Development of shaking table tests for seismic slope stability problems

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Abstract

Simulations of geotechnical problems with cyclic or dynamic loads such as those caused by earthquakes are still the subject of research worldwide. There is often a lack of reliable measurement data for validating the simulations. Model tests in the earth's gravity field (1g) and in centrifuges can provide important insights and measurement data for the derivation and validation of theoretical approaches and simulations.

As part of a current research project at the National Polytechnic University (EPN) in Quito Ecuador in collaboration with the researchers of the Leipzig University of Applied Sciences, small-scale model tests with a one-dimensional shaking table are being developed.

The project aims to contribute to the stability assessment of slope systems under the effects of earthquakes. The main aim of the tests was to record the behavior of a regional soil and later the interaction with buildings on models and to obtain reliable measurement data for later validation of calculations and simulations. Therefore, the behavior of embankments and slopes must be recorded and assessed in detail. It is to be shown to what extent the central measurement method of digital image correlation from recordings of a digital camera can measure the movement behavior of the model and the emergence and progression of the failure mechanisms.

The following content is presented in the contribution:

- *The development and functioning of the test components such as the diffuser for installing the test soils, the shaking table and the test container are explained.*
- *In preliminary tests, the movement behavior of the shaking table was measured and evaluated in different frequency levels using acceleration sensors.*
- *In addition, this experiment was used to assess the suitability and quality of the DIC measurements by comparing with the acceleration data.*
- *For the calibration of the test setup, a separate test study was realized, in which the dynamic amplification of the soil was evaluated.*
- *Finally, the first results of tests and DIC evaluation with a reference slope are illustrated and discussed.*

1 INTRODUCTION

Numerous established analytical and numerical methods exist for the analysis of the stability of embankments and slopes of soils. The stability under seismic effects is usually calculated indirectly using factors. In our work, suitable model tests are to be developed that allow theoretical approaches and dynamic simulations to be validated using the finite element method (FEM). Validated simulations will make it possible to reliably assess real stability problems under seismic influences. Digital image correlation (DIC) is the central measurement method and is supplemented by acceleration measurements with sensors.

2 DESIGN AND PREPARATION

2.1 Uniaxial shaking table

A small shaking table with a base area of 70 cm x 30 cm is used with two 500 W motors for the experiments for model masses up to approx. 1.2 kN. One-dimensional sinusoidal vibrations can be selected by remote control in 10 steps between approx. 2 Hz and 6 Hz. In all of the experiments presented below, an identical load regime according to Table 1 was applied: Starting with the slowest load level we switched after 10 seconds to the next higher load level.

2.2 The used container

For the experiments A metal box with the base area of the shaking table and a height of 35 cm was constructed. A 10 mm thick safety glass was integrated in the front of the box. The box is firmly screwed to the shaking table. Due to the rigid design of the box, on the left and right side of the box a distortion of the free movement cannot be avoided when it comes into contact between container and soil. In order to minimize this negative effect, 15 mm thick foam panels were arranged in the current version.

2.3 Installation of soils

An important quality criterion of model tests is the reproducibility of results in a series of tests. When working with soil, a suitable method must be selected with allows to specify the soil condition - in particular the density of storage. In our experiments, a dry regional sand is used, which is installed using a pluviation process. The storage density can be adjusted within certain limits between medium-dense and dense by choosing a certain falling height of the sand between 15 cm and 60 cm. In addition, a very loose to loosen density of the sand can be reproducibly adjusted by attaching the pluviator on the container floor and slowly pulling it up. The following picture 01 shows the principle sketch of the sand installation.

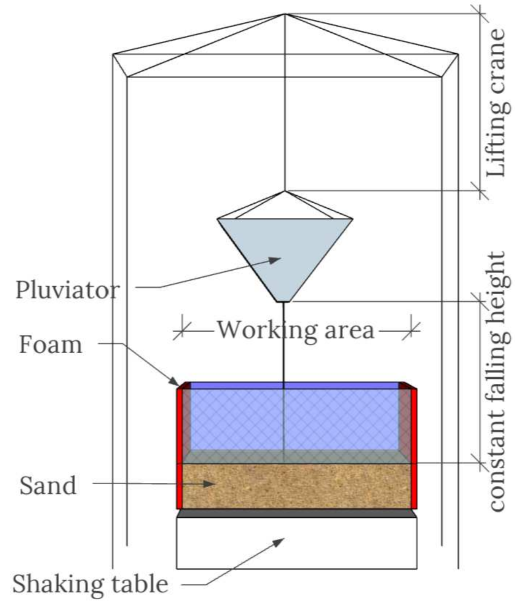

Figure 1. Principle sketch of the installation of sand.

3 CALIBRATION OF SHAKING TABLE AND OF DIC

3.1 Digital image correlation (DIC)

The most important measurement principle for the experiments was digital image correlation (DIC). This method uses gray value analysis to compare discrete image areas between two digital images. In this way, without contact object changes can be detected compared to an initial state.

Our tests are evaluated assuming plain deformation conditions. The horizontal and vertical strain components (ε_x and ε_y) and thus the strains of the volume change ε_v (hereinafter: ε) or shearing γ can also be determined from the displacement components using the following formulas:

$$\varepsilon = \varepsilon_x + \varepsilon_y \tag{1}$$

$$\gamma = \sqrt{(\varepsilon_x - \varepsilon_y)^2 + 4\varepsilon_{xy}^2} \tag{2}$$

In the presented work, the software *ISTRA4D* (Dantec Dynamics) was used for the DIC analysis.

3.2 Idealized model test

During the development of the model tests, experimental studies were carried out initially without soil. The aim was to characterize the movement behavior of the shaking table (input motion) and, at the same time, to evaluate the performance of the measuring method by means of comparisons.

The following figure shows an idealized model test, in which the movement behavior of the shaking table was investigated using a series of measurements with all 10 speed levels. Accelerometers of the types ASC (measuring range up to +/- 50g) and ADXL345 (measuring range up to +/- 16g) with sampling rates of 200 Hz and 1,000 Hz were used. In addition, a digital camera type Canon EOS 2000D was used to take photos with a resolution of 2 megapixels (MP) at 25 frames per second (fps) of a partial area on the glass pane of the model container.

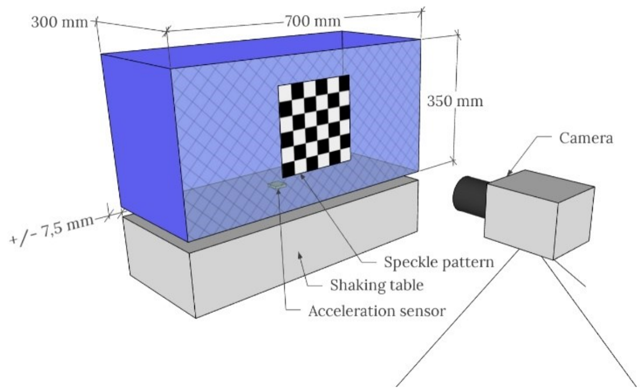

Figure 2. Principle sketch of the idealized model test with representation of the sensor on the container bottom and representation of the partial area for the DIC evaluation.

The following diagram shows the results of the acceleration measurements (a)in the horizontal axis over time (t) for the minimum and maximum load level of the shaking table (min = Level 01, max = Level 10, see Table 1):

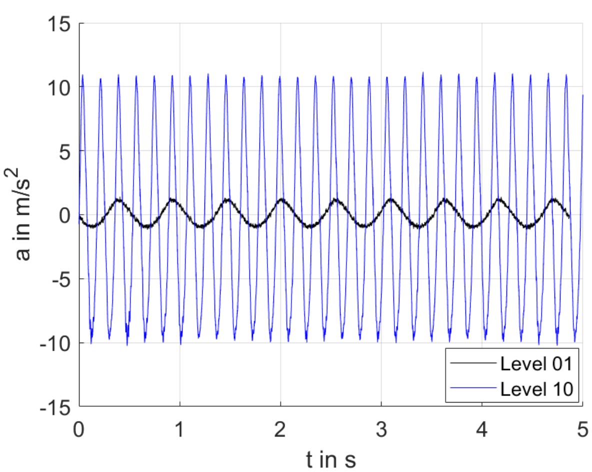

Figure 3. Accelerations (horizontal) on the shaking table at the lowest and highest load levels (input motion).

Figure 4 illustrates that the speed and the displacements (u) can also be determined from the acceleration data. For this purpose, the acceleration data were integrated using the trapezoidal method. A numerical filter was not applied.

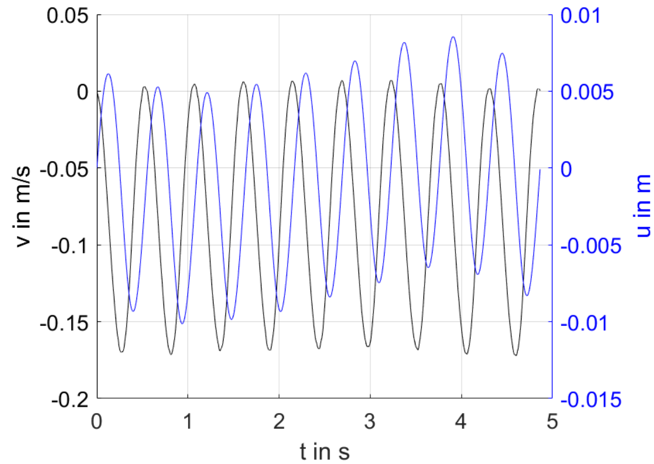

Figure 4. Velocity (v) and displacements (u) on the shaking table at the lowest load level (f = 1,86 Hz, a_{max} = 1,03 m/s²), determined from acceleration measurements.

The basic movement behavior of the shaking table (= input motion) was measured according to this principle and was summarized in Table 1 (f: frequency, a_{max}: maximum acceleration, v_{max} = maximum velocity). The table also shows the time sequences of the respective load level that were used in the load regime for all tests in this article:

Table 1. Input motion on the shaking table and timing for the load regime in the tests presented.

level	f	a_{max}	v_{max}	load timing
-	Hz	m/s²	m/s	s
01	1,86	1,03	0,087	0 – 10
02	2,27	1,64	0,107	10 – 20
03	2,73	2,22	0,128	20 – 30
04	3,19	3,06	0,150	30 – 40
05	3,60	3,92	0,169	40 – 50
06	4,01	4,93	0,188	50 – 60
07	4,41	5,96	0,207	60 – 70
08	4,84	7,48	0,227	70 – 80
09	5,25	8,59	0,246	80 – 90
10	5,63	9,97	0,264	90 – 100

The DIC method was used for this idealized model experiment to record the movement behavior of a discrete image area. Figure 5 shows the evaluation of the horizontal displacements (u) of the model container during the 2nd load level (f = 2.27 Hz, a_{max} = 1,64 m/s²).

As a result of the idealized model test, the quality of both measurement methods could be proofed via the horizontal displacements (amplitude) of the shaking table at the individual load levels. The production-related constant maximum amplitude (input motion) of 15 mm (+/- 7.5 mm) was confirmed using both measurement methods.

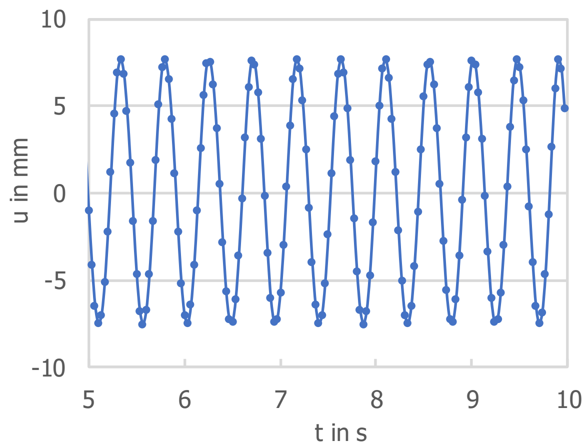

Figure 5. Displacements (u) on the shaking table at load level 02 (f = 2,27 Hz), determined from DIC measurements.

3.3 Test of dynamic amplification and frequency dependency

When developing model tests, two essential criteria are very important:

1. Boundary conditions of a model experiment should be known as well as possible or must be recorded using measurement technology.
2. My model should reflect the principles of my real problem as realistically as possible.

One reason is that it must be possible to apply the boundary conditions of the experiment as accurately as possible in subsequent calculations and simulations, if necessary. On the other hand, a model that is as realistic as possible facilitates the later "upscaling" of calculations and simulations to the dimensions of real problems.

In contrast to the real situation, shaking table tests with container boxes prevent the movement behavior when the soil gets in contact with the rigid side surfaces. In our experiments, attempts were therefore made to at least partially allow lateral movements by padding the side surfaces with foam and thus to allow the creation of a dynamic amplitude over the model height.

To evaluate this boundary condition, an experiment was carried out, in which the test container was filled with sand up to a height of 25 cm and 4 acceleration sensors of the type ADXL were arranged one above the other in the sand and scanned at 200 Hz. In addition, one sensor was arranged directly at bottom of the container (see figure 6):

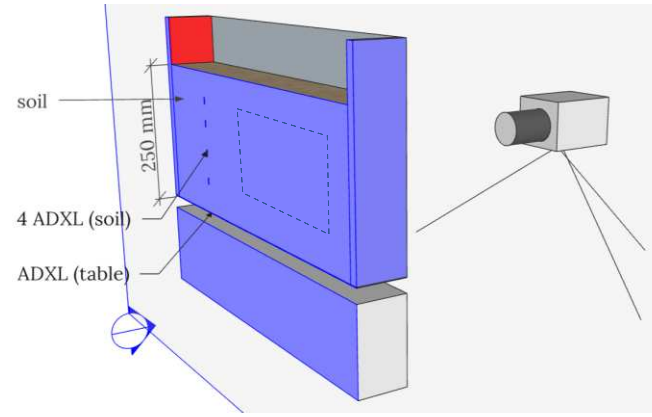

Figure 6. Principle sketch of the dynamic amplification test (sectional view) with representation of the sensors in the soil and on the container bottom and representation of the partial area for the DIC evaluation.

The following diagram compares the accelerations at the bottom of the model container ("table" = input motion) and in the sand ("soil"), which are measured by sensors during the second load level (load level 02, f = 2,27 Hz, a_{max} = 1,64 m/s²) were measured:

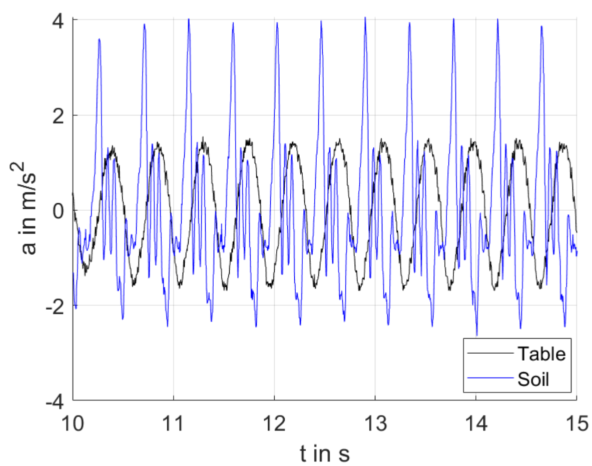

Figure 7. Accelerations (horizontal) on the shaking table ("Table" = input motion) and in the soil ("Soil" = amplified motion) at (load level 02, f = 2,27 Hz, a_{max} = 1,64 m/s².

The acceleration data for the soil permits only a limited evaluation of the maximum amplitude and requires the use of suitable mathematical filters. Nevertheless, the measurement results indicate that there is a dynamic amplification of the load introduced by the shaking table (input motion) in the ground. However, quantification of the amplification is only possible to a limited extent using this acceleration measurement.

In the same experiment, soil deformations were evaluated using the DIC method. DIC measurement results were averaged over a partial area of approx. 30 cm x 15 cm (see Figure 6). The following diagram shows the horizontal displacements (u) of the partial area as an example for the load level 07 (f = 4,41 Hz, a_{max} = 5,97 m/s²):

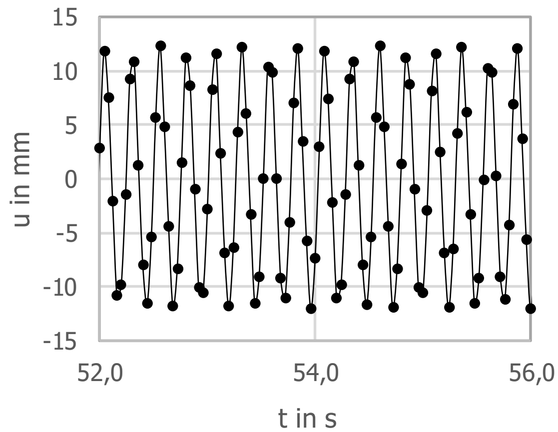

Figure 8. Displacements (u) of the soil at load level 07 (f = 4,41 Hz, a_{max} = 5,97 m/s²), determined from DIC measurements.

The DIC results also clearly show the vibrations entered in the soil. The measured amplitude of the displacements of +/- 12 mm indicates a slight amplification of the input motion entered on the shaking table (+/- 7.5 mm, factor approx. 1.6). Ldefae and Knappett, 2014, Brennan and Madabhushi, 2009 or Shamkhi, 2018 also reported a factor of amplification of 1.6 between the input motion and in the soil, measured with acceleration sensors.

The following figure shows results of the volumetric strains (ε) and the shear strains (γ) of the soil sample as a function of the maximum accelerations (a) of the respective load level for the partial area according to Figure 6.

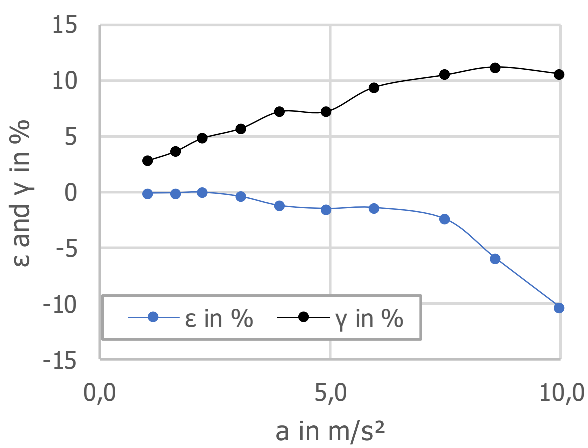

Figure 9. Volumetric strains (ε) and shear strains (γ) of the soil as a function of the maximum accelerations (a).

The evaluation of the DIC measurements clearly shows how the shear strains (γ) in the soil sample steadily increase to γ> 10% due to the gradual increase in the load levels. The graph of volumetric strains (ε) shows significant compression effects, especially at the load levels with maximum accelerations of a > 7.5 m / s². After the end of the test, the recorded partial area of the soil became significantly denser (ε = -10%).

4 SLOPE STABILITY MODEL TESTS

For us it is important to investigate the deformation behavior of embankments under seismic effects. The aim is to carry out model tests under well-known and simplified boundary conditions, with allows us to later to derive approaches and validate simulations.

The results of the experimental and numerical studies for real cases in Ecuador are to be applied in perspective. It is based on the fundamental studies on the possibilities and limits of your own model structures and the measurement principles used.

The following pictures were taken during an experiment on a reference slope made of sand in dense storage with a slope of 65 °. They show the current state after 30 s, 60 s, 70 s, 80 s, 90 s and at the end of the experiment after 100 s:

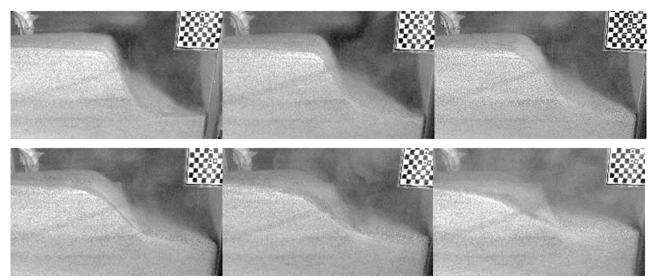

Figure 10. Recordings of the slope stability test after 30 s, 60 s, 70 s, 80 s, 90 s and at the end of the experiment (100 s).

The progressive failure of the model slope can be clearly seen from the photos. In the higher load levels after 70 s a complete collapse of the embankment occurred (see load regime in Table 1).

To quantify this experiment, a DIC evaluation for approx. 180 grid points was considered in more detail as shown in figure11. Due to the progressive collapse of the embankment, the number of measuring points was reduced to approximately 160 at the end of the experiment. Two partial areas were considered in more detail as shown in figure11.

The movement behavior in the embankment was examined using the mean displacements of the partial areas. The diagram in figure 12 compares the horizontal displacements (u) of the two partial areas during load level 01 (f = 1.86 Hz, a_{max} = 5,97 m/s²).

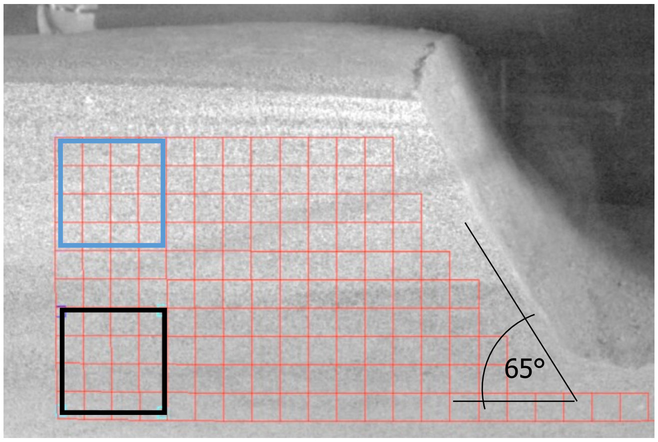

Figure 11. Recording at the beginning of the slope stability test with representation of the partial areas for the DIC evaluation.

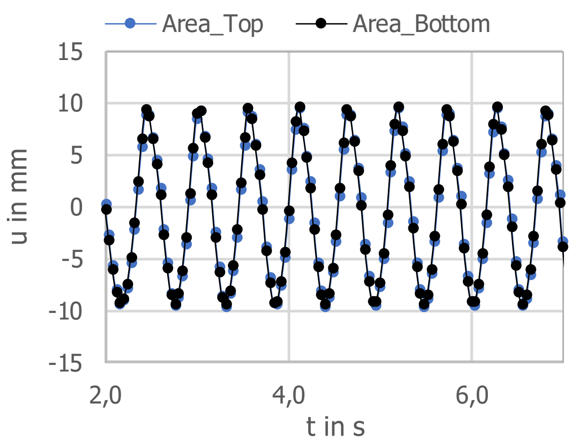

Figure 12. Displacements (u) of the two partial areas of the soil at load level 01 (f = 1,86 Hz, a_{max} = 5,97 m/s²), determined from DIC measurements.

The two graphs shown in figure 12 are nearly identical and indicate a slightly dynamic amplification with amplitudes of +/- 9 mm compared to the input motion entered on the shaking table of +/- 7.5 mm (factor: approx. 1.2).

For a more detailed assessment of the deformation of the embankments, the following diagrams analyze the volumetric strain (ε) and the shear strain (γ) of the two partial areas according to Figure 11 over the entire test period.

The results for the volumetric strains (ε) shown in figure 13 indicate that strains of ε = +/- 5% occur in lower partial area ("Area_Bottom") during several load levels. When the effects have subsided (after approx. 100 s), the original volume is restored (ε = 0%). In the upper partial area ("Area_Top"), at higher load levels after approx. 60 s (a_{max} > 6 m/s²), the positive strains (ε> 0%) initially show a loosening / dilation. From the highest load level (after 90 s, amax = 9.97 m / s²) there a significant reduction in the volume (ε <0%) can be noticed, which occurs at ε = - 8% after the end of the test.

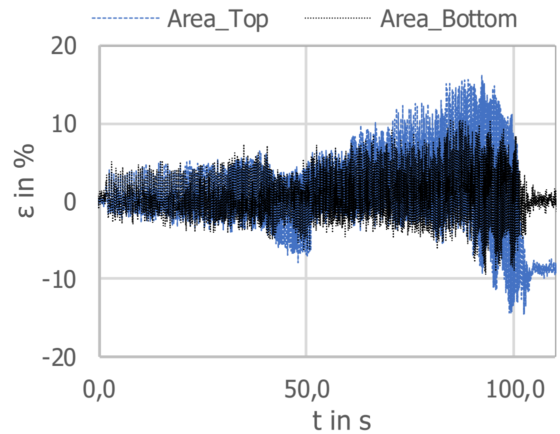

Figure 13. Volumetric strains (ε) of the two partial areas according to Figure 11 over the entire test period, determined from DIC measurements.

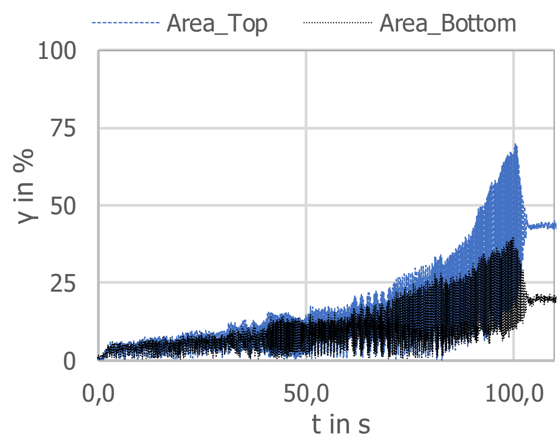

Figure 14. Shear strains (γ) of the two partial areas according to Figure 11 over the entire test period, determined from DIC measurements.

The graphs of the shear strains (γ) in figure 14 indicate a steady increase in the shear strains for both partial areas, which increase more and more with each increase of the load level. After completion of the tests, shear strains were determined at the upper area (“Area_Top”) with γ = 43 % and at the lower area (“Area_Bottom”) with γ = 20%.

5 SUMMARY

Measurements with acceleration sensors allowed recording the movement behavior of the shaking table in the 10 load levels and calculate speeds and displacements at very plausible values (input motion).

Due to the possible change of the frequency levels between approx. 2 Hz and 6 Hz the shaking table in principle is suitable for model tests evaluating the effects of seismic activities.

The DIC method was successfully applied to record the movement behavior of the shaking table. In addition, the quality of the DIC method could be confirmed by comparing the displacements between acceleration data and the DIC evaluation. This justified the use of the DIC method in the further model tests with soil.

In further experiments a dynamic amplification in the soil compared to the entered motion (input motion) was detected based on the horizontal displacements measured with the DIC method. This justifies the chosen variant for damping the contact behavior on the side surfaces of the model container with foam panels.

The deformation behavior of a model slope could be quantified on two partial areas using the DIC method. The analysis of the displacements confirms a dynamic amplitude in the ground. The evaluation of volumetric strains and shear strains allows detailed conclusions about the local deformation behavior in the embankment depending on different load levels. This allowed differentiated statements to be made about the volumetric strains and shear strains.

6 CONCLUDING REMARKS AND OUTLOOK

In the article, a number of important steps in the development and application of a shaking table test for model slopes using the DIC method and / or acceleration sensors could be shown at own experiments. From the authors' point of view, this methodology offers a multitude of possibilities for studying and understanding problems under seismic effects in detail by examining models.

Despite some promising results, the limits of such an experimental setup must be clearly pointed out, which we will deal with in our further work:

- The small dimensions and the application in the earth's gravity field (1g) only partially reflects the strongly stress-dependent soil behavior of real problems. Upscaling of results is only partially and indirectly possible via suitable intermediate steps such as numerical simulations.
- The prevention of movements of the soil in contact with the side surfaces limits the free field behavior and can only be minimized to a limited extent on rigid model containers. More suitable are e.g. Laminar-box constructions. However, with this model type, the integration of a view plane poses a certain challenge.
- The DIC method was used in our experiments on 25 fps videos. It was noticed in individual cases that camera recordings with a higher temporal resolution such as 60 fps or 120 fps with at least identical image resolution of 2 MP are advisable for recording dynamic processes at frequencies of $f > 2$ Hz.

7 ACKNOWLEDGMENT

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