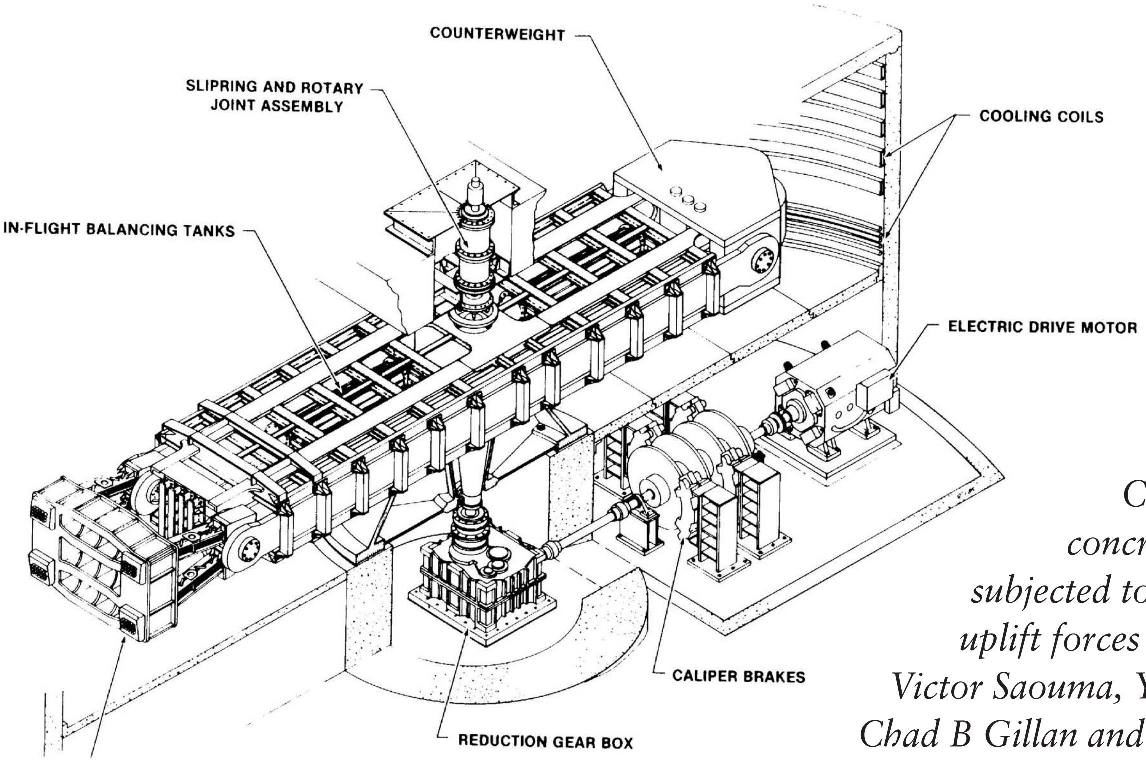


Figure 1: Schematic of the University of Colorado 400~g-ton

Centrifuge tests of concrete gravity dams subjected to hydrostatic and uplift forces are presented by Victor Saouma, Yoshihisa Uchita, Chad B Gillan and Takashi Shimpo

Testing times

ANY laboratory test of a structure must satisfy, in as much as possible, all laws of similitude. Whereas this does not pose a problem for all structures where the effect of gravity is either negligible or can be simulated by additional mass, it is a particularly difficult problem for massive structures with distributed mass such as concrete gravity dams. Hence, to properly satisfy all the laws of similitude in a dam, gravity of the model must be inversely proportional to the one of the prototype. Hence, a correct laboratory test of a concrete gravity dam must be performed in a centrifuge.

Large scale centrifuges have been used mostly (if not exclusively) for geotechnical applications (including embankment dams). In the mid 1960s, centrifuge tests on models made of Plexiglas were undertaken. In those tests, a small cross section of a gravity dam (about 20cm in height) was subjected to a high g field while it was heated to freeze the stress pattern (Takata et al., 1961). Pioneering experimental centrifuge tests were undertaken in the former Soviet Union but yielded no significant results; thus no scientific publications resulted, (Trapeznikov, 1991). The first centrifuge tests addressing fracture mechanics were performed by Broz et al. (1991). It was not until the early 1990's that the first comprehensive centrifuge test program for dams was initiated, (Waggoner et al., 1993, 1995). In those early tests, the focus was on developing a methodology to perform the test, instrumentation, impounding and data analysis. Although nothing has yet been reported, a concurrent research effort focusing on centrifuge experimentation of concrete gravity dam models is underway at ISMES in Bergamo (Plizzari et al., 1992).

Whereas most laws of similitude can be respected in a centrifuge test of concrete, some cannot. In particular the stress-softening curve (stress-displacement) cannot as there are conflicting scaling ratios (1 and λ respectively). This was first pointed out in a pioneering paper by Palmer and Rice (1973). A size effect exists between the model and the prototype. Thus, for nonlinear fracture analyses of concrete models, subjected to tensile strengthening (where tensile stress is a function of crack opening displacement), direct comparisons of experimental versus analytical results cannot be made unless the material is properly modelled.

Hence this paper will present results of recent tests, where for the first time uplift has been modelled at the dam base using a special concrete mix, which attempts to properly simulate the permeability and the stiffness of the rock foundation. The objective is not to model a particular dam, but rather to model a generic dam, with a certain type of permeable foundation, and then to determine if a finite element code can be validated through those tests. First we will describe the centrifuge used, then the specimen preparation instrumentation, and testing procedure. Finally test results and finite element analysis results will be presented. More details can be found in Gilan (2002).

Centrifuge description

An overview of the University of Colorado 400 g-ton centrifuge is shown in Figure 1 (Ko, 1988).

The University of Colorado 400 g-ton centrifuge shown in Figure 1 has been operational since 1988. It ranks among the world's leaders in capacity (in terms of g-tons). Its unsymmetrical rotor arm, weighing approximately 40 tons and housing an in-flight balancing system, has a swinging platform which carries the payload on one end, and a fixed counterbalance on the other. Fully extended, the top of the swinging platform has a radius of 18ft (5.5m). Payloads as large as 4ft by 4ft by 3ft (1.2m x 1.2m x 0.9m) and weighing two tons can be taken to a maximum of 200 g by a large DC electrical motor. The centrifuge is housed in a completely underground chamber with liquid cooled chamber walls to dissipate any heat. An automatic control system, operated by two computers, operates the centrifuge. One computer is a programmable logic controller, which regulates the drive motor and brakes. The other receives signals from various transducers monitoring performance parameters of the entire system and, after comparisons with reference values, commands the logic controller to execute speed control of the rotor. The centrifuge has 100 electrical slip rings, 50 of which are committed to system control, with the remainder used for data acquisition.

Specimen preparation

Geometry
The adopted geometry closely resembled an existing dam, but more importantly an attempt was made to simulate both the foundation stiffness (as characterised by its elastic modulus), and its permeability. Despite the capacity of the centrifuge to deliver 200 g, it was decided to test the dam at 30 g in order not to overstress the delicate instrumentation, which was going to be used for the first time. Hence, a small dam of 13m was considered, to which another 14m of rock was added, thus resulting in a total model height of 27/30=0.90m high. This height was the maximum which could be accommodated in the authors' container. Hence the dam height (without the foundation) was 465mm, the dam base 313mm, and the downstream slope was set to 1:0.57. The dam rested on a monolithic block of concrete, simulating the foundation, having the same width as the one of the dams – 500mm.

Design mix
As indicated earlier, the authors' particular interest was to develop a concrete mix for the foundation having nearly similar elastic modulus and permeability as the one of the prototype foundation (set to 51,000kg/cm^2, and 3cm/sec respectively). Whereas there was no difficulty achieving the desired stiffness, permeability was approached by adding bentonite to the concrete mix. After approximately six months of concrete mix design testing, a base mix design was used. From this base mix design a total of four batched were used to create seven different foundation by slightly varying the base mix design. The two major mix designs are reported in Table 1. The resulting strength, stiffness and permeability are shown in Table 2. Finally, the 11cm slump dam mix is shown in Table 3, it yielded a modulus of elasticity of 14,20Mpa, and a compressive strength of 20.2Mpa.

Specimen preparation
The foundation was cast first. Great care was exercised in placing five 2mm ID flexible tubes inside the foundation. At one end, one tube was aligned upstream from the upstream face of the dam, and four others ran along the interface of the foundation and soon-to-be dam base. At the other end, those tubes day lighted on the downstream side to be connected with pressure transducers. Following the foundation casting, the surface was wire brushed to remove all laitance and the dam concrete formed and placed on top of it. The model was then left in the 'fog-room' to cure for two weeks. Following the curing process, the model was left outside the fog room to surface dry overnight in the structure's laboratory before a rubber membrane was epoxied over its four sides and bottom surfaces. A layer of epoxy was also generously placed on the top of the downstream surface of the foundation to control the migration of water through the foundation. Then the dam was placed inside a specially built 2.54cm thick aluminium container. Sikaflex (a sealer) was generously applied along all the edges to prevent leakage. Figure 2 shows the dam model prior to testing, and prior to a 2.5cm thick Plexiglas plate which secures the dam inside the container, and provides a translucent surface through the which to view the dam with two video cameras. In addition to the Plexiglas securing the side of the dam, a piece of Plexiglas was also installed over the crest of the dam (still allowing movement of the dam crest) and the upstream portion of the foundation.

Instrumentation and testing procedure
Instrumentation (Figure 3) consisted of the following:

- *Displacements: Two linear variable displacement transducers* (LVDT) were used to measure crest displacement with respect to the container; another LVDT and a proximity probe were used to measure the displacement of the foundation with respect to the container. Hence through the algebraic addition of those two measurements, the crest displacement with respect to foundation was determined (hence eliminating any effect of the model sliding inside the container).
- *Strains were recorded by fur strain gages* placed on the upstream and downstream faces of the dam.
- *Uplift pressures were recorded by five pressure transducers* mounted inside a sealed box on the downstream side of the foundation.
- *Crack mouth opening displacement (CMOD)* was recorded by a clip gage and a proximity probe.

Once the specimen was installed in the container, and then mounted on the centrifuge basket, all the instrumentation was connected to the data acquisition system. The test began by ramping the centrifuge to the desired g-level, and then the specimen was given about 30 minutes of constant g to undergo 'self-weight' displacements. During that time, the water valve was carefully opened in order to saturate the foundation, without impounding the dam. Once the

Figure 2: Dam model inside the container

Table 1: Foundation mix design

	Batch 3	Batch 4
Water (C)	305kg/m^3	217kg/m^3
Cement (C)	277kg/m^3	277kg/m^3
Bentonite (B)	69kg/m^3	69kg/m^3
Aggregate	1485kg/m^3	1485kg/m^3
W/C	110%	78%
B/(C+B)	20%	20%
B/W	23%	32%

Table 2: Foundation concrete properties

			Batch 3		Batch 4	
		Target	7 days	28 days	7 days	28 days
Compressive strength	(MPa)	-	3.9	8.5	9.8	12.1
Youngs Modulus	(MPa)	5000	4580	6070	7360	7850
Permeability x 10-4	(MPa)	3.00		0.64		1.01

Table 3: Dam concrete mix

SG - Specific Gravity	1.00	3.15	2.70	2.70	1.2	1.01
Mix	W	C	S	G	A	Additives
	Water	Cement	Sand	Gravel	No.80	AE 90
	Kg/m^3				**% of cement**	
	167	267	847	1035	0.6	0.03%

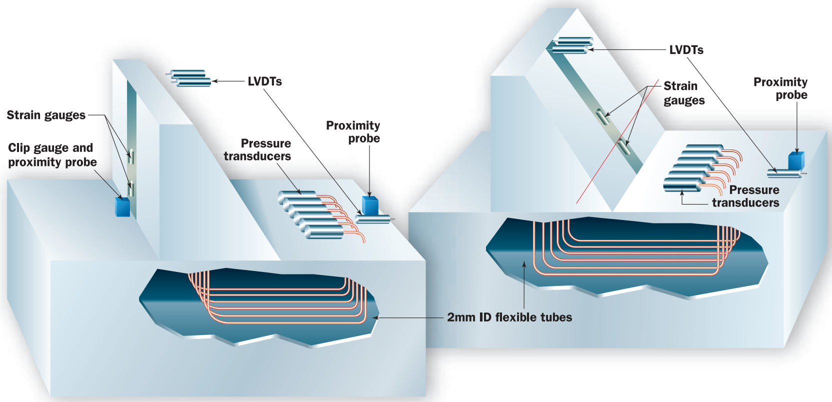


Figure 3a: Instrumentation

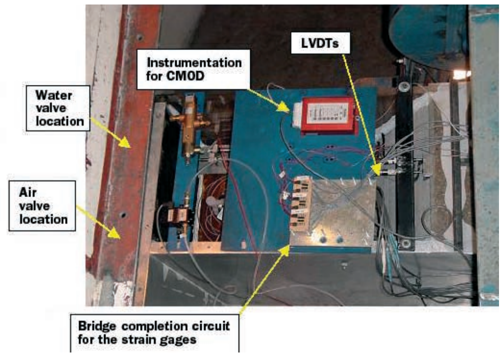


Figure 3b: Top view of container

foundation was fully saturated and the instrumentation showed no further sign of settlement, the upstream side of the dam was impounded. When water reached the dam crest (as determined from the pressure transducer readings and views though the video-cameras), the water was shut down, and an air-valve opened to allow overtopping simulation. This was achieved by applying compressed air on the upstream side of the dam. In order to achieve proper uplift pressure distributions under the dam, water was allowed to migrate through the foundation and be pumped back to the upstream side of the dam using a compressed air driven pump. The pump also mitigated problems associated with potential unwanted leakage of water to the downstream face. Finally, all data acquisition, and control of the test was performed, viewed and recorded in real time through a LabView environment in the centrifuge control room (Figure 4).

Test results

Given the complexity of the experiment, numerous pilot tests were performed, before successful ones could be completed. Most major difficulties encountered were related to unwarranted leakage of the water from the side, difficulties with some of the instrumentation, or in one case premature failure due to uneven support for the foundation. Hence only three satisfactory tests were performed before the project was completed.

Whereas more details about all the tests can be found in Gillan (2002), the author's report on test 6-3 in particular. In this test the dam was completely filled with water, and pressurised with air to simulate overtopping. Figure 5 shows the true crest displacement and a factored water level versus time. The factored water level is the hydrostatic pressure (in terms of water level) seen by the dam divided by a scaling factor that allows the correlation between the true crest displacement and the water level to be shown. True crest displacement is the measured crest displacement minus the measured foundation displacement, to take into account sliding of the model in the container. As seen in Figure 5, two cycles of rapid overtopping were simulated twice to view the elastic response of the true crest displacement.

Out of the two LVDTs measuring crest displacement, only one gave accurate results. The second seemed to stick under the g-force; it gave the same max displacement, but did not show the dam move back upstream when the overturning pressures decreased. The dam did not fail due to overtopping pressure; instead there was a localised failure in the seal that contained the water in the foundation. This is noted in Figure 5 where depressurisation is marked.

Figure 6 shows the variation in both the upstream hydrostatic pressure, as well as the uplift pressures below the dam. With the exception of PT-4 (probably a malfunctioning pressure transducer) uplift measurements appear to be qualitatively correct; the highest pressures were closest to the dam heel, and the lowest pressures were closest to the dam toe. Notice that after the first cycle of simulated overtopping the residual true crest displacement is lower than the original true crest displacement, in spite of the slight increased water level (Figure 5). This can be understood from the change of the uplift pressure distribution in Figure 6. After the simulation of overtopping by air pressure, the residual uplift pressure of PT5 and PT6 (located on the downstream side of the dam base) increased much more than PT2, PT3 and PT4 (located on the upstream side of the dam base), therefore decreasing the overturning moment on the dam and effectively reducing the true crest displacement.

As for the strain gages, the upstream left and downstream left strain gages gave good results. Finally, the CMOD measurement (with the proximity probe and clip gage) was discarded, because any displacement would have been much smaller than the resolution recorded from the instrumentation. The harsh environment of the centrifuge can cause unexpected effects on instrumentation especially when the instrumentation is submerged in water. However, we can assume crack propagation from the heel to the toe of the dam base from the fact that all residual uplift pressures (except PT4) became almost the same value as the upstream water pressure.

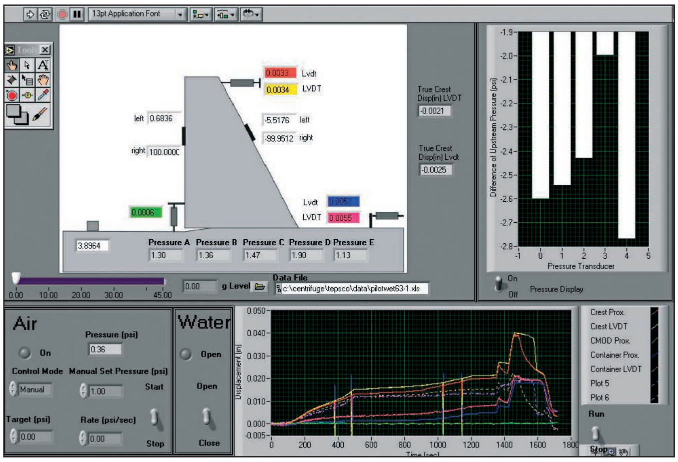


Figure 4: Labview control panel

Finite element analysis

A major objective of this research was to provide reliable experimental data to asses the capability of the authors' finite element program to make first post mortem prediction, and should the results be satisfactory, to subsequently make reliable predictions.

Whereas a 2D analysis would have been sufficient for the dam, the complexity introduced by the Sikaflex along the edges warranted a three dimensional one. Furthermore, in this 3D analysis, displacements caused by gravity were ignored (as they took place prior to impounding), and focus was exclusively on crest displacement and uplift forces in terms of water elevation. Analysis was performed by the computer code Merlin.

Hence, Interface elements using the Interface Crack Model (ICM) were inserted between the foundation and the dam in order to model the true dam/foundation interface, and along the side of the dam (between container and dam) to simulate the effect of the Sikaflex. The interface elements between the dam and the foundation were initially closed, and when the traction exceeded the tensile strength of the interface they opened up, and thus allowed the influx of the

Figure 5: True crest displacement vs time

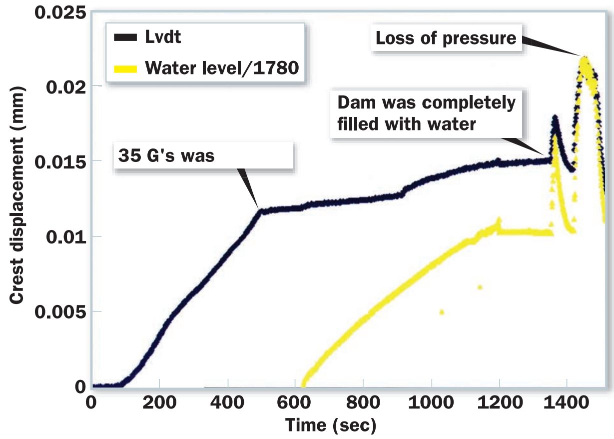


Figure 6: Pressure vs Time test 6-3

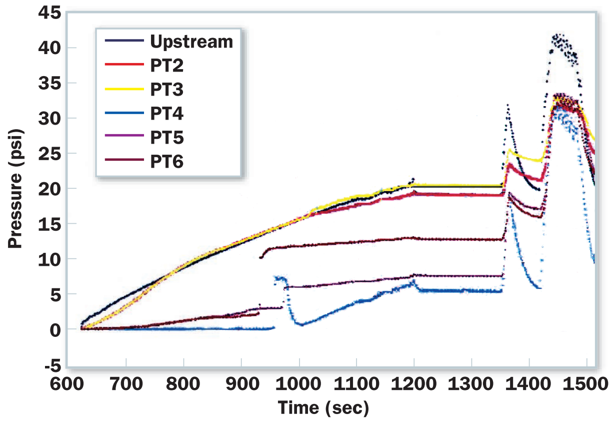
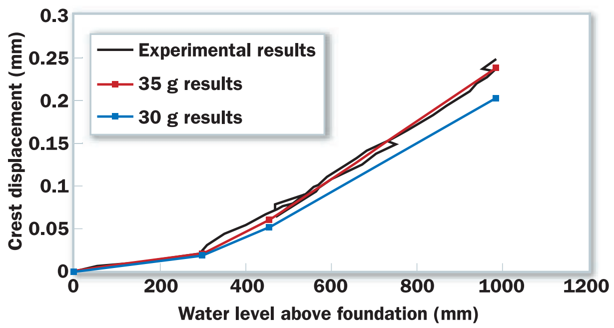


Figure 7: Experimental and numerical crest displacements in terms of water level



water causing the uplift. Hydrostatic forces caused by the dam impounding were applied on both the upstream face of the dam, and the foundation. The corresponding recorded uplift at the dam base was applied on the numerical model.

Two analyses are reported: 30 and 35 g, because whereas the experiment was conducted at 35 g, this maximum acceleration occurs at the base of the foundation. The g-level variation with respect to the centrifuge axis being quadratic, and zero at the axis of rotation, it was determined that the dam centroid will be subjected to 30 g.

The material properties were identical to the one measured from laboratory tests, with the exception of the foundation elastic modulus. It was determined that good correlation between tests and analysis could only be achieved by reducing the foundation's Young modulus from 8300MPA to 1527MPA. This can be explained by the rather coarse aggregate size used in the foundation concrete, the presence of bentonite (which was essential to ensure enough permeability for the uplift to develop), the observed presence of pockets/voids (caused by limited vibration to safeguard the uplift measurement tubes) and the relatively small size of the test cylinders used for the determination of E.

Figure 7 compares the numerical predictions with the experimentally recorded ones. Whereas this good fit was achieved by reducing the foundation modulus, all other physical characteristics were taken straight out of laboratory tests. If the recorded uplift was ignored, yielded crest displacements were off by more than 20% (although not shown in Figure 7).

Summary

Despite limited experimental data, the reported tests are the first in which uplift measurements have been made for a concrete dam in a centrifuge; a special concrete mix with sufficient permeability was developed to model a pervious foundation. The know-how to perform these complex tests has been refined, and is currently exploited in other tests performed under the auspices of the Tokyo Electric Power Company (TEPCO) on the centrifuge facility of Obayahi Corporation where a dam model is mounted on a shaking table installed in a centrifuge. Finally, those tests enable the validation of the authors' finite element code (Merlin) to correctly model static nonlinear dam response with uplift and crack opening. IWP&DC

The authors are Professor Victor Saouma, University of Colorado, Chad B Gillan, URS Corporation, Yoshihisa Uchita and Takashi Shimpo, Tokyo Electric Power Company.

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