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Citation for published version:

Beckett, C, Fourie, AB & O'Loughlin, CD 2016, 'Centrifuge modelling of seepage through tailings embankments', *International journal of physical modelling in geotechnics*, vol. 16, no. 1, pp. 18-30.
<https://doi.org/10.1680/jphmg.14.00045>

Digital Object Identifier (DOI):

[10.1680/jphmg.14.00045](https://doi.org/10.1680/jphmg.14.00045)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

International journal of physical modelling in geotechnics

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Centrifuge modelling of seepage through tailings embankments

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Abstract

Tailings Storage Facilities (TSFs) are manmade geotechnical structures usually comprising a perimeter embankment, fill material (the tailings) and a water level control system. Key issues often raised in TSF operation are uncertainties surrounding likely seepage to the environment and accurate prediction of seepage surfaces for input into stability assessment. Critically, TSFs are much more complex than current numerical models conventionally assume. This paper presents techniques for investigating steady-state and drawdown seepage behaviour of TSF embankments using a fixed-beam geotechnical centrifuge. The development of experimental equipment for centrifuge testing is described and novel methods to preliminarily characterise model materials, using a “desktop” centrifuge, presented. Good agreement is found between experimental results from the fixed-beam centrifuge and those predicted by the GeoStudio SEEP/W software package for steady-state and drawdown conditions at all tested hydraulic gradients.

Keywords: centrifuge, tailings storage facility, seepage, drawdown

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Preprint submitted to Elsevier

August 3, 2015

1. Introduction

It is becoming increasingly difficult to obtain a permit for a new mining operation. One of the abiding concerns is the ‘social licence to operate’, and key issues often raised in this regard are uncertainty surrounding seepage predictions for Tailings Storage Facilities (TSFs) for input into stability assessment. It might be considered that seepage through a TSF is now a completely tractable problem. However, this is not the case. During tailings deposition, distinct layering often occurs, as shown by numerous piezocone field testing programmes (Williams and Jones, 2005). Some of these layers may be relatively thin, but have a disproportionate effect on the seepage regime (Chang et al., 2011). Furthermore, hydraulic conductivities (k_{sat}) often decrease with depth due to consolidation (Edraki et al., 2014). These effects alone can result in reduced seepage rates to the environment and have sometimes been used as justification for the omission of an underliner.

Use of commercially available software to analyse seepage through TSFs is now relatively commonplace. Elegant pre-processing and finite element mesh refinement techniques are widely available. It is also possible, to a limited extent, to account for heterogeneous tailings parameters, such as anisotropic permeability. The problem remains as to how the relevant parameters may be accurately and routinely measured. It is therefore necessary to generate experimental data that can be used to verify any numerical code, including those that will be produced in the future. There are unfortunately no analytical solutions available for the conditions described above that would enable their verification and calibration.

Geotechnical centrifuge modelling is now a well-established technique for investigating soil behaviour (Madabhushi, 2014). However, relatively few studies have used this technique to investigate seepage phenomena in earthen embank-

26 ments. Al-Hussaini et al. (1981) presented results for seepage-induced failure of
 27 coal-waste embankments, and Cargill and Ko (1983) and Sutherland and Rechar
 28 (1984) investigated seepage through homogeneous, trapezoidal earthen embank-
 29 ments to determine phreatic surfaces under steady-state seepage and rapid draw-
 30 down of an upstream reservoir. Resnick and Znidarčić (1990) used a similar
 31 approach to these works to investigate the influence of horizontal drains on homo-
 32 geneous slope stability. More recently, Raisinghani and Viswanadham (2011) and
 33 Rajabian et al. (2012) employed centrifuge testing to investigate seepage through
 34 homogeneous embankments using various geosynthetic reinforcement techniques.
 35 These studies all used pressure measurement, digital image correlation (DIC)
 36 and/or particle image velocimetry (PIV), to identify total head levels and the
 37 position of the phreatic surface during testing. However, all encountered diffi-
 38 culties when comparing experimental results to numerical analyses, due to the
 39 creation of complex seepage flow regimes, highlighting inherent challenges in cen-
 40 trifuge testing. This paper presents the development of experimental equipment
 41 designed to address these difficulties. Scaling factors necessary for seepage analy-
 42 sis using a geotechnical centrifuge are introduced and the equipment development
 43 process described. An experimental programme is then presented for testing
 44 steady-state and drawdown seepage flow through a homogeneous embankment,
 45 where results are compared to predictions made using the GeoStudio SEEP/W
 46 software package (Geo-Slope International). Novel tests for the preliminary ma-
 47 terial characterisation are also discussed.

Figure 1: Sectional views through centrifuge strongbox showing principal equipment components and model container

2. Equipment development

2.1. Model container

The equipment used in this investigation was based on that used by Sutherland and Rechar (1984) and Resnick and Znidarčič (1990) comprised a model container housed within a centrifuge “strongbox”, as shown in Figure 1. The assembled strongbox is shown in Figure 2 and an isometric view of the isolated model container in Figure 3.

(Insert Figure 1 somewhere near here)

(Insert Figure 2 somewhere near here)

(Insert Figure 3 somewhere near here)

The model container comprises a central compartment and two flanking reservoirs, separated from the model by porous screens. O-rings were used to prevent seepage around component edges or into the main strongbox. The screens prevent particles from entering the reservoirs whilst allowing water to flow into or out of the model freely. Screens were made from a layer of porous polyethylene

Figure 2: Centrifuge strongbox with installed model container, camera and lighting system

Figure 3: Model container: schematic view and components. 1) Perspex screen; 2) backing plate; 3) porous polyethylene sheets; 4) porous screen frames; 5) bolt holes; 6) O-rings; 7) embankment PPTs (under filters); 8) reservoir PPTs (under filters).

63 (pore size $35\mu\text{m}$), held between a 2mm-thick stainless steel reinforcing grid. An
64 advantage of the use of polyethylene is that sheets can easily be replaced if they
65 become contaminated. The model container was separated from the remainder
66 of the strongbox by a 25mm thick Perspex screen (item 1 in Figure 3), into
67 which markers were embedded to provide a grid of known, fixed coordinates.
68 The use of a Perspex screen allows reservoir fill and phreatic surface levels to be
69 observed during testing. A 5 Megapixel camera (AVT Prosilica GC2450C, Fig-
70 ure 1) was mounted within the strongbox to capture images for future DIC/PIV
71 calculations. The lens can be locked so that the aperture and focus do not unin-
72 tentionally change in-flight (Stanier and White, 2013).

73 Pore pressures within the model during testing were measured using four
74 pressure transducers (PPTs), mounted in the strongbox base and protected by
75 $\text{Ø}25\text{mm}$ sintered bronze filters, as shown in section in Figure 1 and in more
76 detail in Figure 3. PPTs were positioned to lie between the lines of porous
77 screen reinforcement to ensure uninterrupted flow (see Figure 3). PPTs were
78 also installed in the reservoir bases to monitor water levels during testing.

79 *2.2. Pumping system*

80 A number of studies including Sutherland and Rechar (1984) and Resnick
81 and Znidarčić (1990) used overflows in upstream (U/S) and downstream (D/S)
82 reservoirs to control water levels during testing. Flow rates through the model
83 were assumed to equal the flow rate into the U/S reservoir. This is a robust
84 method to ensure consistent water levels, a further advantage of which is that
85 excess water is immediately removed from the centrifuge strongbox, preventing
86 unbalance. However, for mine tailings, consolidation following deposition will
87 result in the expulsion of pore water and so additional (and variable) D/S flow.

Therefore, the simplifying assumption that the rate of injection equals the seepage flow rate is not appropriate.

In this work, D/S water level was maintained by a custom-built syringe pump (internal $\varnothing 50\text{mm}$, 200mm stroke, maximum displacement rate 6.5mm/s, maximum drive pressure 2MPa). The rate of pumping (i.e. the rate of displacement of the syringe) was controlled by an automated process where the syringe actuator was continually adjusted in a closed loop using the analogue signal from the D/S reservoir PPT; if the water level increased, the pumping rate increased to compensate to reestablish the target value. As the stroke and volume of the syringe are known, the flow rate out of the model can easily be calculated from the syringe displacement rate. The use of a pump allowed any D/S water level to be selected; a significant advantage over the use of a fixed overflow, enabling multiple model geometries to be accommodated. The pumping system's hydraulic configuration is shown in Figure 4, where symbols have been selected to be consistent with those used in Shepley and Bolton (2013).

(Insert Figure 4 somewhere near here)

3. Experimental programme

3.1. Model geometry and centrifuge scaling laws

Different scaling factors must be applied to different properties to relate their values in a centrifuge model to those in the full-scale prototype. A summary of similitude laws for centrifuge seepage testing is given in Table 1. For this investigation, geometric and dynamic similarity were achieved by setting $\lambda = \frac{1}{n}$ where λ and n are the length and acceleration ratios between the model and the prototype. A scale factor of $n = 100$ was used for the tests considered here, where

Legend:

Pressure transducer

Syringe pump actuator

Variable flow rate valve

Figure 4: Container hydraulic diagram

Table 1: Summary of scaling factors for centrifuge seepage modelling assuming geometric and dynamic similitude. $X^* = \frac{X_m}{X_p}$ where X_m and X_p are the property vales in the model and prototype respectively. †At steady state

Property	Scaling factor
Model parameters	
Acceleration, g^*	n
Length, λ	$\frac{1}{n}$
Soil parameters	
Angle of friction, ϕ'^*	1
Apparent cohesion, c'^*	1
Soil density, ρ^*	1
Seepage parameters	
Effective stress†, σ'^*	1
Hydraulic conductivity, k^*	1
Hydraulic gradient, i^*	n
Pore pressure†, u^*	1
Seepage velocity, q^*	n
Seepage flow rate, Q^*	$\frac{1}{n}$
Time (kinematic), τ	n
Time (seepage phenomena), t^*	$\frac{1}{n^2}$

112 n is set at the centre of the model base. This value was used following the work
113 of Al-Hussaini et al. (1981) to avoid potential turbulent seepage flows within the
114 model.

115 (Insert Table 1 somewhere near here)

116 The shape chosen for the model was typical of TSF embankments (see Fig-
117 ure 5); a shallow slope was included on the U/S side to represent the tailings
118 pond. It should be noted that the lateral extents of prototype-scale TSFs are
119 much greater than the 37m half-width tested here; a realistic half-width would
120 be of the order of 500m. However, it was necessary to select a truncated profile
121 in order to fit the model within the strongbox whilst testing a sensible range of
122 reservoir head levels.

Figure 5: Model dimensions (not to scale)

(Insert Figure 5 somewhere near here)

3.2. Material selection

Although tailings are a distinctly heterogenous material, testing in this investigation was conducted on homogeneous models in order to validate the developed experimental procedures. Silica silt (Unimin Silica 200G) was selected for the main body of the embankment, selected as preliminary testing indicated its hydraulic conductivity to be sufficiently low to keep flow rates within the limits of the pumping system when tested at $n = 100$.

Sand filters (shown in Figures 1 and 5) were used to prevent silt particles migrating into and blocking the porous screens during testing. FEMA (2011) guidelines showed that Unimin RC sand would be a suitable filter material. Silt and sand particle grading curves, as well as the FEMA filter limits, are shown in Figure 6.

(Insert Figure 6 somewhere near here)

Figure 6: Embankment and filter material particle grading curves. $\square$ RC sand; $\circ$ Silt; $\times$ FEMA (2011) filter limits

Table 2: Silt and sand material properties

Property	Symbol	Silt	Sand
Void ratios (-):	e	Figure 8	0.52
	e_{min}	Figure 8	0.47
	e_{max}	Figure 8	0.74
Particle sizes (mm):	d_{10}	0.003	0.299
	d_{60}	0.031	0.496
Specific gravity (-)	G_s	2.65	2.65

137 (Insert Table 2 somewhere near here)

138 3.3. Silt consolidation

139 A small customised desktop centrifuge, shown in Figure 7, was used to deter-
140 mine silt consolidation properties, following the work of Kayabali and Ozdemir
141 (2012) and Reid et al. (2012). The desktop centrifuge is a modified Clements
142 model Orbital 420, commonly used for medical centrifugation. It is equipped with
143 four customised sample canisters, with internal dimensions $\varnothing 42\text{mm} \times 92\text{mm}$. The
144 desktop centrifuge can spin at speeds of up to 3500RPM, allowing for a maxi-
145 mum acceleration $n = 2400$ at a radius of 175mm, coincident with the base of
146 the canister (Reid et al., 2012). The desktop centrifuge is sufficiently small to
147 be operated for extended periods without the need for specialised facilities. The
148 advantage of this technique over a typical oedometer or Rowe cell is that multiple
149 effective stress states can be examined in a single sample, due to the variation in
150 n with rotation radius.

151 (Insert Figure 7 somewhere near here)

152 Consolidation behaviour of the silt was determined by accelerating four sam-
153 ples of silt slurry (at approximately 100% water content by mass) with initial
154 sample heights of 72mm to $n = 100$ (at the canister base) for 24 hours. A
155 customised reaming tool (Reid et al., 2012) was used to remove 2mm slices of
156 consolidated material at specific depths (and so effective stress levels), which were
157 then oven dried to determine their water contents and void ratios. Results are
158 shown in Figure 8. Note that only results for two of the four tested samples
159 are shown in Figure 8 for clarity. Silt void ratios reach a minimum value of 0.7
160 for effective stresses above 3kPa, indicating that the majority of the silt forming
161 the model embankment is of homogeneous void ratio and so permeability. Such

Figure 7: Desktop centrifuge with laptop, customised containers and RPM controller

behaviour is associated with a maximum packing density for the silt particles due to its largely uniform particle size (Figure 6).

(Insert Figure 8 somewhere near here)

3.4. Filter integrity: Desktop centrifuge and image analysis

Given the importance of the sand filters to porous screen integrity, it was necessary to test the ability of the sand filters (Figure 5) to prevent fine particle migration. Testing was conducted using the desktop centrifuge. Centrifuge canisters were filled with a layer of silt slurry, poured over a layer of RC sand. Canisters were then accelerated to $n = 100$ for a period of 7 days, allowing silt to migrate into the underlying sand under gravity. Whilst it is acknowledged that there is no seepage flow in the canister, migration is still possible due to the varying gravitation field.

The reaming tool could not be used to determine the extent of silt migration into the sand as it was not possible to obtain incremental samples from the sand layer. An image-based technique was therefore devised to non-intrusively examine the extent of silt migration, a summary of which is shown in Figure 9. Images of the side wall of each canister were taken from a fixed distance using an 8 Megapixel digital camera. An identically-sized section, corresponding to the interface region between the materials, was then cropped from each image (150×300 pixels). The variation in pixel intensity in each of the red, blue and green channels was then analysed. To account for any changes in lighting conditions between samples, pixel intensities were normalised using

$$I' = \frac{I - I_{min}}{I_{max} - I_{min}} \quad (1)$$

where I_{max} and I_{min} are the maximum and minimum intensities found in the

Figure 8: Silt consolidation as determined using the desktop centrifuge

Figure 9: Process used for filter integrity testing

185 image and I' is the normalised pixel intensity value. Using Eqn 1, the brightest
 186 pixel intensities (i.e. white) equal 1 whilst the darkest (i.e. black) equal 0.

187 (Insert Figure 9 somewhere near here)

188 Results for four tested silt-sand samples are shown in Figure 10, where depths
 189 have been determined directly from the captured images. Note that results in
 190 Figure 10 are for the blue channel only, as this provided the greatest contrast
 191 between materials. A clear discontinuity in pixel intensity is visible between
 192 depths of 19 to 25mm, corresponding to the transition between lighter silt and
 193 darker sand particles. Also evident in Figure 10 is an increase in pixel intensity
 194 from 0 to 19mm. Although darker intensities might suggest the presence of sand,
 195 this feature is instead due to shadowing from the canisters' rims; no sand was
 196 found above the layer interface. The transition depth of 6mm between the two
 197 materials in Figure 10 suggests that a minimum filter width of 6mm is required
 198 to prevent particle migration. Given that seepage flow was not present in the
 199 desktop centrifuge canisters, a final filter thickness of 32mm was selected to ensure
 200 that the porous screens remained uncontaminated.

201 (Insert Figure 10 somewhere near here)

Figure 10: Normalised pixel intensities against depth (results for every 10th pixel only for clarity). Inset: Example photograph showing analysed cropped image section.

202 3.5. Model construction

203 The embankment and toe filter were constructed by pouring silt slurry (roughly
204 30% water content by mass) and dry sand either side of a temporary plastic di-
205 vider. Dry sand was deposited at a relative density of 90% by pluviation through
206 air. U/S and D/S reservoir water levels were maintained above those of the fill
207 during construction to prevent seepage from the model into the U/S reservoir
208 (which might cause blockage) and to saturate the sand filter. Sand was also
209 poured into the U/S reservoir to act as a support for the porous screen during
210 testing. Sand was not used in the D/S reservoir to avoid migration of particles
211 into the pumping system. The plastic divider was slowly removed once the fill
212 reached the required depth, and water levels increased to inundate the entire
213 model. The model was then consolidated in the centrifuge at $n = 100$ for 24
214 hours, after which the water level was reduced and the embankment formed by
215 profiling the silt to create the required geometry (Figure 5).

216 3.6. Steady-state seepage and drawdown testing

217 Steady-state seepage conditions are representative of those present in the TSF
218 embankment during normal operations, where tailings are deposited as a slurry
219 within the facility and water levels are controlled by the ponding systems. Steady-
220 state seepage testing was conducted by selecting a constant D/S reservoir level (at
221 a depth below the surface of the sand filter) and raising the U/S reservoir water
222 level above that value. The U/S reservoir water level was maintained at that
223 level until steady-state seepage conditions were achieved (as demonstrated by
224 the container PPTs), a process that took approximately 2 hours. The U/S water
225 level was then increased to the next testing value. This process was repeated until
226 ponding was observed on the U/S embankment slope. Flow to the U/S reservoir

227 was then terminated and water levels allowed to reduce until equilibrium was
228 re-established with the D/S reservoir level, simulating reservoir “drawdown” at
229 the closure of a TSF. The entire testing cycle was then repeated for a different
230 set of target U/S reservoir water levels.

231 4. Head level calculations

232 4.1. PPT responses

233 The pore pressure response for one complete testing cycle (i.e. a series of
234 U/S reservoir height increases followed by drawdown) are shown in Figure 11.
235 An example extracted section of these data, corresponding to a period of steady-
236 state seepage, is shown in Figure 12, where linear regression lines have been added
237 to the data to demonstrate that steady-state conditions were achieved. It is noted
238 that regressions fitted to measured PPT responses have negligible, rather than
239 zero, gradients. However, pressure gradients in Figure 12 correspond to pressure
240 variations of no greater than 0.25kPa over the 100s period, so that conditions
241 were effectively steady-state.

242 Due to the use of a syringe pump, a series of spikes can be seen in the PPT
243 responses shown in Figure 11. These are due to the emptying of the pump
244 via the outflow (Figure 4), which resulted in a temporary increase in the D/S
245 reservoir water level. Hence, spikes decrease in severity with distance from the
246 D/S reservoir and increase in magnitude with increasing hydraulic gradients due
247 to higher flow rates. Care was therefore taken to avoid emptying the pump
248 towards the end of an equilibration period, to prevent erroneous readings. A
249 large spike is seen in Figure 11 at roughly 7600s; this was due to an error in
250 the operation of the control valve (Figure 4), resulting in the pump drawing

Figure 11: PPT measurements obtained during one full test cycle: E) initial equilibration; 1-6) steady-state flow equilibration periods; DD) U/S reservoir drawdown. Inset: PPT numbering and direction of flow.

additional water from the D/S reservoir after emptying. With the exception of these spikes, Figure 11 shows that the syringe pump provided excellent control over the D/S water levels for the duration of the test. This system can therefore be used to control more complicated seepage regimes in heterogeneous materials, e.g. tailings.

(Insert Figure 11 somewhere near here)

(Insert Figure 12 somewhere near here)

4.2. Calculation of equivalent head levels

Two corrections are required to determine the position of the prototype phreatic surface from model head levels, h_m :

Figure 12: Example extracted PPT pressure measurements (P) against time (t) at steady state (data and PPT numbering as per Figure 11)

261 • Correction for the centrifuge’s radial gravitation field; PPTs detect the
 262 pressure at the base of a water column with an axis that extends from the
 263 point of measurement towards the centrifuge hub, rather than vertically
 264 upwards.

265 • Correction for the average gravity acting on the water column; the gravita-
 266 tional field varies linearly with radius from the centrifuge hub, so that the
 267 average gravity acting on the water column also varies with its length.

268 Total model head can be calculated from measured PPT pressures, P , via

$$h_m = \frac{P}{\rho_w n_{av} g} \quad (2)$$

269 where ρ_w is the density of water at the testing temperature, g is the acceleration
 270 due to Earth’s gravity (i.e. 9.81 m/s^2) and n_{av} is the average acceleration scale
 271 factor for the water column. As n varies linearly with radius from the centrifuge
 272 hub, n_{av} is found from the average of the n values at the bottom and top of the
 273 water column:

$$n_{bottom} = n \left(\frac{r}{R} \right) \quad (3)$$

$$n_{top} = n \left(\frac{r - h_m}{R} \right) \quad (4)$$

$$n_{av} = \frac{n}{2} \left(\frac{2r - h_m}{R} \right) \quad (5)$$

274 where r is the radius from the centre of rotation to the PPT location and R is
 275 the radius from the hub to the base of the model along its centreline, as shown
 276 in Figure 13. For Eqns 4 to 5, $n = 100$ at $R = 1760\text{mm}$ (i.e. the distance from
 277 the centre of rotation to the model base along its centreline, as shown in Figure

278 13). Equivalent non-radial head, H_m , can then be determined via

$$H_m = h_m - (r - R) \quad (6)$$

279 Given the non-vertical orientation of the water column, the length-wise coordinate
280 of the top of the water column (i.e. the predicted location of the phreatic surface),
281 X_m , must also be determined from the PPT lengthwise coordinate, x_m , via

$$X_m = (x_m \pm \Delta x_m) = \left(x_m \pm h_m \sin \left(\arccos \left(\frac{R}{r} \right) \right) \right) \quad (7)$$

282 where Δx_m is additive or subtractive depending on whether the PPT lies to
283 the left or right of the centreline. Eqns 2 to 7 relate measured pressures to the
284 equivalent total head at the model centreline. Hence, prototype head level, h_p ,
285 and corresponding lengthwise coordinate of the phreatic surface, x_p , can then be
286 found via $h_p = nH_m$ and $x_p = nX_m$.

287 (Insert Figure 13 somewhere near here)

288 5. Steady-state behaviour

289 The software package GeoStudio 2007 SEEP/W was used to predict prototype
290 performance, given calculated prototype U/S and D/S reservoir water levels and
291 scaling laws provided in Table 1. Experimental and predicted results for total
292 head levels are shown in Figures 14. Note that, as PPTs are mounted in the
293 model container base, predicted results shown in Figure 14 are those calculated
294 at the mesh base nodes. A comparison of experimental results and those found
295 at these nodes is shown in Figure 15.

296 Figures 14 to 15 show good agreement between measured and predicted head

Figure 13: Conversion between model and equivalent prototype head levels.

Figure 14: Example Predicted and measured results for steady-state seepage. Legend numbers correspond to U/S head increase periods shown in Figure 11.

values, as demonstrated in Figure 15 by results falling on or near to the line of equality. Although it might be expected that errors would be a function of the imposed hydraulic gradient, Figure 15 suggests that an upper error limit of 0.3m exists for all measured head levels. It is therefore likely that this error is due to the simplifying assumptions made in the numerical analysis, for example that no significant head drop occurred across the U/S porous screen.

(Insert Figure 14 somewhere near here)

(Insert Figure 15 somewhere near here)

Notably, Figure 14 shows that predicted U/S head levels are consistently lower (by much more than 0.3m) than those measured in the U/S reservoir. This is unexpected, as U/S reservoir water levels were used as a boundary condition

Figure 15: Predicted against measured steady-state embankment head levels for all U/S head levels (not including U/S reservoir elevations)

in the numerical analysis. A similar error is not seen for D/S reservoir levels, also used as a boundary condition; predicted and measured D/S head levels match. Figure 16 compares measured and predicted head levels as obtained from SEEP/W for PPT results given in Figure 12. Figure 16 shows that the predicted SEEP/W phreatic surface agrees with measured U/S and D/S values, as expected. However, the inclusion of a short impermeable section in the U/S porous screen, shown in Figure 5, results in the distortion of the equipotential lines so that they are not perpendicular to the model base. Hence, the full total head range is not detected by the base-mounted PPTs. Although a deep embankment base was used to attempt to elevate flow above this restriction, it is clear from Figure 16 that insufficient clearance was provided. A similar issue was experienced by Raisinghani and Viswanadham (2011) due to the presence of layers of geosynthetics. It is clearly essential, therefore, that seepage phenomena investigated using this technique are designed so that flow is, as far as practicable, parallel to the model base. Provided that these issues are accommodated, results shown in Figures 14 to 15 demonstrate that the experimental approach developed in this investigation can accurately reproduce steady-state seepage conditions within homogeneous embankments.

(Insert Figure 16 somewhere near here)

6. Drawdown behaviour

Drawdown of the U/S reservoir was modelled using transient seepage analysis in SEEP/W. Steady-state analyses were used to establish the phreatic surface, after which a reducing head boundary condition was applied to the U/S face of the reservoir, whilst maintaining a constant head level at the D/S model face. The reduction in U/S head level with time was determined directly from mea-

Figure 16: SEEP/W analysis for data given in Figure 12 compared to measured values (equipotential values given in m)

333 sured data for the U/S PPT, as shown in Figure 11, using an analysis period of
334 3.5×10^7 s.

335 As transient seepage modelling was used, estimates for material retention and
336 hydraulic properties were required. Initial estimates for material water retention
337 curves for silt and sand are shown in Figure 17, based on data provided in Fred-
338 lund and Xing (1994) and known values of e (Table 2). Estimates for k_{sat} were
339 obtained using

$$k_{sat}(\text{cm/s}) = C_0 \frac{\mu_0}{\mu_T} \left(\frac{n - 0.13}{\sqrt[3]{1 - n}} \right)^2 d_{10}^2 \quad (8)$$

340 where $C_0 = 8$ for smooth particles, $\frac{\mu_0}{\mu_T} = 1.3$ for testing at 20°C , $n = \frac{e}{1+e}$ and e
341 and d_{10} (in mm for use with Eqn 8) are as given in Table 2 (Terzaghi, 1925). It
342 should be noted that the transient phreatic surface experiences increasing accel-
343 erations, and so increasing values of k_{sat} , as its level reduces. However, as this
344 change is small for small changes in elevation, analyses were conducted assuming
345 $n = 100$ for all head levels.

346 (Insert Figure 17 somewhere near here)

347 Although drawdown is a transient phenomenon, negligible difference was
348 found between analyses for variations in k_{sat} of several orders of magnitude,
349 due to the experimentally-defined U/S boundary condition. Seepage was there-
350 fore suggestibly sufficiently slow to be largely independent of hydraulic properties
351 (i.e. quasi-static). Initial estimates for retention and hydraulic properties were
352 therefore deemed sufficient for comparison to experimental data. Note that, for
353 heterogeneous materials such as mine tailings, this simplification would not be
354 valid and accurate retention and hydraulic conductivity functions would be re-
355 quired.

356 Figure 18 shows example experimental and predicted results for total head

Figure 17: Estimated soil-water retention curves for silt and sand

357 levels (predicted at the embankment base) during drawdown. Predicted and
358 experimental values are compared in Figure 19. Good agreement is seen in Fig-
359 ure 18 between measured and predicted results throughout the embankment pro-
360 file. This is also shown in Figure 19, where errors are within $\pm 0.4\text{m}$ and fall
361 evenly about the line of equality. Drawdown was largely complete after 3200s,
362 equivalent to roughly 370 days at $n = 100$. As discussed previously, however, the
363 larger lateral extents of full-scale TSFs mean that drawdown times in practice
364 are likely to be far longer than those found in this work, suggesting that pumping
365 might be required for decades in order to fully restore groundwater equilibrium.

366 Unlike in Figure 15, both positive and negative differences are seen in Fig-
367 ure 19. A potential cause of this error is the assumption that $n = 100$ at all
368 times during drawdown. Overprediction of processes dominated by horizontal
369 flow (i.e. steady-state seepage surfaces) and underprediction of those dominated
370 by vertical flow (i.e. reducing head levels during transient seepage) also suggests
371 that a degree of heterogeneity existed within the embankment material, so that
372 $k_{sat,h} > k_{sat,v}$. This is consistent with the deposition of the silt slurry in lay-
373 ers during model construction; although material was subsequently consolidated,
374 preferential flow in the horizontal direction may have remained. This is an im-
375 portant observation, as it is well-known that layered structures are also created
376 during tailings deposition in TSFs. Scale models should therefore incorporate
377 this layered structure in order to capture the effects of hydraulic heterogeneity
378 on seepage performance.

379 (Insert Figure 18 somewhere near here)

380 (Insert Figure 19 somewhere near here)

381 The good agreement found between measured and predicted steady-state and
382 drawdown results demonstrates that experimental techniques developed and em-

Figure 18: Example predicted and measured results for times following U/S reservoir drawdown.

Figure 19: Predicted against measured steady-state embankment head levels for all U/S head levels during drawdown (not including U/S values)

383 ployed in this investigation are able to accurately capture embankment seepage
384 behaviour. Notably, these techniques offer greater flexibility than those previ-
385 ously used in terms of D/S flow rate measurement and accurate control of U/S
386 and D/S water levels. This facility can now be used to investigate more com-
387 plicated seepage scenarios, for example those encountered in full-scale TSFs, to
388 provide data for improving current seepage prediction models.

389 7. Conclusion

390 Seepage conditions within TSF embankments are likely to be far more com-
391 plicated than current models predict. There is therefore a need for experimental
392 data against which updated numerical models can be verified. This paper has de-
393 scribed the design and development of apparatus for measuring seepage through
394 model TSF embankments using a geotechnical centrifuge. The use of a syringe
395 pump was shown to be an effective method to control D/S water levels and to
396 measure seepage flow rates. Novel processes for determining material consol-
397 idation behaviour and sand filter effectiveness using a desktop centrifuge and
398 image-based analysis were also described, each providing rapid alternatives to
399 conventional testing methods.

400 Results for steady-state seepage through a homogeneous model were presented
401 and good agreement was found between measured results and those predicted for
402 an equivalent full-scale prototype using SEEP/W. A maximum error of 0.3m was
403 found between measured and predicted results, which was seemingly independent
404 of testing hydraulic gradient and attributed to assumptions made during numer-
405 ical modelling. It was also demonstrated that flow through the model must be
406 designed so that it is parallel to the model base if seepage behaviour is to be
407 tested using equipment similar to that developed in this work.

Predicted results for changes in total head during U/S reservoir drawdown, based on simplifying quasi-steady assumptions, showed good agreement with numerical predictions. Differences of $\pm 0.4\text{m}$ between measured and predicted values were similar to those found for steady-state seepage. A comparison of steady-state and drawdown experimental results suggested that these differences were due to a slight material heterogeneity developed during deposition. A drawdown time of roughly 370 days was predicted for the tested embankment profile. Based on these results, there is confidence that techniques developed here can reliably reproduce seepage conditions within full-scale heterogeneous embankments.

8. Acknowledgements

The authors would like to gratefully acknowledge funding awarded from The Integrated Tailings Management Project, funded through AMIRA International by; Anglo American, Freeport McMoran, Gold Fields, Total E&P Canada, Newmont, Shell Canada Energy, BASF, Nalco and Outotec.

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462 Figure captions:

- 463 1. Sectional views through centrifuge strongbox showing principal equipment
464 components and model container
- 465 2. Centrifuge strongbox with installed model container, camera and lighting
466 system
- 467 3. Model container: schematic view and components. 1) Perspex screen; 2)
468 backing plate; 3) porous polyethylene sheets; 4) porous screen frames; 5)
469 bolt holes; 6) O-rings; 7) embankment PPTs (under filters); 8) reservoir
470 PPTs (under filters).
- 471 4. Container hydraulic diagram
- 472 5. Model dimensions (not to scale)
- 473 6. Embankment and filter material particle grading curves. $\square$ RC sand; $\circ$ Silt;
474 $\times$ FEMA (2011) filter limits
- 475 7. Desktop centrifuge with laptop, customised containers and RPM controller
- 476 8. Silt consolidation as determined using the desktop centrifuge
- 477 9. Process used for filter integrity testing
- 478 10. Normalised pixel intensities against depth (results for every 10th pixel only
479 for clarity). Inset: Example photograph showing analysed cropped image
480 section.
- 481 11. PPT measurements obtained during one full test cycle: E) initial equi-
482 libration; 1-6) steady-state flow equilibration periods; DD) U/S reservoir
483 drawdown. Inset: PPT numbering and direction of flow.
- 484 12. Example extracted PPT pressure measurements (P) against time (t) at
485 steady state (data and PPT numbering as per Figure 11)
- 486 13. Conversion between model and equivalent prototype head levels.

- 487 14. Example Predicted and measured results for steady-state seepage. Legend
488 numbers correspond to U/S head increase periods shown in Figure 11.
- 489 15. Predicted against measured steady-state embankment head levels for all
490 U/S head levels (not including U/S reservoir elevations)
- 491 16. SEEP/W analysis for data given in Figure 12 compared to measured values
492 (equipotential values given in m)
- 493 17. Estimated soil-water retention curves for silt and sand
- 494 18. Example predicted and measured results for times following U/S reservoir
495 drawdown.
- 496 19. Predicted against measured steady-state embankment head levels for all
497 U/S head levels during drawdown (not including U/S values)
- 498 Table captions:
- 499 1. Summary of scaling factors for centrifuge seepage modelling assuming ge-
500 ometric and dynamic similitude. $X^* = \frac{X_m}{X_p}$ where X_m and X_p are the
501 property vales in the model and prototype respectively. †At steady state
- 502 2. Silt and sand material properties