STUDY ON UPWARD MOVEMENT OF FINES FROM SANDY SEABED UNDER CYCLIC WATER PRESSURE CHANGE DUE TO WAVES

Takashi TSUCHIDA[1], Akihiro MATSUI[2] and Ryoichi ASAUMI[3]

[1]Member of ISSMGE, Professor, Dept. of Social and Environmental Eng., University of Hiroshima
(1-4-1, Kagamiyama, Higashi Hiroshima, Hiroshima, 739-8527, Japan)
E-mail:ttuchida@hiroshima-u.ac.jp
[2]Member of JGS, Student,Dept. of Social and Environmental Eng., University of Hiroshima
(1-4-1, Kagamiyama, Higashi Hiroshima, Hiroshima, 739-8527, Japan)
E-mail: m086028@hiroshima-u.ac.jp
[3]Member of JGS, Shimizu Corporatin

The artificial tidal flats have been constructed in order to revitalize coastal environments. The covering sand layer of tidal flats should contain 5-20% fines to maintain an ecosystem favorable to benthos. However, the fines contained in covering soils of artificial tidal flat sometimes disappeared in a few years after the construction. In this study, the sandy soil containing 10% fines were subjected to the cyclic water pressure change, and in some conditions, it was observed that the fines moved to the upper directions in the soil and finally reached to the surface. Under the one-dimensional water pressure changes, the liquefaction phenomena occurred at the surface of the ground due to the delay of the water pressure response of soil, and the upward movement of fines seems to take place related to the liquefaction. When the cyclic water pressure changes were subjected to the ground with permitting the lateral displacement as much as 1.0%, the rise of excess pore water pressure in the ground was not observed, but the upward movement of fines occurred more quickly than the case without the lateral displacement. The shear deformation of ground also accerelates the upward movement of fines in soil under the cyclic water pressure loading.

Key Words : *artificial tidal flat, fines, wave-induced liquefaction, cyclic water pressure,clay,sand*

1. INTRODUCTION

The artificial tidal flats have been constructed in coastal areas in Japan for the purpose of revitalization of near-shore environments. For the inhabitation of benthos (calm, mussel worm or eelgrass) in the coast, it is known that the surface soils in tidal flats have to contain about 10% fines. However, in some of the tidal flats, it was observed that the fines contained in covering soil layers had been washed out for a few years after the construction.

In Itsukaichi area in Hiroshima Port, the artificial tidal flat was constructed in 1992 to mitigate the loss of natural tidal flat nearby, where was the stopping point for migratory birds, due to the expantion of Hiroshima port. According to field investigation immediately after the construction, the surface soil contained 5-10% fines the standing stock benthos were same as natural tidal flats, and the number of visting migratory bird was almost same as that of natural tidal flat before the construction. However, in the inveatigation of 1996, the fine content of surface soils were almost zero, the standing stock benthos was a fifth of that in 1992 and the number of visiting migratory bird was a fifth or forth of that in 1992. It is considered that the loss of fines in surface soils had damaged the growth of benthos and made the reduction of visiting birds.(Port and Harbor Promotion Bureau of Hiroshima Prefecture,2001).

The reason why the fines in surface soils in artificial tidal flats disappeared for 4 years is not known. In this study, the movement of fines from surface sandy soil is studied with two types of laboratory model tests, in which the cyclic water pressure changes were subjected to sandy ground containing 10% fines, with and without the lateral deformation of the ground.

2. EFFECT OF ONE-DIMENSIONAL WATER PRESSURE CHANGES

(1) Test apparatus and soil sample

Cyclic water pressure change due to wave takes place at the surface soil of tidal flat. In geotechnical engineering, it is known that, under one-dimensional water pressure change, the excess pore pressure takes place in seabed due to the delay of water pressure responses, and that the liquefaction can occur making the surface of seabed unstable condition, when the excess water pressure exceeds the effective stress (Zen and Yamazaki, 1990). As the wave-induced liquefaction can be a potential reason of movement of fines in surface soils, the effects of one-dimensional water pressure change on the stability of fines in the seabed were investigated in laboratory model tests(Tsuchida, et al.,2007).

Fig.1 shows the test apparatus. In the acrylic cylinder of 22cm diameter and 50cm height, the sand containing 10% fines was made up to 18cm height with 50% relative density. After filling the cylinder with water, the cyclic water pressure (sine-wave) was continuously given at the top of the cylinder for 24hour. The measurements of pore water pressure were carried out at the depth of 0cm, 2cm, 4cm, 6cm and 8cm, by pore pressure gages attached to the special needles through the holes installed in the cylinder.

Table 1 and **Table 2** show soil samples and conditions of cyclic water pressure, respectively. Loading conditions was decided referring the design wave height of the artificial tidal flat in Itsukaichi area of Hiroshima Port. For the soil sample, Keisa sand No.5 (D_{50}=0.2mm) was mixed with 3 different fines with the fine content 10%. To control the

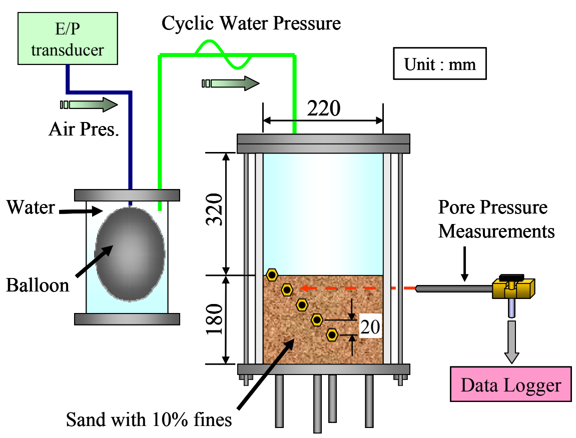


Fig.1 Test Apparatus
(1-D Water pressure changes model experiment)

property of fine, the marine clay taken at the seabed in Hiroshima Port Dejima District (high plastic clay with the liquid limit of 118.8%) and the stone flour (a byproduct at quarry, non-plastic fines) were mixed and used. The sample name such as C2-SF8 means that the sample contains 90% Keisa sand, 2% marine clay and 8% stone flour.

"Fully saturated" in **Table 1** shows that a level of saturation in the ground was increased by filling deaerated water after ventilation did CO_2 in the sample. "Unsaturated" is filled with the tap water statically, and no action was specially done to increase a level of saturation. **Fig.2** shows the responce of the pore water pressure in different depths after a water pressure was increased, where the response was shown as a value of water pressure coefficient B given by the following equation;

$$B = \Delta u_d / \Delta u_s$$

where, Δu_s is the pore pressure increment at the surface and Δu_d is the pore pressure increment in the ground at the depth.

When the B value is more than 0.95, the soil is considered to be fully saturated. As shown in **Fig.2**, it took about 3 seconds before the B value raises to more than 0.95 in the case of "unsaturated". On the other hand, it took 0.5 seconds in the case of "saturated".

Table 1 Soil Samples

Sample Name*	Sand (%)	Mixed Fines(%) Marine clay	Stone flours	Saturation
C0-SF10	90	0	10	unsaturated
C0-SF10	90	0	10	fully saturated
C2-SF8	90	2	8	unsaturated
C2-SF8	90	2	8	fully saturated

*C and SF means marine clay and stone flour,respectively

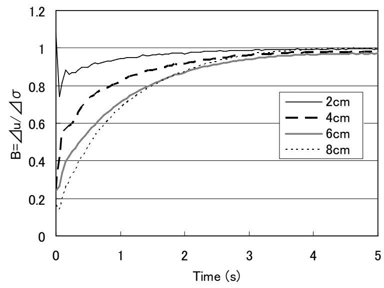
Table 2 Conditions of Cyclic Water Pressure.

Double Amplitude of Water Pres. $2p_0$(kN/m^2)	Period (second)	Loading Time (hour)
11.76 (*H**=1.2m)	5	24

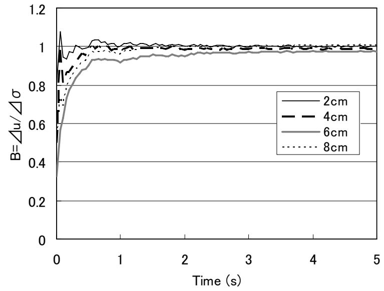
* *H**: Wave height

(2) Results of experiments

Fig. 3 show the comparison of fine contents of soil sample before and after cyclic loading of water pressure in Test No.1. As shown in **Fig.3**, for Clay0-SF10 and Clay1-SF9, the fines in the soil at the depth of 0-14cm moved upward after 24 hours loading of one-dimensional cyclic water pressure changes. However, as a result of Clay3-SF7 whose



(a) Clay0-SF10 unsaturated



(b) Cray0-SF10 saturated

Fig.2 Response of pore water pressure
(Change of B value after increase of water pressure)

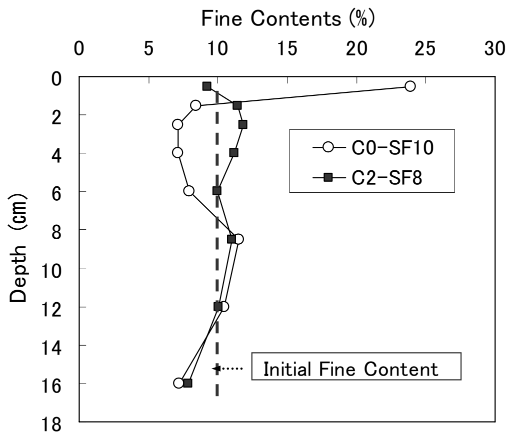


Fig.3 Change of fine contents after cyclic loading of 1-D water pressure (Clay0-SF10 and Clay2-SF8 unsaturated)

liquid limit was 40.1%, no major movement of fines was observed.

Fig.4 shows the particle size distribution of fine contained in Clay0-SF10 with different depths after experiment. The fines in sand became coarser from the surface, meaning that the coarse particles beyond about 30μm moved upward during the cyclic water pressure change. **Fig.5** shows fine contents after experiment when a level of saturation changed (Clay0-SF10). When the soil was fully saturated, the movement of fines in soil was not observed.

To consider the reason of the movement, the excess pore water pressure during cyclic water pressure changes were shown in **Fig.6 (a)** and **Fig.6 (b)**. In the case of Clay0-SF10, the excess pore pressure near the surface exceeded the initial effective stress in the ground making the wave-induced liquefaction. It is known that this phenomenon takes place due to the delay of ground water pressure response when the

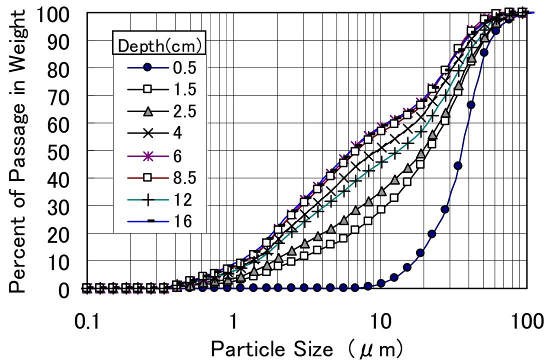


Fig. 4 Particle size distribution of fine after cyclic loading of 1-D water pressure (Clay0-SF10, unsaturated, boundary of cell)

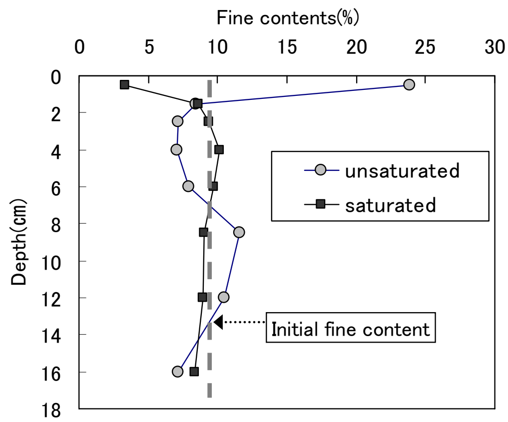


Fig.5 Change of fine contents after cyclic loading of 1-D water pressure (Clay0-SF10)

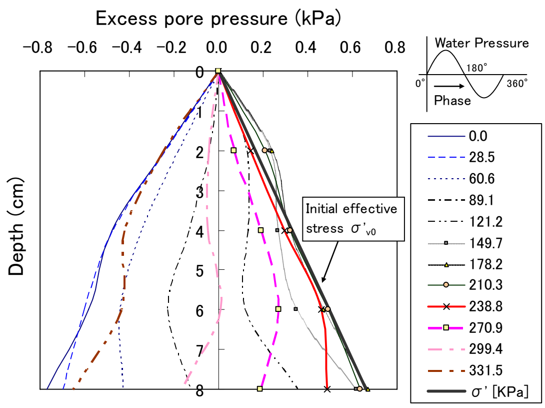


Fig.6 (a) Excess Pore pressure during 1-D cyclic water pressure changes (Clay0-SF10, unsaturated, after 12 hour) surface water pressure decreases (Zen and Yamazaki, 1990) when the water pressure decreases. On the other hand, in the case of Clay2-SF8 (**Fig.6 (b)**), the wave-induced excess pore water pressure was smaller than the initial effective stress and the liquefaction did not occur. For saturated samples of Clay0-SF10 and Clay2-SF8, the rise of excess pore water pressure was small and the liquefaction did not occur because of the quick response of ground water pressure.

Fig.7 is the state of the surface when water pressure decreases in the case of C0-SF10, unsaturated. A surface was raised 1 mm after a decrease in water pressure and it was observed that when the ground level rose, the fines particles moved with the pore water among the coarse particles which did not move.

The movement of fines in soil under one-dimension -al water pressure changes is summarized as follows;

1) When the sandy soil containing 10% fines were subjected to cyclic water pressure change, the upward movement and washout into the ground surface of fines were observed in some condition.
2) The upward movement occurred when the fines are not plastic and the saturation is not enough.
3) The upward movement of fines occurred when the water pressure decreased and the liquefaction took place near ground surface.

3. EFFECT OF CYCLIC WATER PRESSURE CHANGES WITH PERMIT -TING LATERAL DISPLACEMENT

(1) Test apparatus and soil sample

In one dimension water pressure changes model experiment, the upward movement and the liquefaction due to the delay of water pressure response was observed in the case of Clay0-CF10 fines.

Considering the actual situation of ground surface of tidal flat, the ground is subjected not only to the one-dimensional water pressure change, but also to the shear deformation by progressive waves. Although the value and the direction of principal stresses of ground under progressive waves changes continuously, a model test of soil under cyclic water pressure change with lateral displacement was carried out in the simplified manner as shown in **Fig. 8.** As shown in **Fig.8**, the soil in the cylinder was supported by air bag made of rubber membranes. When the water pressure rises or decreases, the soil sample deforms laterally. The lateral displacement was adjusted to be about ± 1% by the strain to the diameter. **Table 3** shows an experimental condition

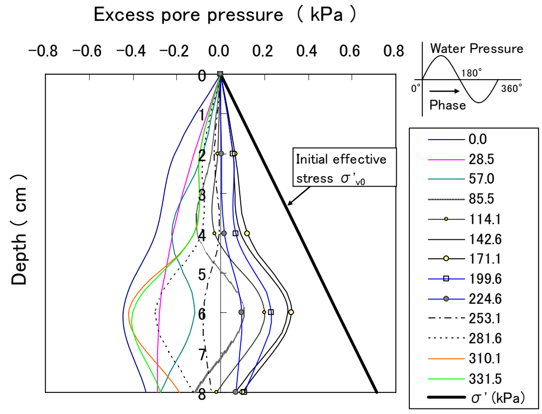


Fig. 6 (b) Excess Pore pressure during 1-D cyclic water pressure changes (Clay2-SF8, unsaturated, after 12 hour)

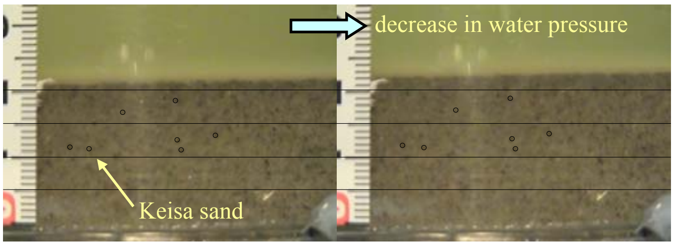


Fig. 7 The movement of the particles from the side of the experiment model (C0-SF10 unsaturated)

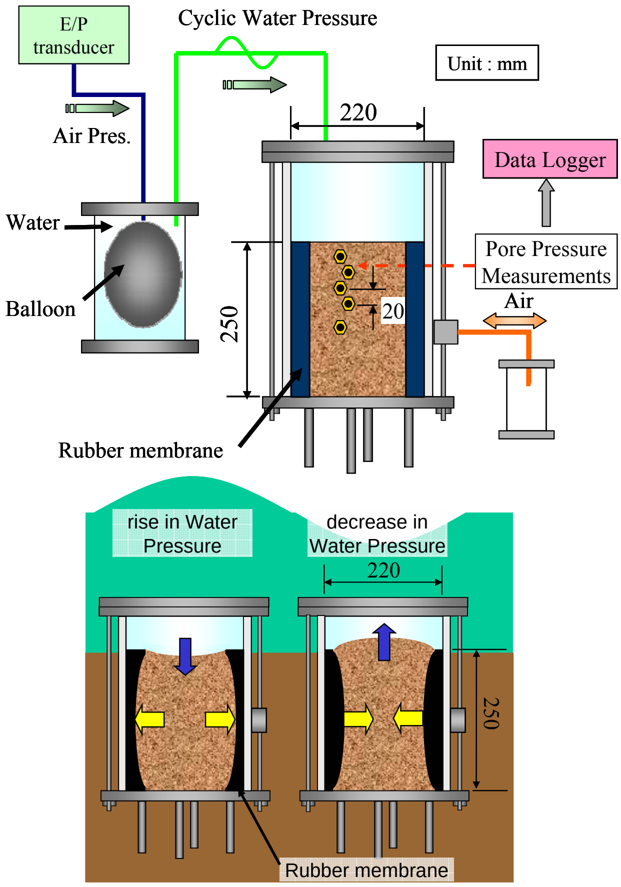


Fig. 8 Test Apparatus for Cyclic Water Pressure Changes with Lateral displacements

and soil samples. In the experiments, the time of water pressure loading was made 2 hours, considering the duration time of unusual waves.

Table 3 Condition of Tests

Type of Test	Sample	Sand (%)	Mixed Fines (%) Marine clay	Mixed Fines (%) Stone flours	Saturation
1-D water pressure change	C0-SF10	90	0	10	unsaturated
	C0-SF10	90	0	10	fully saturated
	C3-SF7	90	3	7	unsaturated
	C3-SF7	90	3	7	fully saturated
Water pres. change with lateral dis-placement	C0-SF10	90	0	10	unsaturated
	C0-SF10	90	0	10	fully saturated
	C3-SF7	90	3	7	unsaturated
	C3-SF7	90	3	7	fully saturated

*Time of loading is 2hours, Period=5 seconds

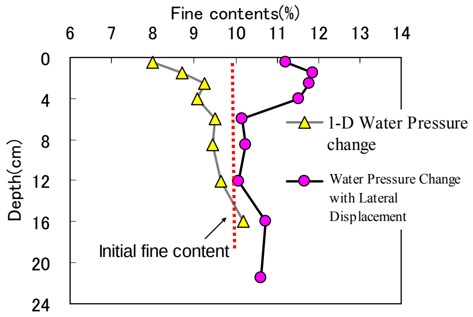
(2) Results of experiments

Fig.9 shows change of fine contents after cyclic loading of water pressure. When the lateral displacement was not permitted (one-dimensional condition), the upward movement and washout of fines was not observed for 2 hour loading time. In the case with the lateral displacement, fine contents in the surface increased with the unsaturated samples (**Fig.9 (a)**, **Fig.9 (b)**). However, for the saturated samples, the movement of fines was not observed (**Fig.9(c)**).

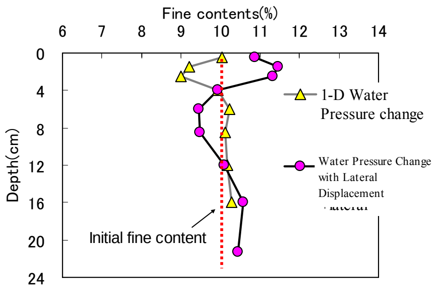
Fig.10 shows pore water pressure during cyclic water pressure loading (Clay0-SF10, unsaturated condition with lateral displacement). It is shown that the pore pressure in the ground did not rise at all with the case with the lateral displacement. As the positive excess pore pressure and the liquefaction didn't occur, the cause of movement of fines in this condition is not related to the liquefaction.

It was observed from the side of the acrylic cylinder in the cyclic water pressure loading, the ground surface rebounded with the decrease of water pressure, and the movement of fines was observed with the flow of the upward pore water. And, the reverse movement took place with the increase of water pressure.

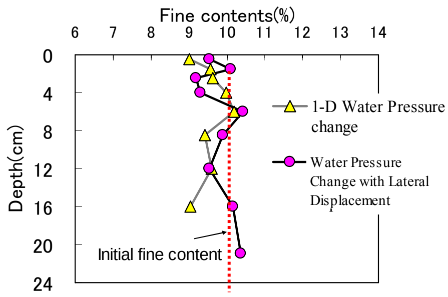
Based on these phenomena, it is considered that, for unsaturated samples, as the compressibility of water containing air is larger than that of soil skeleton, the flow of the pore water into ground takes place with increase of water pressure, and that the pore water will expand with decrease of water pressure, which makes a upward pore water flow and the movement of fines in the pore water. Further, the cyclic shear deformation also accelerates the upward movement of fines in soil.



(a)C0-SF10, unsaturated



(b)C3-SF7, unsaturated



(c) C0-S.F.10, saturated

Fig.9 Change of fine contents after cyclic loading of 1-D water pressure

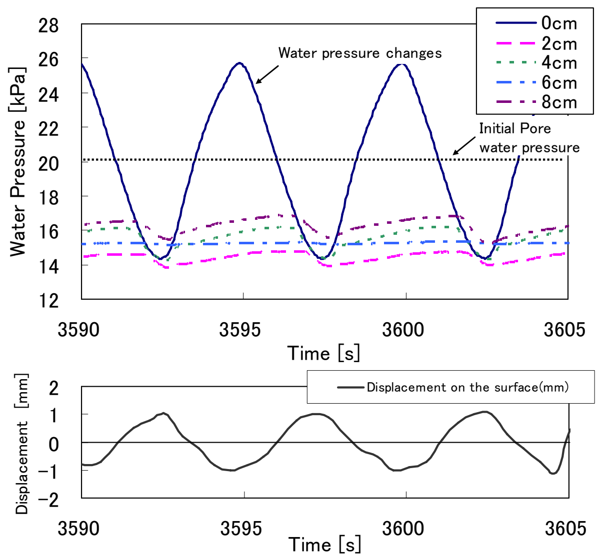


Fig.10 Pore water pressure during 1-D cyclic water pressure changes and Displacement on the surface (C0-SF10, unsaturated, after 1 hour)

4. FIELD OBSERVATION OF PORE PRESSURE RESPONSE OF AIRTIFICIAL TIDAL FLATS

Pore water pressure was measured in Itsukaichi artificial tidal flats seabed to verify for a result in the model experiment. An observation device is shown in **Fig.11**. The device was installed in the ground, and the pore pressure of the depth of 0, 5, 10, 15, 20, 30 and 40cm from the surface was measured. An observation point hardly contained the fines, and it was the condition which was close to the sandy beach. Observation was done when tide was full.

Fig.12 is the measured pore water pressure due to one wave, where the depth of device was about 55cm and the wave height was 15cm. The pore pressures are corrected based on the water pressures measured at the ground surface. As the ground depth becomes deep, a water pressure response was delayed, and the water pressure changes were small. By analyzing the water pressure response, it was known that the degree of saturation of this site was almost the same as the unsaturated case in the experiments in this study.

5. CONCLUSION

It has been reported that the fines contained in covering soils of artificial tidal flat disappeared for a few years after the construction. To study the reason of this phenomenon and the countermeasure, the movement of fines in covering sand layer of artificial tidal flat under cyclic water pressure change was studied experimentally. The results are summarized as follows:

1) The sandy soil containing 10% fines were subjected to cyclic water pressure change for 24 hours. In some conditions, it was observed that the fines moved to the upper direction in soil and finally reached to the surface.
2) The upward movement occur when the fines are not plastic and the saturation is not enough..
3) The upward movement of fines occurred when the water pressure decreased and the liquefaction took place near ground surface.It is suggested that the occurrence of liquefaction is related to the upward movement of fines.
4) In the cyclic water pressure loading with permitting the lateral ground displacement of about 1%, the upward movement was observed for 2 hour loading. although the pore pressure did not rise at all and the liquefaction did not occur.
5)For unsaturated samples, as the compressibility of water is larger than that of soil skeleton, the flow of the pore water into ground takes place with increase of water pressure, and that the pore water will expand with decrease of water pressure, which makes a upward pore water flow and the movement of fines in the pore water.
6) At the surface in the tidal flat subjected to cyclic water pressure change by waves, the shear deformation of ground also accerelates the upward movement of fines in soil.

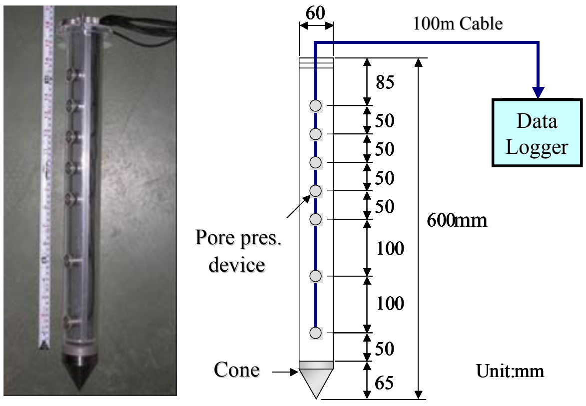


Fig.11 Observation device

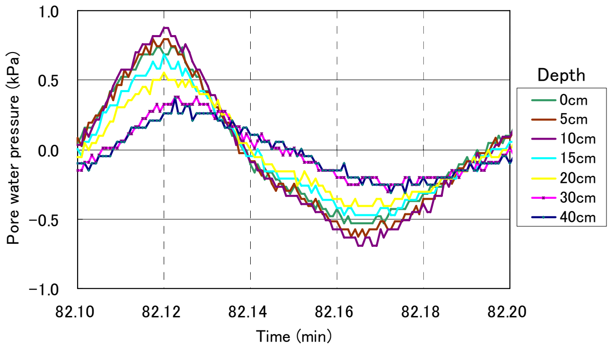


Fig.12 Pore water pressure in the tidal flat surface (base on the water pressure of the surface)

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