Smart Structures and Systems, *Vol. 24, No. 6 (2019) 793-802*
DOI: https://doi.org/10.12989/sss.2019.24.6.793

Two-dimensional deformation measurement in the centrifuge model test using particle image velocimetry

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(Received May 26, 2019, Revised July 21, 2019, Accepted August 21, 2019)

Abstract. The centrifuge model test is usually used for two-dimensional deformation and instability study of the soil slopes. As a typical loose slope, the municipal solid waste (MSW) landfill is easy to slide with large deformation, under high water levels or large earthquakes. A series of centrifuge model tests of landfill slide induced by rising water level and earthquake were carried out. The particle image velocimetry (PIV), laser displacement transducer (LDT) and marker tracer (MT) methods were used to measure the deformation of the landfill under different centrifugal accelerations, water levels and earthquake magnitudes. The PIV method realized the observation of continuous deformation of the landfill model, and its results were consistent with those by LDT, which had higher precision than the MT method. The deformation of the landfill was mainly vertically downward and increased linearly with the rising centrifugal acceleration. When the water level rose, the horizontal deformation of the landfill developed gradually due to the seepage, and a global slide surface formed when the critical water level was reached. The seismic deformation of the landfill was mainly vertical at a low water level, but significant horizontal deformation occurred under a high water level. The results of the tests and analyses verified the applicability of PIV in the two-dimensional deformation measurement in the centrifuge model tests of the MSW landfill, and provide an important basis for revealing the instability mechanism of landfills under extreme hydraulic and seismic conditions.

Keywords: particle image velocimetry; deformation measurement; landfill; centrifuge model test

1. Introduction

Landfill is one of the main means of disposal of municipal solid waste (MSW). Due to the large waste production and limited land resources, landfills in China are usually high and steep. The high water content of MSW in China leads to high water level in landfill, which is likely to induce landfill instability under extreme conditions, such as heavy rain or earthquakes (Koerner and Soong 2000, Merry *et al*. 2005, Zhan *et al*. 2008). The deformation and stability of landfills has caused concern.

Geotechnical model tests were widely used in the study of the deformation and stability of loose slopes such as landfills. Commonly-used observation methods, such as linear variable differential transformers (LVDT) and laser displacement transducers (LDT), were used to capture movement of some points in the soil model (Ng *et al*. 2004, Choo *et al*. 2013, Kim *et al*. 2011, Li *et al*. 2013). However, since the number of measuring points was limited, it was impossible to obtain the full range of deformation of the soil directly. Marking tracer (MT) methods, such as colored sand (Adalier *et al*. 2004, Liu *et al*. 2012) and marker points (Yang *et al*. 2004, Viswanadham *et al*. 2005), were more intuitive and comprehensive, but with a lower degree of accuracy in the measurement. The fiber Bragg grating sensing technology could greatly improve the accuracy of measurement (Zhang *et al*. 2017). However, the full range of deformation was usually inferred based on several points or lines using these methods. There might be some deviations in the judgment of the trend of deformation, the slip surface, and the instability mechanism.

The image-based measurement technique was widely used in field and model tests (Ye *et al*. 2013, 2016a, b). The methods of X-ray (Butterfield *et al*. 1970) and CT scans (Heijs *et al*. 1995) could track the external and internal displacement of the models, and even capture the shape of cracks and soil particles. Nevertheless, widespread use of these methods were difficult due to the complex equipment involved. Particle tracer technology (Zhang *et al*. 2009) could obtain the deformation of the soil by tracking the pre-incorporation particles in the soil. However, measuring errors could be caused by the asynchrony between the soil and tracer particles and the absence of the tracer.

The particle image processing technology based on the soil itself could realize the observation of the continuous deformation of the target soil, with the advantages of high precision, remote control and little interference with the model. Particle image velocimetry (PIV) has been applied to soil deformation measurements for the past two decades (Gil *et al*. 2001, White *et al*. 2003, Rechenmacher and

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ISSN: 1738-1584 (Print), 1738-1991 (Online)

Finno 2004, Baba and Peth 2012, Take *et al*. 2015). Geotechnical centrifuge modeling exhibited unique advantages in the simulation of deformation and failure of geotechnical infrastructure, putting forward higher requirements for the accuracy of deformation observations. It made PIV technology more widely applied in centrifuge model tests (Take *et al*. 2004, Bransby *et al*. 2008, Lee *et al*. 2008, Viswanadham *et al*. 2009, Idinger *et al*. 2011, Stanier and White 2013, Huang *et al*. 2015, Stanier *et al*. 2016).

Due to the complex composition, the large size of the particles and obvious heterogeneous characteristics, the use of real MSW had many concerns, such as the dependence of the test result on the material source and the repeatability. Synthetic MSW with similar engineering characteristics as real MSW, was used for the centrifugal model tests (Thusyanthan *et al*. 2006, Chen *et al*. 2017). Since the synthetic MSW contained lots of organic fibers, which were not granular materials, the applicability of the PIV method in the deformation measure of landfill should be explored.

In the present study, several batches of centrifuge model tests of landfill stability were carried out, and the application of the PIV method in the study of landfill deformation and instability was discussed compared with the MT and LDT methods. The effects of different centrifugal accelerations, water levels, and earthquake magnitudes were analyzed, and the deformation and instability modes of the landfill when water level rose and earthquake occurred were observed.

2. Centrifuge model test

2.1 Test apparatus

The model tests were performed using the ZJU400 centrifuge at Zhejiang University in Hangzhou, China (Chen *et al.* 2010), as shown in Fig. 1(a). The maximum capacity and acceleration of this beam-type centrifuge are 400 g.ton and 150 g, respectively. The effective arm radius of the centrifuge is 4.5 m. An inflight uniaxial electro-hydraulic shaking table was used to simulate seismic excitation, as shown in Fig. 1(b). The shaking table has vibration frequencies ranging from 10-200 Hz. Its payload capacity is 500 kg, and its maximum lateral displacement and acceleration are 6 mm and 40 g, respectively.

Two rigid containers were used for preparing the landfill models of centrifugal tests. One was for the static tests, with an inner dimension of 1000 mm (length) × 400 mm (width) × 1000 mm (height), and the other with an inner dimension of 770 mm × 400 mm × 530 mm was for seismic tests. Both of them had a front window, which was made of perspex for direct observation of the model. A water level control system was designed for real-time control and for regulating the flow rate. The water level in the water supply cavity was controlled by a flow pump with a flow range of 0.001-2.24 L/min. In the static tests, the water in the cavity seeped into the landfill through the porous drainage plate, as shown in Fig. 2(a). And in the seismic tests, the water was supplied to the landfill model through a flexible pipe, which was buried under the landfill. The overflow water from the slope toe flowed into the reservoir through a drain pipe.

(a) Centrifuge

(b) Shaking table

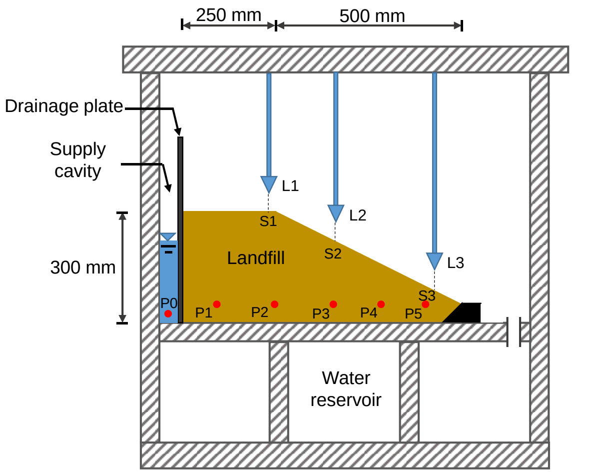
Fig. 1 ZJU400 centrifuge and shaking table

2.2 Test material and modeling

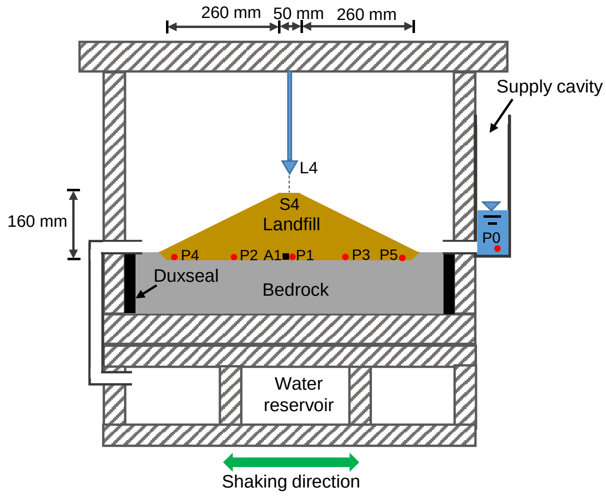
The synthetic MSW was manufactured depending on the engineering characteristics of real MSWs of the Suzhou Qizishan Landfill in China (Chen *et al*. 2017). Its physical and mechanical properties were consistent with those of the real MSWs. The model landfill was simplified to a homogeneous synthetic MSW landfill with a model geomembrane barrier at the bottom. No interim or final cover was used. The synthetic MSW was poured on the geomembrane in 50 mm-thick layers, compacted to the expected unit weight of 9 g/cm^3, with a pore ratio of 1.6 and a water content of 45%. When the predetermined height was reached, the transducers and markers were buried. The MSW model was carefully excavated to form a designated slope when it reached the final height.

The static tests were performed at 66.7-gravities (66.7 g). As shown in Table 1 and Fig. 2(a), three landfill models with a height of 300 mm and with different slope ratios were used to reveal the developing processes and mechanisms of MSW landfill failures induced by rising water level. The influences of the slope ratio on the deformation and stability of the landfill were investigated.

The seismic tests were performed at 50-gravities (50 g). As shown in Table 1 and Fig. 2(b), a landfill model with a height of 160 mm and a slope ratio of 1:2 was used to reveal the seismic response of the landfill with different water levels and its influence on the stability of the landfill. A 25 mm-thick piece of moldable Duxseal was placed on each side of the container to reduce reflecting incident stress waves.



(a) Static test model



(b) Seismic test model

Fig. 2 Layout of test setup

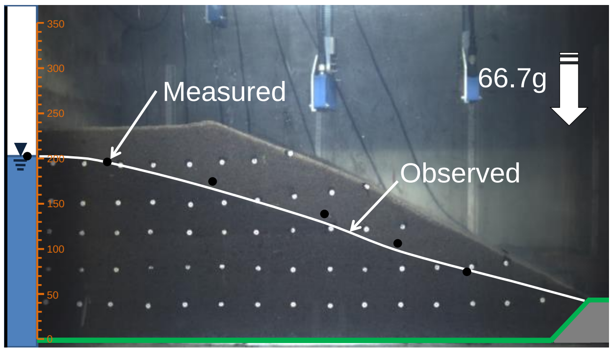
2.3 Test program

In tests 1-3, the centrifuge was spun up to 20 g, 40 g, and 66.7 g in turn, and it finally stabilized at 66.7 g. The settlement of the landfill at different centrifugal accelerations was measured. At every stage, the settlements were nearly stabilized. It generally took approximately 1 hour to stabilize the settlement of these 300 mm-high landfills at 66.7 g. The water was supplied when the development of the settlement of the landfill was stabilized. During the tests, the water level in the supply cavity was raised in four stages, increasing to 50 mm, 100 mm, 150 mm, and 200 mm in 1 minute at a constant flow rate of 1 L/min. The centrifuge operated for an extra 20 minutes after the water level in the supply cavity reached the expected height for each water supply stage. In test 4, a Taft wave with a primary period of 0.5 s was adopted. The water level in the supply cavity was raised in two stages (with a water level of 40 mm and 85 mm respectively) when the development of the settlement of the landfill was stabilized at the designed gravity. In each stage of the water level, the process of seismic excitations was divided into four shaking stages (about 0.1-0.4 g) based on the acceleration amplitudes from weak to strong. There was enough of an interval between two shaking stages for the excess pore pressure to dissipate entirely. After all the excitations were applied, the next stage of water level was supplied.

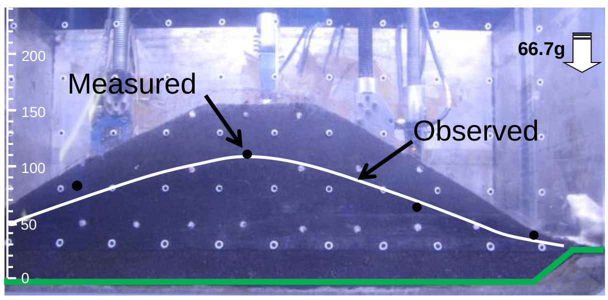
2.4 Measuring methods

As shown in Figs. 2 and 4, in the static and seismic tests, a series of micro-pore water pressure transducers (P0-P5) were buried at the bottom of the model, with a range of 300 kPa and an accuracy of 0.1 kPa, to measure the water level in the landfill. In the static tests, three laser displacement transducers (L1-3) were set at the corresponding positions of the top (S1), slope (S2), and toe (S3). The seismic test was equipped with a laser displacement transducer (L4) at the top (S4) of the landfill to monitor the vertical deformation with a range of 50mm and a precision of 0.001mm. An accelerometer was buried at the bottom of the model to measure the acceleration response.

A series of control points were arranged on the inner surface of the plexiglass side of the model box for the analysis of the image vector. The control points consisted of two concentric circles, the inner circle was black with a 3 mm diameter, the outer circle was white with a 5 mm diameter, and the interval was 50 mm. A digital camera was fixed on the arm of the centrifuge basket, facing the plexiglass plate.



(a) Static: water level stage-4

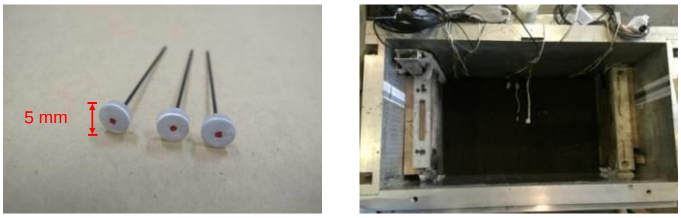


(b) Seismic: water level stage-2

Fig. 3 Water level control in the tests (unit: mm)

Table 1 Test program

Number	Test type	Landfill height (mm)	Slope ratio	Centrifugal acceleration (g)	Water level (mm)	Shaking stage (g)
Test 1	Static	300	1:1	20	/	/
				40	/	/
				66.7	50	/
					100	/
					150	/
					200	/
Test 2		300	1:2	20	/	/
				40	/	/
				66.7	50	/
					100	/
					150	/
					200	/
Test 3		300	1:3	20	/	/
				40	/	/
				66.7	50	/
					100	/
					150	/
					200	/
Test 4	Seismic	160	1:2	50	40	0.1
						0.2
						0.3
						0.4
					85	0.1
						0.2
						0.3
						0.4

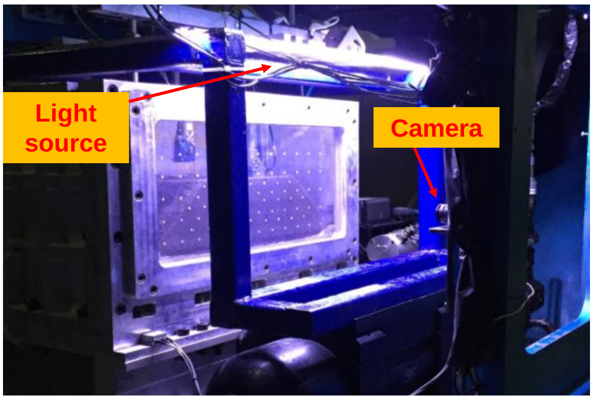


(a) Marker (b) Buried transducer

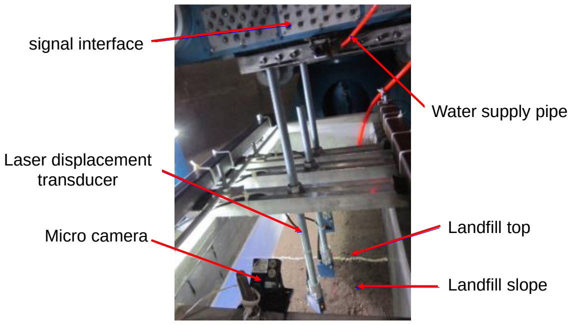
Fig. 4 Modeling transducer

During the test, a high-definition photo of the landfill model was taken through the plexiglass observation window for deformation analysis, as shown in Fig. 5. The deformation of the model in static tests was analyzed with no control points and conversed from the pixel coordinates according to the scale relation.

A series of markers were placed on the surface of the MSW close to the glass plate and with a spacing of 50 mm when each MSW layer was laid. The test used self-made markers consisting of a white rubber circle with a diameter of 5 mm and a thin iron wire with a length of 30 mm, as shown in Fig. 4(a). Two mini-cameras were attached to the top of the model box for experimental observation.

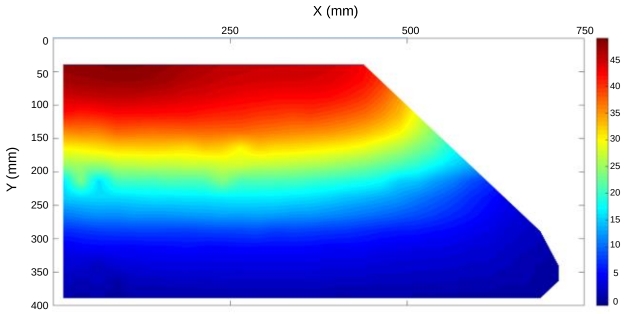


(a) Side view

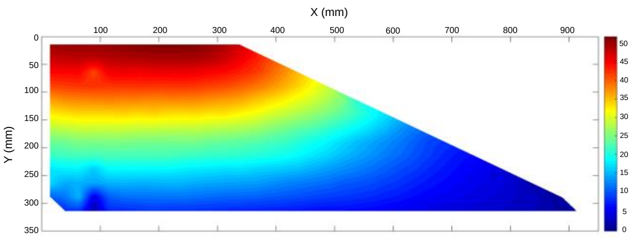


(b) Overlook

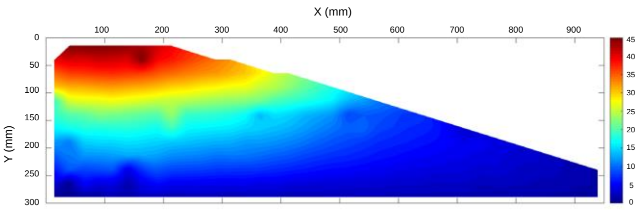
Fig. 5 Test methods



(a) Slope ratio 1:1



(b) Slope ratio 1:2



(c) Slope ratio 1:3

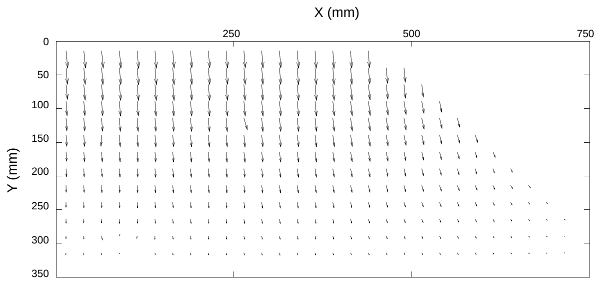
Fig. 6 Deformation of the landfill in tests 1-3

3. Test results and analysis

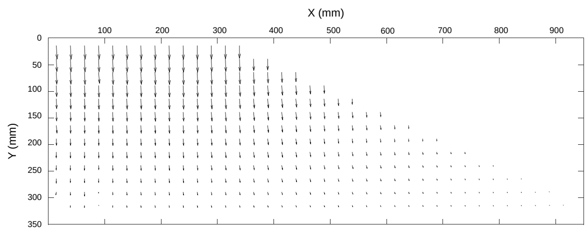
3.1 Landfill deformation when the centrifugal acceleration was rising

The centrifugal acceleration process in Tests 1-3 was divided into three steps of 20 g, 40 g, and 66.7 g, which could be used to analyze the deformation of the landfill during centrifugal acceleration. Using the high-definition photos obtained, the deformation of the landfill from 1g to 20 g, 40 g and 66.7 g was analyzed by the PIV method. Fig. 6 shows the deformation of the model in tests 1-3 when the centrifugal acceleration was raised from 40 g to 66.7 g. It can be seen that the results of the analysis showed a good layered distribution. Fig. 7 shows the deformation vector of the landfill in the centrifugal acceleration process of tests 1-3. The overall deformation of the landfill was a vertical settlement during the process of acceleration of the centrifuge, and a small horizontal deformation occurred at the slope toe.

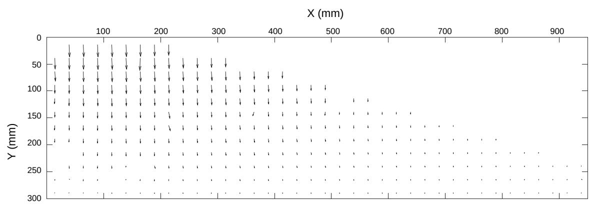
Figs. 8 and 9 show the measured and analyzed settlement values at various positions of the landfill under various stages of centrifuge acceleration. As shown in Fig. 8, the settlement of the landfill obtained by the PIV analysis corresponded to the time history curve obtained by the LDT measurement. Fig. 9 shows that the settlement of the landfill increased linearly with the centrifugal acceleration, and similar rules were obtained for the PIV, LDT and MT methods. The slope ratio had little effect on the settlement of the landfill.



(a) Slope ratio 1:1

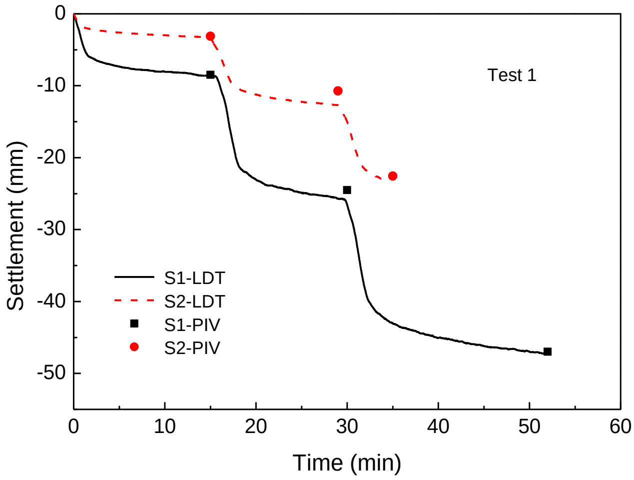


(b) Slope ratio 1:2

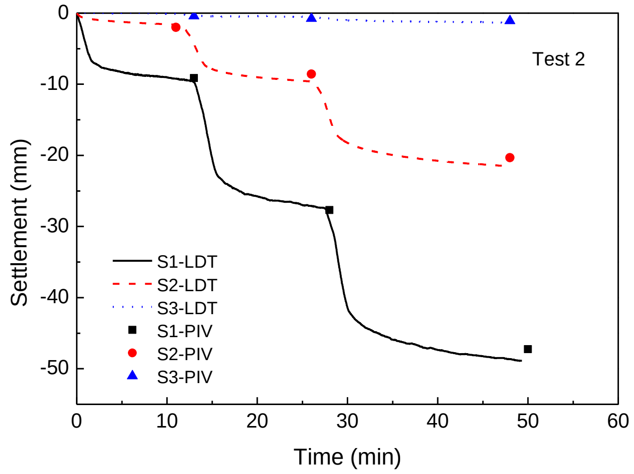


(c) Slope ratio 1:3

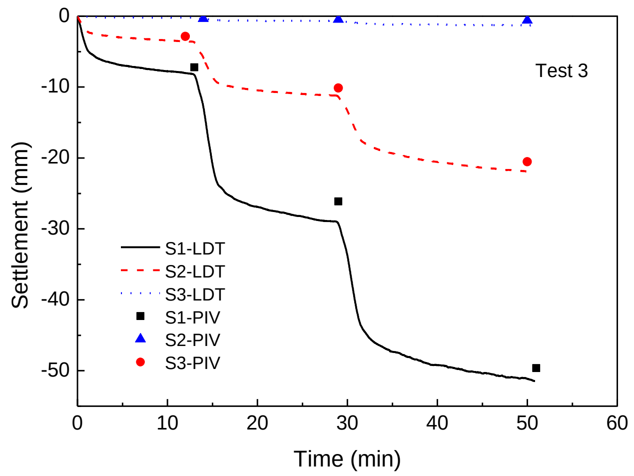
Fig. 7 Deformation vector of tests 1-3



(a) Slope ratio 1:1



(b) Slope ratio 1:2



(c) Slope ratio 1:3

Fig. 8 Settlement time history curve of the landfill under different centrifugal accelerations

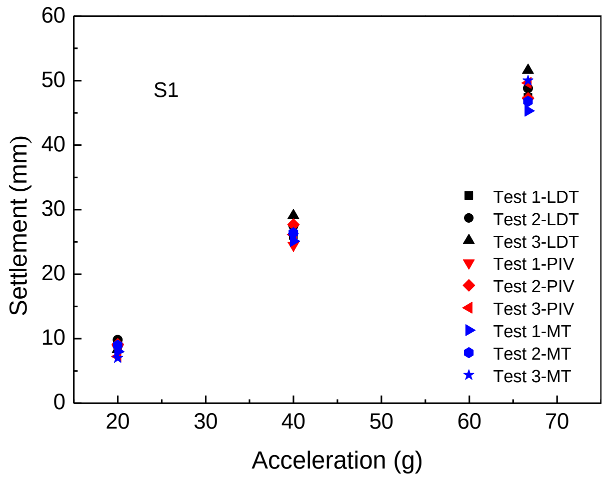
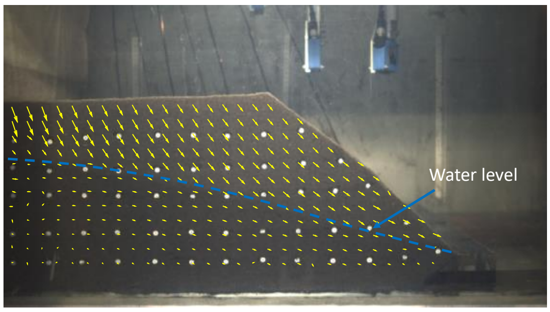


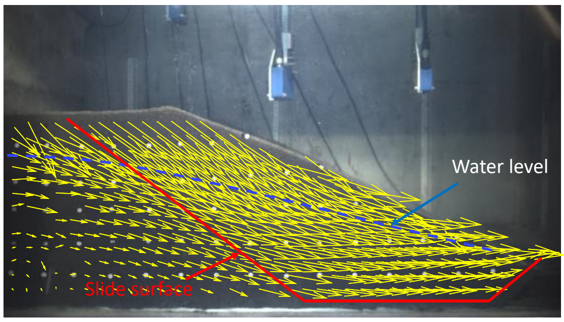
Fig. 9 Relationship between deformation and centrifugal acceleration

3.2 Landfill deformation when the water level was rising

In the static test, the water level in the landfill was increased at four levels. Fig. 10 shows the deformation vector of the landfill at different water levels. As the water level rose gradually, the saturated MSW below the water level mainly moved towards the slope toe horizontally and slowly. Due to the horizontal movement of the bottom MSW, the MSW above the water level had a large traction phenotype, and its tendency to slide downward increased as the water level increased. When the critical water level was reached, an overall slide surface was formed, as shown in Fig. 11.

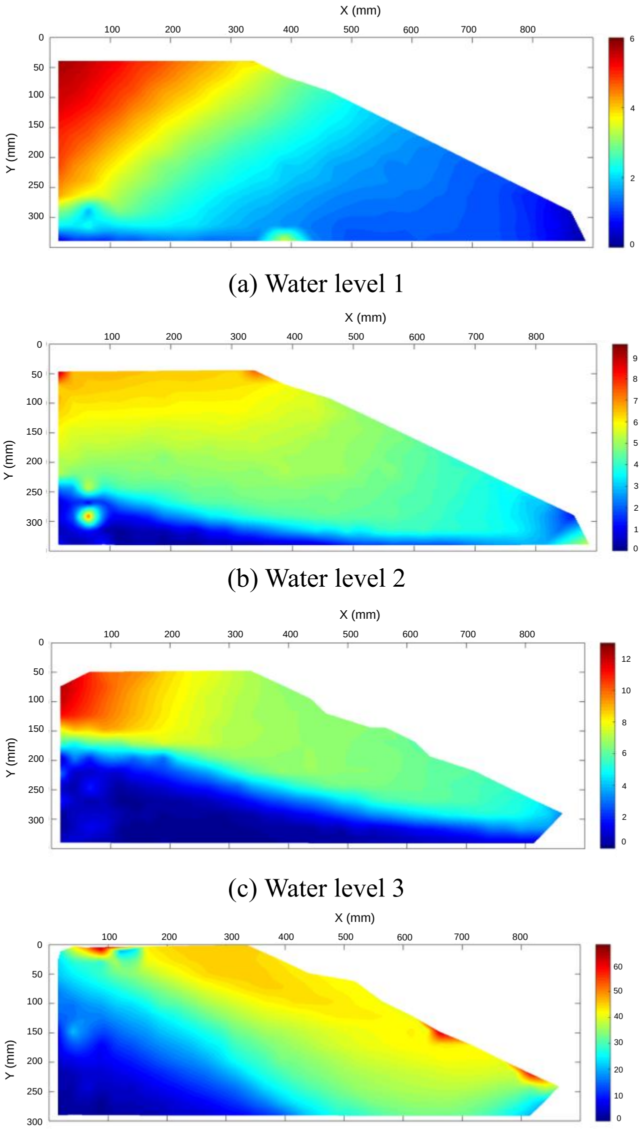


(a) Before slide



(b) Slide

Fig. 10 Deformation vector of the landfill under different water levels



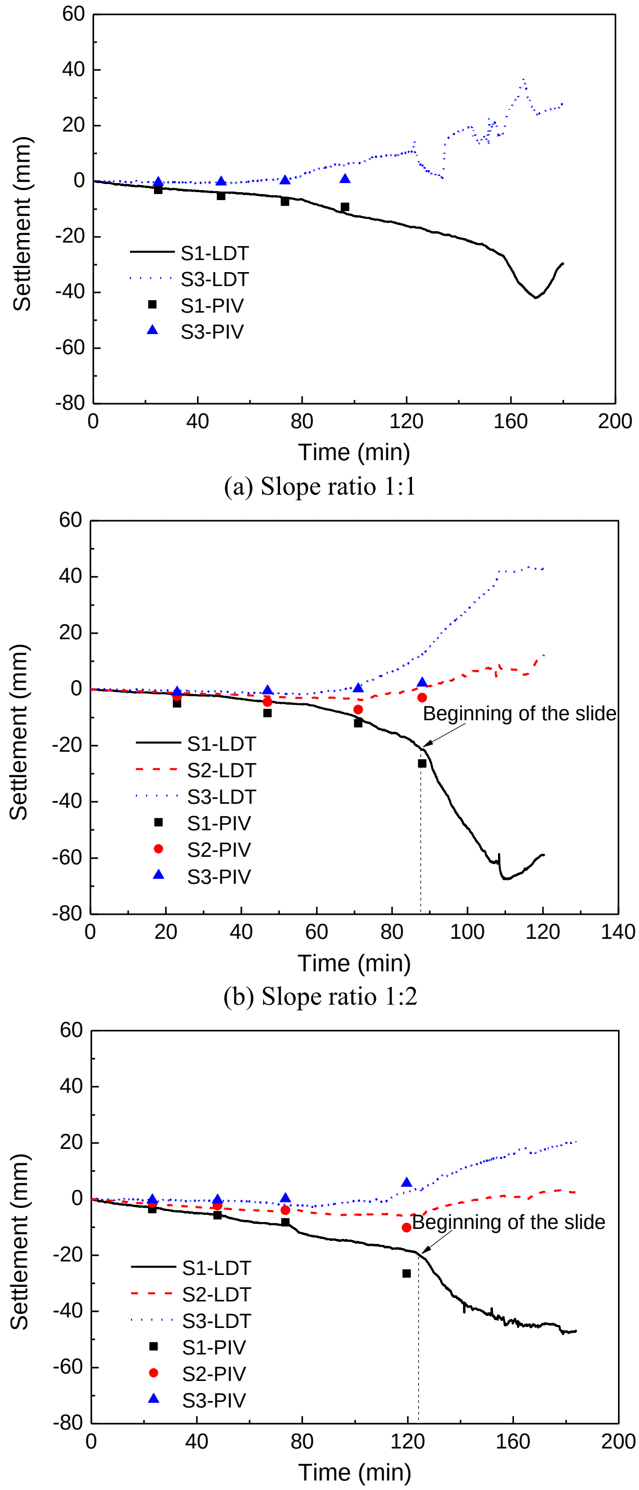
(a) Water level 1

(b) Water level 2

(c) Water level 3

(d) Water level 4

Fig. 11 Deformation mode of the landfill under different water levels



(a) Slope ratio 1:1

(b) Slope ratio 1:2

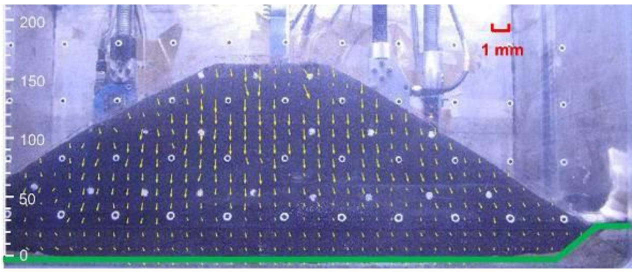
(c) Slope ratio 1:3

Fig. 12 Settlement time history curve of the landfill under different water levels

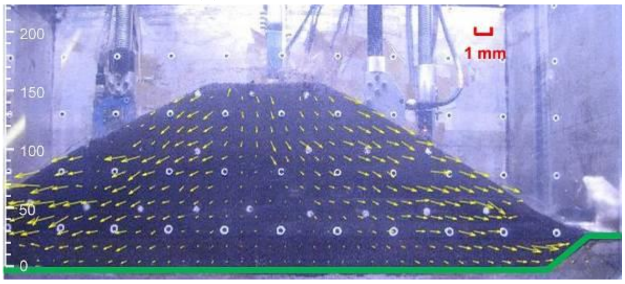
Fig. 12 shows the development of the settlement on different positions of the landfill while the water level was rising. The settlement values of the corresponding points obtained by the PIV analysis were similar to those measured by LDT. During the first three water levels, the settlement of the top of the landfill (S1) increased slowly. There was no significant instability or slippage. While the fourth level of water was rising, the settlement on the top of the landfill began to increase suddenly. The landfill began to gradually slide, and an overall slide surface was formed (see Figs. 10 and 11). The sudden change of water level and settlement of the landfill could be used as the basis for determining the instability of the landfill.

3.3 Landfill deformation under different earthquake magnitudes

Fig. 13 shows the deformation vectors of the landfill after the earthquake with an acceleration magnitude of 0.4 g. At water level stage-1 (water level 40 mm), the deformation of the landfill occurred mostly vertically downward and the MSW got denser after the excitations. While at water level stage-2 (water level 85 mm), significant horizontal displacement occurred under the slopes. The settlement on the top of the landfill induced by the earthquake was measured by a laser displacement transducer, as shown in Fig. 14, and it increased with the acceleration amplitudes of the earthquake.



(a) Water level 40 mm



(b) Water level 85 mm

Fig. 13 Seismic deformation of landfill under different water levels

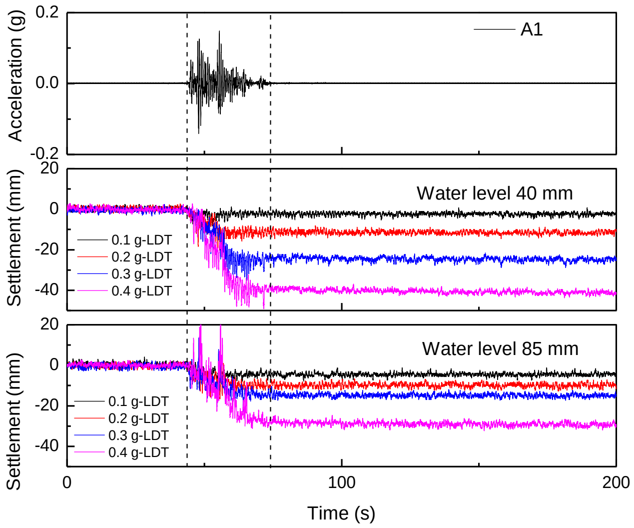


Fig. 14 Settlement time history curves of the landfill under different earthquake magnitudes

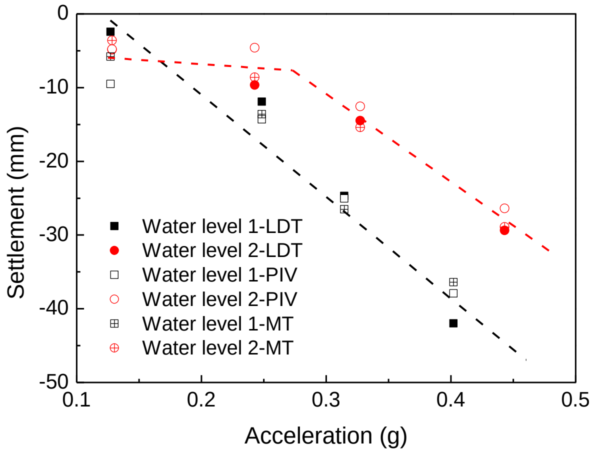


Fig. 15 Comparison of seismic deformation of the landfill under different water levels

Fig. 15 summarizes the settlement at the top of the landfill obtained by PIV, LDT and MT methods under different water levels and earthquake magnitudes, which showed similar deformation trends. At a low water level, the settlement at the top of the landfill increased linearly with the magnitude due to vertical compaction by self-gravity. However, at a high water level, the settlement at the top of the landfill increased with the magnitude as a double-fold line. At a certain water level and earthquake magnitude, significant horizontal deformation occurred on the slope of the landfill, which caused further deformation of the top of the landfill. The change of the deformation mode could be seen as an indication of landfill failure under the effect of seepage and earthquake.

4. Conclusions

The deformation of the landfill under static and seismic conditions in the centrifugal model tests was studied. Combined with the three measurement methods of PIV, LDT, and MT, it was verified that the PIV technology was applicable for the analysis of the deformation of the centrifugal model test of the landfill. The main conclusions were as follows:

(1) The two-dimensional deformations of the landfill obtained by PIV and MT were similar. The settlement of the landfill obtained by PIV was closer to that obtained by LDT which had higher precision than the MT method.

(2) During the acceleration of the centrifuge, the main deformation of the landfill occurred vertically, and increased linearly with the acceleration. A very slight horizontal deformation occurred at the toe of the slope. The slope ratio had little effect on the settlement of the landfill.

(3) As the water level rose, horizontal deformation occurred under the water level line due to seepage, and the landfill above the water level line was affected by the deformation of the MSW below that line. The landfill above the water level had a large traction force deformation, and its tendency to slide downward increased as the water level increased. When the critical water level was reached, an

overall slide surface was formed. The sudden change in the water level and the deformation of the landfill could be used as the basis for determining the instability of the landfill.

(4) At a low water level, the seismic deformation of the landfill was mainly vertical. While at a high water level, significant horizontal deformation occurred under the slopes. The settlement of the top of the landfill increased linearly with the magnitude at a low water level, but showed a double-fold line increase at a high water level. The change in the mode of deformation could be seen as an indication of landfill failure under the effect of seepage and earthquakes.

Acknowledgments

The work described in this paper was jointly supported by the Basic Science Center Program for Multiphase Evolution in Hypergravity of the National Science Foundation of China (Grant No. 51988101), the National Science Foundation of China (Grant Nos. 51822810 and 51778574), the Zhejiang Provincial Natural Science Foundation of China (Grant No. LR19E080002), and the Fundamental Research Funds for the Central Universities of China (Grant Nos. 2019XZZX004-01 and 2019QNA4035).

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