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Deformation behaviour of a slope composed of a dump sand under dynamic load

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ABSTRACT: In the Rhenish mining area in Germany, lignite is excavated in three active opencast mines. The areas occupied by these mines must be restored after the end of active mining in year 2030. Due to the volume deficit resulting from the mining, the area cannot be completely backfilled and pits remain. In these pits large artificial lakes will be created. These lakes will be surrounded by embankment systems consisting of several individual slopes connected by berms. During excavation several geological layers are intersected, and the different soils are mixed. In that way artificial cohesive and non-cohesive soil materials are generated, which are deposited on the dump side forming the future embankments with a defined soil profile. The opencast mines under consideration are located in an area with seismic activity. Thus, the stability of the embankments under earthquake loading must be proven. This is done using pseudo-static approaches and numerical simulations with advanced constitutive models. To validate these numerical models, a series of centrifuge model tests were carried out at the University of Gustave Eiffel in Nantes, investigating the deformation behaviour of a single slope under dynamic loading. The model slope has been formed from a non-cohesive soil taken from the dump side of an opencast mine. This article focuses on the instrumentation and installation of the model tests. Furthermore, results regarding the deformation of the slope surface due to saturation, spin-up and base shaking are presented.

1 INTRODUCTION

One of the geotechnical challenges in the near future is the restoration of the areas occupied by the opencast mines in the Rhenish lignite mining area in Germany. To restore the areas of the active opencast mines Inden, Hambach and Garzweiler, the remaining pits will be transformed into artificial lakes. These lakes are surrounded by embankment systems (overall inclination 1:5, slope angle approx. 11°) consisting of single slopes (inclination 1:2.5, slope angle approx. 22°) connected by berms. The slopes are built up of soils quarried on the excavation side of the mine. These soils represent artificial mixtures since several geological layers are cut simultaneously and mixed. The mixed materials are classified in coarse-grained and fine-grained soils, where the coarse-grained soil is dominating.

From the excavation side, the material is transported to the opposite side of the mine, the dumping side, by means of conveyor belts. On the dumping side the material is dumped according to a predetermined geometry using spreaders. As a result of the falling height and the residual water content of the coarse-grained material, loose to medium-dense deposits of around 30% average relative density are generated (Wichtmann et al., 2019). During the dumping process of the coarse-grained soil, dam-like geometries are built up. In the space between two dams the fine-grained material is placed (‘poldered’), which can then consolidate under its own weight and the load of the overburden layers.

As an example, a typical section of the embankment system of the future lake Inden has a length of around 850 m and a height of around 120 m. The loose to medium-dense soil in the embankments will get water-saturated during filling of the lake.

The Rhenish mining area lies in a seismically active zone. It is well known that in the case of loose to medium dense, water-saturated granular soils, dynamic loading (e.g. due to earthquakes) can result in a build-up of excess pore water pressure accompanied by a decrease of effective stress and thus shear strength. The extreme case, where effective stress and shear strength completely vanish, is referred to as 'soil liquefaction', leading to large deformations of the soil. Consequently, the stability of the embankment system must be verified under static as well as under earthquakes loads. The verifications must be carried out in accordance with the German guideline RfS for analysing the stability of embankments in lignite opencast mines (Mittmann and Kuntsche, 2014).

First of all, according to RfS it has to be shown that a soil liquefaction cannot occur in the embankment. Furthermore, the stability of the embankment system under seismic loading is studied using pseudo-static approaches. If a global factor of safety lower than 1 is obtained with these approaches, the deformations of the embankment systems need to be further quantified using numerical simulations with appropriate constitutive models (Machaček, 2020). However, such numerical models should be validated on well-defined boundary value problems. In the present case physical models with comparable boundary conditions and material properties are tested to establish benchmarks, which will be simulated with the numerical models. The validation will be done by comparing the results (e.g. deformations, pore water pressure, accelerations) of the physical model tests and the simulations.

In the literature studies investigating the liquefaction potential of geotechnical structures are mostly related to shallow slopes or dam structures. The aim of the present study is to identify the deformation behaviour of a single, water-saturated slope of the embankment system, composed of coarse-grained soil and inclined by 22°.

2 MODEL TESTS

The centrifuge model tests have been carried out in Nantes, France in cooperation with the University Gustave Eiffel. The radius of the centrifuge is 5.5 m and its maximum acceleration is 100g. To simulate the base shaking, a servo-hydraulic shaking table is installed in the basket which can carry a container with outer dimensions of 0.9 x 0.45 x 0.7 m (length x width x height) and with a maximum total mass including the model of 400 kg. The shaking table can be used up to a centrifuge acceleration of 80g. For the series of tests, the samples are loaded with sinusoidal signals, whereby the chosen maximum acceleration corresponds to typical earthquakes in the Rhenish mining area with a return period of 500 (lake filling phase, a_{max} = 0.98 m/s^2) and 2500 (operating phase, a_{max} = 1.96 m/s^2) years.

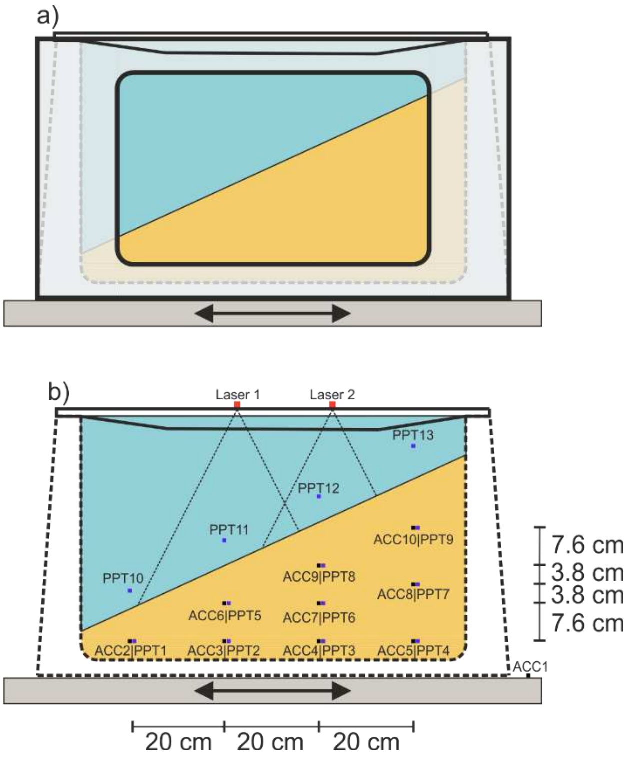

Figure 1: a) Schematic drawing of the container with a sample b) Schematic drawing of the sensor positions

2.1 Model container

The rigid container with internal dimensions of 0.8 x 0.43 x 0.41 m (length x width x height) consists of steel profiles that form the base and the surroundings. The lateral sides are formed on the one hand by a steel plate and on the other by a glass plate supported by a steel frame. In addition, the container is partially closed at its top by a plexiglass lid to prevent the formation of waves. The lid is immersed in the liquid filling to minimise light refraction for the optical measuring systems. The lid is fixed to the container with a steel frame to prevent it from slipping, but also to realise mountings for laser sensors and cameras.

There are filters in the bottom of the container through which it can be filled with water. For a better transmission of the dynamic load from the container to the soil sample during shaking in horizontal direction, double-sided adhesive tape was glued to the bottom with openings for the filters. This allows a thin layer of soil to adhere directly to the container. In addition, after finishing the final slope geometry, rectangular blocks are glued onto one of the lateral sides to fix pressure sensors outside the slope.

2.2 Instrumentation

In the tests, nine pressure sensors were installed within the slope at a distance of 11 cm from a lateral side (Figure 1: *PPT* 1 to 9). In addition, four further pressure sensors were installed outside the slope to obtain a reference measurement (Figure 1: *PPT* 10 to 13). The sensors consist of a metal membrane encapsulated in a brass housing with the associated electronics. A cavity is in front of the membrane, which is separated from the surrounding soils by a metal mesh. As the saturation of this cavity is essential, but not easy to achieve, the space is filled with a silicone grease. The maximum measuring range of all sensors varies between 1 to 7 bar.

To measure the acceleration in the slope, nine one-dimensional accelerometers were installed in the soil (Figure 1: *ACC* 2 to 10). In addition, 10 accelerometers were placed on the container to check whether there was a homogeneous acceleration along the axis of movement and over the height of the container. Furthermore, the accelerations in the other directions were measured to check whether unwanted movements occur or whether the natural frequency of the system has been reached. An accelerometer (Figure 1: *ACC* 1) was further used to check if the acceleration of the shaking table corresponds to the desired signal. All sensors have a measuring range of 1 Hz to 50 kHz.

Also, two line-lasers were used to measure the settlement along the slope surface. As shown in Figure 1, the laser sensors are located above the lid. The vertical position of the central part of the slope surface is detected by combining the results of both sensors.

3 MATERIAL AND METHODS

3.1 Soil material

The material was extracted from the dump side of the opencast mine Inden and is considered representative for a large proportion of the coarse-grained soils found there. It is an artificial mixture of different natural layers, with the grain size distribution as given in Figure 2. The fines content of the material is 10.7%, the mean grain size is d_{50} = 0.55 mm and the coefficient of uniformity is C_u = 3.8. The fines content can play a key role both in the saturation process due to the reduced permeability and in the optical deformation measurement due to a possible clouding of the fluid. Furthermore, the maximum and minimum void ratios of the soil are e_{max} = 0.868 and e_{min} = 0.481, while specific gravity is 2.65.

3.2 Pore fluid

It is well known that in centrifuge model tests with dynamic loading of water-saturated soils, a scaling

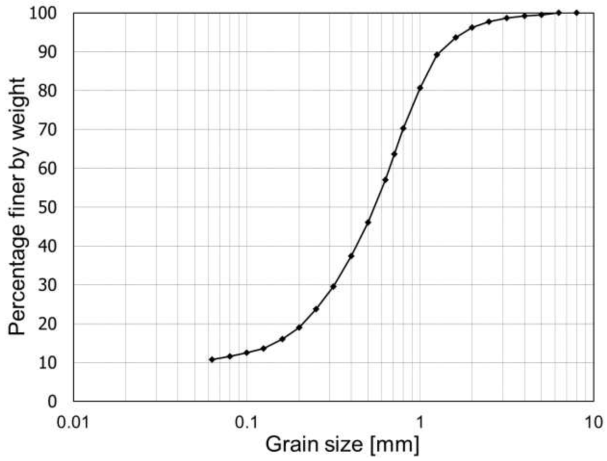

Figure 2: Grain size distribution curve

conflict between the dynamic and diffusion times need to be solved. Otherwise, the accumulation of pore water pressure and consequently the liquefaction potential would be underestimated. To overcome this problem, as the tests were performed at 60g, a hydroxypropyl methylcellulose (HPMC) solution with a viscosity of 60 cst was used as pore fluid in the presented study.

3.3 Sample preparation and saturation

For the series of tests presented in this paper, the slope model was prepared with a relative density of 30 %. The soil was dried completely and afterwards mixed with the HPMC solution to achieve a final moisture content of 5%. The moist material was tamped in layers over the entire length of the container with a layer thickness of 3.8 cm. The uncompacted material was first spread out evenly until it reached a maximum deviation in height of 2 to 3 mm. The material was then carefully compacted to the target height, which was previously defined with a degree of under-compaction of 5% after Ladd (1978). The pore pressure and acceleration sensors were installed between each layer (Figure 1).

The resulting sand column was then trimmed into the slope geometry with an inclination of 23°. The increased inclination was chosen to achieve the intended 22° after saturation. In a first step the excessive material was roughly removed until the final geometry was reached with an overhang of 2 cm. Then the material on the surface was carefully extracted to the final geometry using a template, which was mounted on the container, and a scraper.

The saturation was done at 1g under vacuum. First the container was placed in a vacuum chamber. To reduce the saturation time a wedge-shaped body was installed in the container with its lower surface 2 cm above the slope surface. The wedge serves as a dead volume which does not have to be filled by the fluid through the less permeable soil. Once in place, the saturation with HPMC solution was done following the method described by Kutter (2013). When the slope was completely submerged, the vacuum was removed and the wedge-shaped body was slowly lifted while HPMC solution was added from above. Once the container was filled with fluid, a float was placed on the surface of the liquid and the chamber was closed again. A laser sensor was then used to measure the variation of the height of the fluid surface induced by the gradual increase of the chamber pressure. This allows an indirect quantification of the degree of saturation of the sample, as any remaining gas bubbles in the pore space are compressed when the pressure is increased (Okamura and Inoue, 2012). Three tests are presented in this paper. In tests Nos. 2 and 3, a very good saturation of around $S_r = 99\%$ was achieved. During the saturation of test No. 1, the tube of the peristaltic pump bursted two times during the saturation process, so that the saturation had to be restarted twice. The subsequent measurement of the degree of saturation didn't lead to a reasonable result. So, S_r was assumed to be lower than in tests Nos. 2 and 3.

The line-laser sensors were also used to measure the surface of the slope before and after saturation. The measurements were taken at different horizontal distances from the container wall to get a complete profile of the entire slope surface. In Figure 3, the measurements in a distance of 94 mm from the container wall are shown for test No. 2. This position was chosen so that any friction between the soil and the lateral wall will have no influence on the settlements. An average settlement of 23 mm (model scale) occurred in the lower part of the slope (between 200 und 300 mm length), whereas a settlement of 43 mm was measured in the upper part (between 400 and 500 mm length). As a result, the slope angle of 23° used during preparation was reduced to the intended 22°.

3.4 Base shaking

Sensor *ACC 1* was installed on the shaking table to monitor the base shaking inputs. Figure 4 shows the measurements of *ACC 1* in test No. 2 in protype scale. Here, 20 sinusoidal cycles with a targeted acceleration of 0.981 m/s² (red lines) and a frequency of 1 Hz were to be applied to achieve the peak ground acceleration (PGA) of 0.1g. Comparing the required maximum and minimum accelerations (red lines) with the measured values of *ACC 1* (black curve), it is evident that some high frequency components were recorded exceeding the target acceleration. These undesirable deviations from the target signal are

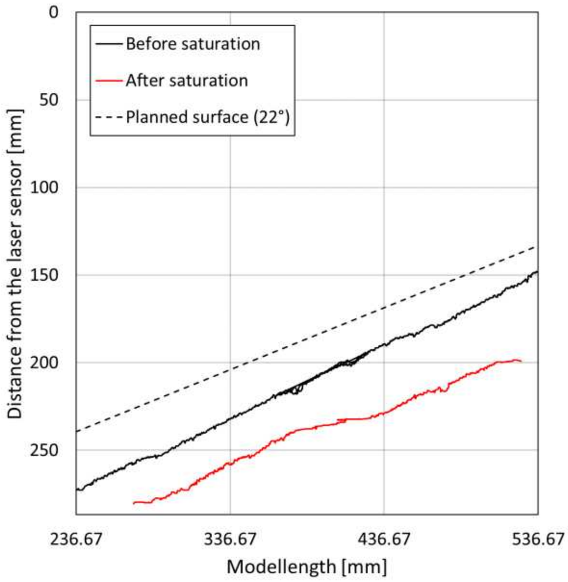

Figure 3: Deformation of the central part of the slope surface due to saturation in test No. 2 in model scale

known in centrifuge modelling and are caused by the characteristics of the used servo-hydraulic shaker (Kutter et al. 2020). If the principal frequency component for 1 Hz is considered as a filter a good agreement with the targeted accelerations is achieved. Further information on the measured accelerations in the experiments can be found in Escoffier et al. (2024). Nevertheless, this unfiltered signal must be used in further numerical analyses because the actual acceleration is higher than the planned one. Using the target acceleration would lead to an overestimation of the liquefaction potential.

3.5 Test program

The boundary conditions of the three tests presented in this paper are summarized in Table 1. The relative density was fixed to 30% as well as the slope angle before saturation to 23°. In the whole test series, the same g-level (60g) was chosen and 20 cycles with a constant amplitude were applied. The combination of frequency and amplitude was chosen to achieve a maximum acceleration of 0.1g (tests Nos. 1 and 2) and 0.2g (test No. 3). In all tests two base shakings were applied successively to the model. However, in this paper only the first base shaking was considered as it was applied on a virgin slope.

4 TEST RESULTS

4.1 Repeatability

Figure 5 shows the central part of the slope surface after saturation and installation in the centrifuge

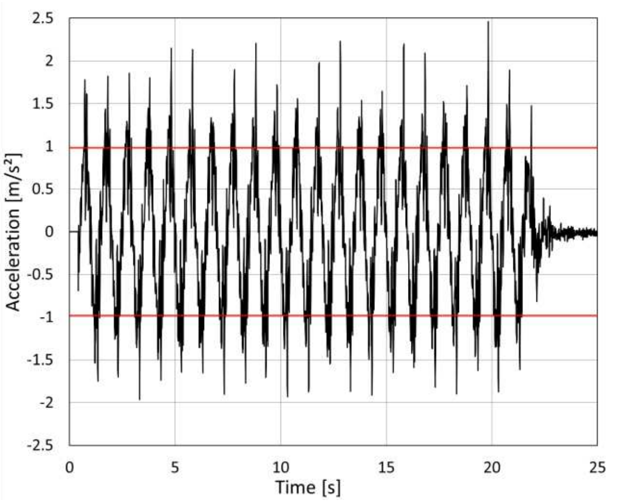

Figure 4: Example of unfiltered acceleration of sensor ACC 1 (black line) and target acceleration (red lines) in prototype scale

basked (1g) compared with the surface after spin-up (60g). For test No. 3 no data are available at 1g state. The original signals of the sensors show significantly deviating results for some locations. It is assumed that these deviations are caused by faulty reflections of fine and light particles rising from the soil surface to the top of the fluid. These faulty recordings are eliminated. Furthermore, there is an overlap of both sensors in one area, which can lead to a discontinuity in the measured surface. This may be caused by the refraction of the laser beam as it passes through the plexiglas and into the HPMC solution.

However, comparable settlements of the slope surface after spin-up and consolidation are detected for tests Nos. 1 and 2. For test No. 1 settlements are between 13 mm (lower part of the slope) and 17 mm (upper part), whereas settlements of test No.2 are between 10 mm and 13 mm. The differences between the settlements in the lower and the upper part are about 5 mm and thus the inclination of the slope did not change significantly. The final position of the surface in test No. 3 is close to the one observed in tests Nos. 1 and 2. These measurements indicate that the influence of the repeated saturation process and of a probably lower degree of saturation is small in case of test No. 1. Generally, the comparison of the three tests reveals a good repeatability.

4.2 Influence of the PGA

The position of the slope surface before and after base shaking is shown in Figure 6 in prototype scale. There are hardly any recognisable changes of the surface along the lower part of the slope within all three tests. Larger settlements are observed in the upper part. In tests No. 1 and 2, both with PGA of0.1g, the upper part of the slope settled about 0.43 m or 0.34 m, respectively. Settlements smaller than 0.08 m were measured in test No. 3 with PGA of 0.2g, which is less than half the values obtained in tests Nos. 1 and 2. Due to the higher induced energy, one would expect a higher settlement. However, since both the amplitude and the frequency have been changed from tests Nos. 1 and 2 to 3, there may be opposing effects that have led to a smaller

Table 1: Test program in prototype scale

No.	**PGA [m/s²]**	**Frequency *f* [Hz]**	**Amplitude *u* [mm]**
1	0.1g	1	24,84
2	0.1g	1	24.84
3	0.2g	2.5	7.98

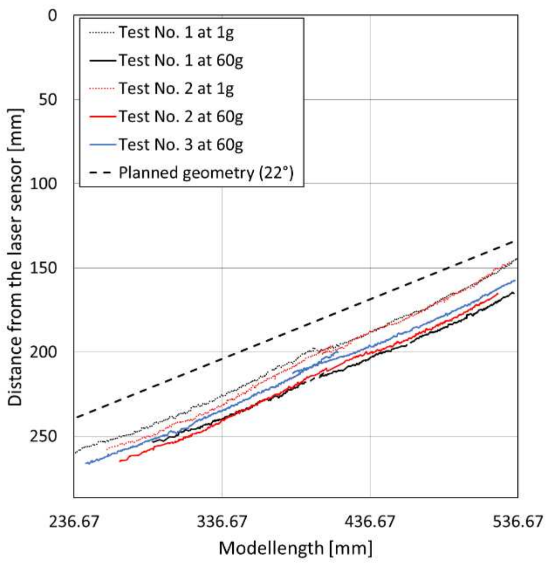

Figure 5: Deformation of the central part of the slope surface due to the spin up in model scale

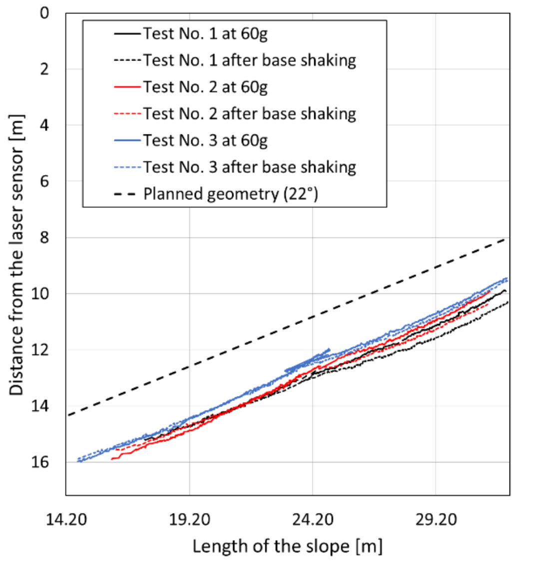

Figure 6: Deformation of the central part of the slope surface after base shaking in prototype scale

deformation. Therefore, only one of these parameters will be varied in the next tests to analyse their individual influence.

4.3 Influence of the degree of saturation

The degree of saturation in test No. 1 was estimated to be lower due to the above-mentioned problems during saturation. Therefore, the influence of the saturation on the settlements due to base shaking is analysed in Figure 6 by comparing the results from tests Nos. 1 and 2. Similar values of surface settlement under 60g can be recognised. In the lower part of the slope, hardly any differences can be observed between the two tests. In the upper part, the settlements due to base shaking observed in test No. 1 are 0.09 m larger compared to the ones observed in test No. 2. Thus, the settlements are in a comparable range despite the lower saturation. The slight increase in settlement may be due to compression or the release of any air bubbles trapped in the pore space. Based on the results, the potential influence of a lower degree of saturation can be judged as low.

CONCLUSION

Centrifuge model tests were performed to analyse the behaviour of water-saturated slopes under dynamic loading. The slope models were formed from a loose non-cohesive soil taken from the dump of an opencast mine. Within this paper the settlement of the slope surface during model preparation and due to base shaking is discussed.

In detail it was investigated whether the intended slope angle is obtained after saturation and spin-up of the model from 1g to 60g. The slope angle was found to reduce from an intial 23° to 22°, which corresponds to the target slope inclination. The observed deformations of the slope during saturation, spin-up and consolidation before base shaking was similar in all tests, showing a good repeatability.

The test with higher PGA caused less deformations during base shaking which probably is due to contrary effects of the change of both, frequency, and amplitude. Additional tests keeping one parameter constant while varying the other will be performed.

The influence of the degree of saturation on the deformation behaviour of the slope was found small within this test series.

At this point, it should be noted that by applying a base shaking with 20 cycles of constant amplitude a significantly higher energy was induced than typical for an earthquake. Tests with an artificial earthquake signal are therefore planned.

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