d) End of construction (e,f) Under wave loading

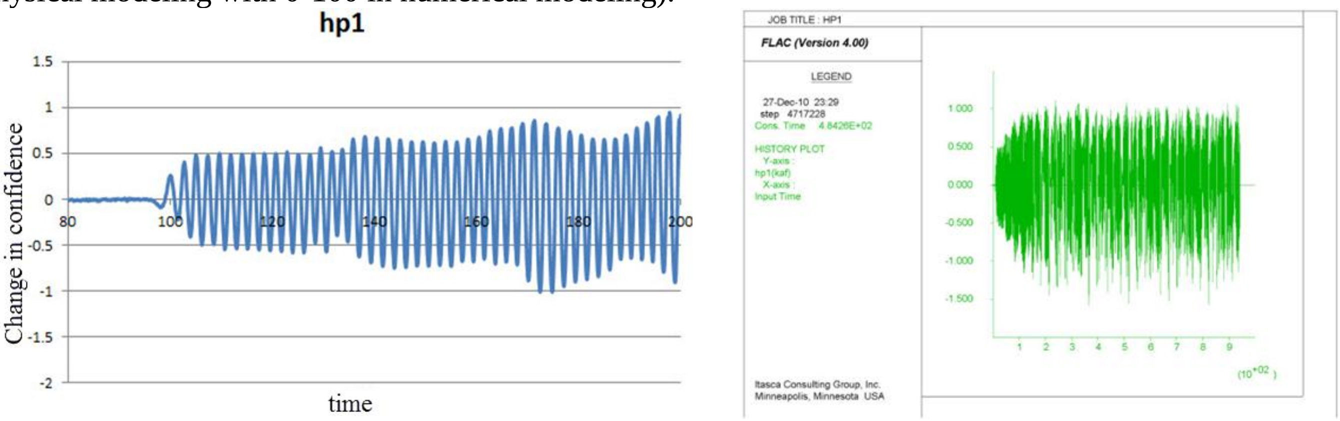
3.3 *Numerical model results*

For comparing the results of experimental and numerical modeling, some tests are chosen that the properties are listed in table 4. For comparing experimental and numerical model, MC model and Finn model has been used.

Table 4. Selected test for comparing numerical results with physical modeling

Test No.	Geometry	Fill Material	Steady Water Height(m)	Wave Height (H_s, m)	Wave Period (T, Sec.)
GCS 1-1	Square section	Firouzkooh 161 Sand	0.65	0.343	2.27
GCS 1-2			0.65	0.308	1.83
GCS 1-3			0.65	0.393	1.61

For dynamic analysis only 100 second of the physical test are be used in numerical modeling. The reason is the time of calculation in software and the constant trend of result of physical outputs. Figure 7 shows the applying hydraulic pressure in HP1 in FLAC and physical modeling (Comparing 100-200 in physical modeling with 0-100 in numerical modeling).



(a) (b)

Figure 7. (a) HP1 confidence amount in physical modeling (b) HP1 confidence amount in numerical modeling – HP: Hydrostatic Pressure

3.3.1 *Comparing pore water pressure and total stress*

Figure 6 shows the results of physical and numerical pore water pressure in PWP4 in GCS 1-2. It can be seen that the trend is very similar and at the peak point there is a maximum of 5% error (at a time equal to 83 seconds). For total stress the maximum difference between numerical and physical modeling is 6%.

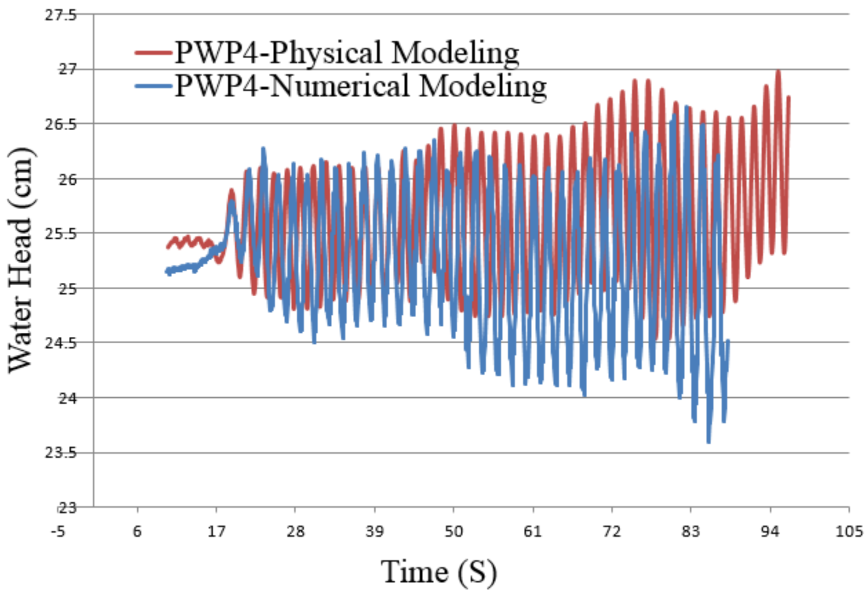


Figure 8. Comparing pore water pressure in physical and numerical modeling (PWP4) – PWP: Pore Water Pressure

3.3.2 *Comparing liquefaction potential*

According to Finn model, which was assigned to soil properties, the results show that liquefaction does not occur, which is similar to the experimental study results.

4 PARAMETRIC STUDY

In this section we are studying the effect of soil properties, geometry of GCS and wave characterizations on the stability of GCS.

4.1 *Effect of the soil parameters*

In the numerical and experimental study, the different of two type of soil (Firouzkooh 161 Sand and Silt) are considered. According to the results, the more possibility of occurrence of the liquefaction is greater to use of finely divided aggregates (silty materials). For the GCS model with the same conditions in construction, geometry, geotextile type and wave characterization, experimental modeling shows increased about 25% of the r_u ratio, and in numerical studies, an increase of about 22% probability of liquefaction. It is important to note that settlement in the model with silty soil are more than sand model due to the low permeability of silicate materials compared to sand aggregates.

4.2 *Effect of the geometry of the structure*

GCS geometry is one of the most important components in general and internal stability of this breakwater. As already mentioned, the stability of GCS depends directly on its weight. The weight of this type of breakwater depends on the geometry (soil content) and the density of the soil. Numerical and experimental results were compared in the same densities for square, trapezoidal, and rectangular geometries. Regarding the physical models of the rectangular section, due to its smaller dimensions, it experienced greater amounts of r_u, and during the experimental tests of the model, the model slipped due to the loss of part of its weight due to the occurrence of liquefaction. Based on experimental study (r_u) and numerical (pore water pressure values) comparison, trapezoidal models have been found to be less recent value. The reason is due to the removal of the wave pressure values in the experimental, which can be justified by the slope of the trapezoidal geometry, which transmits less pressure into the model.

4.3 *Effect of the wave characterizations*

Regarding wave characteristics, the wave height profile is less studied in the experimental model, and according to different period, decreasing in wave period leads to larger pore water pressure in fill materials. With regard to wave height, in numerical modeling, the heigh of wave is increased so that the wave force increases, causing an increase in the pore water pressure and more settlements occure in the rectangular geometry, it causes overall instability (slip and overturning).

5 CONCULOSION

GCS models, as new idea for coastal structures has been evaluated under wave action in flume. According to the experimental modeling, numerical modeling and parametric study following items are mentioned:

- FLAC 2D software has the ability to model GCS with an error rate of 5-10%.
- According to experimental and numerical studies, the stability of GCS is directly related to the total weight of the structure and the location of the center of gravity. The more weight of the structure and the lower location of the center of gravity to the bedding soil, the stability increases, and there the occurrence of liquefaction decreases.
- Considering the benefit of sand and silicate materials in experimental and numerical modeling, the probability of liquefaction occurrence with regard to the related ratio (r_u) and numerical results is estimated to be approximately 35% higher.
- The period of the wave is less, the probability of a liquefaction event increases because of the time for water drainage from the soil in the GCS structure decrease.
- According to experimental study experiments, the construction of a GCS (pouring of dredging materials) happen in a calm water turbulence cause lower the density of soil and there for increase the occurrence of liquefaction.

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