Title
NGC FACILITY AND TRENDS IN COST OF CENTRIFUGES

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A symposium on Recent Advances in Geotechnical Centrifuge Modeling was held on July 18-20, 1984 at the University of California at Davis. The symposium was sponsored by the National Science Foundation's Geotechnical Engineering Program and the Center for Geotechnical Modeling at the University of California at Davis.

The symposium offered an opportunity for a meeting of the International Committee on Centrifuges of the International Society for Soil Mechanics and Foundation Engineering. The U.S. participants also met to discuss the advancement of the centrifuge modeling technique in the U.S. A request is being transmitted to the American Society of Civil Engineers to establish a subcommittee on centrifuges within the Geotechnical Engineering Division.

NGC FACILITY AND TRENDS IN COST OF CENTRIFUGES

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THE NGC FACILITY

The National Geotechnical Centrifuge is the largest capacity centrifuge of its type in the Western World. Located at NASA Ames Research Center at Moffett Field, California, the NGC will be open for use by any bona-fide researcher. The capabilities and acceleration goals of the machine are listed in Tables 1 and 2. Figure 1 shows an isometric view of the machine. Several pieces of the data acquisition system and sample preparation equipment of the NGC have been acquired. The data acquisition system consists of a DEC LSI 11/23 computer with an ADAC "Direct Memory Access" analog to digital converter (which digitizes 100,000 data points per second), a plotter, printer, terminal, and an onboard signal conditioning system. A 35 mm camera, two video cameras and high speed movie cameras are available. Bins, hoppers, an overhead crane, and a soil delivery system have also been acquired.

Construction of this large centrifuge was made possible by a grant from NSF along with hardware and engineering support from NASA Ames Research Center. NASA provided an obsolete manned motion simulation centrifuge which could be modified for geotechnical research. It was possible to use the rotunda, slip rings, drive motor, and power supply from the old centrifuge, which greatly reduced the required costs.

After reaching 35 g accelerations in several separate runs, the drive motor thrust bearing failed and caused significant damage. The bearing was carrying loads well within its capacity, but improper lubrication caused a premature failure. Presently, funding is being sought to carry out the repair and completion of the centrifuge.

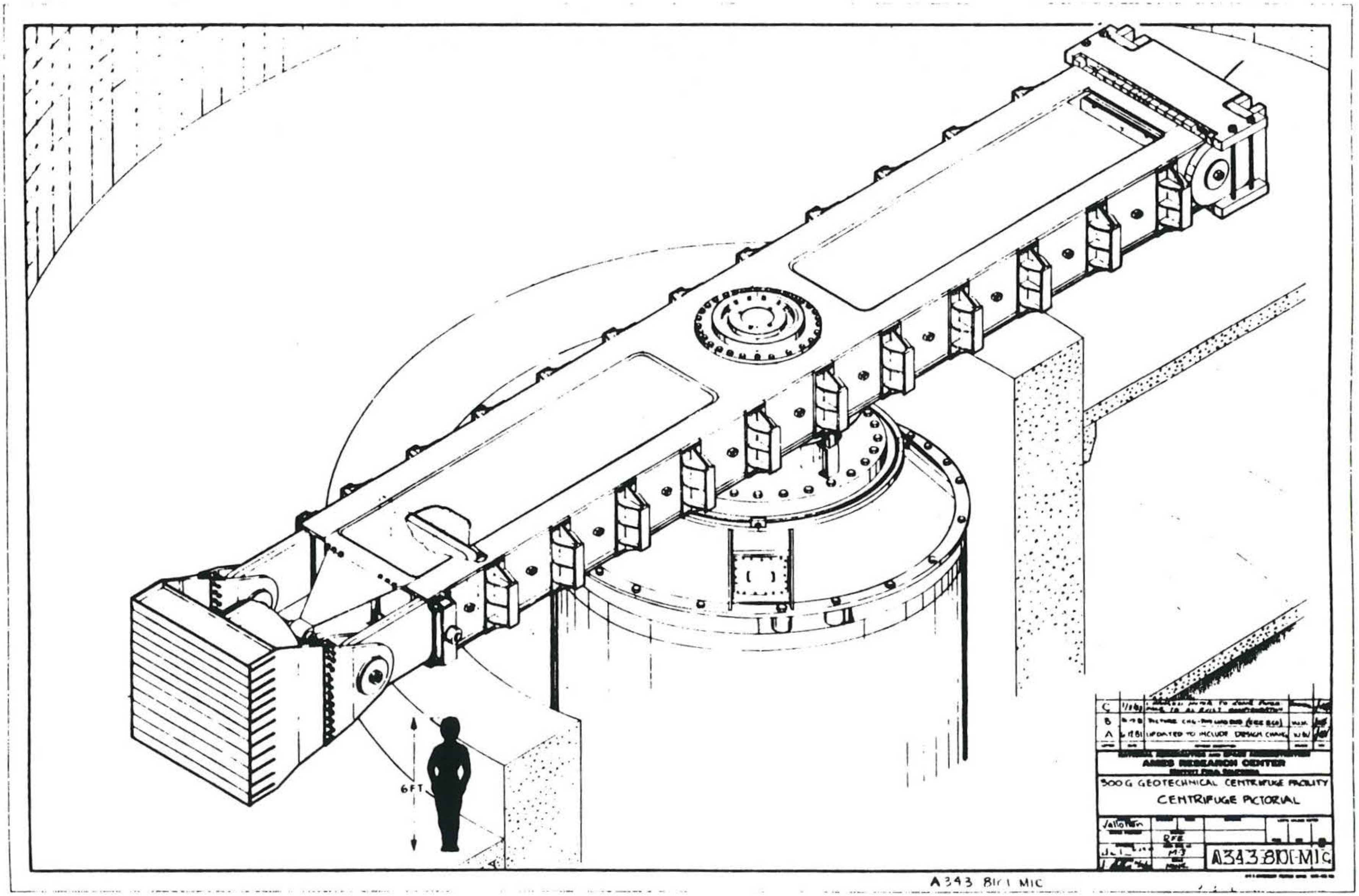

FIGURE 1. Isometric View of the National Geotechnical Centrifuge

Achievement of a 300 g acceleration capability will require significant architectural modifications to improve the aerodynamics of the rotunda in order to reduce power requirements. This may include lowering the ceiling, reducing the radius and smoothing the walls of the centrifuge chamber. Our analyses show that faring the centrifuge arm would be difficult and would only provide secondary reductions in power requirements. Streamlining the arm results in an increase in the relative velocity between the arm and the air so that the power requirements are not reduced in proportion to the reduction in the drag coefficient as may be intuitively expected.

TABLE 1

NGC Capabilities

Payload Capacity	6,000 lb	2,700 kg
Allowable Out-of-Balance Mass (at 300 g)	600 lb	270 kg
Radius to Platform Surface	30 ft	9.2 m
Platform Dimensions	6 x 7 ft	1.8 x 2.2 m
Platform Area	42 ft^2	4.0 m^2

TABLE 2

Acceleration Goals

35 g	achieved December 1983
70 g	goal for February 1984 not achieved due to bearing failure
100 g	can be achieved after bearing repair
300 g	requires aerodynamic modification
2000 g-ton	100 g, 20 ton payload requires new platform and swinging counterweight

The free body diagram in Figure 2 shows the tensile force, F, at the centerline opposing the inertia force of the payload (Nw), and the inertia force on half the arm ($\frac{N}{2}\frac{W}{2}$). The center of gravity of half of the arm in the free body diagram is assumed to be at D/4, where the centripetal acceleration is N/2. Equilibrium gives:

$$F = (\frac{N}{2}\frac{W}{2} + wN) \tag{1}$$

$$F = (w + \frac{W}{4})N \tag{2}$$

where W is the weight of the arm. The minimum cross-sectional area of the arm is related to this force by the allowable tensile stress, σ_{all}

$$F = \sigma_{all}A \tag{3}$$

Eliminating F from (2) and (3) we obtain

$$\sigma_{all}(A) = (w + \frac{W}{4})N \tag{4}$$

We can then multiply both sides by $D\gamma$ giving

$$\sigma_{all}(AD\gamma) = (w + \frac{W}{4})ND\gamma \tag{5}$$

where D = length of arm, γ = unit weight of metal, and $AD\gamma$ is simply the weight of the arm, W. Solving equation (5) for W gives

$$W = \frac{w}{\frac{\sigma_{all}}{ND\gamma} - \frac{1}{4}} \tag{6}$$

This relation indicates that a centrifuge of uniform cross-section approaches infinite weight as $\frac{\sigma_{all}}{ND\gamma}$ approaches $\frac{1}{4}$. For typical high-strength steel, γ = 500 lb/ft^3 and σ_{all} = 30,000 lb/in^2. The critical value of ND, when the denominator becomes zero, can be determined from

$$\frac{30,000\ \mathrm{lb/in^2}}{ND\ (500\ \mathrm{lb/ft^3})} = \frac{1}{4} \tag{7}$$

$$ND = 414,720\ \mathrm{in} \tag{8}$$

for a 30' radius (720" diameter), the critical g-level is N = 576. Again, assuming σ_{all} = 30,000, and γ = 500 lb/ft^3, if the model dimension is to be no larger than one-tenth of the diameter, there is a limiting prototype dimension D_p that can be simulated on the centrifuge:

$$D_p = \frac{ND}{10} = \frac{414,720''}{10} = 3,456\ \mathrm{ft} \tag{9}$$

Equation (6) assumes that all the steel in the centrifuge structure acts in pure tension. In reality, a major portion of the centrifuge mass is required to hold the centrifuge up under the 1 g loading of earth's gravity. However, the design of the NGC and other recently designed machines use a scheme that separates the primary centrifugal loads from the 1 g down loads. Centrifugal loads are taken almost in pure tension of straps. Equation (6) probably provides a reasonable estimate of the required weight of tension straps for centrifuges where the centrifugal tension and the 1 g bending loads are de-coupled. However, for all centrifuges the weight determined from equation (6) may be approximately proportional to the actual required arm weight. The equation does serve to indicate the trends in centrifuge weight which in turn can be assumed to be roughly proportional to centrifuge cost.

To obtain a consistent comparison between the costs of three hypothetical centrifuges, let us assume the characteristics listed in Table 3. To approximately account for the fact that the tensile members will be subject to loads other than pure tension, the allowable tensile stress in Table 3 has been reduced to 20,000 psi instead of 30,000 psi as used in the above calculations.

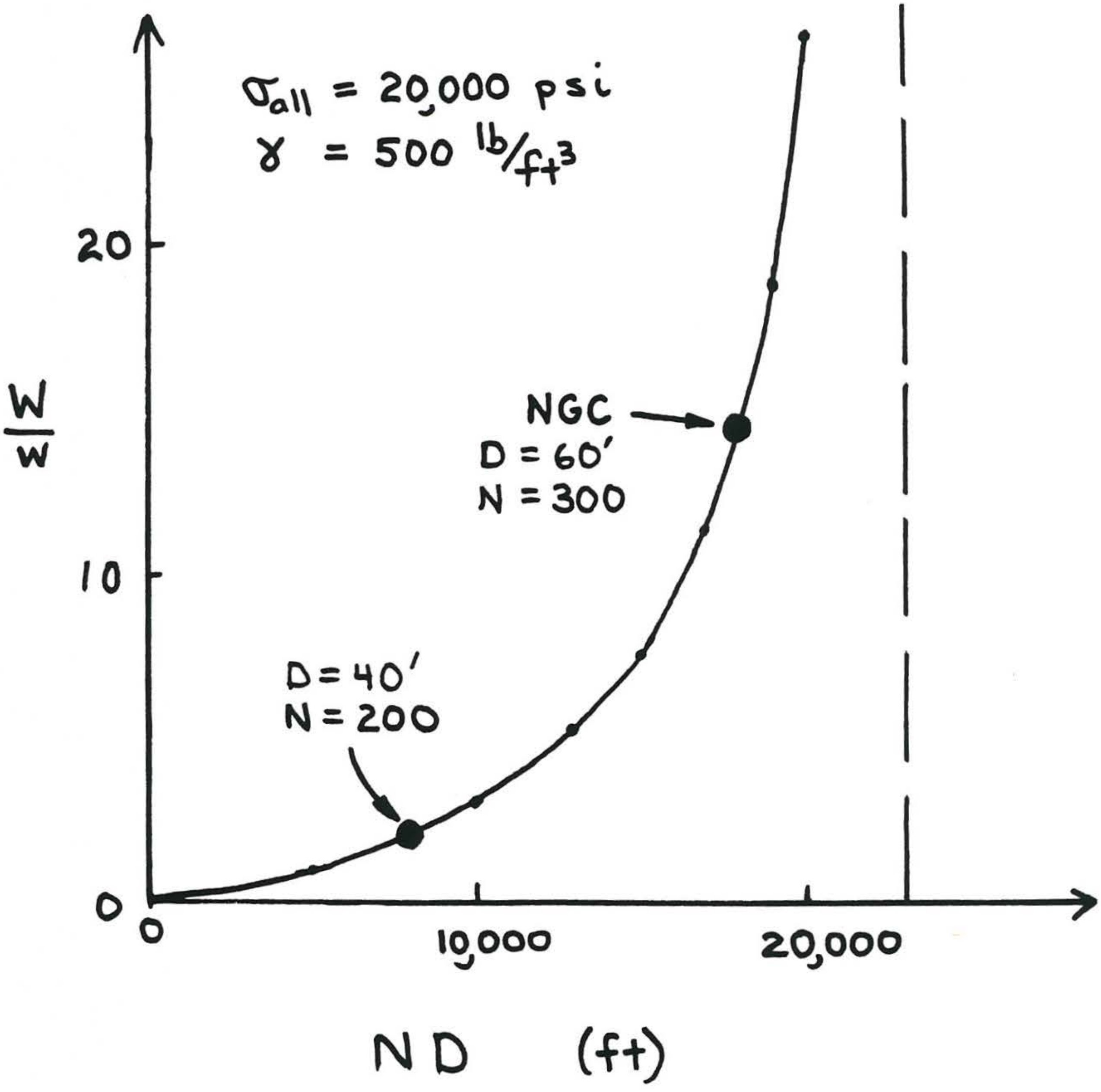

FIGURE 3. Relation Between the Ratio of Arm Weight to Payload Weight and Centrifuge Diameter According to

$$\frac{W}{w} = \frac{1}{\frac{\sigma_{all}}{ND\gamma} - \frac{1}{4}}$$

TABLE 3

Centrifuge	I	II	III
Payload Weight, w (lb)	4,000	6,000	40,000
Centrifuge Acceleration N (g)	200	300	100
Centrifuge Diameter, D (ft)	40	60	60
Density of Structural Material, $\gamma\ (\frac{lb}{ft^3})$	500	500	500
Allowable Tensile Stress σ_{all}(ksi)	20	20	20
$\frac{ND\gamma}{\sigma_{all}}$	1.39	3.125	1.04
$W = \frac{w}{\frac{\sigma_{all}}{ND\gamma} - \frac{1}{4}}$ (lb)	8,521	85,700	50,600

The final row in Table 3 indicates that the tension straps for centrifuge II (a 900 g-ton machine) would weigh an order of magnitude more than for centrifuge I (the 400 g-ton machine). Part of the reason for this dramatic increase in centrifuge weight is that centrifuge II is approaching the theoretical limit where, as $\frac{ND\gamma}{\sigma_{all}}$ approaches 4, the centrifuge weight approaches infinity. It is recognized that the selected values of γ and σ_{all} can be altered for various centrifuge designs, but the trends in cost indicated by Table 3 should be valid. Figure 3 illustrates the dramatic rate of increase of centrifuge weight as the factor ND increases.

Power Requirements

Since a large centrifuge requires more power than a smaller one, costs are expected to increase. Consider an element of area dA of the cross-section of the arm where $dA = hdr$ and h is the thickness of the arm. The torque dT required to push this element through the air is

$$dT = rdF \tag{10}$$

where r is the radius to the element and dF is the drag force on the element:

$$dF = C_D \rho V^2 dA \tag{11}$$

where C_D is the drag coefficient, ρ is the air density, and V is the relative velocity between the arm and the air. If V is assumed to be a constant factor k times the absolute arm velocity,

$$dF = C_D \rho \ (k^2 \omega^2 r^2) \ h \ dr \tag{12}$$

$$T = (C_D \rho \omega^2 k^2 h) 2 \int_0^R r^3 dr \tag{13}$$

$$T = (C_D \rho \ k^2 h) \ \frac{\omega^2 R^4}{2} \tag{14}$$

The power, P, required is simply ωT

$$P = C_D \rho h k^2 \ \frac{\omega^3 R^4}{2} \tag{15}$$

$$P = C_D \rho h k^2 \ (\omega^2 R)^{1.5} \ R^{2.5} \tag{16}$$

which (if C_D, ρ and k are constant) is proportional to what we shall call a power index, P.I.

$$\text{P.I.} = hN^{1.5} R^{2.5} \tag{17}$$

where N is the g level. We can again compare hypothetical machines as in Table 4.

TABLE 4

Centrifuge	I	II	
Arm Thickness, h	2'	3'	
Arm Radius, R	20'	30'	
g-Level, N	200	300	
P.I.	1.0×10^7	7.7×10^7	4.2×10^7

The 900 g-ton machine would require approximately eight times more power than the 400 g-ton machine. This factor of eight will cause a similar increase in the costs of the drive motor, power supply, wiring, and architectural treatment to reduce power requirements.

SUMMARY

The calculations in this paper indicate that the weight of a centrifuge increases disproportionately with an increase in the ratio $\frac{ND\gamma}{\sigma_{all}}$. The calculations show that to support the centrifugal loads alone in a machine similar to the NGC at 900 g-tons would require almost ten times as much steel as a smaller radius 400 g-ton machine. Power related costs were also shown to increase by approximately a factor of eight when increasing the capacity from 400 to 900 g-ton and increasing the radius from 20 to 30 feet.

In the initial conceptual stages of the NGC it was realized that the machine may cost about $10 million to build from scratch. Modification of the existing NASA facility allowed considerable savings. NASA has provided the buildings, the drive motor, a power supply, a large slip ring unit, and a large amount of engineering support. This has enabled the facility to nearly reach 100 g capability at a fraction of the cost of starting from nothing. It is important for the geotechnical community to take advantage of the significant contributions made by NASA. It may never again be possible to obtain such a large centrifuge at such a low cost.