Effect mechanism of cyclic wave loading on geotube dam with seams

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ABSTRACT: The alternating flow through the seams between geotubes in a geotube dam creates a cyclic flow regime distinct from the uni-directional flow that has been previously studied. A new laboratory apparatus has been used to investigate the influence of the hydraulic conditions on the stability of the geotube dam. This apparatus was capable of simulating cyclic flow conditions normal to the seam between the geotubes of the geotube dam. In this study, a series of tests were conducted under two different conditions: water or mixtures of water and air in a pipe(seams between geotubes). The results show that the main influence of the current on the sand in the pipe was the grading of the slope for the condition using air. In the other working condition, the erosion development process of the sand in the sandbox (dam core) was analyzed, the movement law of the particles in pipe was explored, and two migration processes of particles in the pipe were found.

Keywords: cyclic wave loading; geotube dam; core sand; seam between geotubes

1 INTRODUCTION

With the development of protective measures on coasts, geotube dams are increasingly used in estuarine and coastal engineering, such as in reclaiming tidal flats and reservoirs when avoiding saltwater and storing freshwater. The construction process for geotube dams involves filling large geotubes on either side of the dam under water to build cofferdams, reclaiming sandy soil into the middle of the cofferdam on both sides and forming the water retaining dam(Fig. 1).

The typical length of geotube dams is up to tens of kilometers. Geotube dams must be composed of many geotubes along the dam axis. Many seams inevitably occur between geotubes (Fig.2). During the construction and operation of a geotube dam, the seams between the geotubes become scour channels of the dam core sand. The sand in the dam core and seams would be constantly washed away along the joint under the action of water flow. Furthermore, geotube dams are typically located in estuaries and coastal areas, where the current is bidirectional and unstable. When the seams between geotubes are subjected to cyclic water action, such as wave loading and water level fluctuation, the sand in the dam core and seams are easily scoured. The Chenhang Reservoirin Shanghai was unstable 20 years after constructionbecause a mass of sand particles in the dam core gushed through the seams between geotubes. This case shows that the seams between geotubes develop a potential safety hazard to the dam structure.

In foreign countries, studieshave focused mainly on the construction technologies, the structure stability of geotube dams and the related features of geotube materials.

The deformations and runaway process of geotubes under wave loadings were investigated by combining an indoor model test with a numerical simulation method(Juan Recio et al., 2007, 2009). The effect of saturated filling on the stability of geotubes subjected to wave loadings was revealed through large-scale physical model tests (Van Steeg, P et al., 2010).

Geotubes were shown to be viable in dewateringsediment with high moisture contents (Moo-Young et al., 2002; Koerner et al., 2006). The erosion stability of punctured geotextile filters subjected to cyclic wave loadings was tested with a cyclic flow apparatus (Soon Hoe Chew et al., 2000, 2003). The test results showed that the soil-geotextile interface can be stable, even when punctured holes are noted onthe geotextile, as long as the holes do not exceed a certain critical size.The influence of various factors, including the water content, grain composition and size of the geotextile, on the dewatering performance of geotubes was systematically researched (A.E. Muthukumaran et al., 2006).

The settlement deformation of geotubes filled with different fillingmaterials was studied through laboratory tests (Shin EC et al., 2003, 2007). The empirical formulafor calculating the settlement deformation was established and verified via insitu model tests. The stability and settlement deformation of a geotube dam in the reclamation engineering of Tianjin Port were researched through an indoor centrifugal model and insitu test, respectively (S.W. Yan et al., 2010). The test results provideduseful reference data forengineering designs and construction in practice.

In foreign countries, geotubes are mainly comprised of high-strength geotextiles. Therefore, the size of a single geotube can be large, indicating that the seams between the geotubes and the erosion instability caused by the seams are not serious. Therefore, research by foreign scholars has focused on aspects otherthan the seam problem. In China, geotubes are comprised of burst-film yarn-woven geotextiles. With the limitation of the strength of these materials, the size of geotubes is smaller, producing more seams between the geotubes along the dam axis. No studies on the erosion stability of a geotube dam with seams between geotubes subjected to cyclic wave loadings in China have been reported.

After a geotube dam holds back the waters, the fine sand particles in the seams between the geotubes begins to move under the effect of cyclic water action, such as wave loadings and water level fluctuations. This movementindicates that the seepage deformation or contact scour has initiated. A series of in-depth studies on the stability of contact scouring and piping in conventional damshave been performed since 2000.

The development process of contact scouring was simulatedbygeneralizing thepermeability of theunderground layers and by establishing the calculation model (Chen Jian-sheng et al., 2003). A Lagrangian coupling two-phase flow model was used to simulate the scouring processes beneath a marine pipeline with respect to the sediment and fluid phase interactions (Morteza Zanganeh et al., 2012). The movement of thesediment and fluid particles was simulated with smoothed particle hydrodynamics. Seepage piping in levee foundationswas researched bymodel tests (Mao Chang-xi et al., 2004, 2009). The critical gradient formula of the piping for various grain sizes in sandy gravels was derivedusing seepage theory. The failure characteristics and influencing factors of seepage were studied for a uniformsand foundation in a laboratory model test (Liu Jie et al., 2008).

The studiesaboveare mainly designed to investigateseepage deformation and contact scouring in earth-rock dams or other conventional engineering applications. However,large differences between conventional dams and geotube dams with seams are noted for theseepage deformation and contact scouring, such as the initial state of the sand and flow, the boundary conditions and the hydraulic characteristics. Therefore, existing research on seepage stabilityhas limited guiding significance for the construction of a geotube dam. No specialized researchis available on erosion stability of a geotube dam with seams between tubes subjected to water flow, particularly for cyclic wave loadings. Therefore, this paper investigates the key factors affecting the stability of a geotube dam that has multiple seams and studies the arch structure space phenomenon associated with this design.

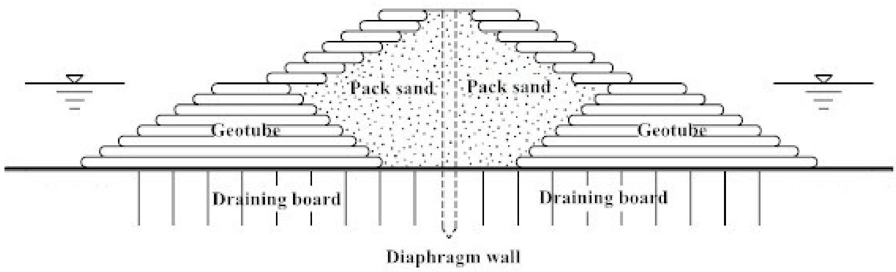
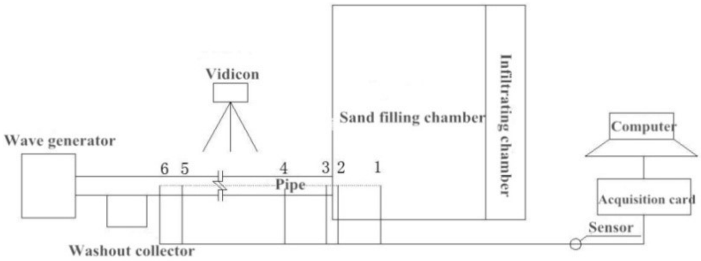


Figure 1. Diagrammatic sectional drawing ofageotube dam.

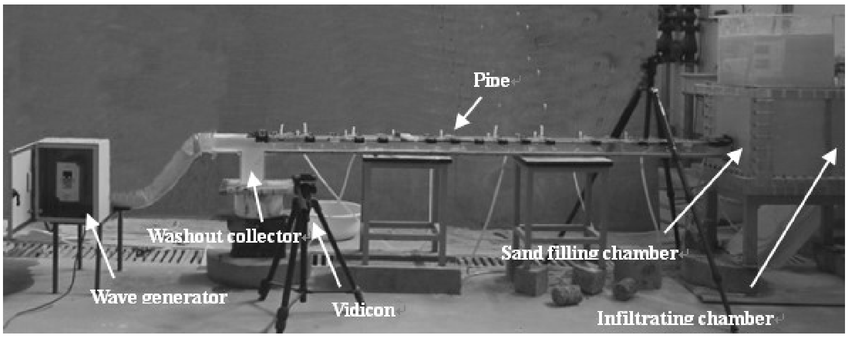
Figure 2. Seam between the geotubes of a geotube dam.

2 TEST APPARATUS

The testing apparatus consists of a cyclic flow apparatus, sandbox and tube model (Fig. 3).



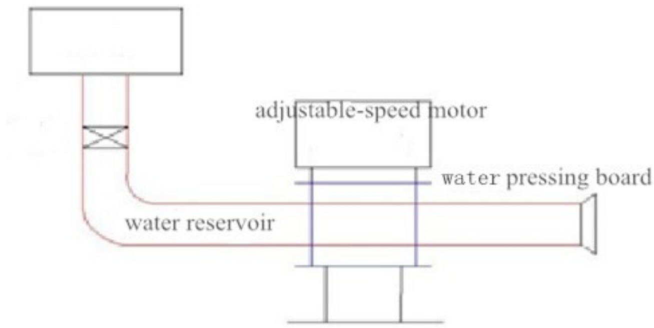
(a) Schematic diagram

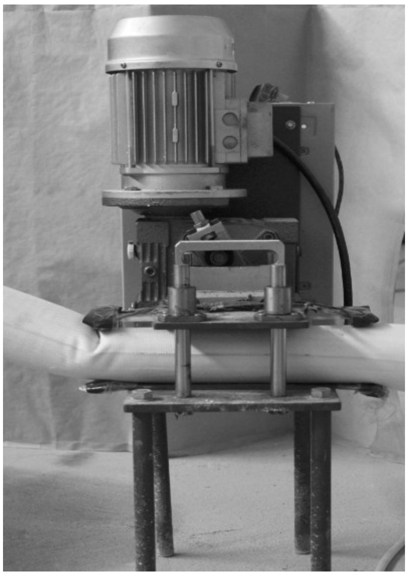


(b) Physical map

Figure 3. Schematic diagram and physical map of the testing apparatus.

The cyclic flow apparatus system mainly consists of a water reservoir, two pieces of water pressing board and anadjustable-speed motor(Fig. 4).The water reservoiris activated by the water pressing board under the action ofadjustable-speed motor generating cycle flow to simulatethe cyclic wave loadings applied toa seam between the geotubes of the geotube dam. The cycle period and pressure can be adjusted with the regulation control of the motor speed and the length of the wave pressing board.





(a) Schematic diagram (b) Physical map

Figure 4. Schematic diagram and physical map of the cyclic flow apparatus.

The sandbox simulates the dam core and is divided into two parts: the sand filling chamber and infiltrating chamber. These two parts are separated by a homogeneous porous flow board. Non-woven fabric attached to the perforated board produces a uniform current andprevents the sand from inflowing into the infiltrating chamber.

The pipe simulates the seam between the geotubes. According to measurements at the construction site, the length of seams between the geotubes in practical engineering applications ranges from 2 to 10 m, whereas the diameter is approximately 50 mm. Based on the principle that a pipe with a minimum diameter and maximum cross-sectional area is most easily damaged, the section of the pipe was designed to be a square witha side lengthof 50 mm. Additionally, the length of the pipe is 2,000 mm.A removable cover plate was set on top of the pipe. The cover plate and pipe are anchored with a screw. The side wall of the pipe was equipped with an access point for the water pressure sensor. The pipe connectsthe cycle flow apparatus to the sandbox.

3 TEST PROGRAM

Before initiating the test, the apparatus must be checkedforexistingwater leaks by adding water after the assembly. The water pressure sensor and flowmetermust also be installed and calibrated. According to the designedporosity, the sand was addedto the sand chamber hierarchically to ensure the homogeneity of thefilling.Quartz sand with a typical distribution was used in this test series. Theparticle size distribution of the sample is identical to the one used in practical engineering applications of geotube dams in the Jiangsu Province, China (Fig. 5).The water should be added slowly by controlling the water tank and infiltrating chamber. The samplemust be soaked for 12 hunder a static head afterbeing filled with water.

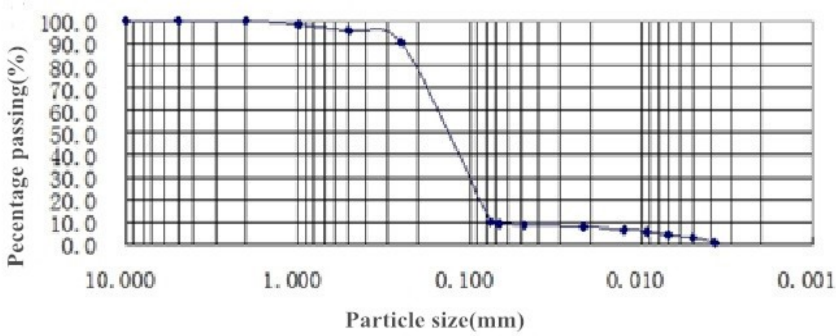


Figure 5. Sand particle size distribution.

A series of tests was conducted under two different conditions: water or mixtures of water and air in the pipe. Different particle porosities (34%, 35%, 40%, and 45%)were employed. The period of the cycle flow was set at 6, 7, 8 and 10 s, respectively. The maximum pressure was set at 200, 250, 300 and 400 mm. According to the method of controlling variables, only one factor could generate one different working condition at a time. The different combinations of various conditions formed the diverse working conditions.

4 TEST RESULTS

4.1 *Working condition of water and air in the pipe*

According to the relative position between the seam andfree water surface of the dam, this study performed an erosion mechanism analysis of a geotube dam for two working cases: water and air in the pipe and only water in the pipe.The water and air in the pipe corresponds to the case with a seam between geotubes as high as the free water surface. In this condition, the seam is not filled with water and contains air (Fig. 6).

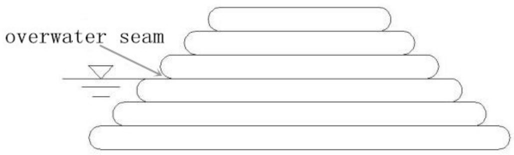


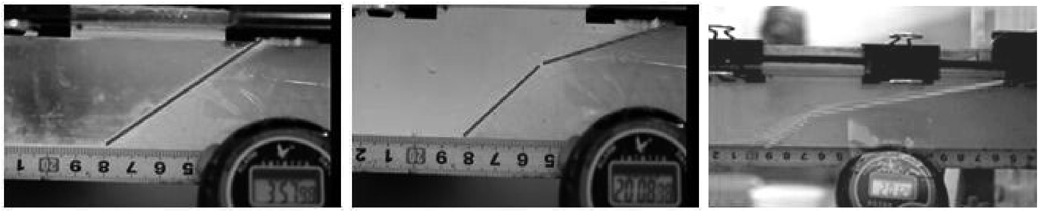
Figure 6. Schematic diagram of the condition of water and air in the pipe.

4.1.1 *Erosion process of the working condition of water and air in the pipe*

The erosion process of the working condition of water and air in the pipe is divided into two stages: increasing phaseand decreasing phase. Air gathers on the top of tube in the initial resting state. In the increasing phase, the current flows into the sandbox and crowd the air out of the seam. Meanwhile, the water surface ascends because of the increasing flow along the slope of the sandpile in the seam. The forces on the particles mainly include the grab-ability and uplift load from the climbing flow and thegravity and interlocking force among particles. The low flow velocity of the climbing flow and the inhibition of gravity and interlocking force among particles prevent the movement of particles during this stage. In the decreasing phase, the current reverses its flow direction and runs into the seam from the sandbox. The water-head in the seam decreases rapidly. The resultant forceis composed ofthe negative hydrodynamic pressure generated by the water-head decreasing,thegrab-ability and uplift load from the backing flow exceeds the interlocking force among particles. Therefore, the backing flow more easilyscours the sand particles on the slope of sand-pile than the climbing flow.

4.1.2 *Effect of the cycle flow in the working condition of water and air in the pipe*

This paper performs a test with a 3.5 cm water depth in the seam. Fig. 7 (a) shows the initial stage, in which the angle of the slope at the front of the sandpile is approximately 38°.As shown in Fig. 7 (b), after 20 min, the slope at the front of the sandpile displays two parts: the lower part remains at38°and the upper part is 20°.Two hours later, the slope at the front of the sandpile remains bifurcated: the lower part remains at 38°and the upper part is 20°, as shown in Fig. 7 (c). Additionally, the forefront of the sandpile displays slight forward movement(2 cm). The main effect of the cycle flow in this condition is the grading of the slope.



(a) Initial stage(b) 20 minutes later(c) 2 hours later
Figure 7. Effect of the water and air in the pipe.

4.2 *Working condition of water in the pipe*

The condition of water in the pipe corresponds to the case of the seam between the geotubes below the free water surface. In this condition, the seam is filled with water (Fig. 8).

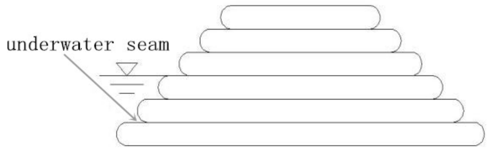


Figure 8. Schematic diagram of the condition of water in the pipe.

4.2.1 *Erosion process of the working condition of water in the pipe*

This paper performs a series of tests with the seam 20 cm below the free water surface. The results show that the erosion process of this working condition can be divided into threephases: the shocking stage, arching stage, and stabilizing stage.
Shocking stage: With the outflow of smog-like particles in the junction of the pipe and sandbox, a small gap appears in the sandbox near the junction. In this stage, the sand production volume is limited. The main influence of the cycle flow is the disturbance of and destruction to the sand structure.
Arching stage: The typical characteristic of this stage is a hole developing in the sandbox near the junction. This hole is called the arch structure space (Fig. 9). Arching provides space for reciprocating the flow. Therefore, the potential energy of the current is easily converted into kinetic energy. Under higher-velocity flows, the liquefied sand particles outflow into the pipe and pile up to form a sandpile along the pipe.

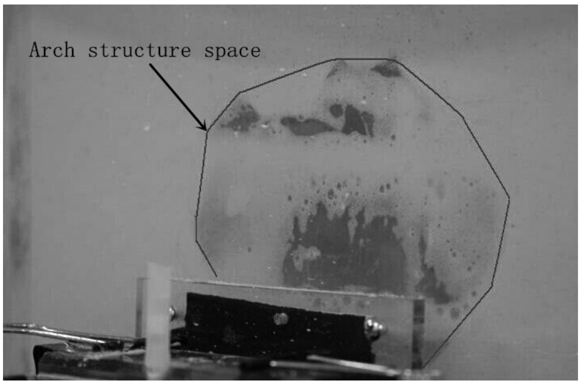


Figure 9. Arch structure space in the sandbox.

Stabilizing stage: With the development of the erosion process, particles on the top of the arching fall down because of their own gravity and the negative hydrodynamic pressure. In this process, the particleredistribution results in the self-filteringby separating the coarse particles on the bottom and fine particles on the top. This phenomenon occurs because of two reasons. The first reason is that fine particles with small volumes and weightsmore easilyascend than coarse particles in the inflowing stage. The second reason is that the distribution of coarser particles on the bottom and finer particles on top prevents the upper particles from enteringthe pipe. Therefore, the sand production volume in this stage declines. Finally, the sand particles stop moving forward in the pipe. The distribution of sand particles during arching is shown in Fig. 10.

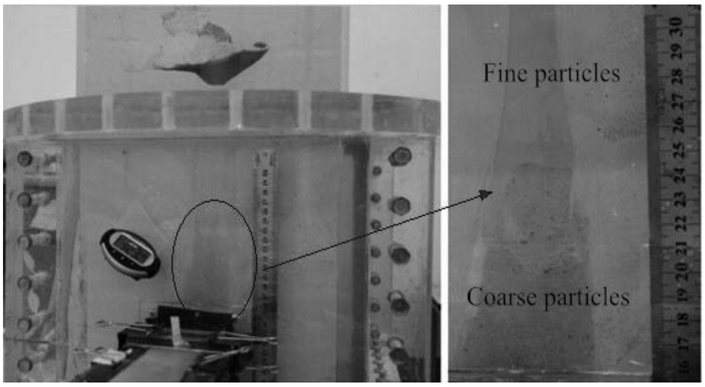
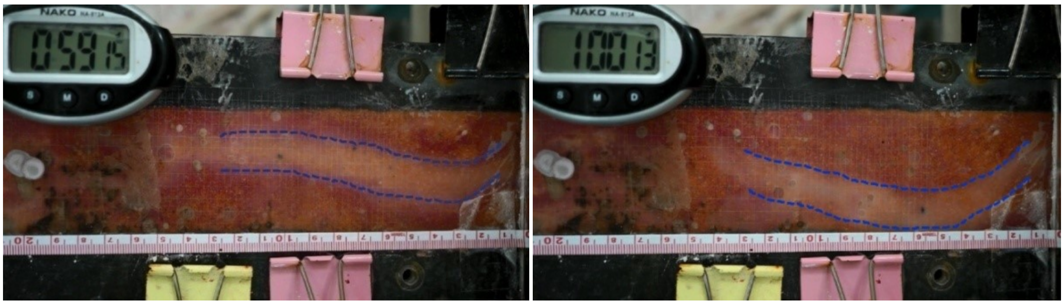


Figure 10. Particle distribution in the arch structure space in the sandbox in thestabilization stage.

4.2.2 *Migration of particles in the pipe*

4.2.2.1 *Type of particle migrationin the pipe*

Particle migration in the pipe displays two types: whole section migration and groove migration. The whole section migration indicates that particles ranging from 2 to 5 cm from the top of the pipe migrate forward along the entire section. This migration occurs in the arching stage. Because of the through-passage appearing near the top of the pipe, the potential energy of the current easily converts into kinetic energy. Under higher-velocity flows, the liquefied sand particles migrate rapidly on the upper pipe space. The groove migration indicates that particles ranging from 2 to 5 cm from the top of pipe migrate forward along the local section (groove). The groove is formed by the cycle alternating motion of the cycle flow. This migration occurs in the early stabilization stage. In this stage, the current with lower energy does not carryparticles in the entire section; most of the particles stop, gather and leave a narrow passage for the current. Under lower velocity flows, the structure of the sand adjusts constantly to produce groovesthat also change continually (Fig. 11).



(a)One minute ago(b)One minute later

Figure 11. Comparison diagram of the groove state at different times.

4.2.2.2 *Distribution of the sand particles in pipe*

To observe the particle distribution and analyzeparticle migration, colored sand particles were applied in the tests. The corresponding instance between the color and size of the sand particles is shown in Table 1.

Table 1 Colors and sizes of particles.

Color	White	Purple	Red	Orange
Size/mm	<0.075	0.075-0.125	0.125-0.18	0.18-0.425

1) Vertical distribution of the sand particles in the pipe

The images collected in the tests show that the particles in the pipe can be divided into two layers: white fine particles on the bottom and multi-color coarse particles appearing alternately on the top (Fig. 12). This distribution reveals the motor process of sand particles to an extent. The fine particles more easily migrate as a suspended loadin the cycling water. With the dissipation of energy in the motor process, the particles stop and subside to the bottom of the pipe. Meanwhile, the coarse particles begin to move forward as a bed loadand pile up on top of the white fine particles that subsided in the early stage. Similarly, with the dissipation of energy in the motor process, particles of different sizesthat stop migrating causes the color of the layer texture (orange, red, purple or white)toalternate.

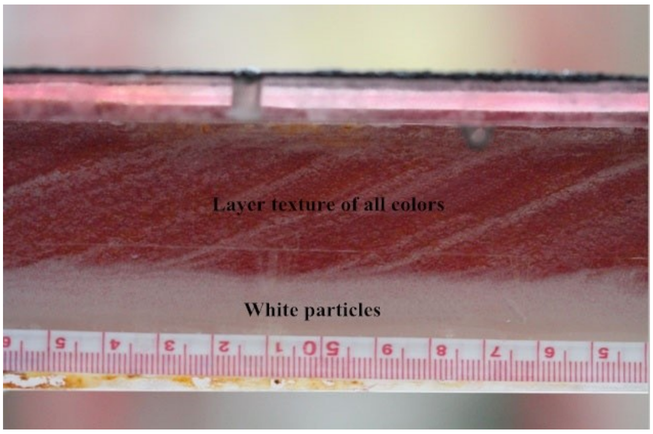


Figure 12. Vertical distribution of particles in the pipe.

2) Longitudinal distribution of the sand particles in the pipe

After the experiment, a sample was withdrawn with a cutting ring along the direction of the piping longitudinal axis to analyze the grain size gradation and porosity. Additionally, a sample was withdrawn using a cutting ring along the direction of the piping vertical axis and arch structure space to analyze the grain size gradation and porosity. The longitudinal distribution of the sample porosity in pipe is shown in Fig. 13. The longitudinal proportion of the fine particles is shown in Fig. 14.

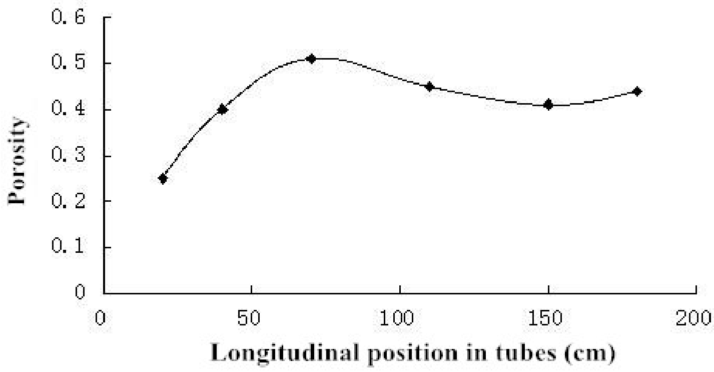


Figure 13. Longitudinal distribution of the porosity.

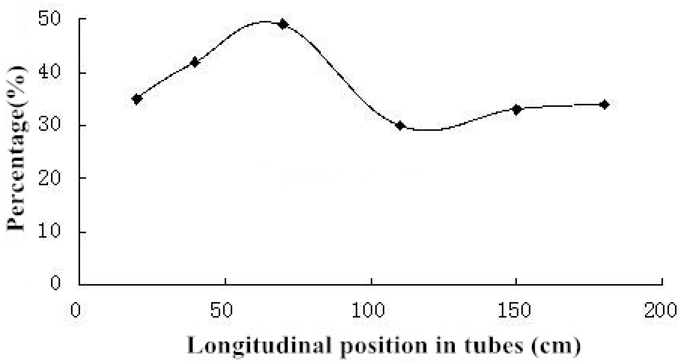


Figure 14. Longitudinal proportion of the fineparticles.

The longitudinal distribution of the porosity and the longitudinal proportion of fine particles in the pipe first increase, then decrease, and then increase gradually (Figs. 13 and 14). The velocity of the sand particles in the shocking stage was sufficiently low that the particles had a sufficient amount of time to rearrange into a new compact structure. Therefore, the porosity in this stage was relatively dense. Additionally, the fine particles washed away more easily than coarse particles. Hence, many coarse particles accumulated in the junction of the pipe and sandbox. The sand particles in the central position of the pipe mainly accumulated in the middle of the arching stage. In this stage, the liquefied sand particles migrated rapidly, producing a relatively loose accumulation. The entire section migrated in this stage, preventing the separation of fine and coarse particles and producing a high proportion of fine particles. The porosity of sand particles decreased gradually with a decreasing sand production volume. The pipe was blocked because of the lower energy of the water flow in the late arching stage and stabilizing stage. In this stage, only the fine particles can be carried away. Hence, the proportion of fine particles decreased. Meanwhile, the porosity of the sandpile in this position achievesaminimum value. After the pipe is blocked by the sandpile, the main influence area of the current is on the front of the sandpile. The periodic current loosens the structure of the sand particles. Hence, the porosity of the sand particles in this position increases slightly. The particles in this position mainly consisted of the fine particles carried in the late arching stage.

Combining the macroscopic-phenomenon of the arching with meso-structure parameter of the particles in the pipe, the scour mechanism of cyclic wave loadings on seams between the geotubes of a geotube dam can be revealed comprehensively.

5 CONCLUSIONS

The newly developed apparatus was capable of simulating cyclic flow conditions normal to the seam between the geotubes of a geotube dam. Tests were conducted for two different conditions:water or mixtures of water and air in pipe.

The results of these studies show the following:

In the pipe, the main influence of the cycle flow on the sand isgrading the slope in the working condition with air in the tube. This condition is more secure when compared with the other condition, which can cause structural failures in the geotube dam.

In the working condition of only water in the pipe, the erosion development process for the sand in the sandbox can be summarizedby the formation of the arch structure space.

The migration of particles can be divided into two types: ‘groove type’ and ‘full face type’. These two types occur at varying points during the erosion process.

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REFERENCES

Chen J. S., Liu J. G. and Jiao Y. H.(2003).Simulation study on the contact scouring development between underground layers. Engineering Science, 5(07): 33-39.

Chew S. H., Zhao Z. K., Karunaratne G. P., et al. (2000) Revetment geotextile filter subjected to cyclic wave loading. Geotechnical Special Publication.

Chew S. H., and Siew A. T., et al. (2003). Erosion stability of punctured geotextile filters subjected to cyclic wave loadings-a laboratory study[J]. Geotextiles and Geomembranes, 21(4): 221-239.

Koerner, G.R. andKoerner, R.M. (2006).Geotextile tube assessment using a hanging bag test. Geotextiles and Geomembranes 24(2), 129-137.

Liu J., Cui Y. H. And Xie D. S.(2008).Failure mechanism of seepage in uniform sand foundation of river levee. Chinese Journal of Geotechnical Engineering, 30(5): 642-645.

Mao C. X., Duan X. B. And Cai J. B. et al. (2004). Experimental study on harmless seepage piping in levee foundation. Journal of Hydraulic Engineering, (11): 46-54.

Mao C. X., Duan X. B. and Wu L. J.(2009).Study of critical gradient of piping for various grain sizes in sandy gravels. Rock and Soil Mechanics, 30(12): 3705-3709.

Morteza Z., Abbas Y. B. and Ahmad K. W.(2012).Lagrangian coupling two-phase flow model to simulate current-induced scour beneath marine pipelines.Applied Ocean Research, 38: 64-73.

Moo-Young H.K., Douglas, A.G., and Mo X. H. (2002).Testing procedures to assess the viability of dewatering with geotextile tubes. Geotextiles and Geomembranes 20(5), 289-303.

Muthukumaran A. E. and Ilamparuthi K. (2006). Laboratory studies on geotextile filters as used in geotextile tube dewatering. Geotextiles and Geomembranes 24(2), 210-219.

Recio J. and Oumeraci H. (2007). Effect of deformations on the hydraulic stability of coastal structures made of geotextile sand containers. Geotextile and Geomembranes, 25 (4-5), 278-292.

Recio J. and Oumeraci H. (2009). Processes affecting the hydraulic stability of coastal revetments made of geotextile sand containers. Coastal Engineering, 56, 260– 284.
Shin E.C. and Oh Y.I. (2003). Analysis of geotextile tube behaviour by large-scale field model tests. Geosynthetics International 10 (4), 134-141.
Shin E.C. and Oh Y.I. (2007). Coastal erosion prevention by geotextile tube technology. Geotextiles and Geomembranes 25 (4-5): 264-277.
Van S. P. And Bezuijen A. (2010). Large scale physical model tests on sand filled geotextile tubes and containers. In: Proceedings of the 9th International Conference on Geosynthetics, Brazil, 2010.
YanS.W. and ChuJ.(2010). Construction of an offshore dike using slurry filled geotextile mats. Geotextiles and Geomembranes, 28: 422-432.