Controlled water-level system for breach analysis of levees within an enhanced acceleration field

W.F. Morales, J. Laue, S.M. Springman
Institute for Geotechnical Engineering, ETH Zurich

Abstract: Correct scaling of breach analysis of river levees is a challenging task that is not easily accomplished by physical modelling. Several small-scale physical model tests have been conducted at 1-g level, which cannot truly represent the stress-dependency of soils, whereas the scaling issues arising from centrifuge modelling have not been fully explored.Two key features have to be considered when modelling the prototype behaviour. On the one hand, the whole embankment should be included in the model to ensure that flow nets are valid. This is not always easy to achieve due to space limitations within the strongboxes used. On the other hand, full control of water levels, prior and during breaching, is of principal interest.This contribution shows how both of these features can be modelled for levee breaching by taking advantage of the availability of space within a drum centrifuge and its versatile toolplate.

Keywords: Levee modelling, enhanced acceleration field, water control system, breaching.

1 INTRODUCTION

Understanding of the performance of levees during a flood is necessary when designing governmental prevention and assistance plans, which are intended to reduce both casualties and material damage. This concern acquires more relevance as flood events occur more frequently and the cost of hazards in terms of materials and life have increased in the last decades, as shown by Hoyois&Guha-Sapir (2003)orBezzola et al. (2008).

Complete modelling of river levees prior and during breaching should include a transientwater level analysis reflecting the state of the levee prior to the overflow process. Springman et al. (2008) and Mayor et al. (2008)show how this has a strong influence on the unsaturated condition of the levee. The unsaturated seepage analysis is also important as the failure mechanism of levees is closely related to the change of matric suction of unsaturated soils, and such a change is induced by unsaturated transient seepage(Huang & Jia, 2009).

Physical modelling of flood problems is well suited since the dam material has to be represented by three phases (solid, liquid, gas) and in three dimensions (Gilbert & Miller, 1991). Previous research projects were aimed to study this problem under an increased gravity field, but were often limited by space in the available strongboxes or by the lack of aneffectivewater control prior and during overflow.This prompted models to be createdwithsteep slopes or models that had to cut either the air or the water side slope, as was done byCargill &Ko(1983),Kusakabe et al.(1988), Okumura et al.(1998)orSeo et al. (2006).

This contribution describes a new system that was developed at ETH Zurich to overcome these problems. It is composed of a new strongbox, a new water level device and a novel model construction procedure. The new system allows all possible water conditions in a levee, from dry state to overflow, to be studied in one model.

2 NEW SEMI-CIRCULAR STRONGBOX

One of the greatest problems for modelling a levee in a centrifuge facility is related toits size. If the response of the levee under a process of transient water level control is to be modelled correctly, then both the air and the water side of the structure have to be represented. Achieving this goalattains morerelevance as the height of the model increases and the slopes are flatter, which becomesrestrictive in some cases.

Model construction for centrifuge testing always represents a challenge not only in geometric terms but also to replicate the soil and the stress history of the planned prototype. Beam centrifuges have the advantage that the model can be built at 1-g and then tilted in-flight as the radial acceleration increases.However, the plan area available might be toosmall formodelling both slopes of a leveein correct relation to the model height. Drum centrifuges, on the other hand, offer a larger area on which the model can be built. Nevertheless, the disadvantage is that the model surfaces must stand in a vertical position for a prolonged time during levee construction and preparation before testing.

Using strongboxes placed in the drum prior to testing is one option to overcome part of this challenge, even though the model still has to be stable when it is tilted through 90° to be installed in the channel of the drum. The drum centrifuge facility at ETHZurich uses two types of strongboxes: a cylindrical boxof0.40m indiameter and0.20m depth(Springman et al., 2001), and a cubic box of dimensions 0.40x 0.40m in plan view and0.20m depth(Chikatamarla, 2005; Weber, 2007).

Preliminary levee modellingwas plannedin the rectangular box, as shown in Figure 1. A representative model height was defined to be 100mm. Slopes hada 1:2gradient. These geometrical characteristics required the water side slope to be cut. Therefore, low water levels could not be simulated.

The above limitations led to the design of a new strongbox that overcomesthesedifficulties. A semi-circular strongbox was found to be the most appropriate design. The new box allows larger levee models to be created with the possibility of varying the slope gradient. Afull description of the new box is presented below.

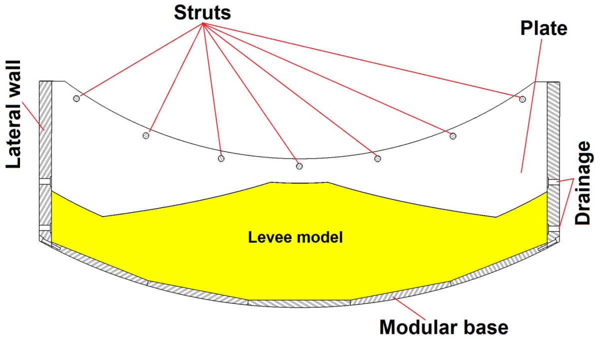
Figure 1: Preliminary concept for levee modellinginside the 40 cm square strongbox (units in mm).

2.1 Description of the new strongbox

The new strongbox (Figure 2) is composed of two plates (bottom and top), two lateral walls, a curved modular base (Figure 3) and seven connectingstruts.The box is fixed to the channel of the drumcentrifuge by eight M12 screws. The form of the box is an annular sector of dimensions 1000x500x300mm, as illustrated in Figure 2. The length (1000mm) is determined by the top and bottom plates (cf. Section 2.1.3 and Figure 4a). The height of the box (500mm) is given by the length the connection struts (The box is designed to stand without the need of both lateral walls, cf. Section 2.1.5). The width (300mm) is given by the length of the shortest dimension of the side walls (cf. Section 2.1.5 and Figure 5b).

This new box allows levee models to be built with different slope gradients and levee heights. For instance, having a 1:2.5 slope gradient, a model of 0.2m height (representing 20m at 100g) can be built inside the box. Models can be built outside the centrifuge in the preparation laboratory. The material is subjected to unsaturated condition, in which suctions help the model to remain stable, so it can be brought into the drum. Further information is found in Section 4.2.

Table 1presents a comparison of the features of the three types of strongboxes. Although the new strongbox has a similar weight, it can hold about 6.3 and 4.9 times the volume of the cylindrical and rectangular boxes, respectively. This allows larger models to be created, which may be more representative of the physical problems to be analysed.The new box was also designed to allow large-size measuring sensors to be inserted, as described in Section 2.1.3.



a) Perspective b) Longitudinal cross section

Figure 2: New semi-circular strongbox at ETH Zurich.

Table 1: Features of the strongboxes at ETH Zurich

Strongbox type	**Available Soil Volume (m^3)**	**Surface area (m^2)**	**Box Weight (N)**	**Max. Weight with soil* (N)**	**Design g-level**
Semi-circular	0.156	0.500	680	3800	100
Cylindrical	0.025	0.125	750	1250	250
Cubic	0.032	0.160	670	1310	200

* assuming γ=20 kN/m^3

2.1.1 *Materials*

The structure, except for the connection struts, is made of anticorodal-110, which is an aluminium alloy of Swiss origin. The struts are made of standard steel*St37-2*. Material properties are listed in Table 2.

Table 2: Material properties of the strongbox components.

	Anticorodal-110	**Steel (St37-2)**	**Steel for bolts**
Composition	Magnesium (0.6%) Silicon (1.0%) Aluminium (98.4%)	Carbon (0.17%) Magnesium (1.4%) Sulphur (0.045%) Iron (98.4)	Carbon (0.25-0.5%) Magnesium (1.5%) Sulphur (0.05%) Iron (98.2-97.25%)
Unit Weight (kN/m^3)	27	78.5	78.5
Yield strength (MPa)	240	235	640
Ultimate strength (MPa)	295	360	800
Young's Modulus (GPa)	69	210	210
Poisson's ratio (-)	0.325	0.28	0.28

2.1.2 *Modular base*

Figure 3 shows the modular base. Its design was driven by the challenges of constructing a massive curved plate of 15mm in thickness and 1.04m in length. Therefore, the whole arc was divided into five sections. Each section is connected to the top and bottom plate by four M6 screws. The joints between sections are sealed with silicon in order to ensure that they are watertight.

Each piece has a curved surface on the exterior face, to fit the drum shape, and a flat surface inside the drum (Figure 3b). This means that the internal surface of the strongbox will be a five-sidedpolygon instead of a curved shape. This is a minor detail thatdoes not hinder correct modelling of the levee.

Figure 3: Modular base.

2.1.3 Top plate

The shape of the top plate,in plan view, is an annular sector.The straight sides are parallel to the line joining the centre of the annulus in the middle of the curved section. The distance between the straight sides is 1000mm (Figure 4a). The external radius is 1100mm to fit the radius of the drum centrifuge (as described in Springman et al., 2001) The distance between the two radii is 300mm.

The plate has variablethicknessto reduceweight, while assuring a stiff response to loading and structural stability. It was designed to work as a waffle slab with25mm and 12.5mm on its thicker and thinner sectors respectively, as shown in Figure 4b.

The plate has 18 holes with M25x1.5 thread. These allowseveral large-size (>15mm) measuring sensors to be inserted within the soil mass to suitthe different slope gradient to be analysed (cf. section4.2.1). Up to four coaxial cables (with their connectors) can be passed through each hole as well. Thus, up to 72 sensorscan be inserted within the soil mass. This is an improvement over the other strongboxes, as sensors can only be embedded up to a diameter of 8mm.

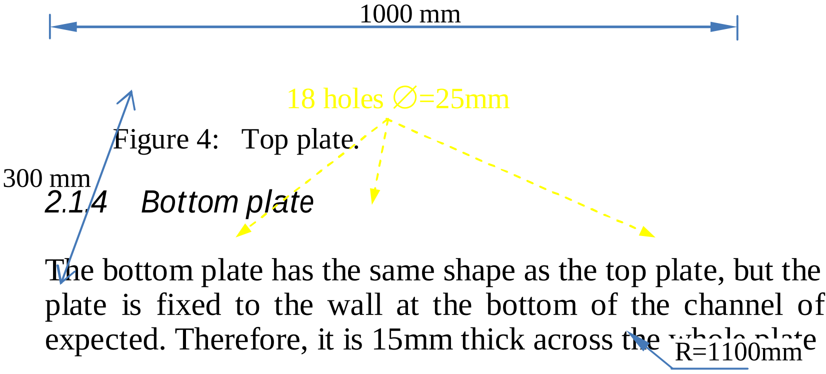


Figure 4: Top plate.

2.1.4 Bottom plate

The bottom plate has the same shape as the top plate, but the difference lies in the design purpose. As this plate is fixed to the wall at the bottom of the channel of the centrifuge, large deformations are not expected. Therefore, it is 15mm thick across the whole plate and does not include any milled sections.

2.1.5 Lateral walls

The lateral walls are rectangular, and of dimensions 540x300mm. Each wall is clamped to the top, bottom plates and modular base by five M10, four M8 and seven M6 screws respectively. The walls are also designed to be removed prior to testing, if needed. This design feature was introduced with future research projects in mind, which might require the use of an external strongbox for building the model,andat the same time, access to the entire channel of the drumcentrifuge for testing.

Each wall has two ports for drainage, as seen in Figure 5b. Each drainage port is 500mm long, 20mm wideand made of a metallic filter plate. The separation between them is 120mm.The lower line is used for saturating the material during the model construction (cf. Section 4.2), whereas the upper drainage line is used for supplying the water on the water side of the levee.

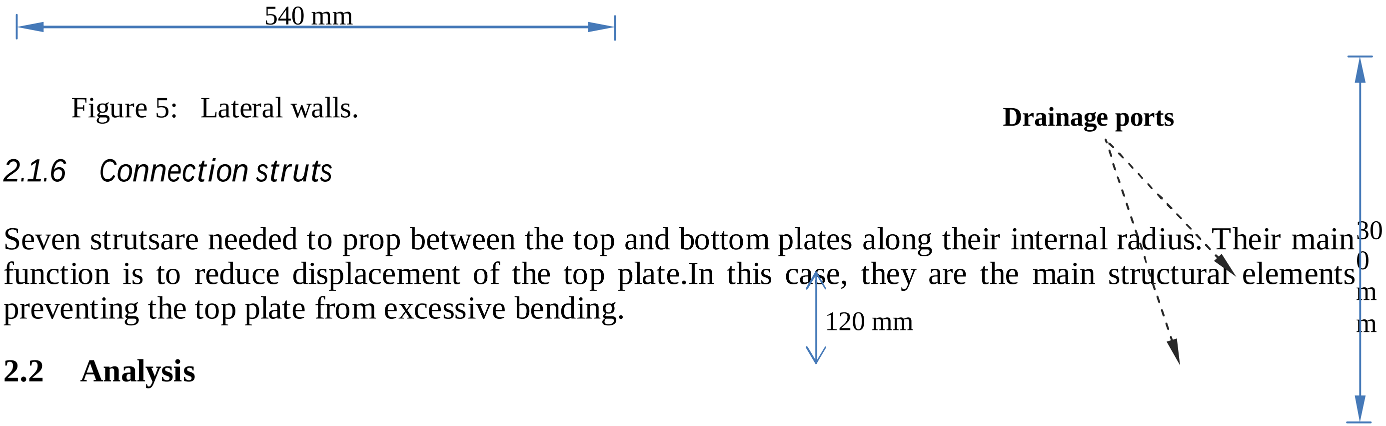


Figure 5: Lateral walls.

2.1.6 Connection struts

Seven strutsare needed to prop between the top and bottom plates along their internal radius. Their main function is to reduce displacement of the top plate.In this case, they are the main structural elements preventing the top plate from excessive bending.

2.2 Analysis

Every new element to be used in a centrifuge facility has to be designed with a sufficient factor of safety, and verified with an initial proof-test according the design principles as given by Schofield (1980).Morales et al. (2012) presents a deeper view of the analyses performed, and the main results for an acceleration field equivalent to 100-gare summarised in Table3.The values of stresses acting under these conditions are evaluated as a von Mises stress (Equation 1) and compared to the ultimate stress of the material to ensure this is smaller and the item can be considered safe (Beer et al., 2002).

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \tag{1}$$

Table 3: Results from the analysis for the new strongbox for an acceleration field equivalent to 100-g.

Item	**Units**	**With lateral walls**	**Without lateral walls**
Maximum von Mises stress on struts	MPa	54.7	52.1
Factor ofsafety in rods	-	*6.6*	*6.9*
Maximum von Mises stress on top plate	MPa	61.5	66.1
Factor ofsafety in top plate	-	*4.8*	*4.8*
Maximum von Mises stress on lateral wall	MPa	51.8	N/A
Factor ofsafety in lateral wall	-	*5.7*	*N/A*
Maximum von Mises stress on strut bolts	MPa	105.4	108.7
Factor ofsafety in strut bolts	-	*7.6*	*7.4*

Table 3: Results from the analysis for the new strongbox for an acceleration field equivalent to 100-g. (continuation)

Item	**Units**	**With lateral walls**	**Without lateral walls**
Maximum von Mises stress on connection bolts	MPa	253.2	361.2
Factor ofsafety in bolts	-	*3.2*	*2.2*
Maximum total displacement top plate	mm	0.179	0.212
Maximumtotal displacement lateral wall	mm	0.293	N/A
Maximumtotal displacement struts	mm	0.362	0.366

3 WATER LEVEL CONTROL SYSTEM

A system is designed to set the water levels and thetransient cycles of raising and decreasingthe water level followed by holdinga constant water level during an overflow phase.A two-chamber box has been developed to provide a controlledwater level to the system. A thin wall separates the two chambers of this device,as shown inFigure 6.The deviceis connected to the arm of an actuator placed on the toolplate of the drumcentrifuge (Figure 6a). The location of the box can be variedalong a radiusfrom the centre of the drum,as shown inFigure 7, so that different positions, hence water levels, can be set in-flight.

The water control device is made of anticorodal 110 i.e. the same material used for the strongbox. The external dimensions of the device are 200x100x85mm with 10mm thick walls, enclosing a volume of 1.22litres. The device has a maximum discharge rate of 500ml/s.

a) Photograph. b) Cross section (dimensions in mm).

Figure 6: Water control device.

Water flows continuously through a pipe connected to an external water supply into the bigger chamber of the device. The outlet of this chamber is connected to the upper drainage line of the strongbox by a plastic hose of 10mm in diameter. When the water reaches the height of the dividing wall, it overflows into the second chamber, which lets the water flow out of the system, maintaining a fixed height given by the height of the dividing wall, as shown in Figure 6b.

The water surface is curved due to the acceleration field.The water height in both the water-level device and the strongbox is the same, due to Archimedes' principle (Figure 7). The water level is measured on the water side of the levee by a PPT sensor.

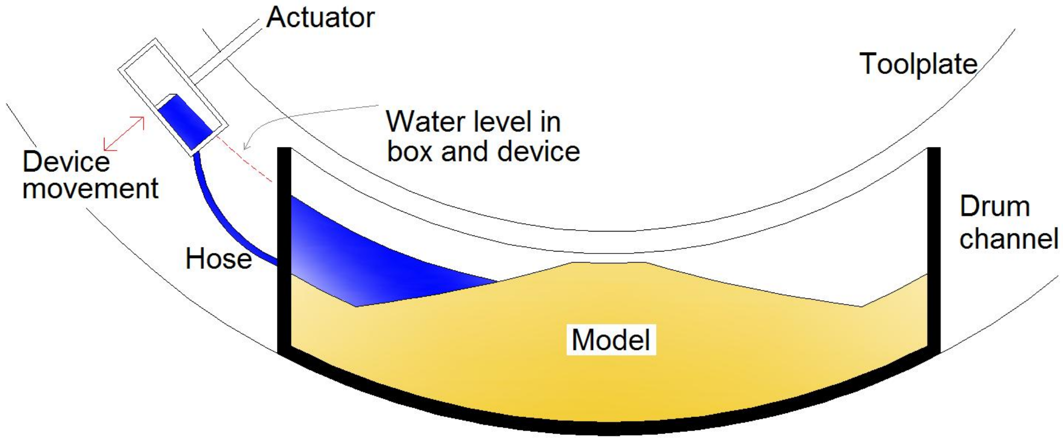


Figure 7: Water level control in the strongbox.

4 MODEL PREPARATION

4.1 Perth sand

Perth sand is used to model the levee. The main material properties and state following pluviationare summarized in Table 4 and the wetting-path of the Soil Water Retention Curve (SWRC), obtained with the axis-translation technique, is shown in Figure 8.

Table 4: Material properties of Perth sand(compiled from Nater, 2005; Buchheister, 2009).

γ_s [kg/m^3]	ν' [-]	ϕ'_{max} [°]	ϕ'_{crit} [°]	d_{10} [mm]	d_{50} [mm]	d_{60} [mm]	e_{max}	e_{min}
2650	0.3	37.5	30	0.165	0.230	0.250	0.755	0.533

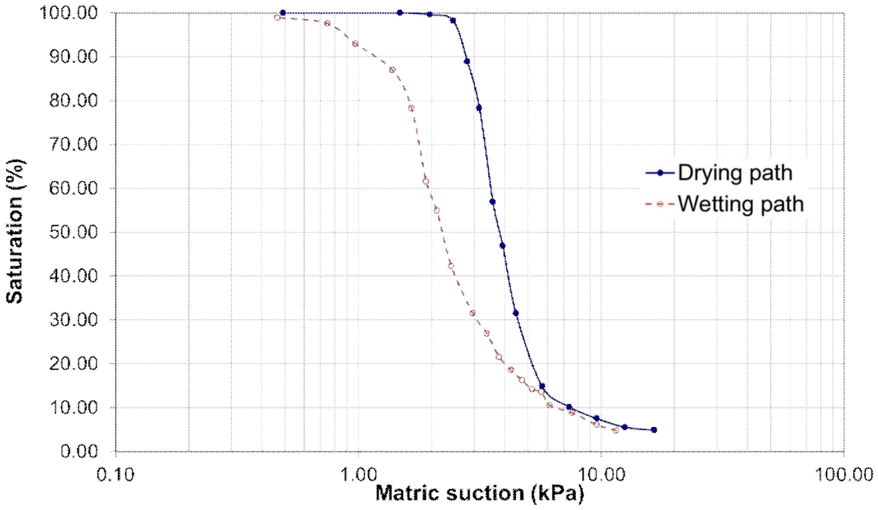


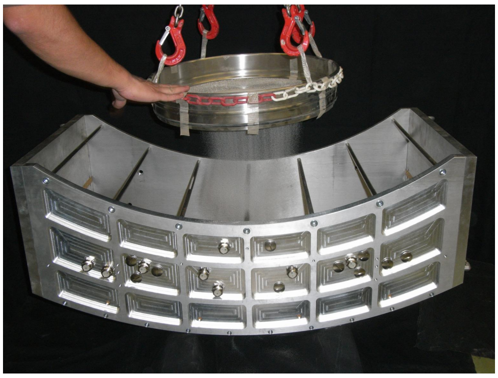
Figure 8: Wetting-path of the Soil Water Retention Curve (SWRC) for the Perth Sand for e=0.55.

4.2 Model construction

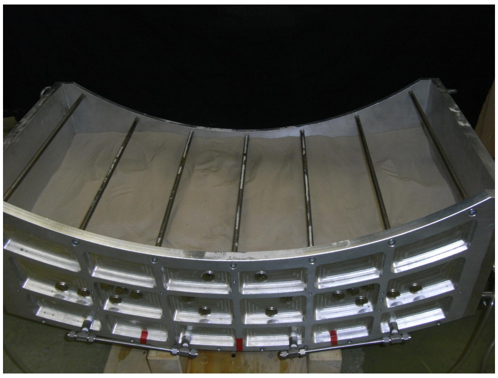
Figure 9 presents the procedure followed to prepare the model. It is based in the procedure given in Nater(2005). Firstly, the box is filled completely with sand by dry pluviation (Figures 9a and 9b),falling freelywith a small flow rate from a constant height of 0.30m. According to e.g. Cresswell et al. (1999), this is a well-known and widely used method for the preparation of sand samples for laboratory testing, and it has the advantage over tamping and vibratory methods of compaction of achieving a uniform density.

Secondly, the sand is saturated by adding water from the bottom of the model through the lower drainage port in the lateral walls (Figure 9c). The water height is set slightly above the soil surface. Once the water table reaches the surface of the soil model, water is then drained out of the sample until a gravimetric water content of 14% is achieved (Figure 9d).A vacuum is applied to suck the water out to the required degree by using a pump.After pumping, the water content is not uniformly distributed in the soil mass. Therefore, an equalisation period of 6 hours is required.

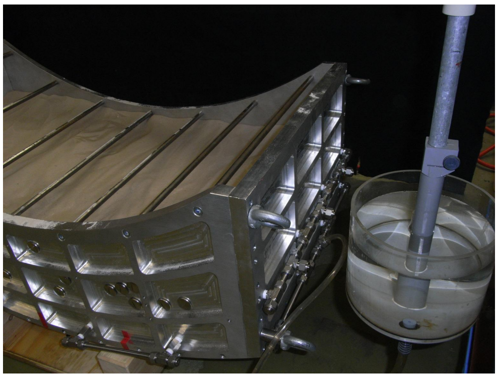
The slopesare shaped next. This is done with a specially designed slope shaper system (*cf.* section4.2.1and Figure 9e). Finally, the model is tilted through 90° to be placed in the drum channel (Figure 9g). The increase of stiffness, as result of the suction in the soil, allows the surface to remain stable in the vertical plane for a short period of time, which is long enough to place and fix the model into the channel of the drum and start the test.



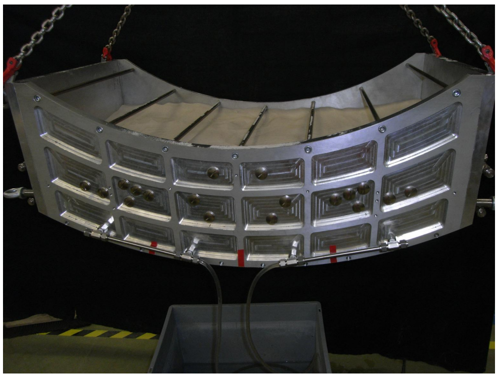
a)Sand is pluviated from a height of 30cm.



b) The box is filled completely with dry sand.



c) The drainage system is connected to a watertank to saturate the sand from the



d) Excess water is drained out by lowering thewater head and pumping.

e) The slopes are shaped with the cutting devices.

f) Once the model is finished, it is tilted through 90°.

Figure 9: Procedure for building the levee model.

Table 5: Densities achieved with the proposed construction method.

Sample	**Volume** (mm^3)	**Soil weight** (N)	**w** (%)	**γ** (kN/m^3)	**γ_d** (kN/m^3)	**e** (-)
1	51.48	0.8678	17.47	16.86	14.35	0.85
2	51.48	0.872	16.89	16.95	14.50	0.83
3	51.48	0.877	18.14	17.05	14.43	0.84

Table 5 shows the measured densities before testing in the centrifuge for different points on the bottom of the model. These were measured with standard cylindrical sampling tubes of 2inches (50.8mm) in diameter and 1inch (25.4mm)in height. It is seen that consistent densities can be achieved with the method describedabove.

4.2.1 Slopes shaper system

According to the US Army Corps of Engineers (2000) guidelines, a 1V on 2H slope is generally accepted as the steepest slope that can be constructed easily and ensure stability, whereas a 1V on 3H slope is the steepest slope that can be traversed conveniently with conventional mowing equipment and accessed during inspectionswithout difficulty. Following these guidelines, a new system was developed to cut slopes with gradients 1:2.0, 1:2.5 and 1:3.0.

The system has a rigid cutter (Figure 10a) and two guiding pieces with the desired slope shape (Figure 10b). All of the components of the system are made of aluminium. The cutterconsists of a plate with a sharp edge and two laterallimbs, whose edges are aligned with the plate edge (side view in Figure 10a).The guiding pieces define the shape of the slopes in the model, which is not completely straight, as the increase of the gravity level with model-depth is taken into account. Figure 10b presents the guides constructed for the three different slope gradients for an increased gravity of 35-g.

Once the container is filledwith unsaturated soil (Figure 9d), the guiding pieces are attached to the bottom and top plates.The cutter is used to remove the excess of material and create the final shape of the levee model,as shown in Figure 9e. As the guides and the sharp edge of the cutter are aligned, the soil inside the box has the same shape as the slope guides.Any combination of slope gradients is possiblefor water and air sides,as the slope guides are interchangeable.Guides of different geometries might also be manufacturedfor future projects.

a) Slope guides.

b) Soil cutter.

Figure 10: Devices for shaping the levee model.

5 SUMMARY

This work describes a new set up for the ETH geotechnical drum centrifuge that was developed to improve levee modellingwithin an enhanced acceleration field. Improvements includemodelling the complete length of the levee slopes,preparing different slope gradients, and providing a fully controlled water level prior- and during overflow. Finally, the influence of the gravity increase with model depth is included by constructingcurved levee slopes instead of straight ones.

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