APPENDIX B — CENTRIFUGE MODELING OF SHORED MSE WALL

Laboratory-scale modeling (i.e., centrifuge testing) was conducted to evaluate the behavior of composite mechanically stabilized earth and shoring wall systems (SMSE) and to obtain guidance for optimization of the design. One of the most important aspects in optimization of the composite system is reduction of the MSE reinforcement lengths, which reduces both the amount of excavation as well as the amount of reinforced fill required. The use of short MSE reinforcements was found to best be evaluated using the centrifuge. The laboratory testing, presented in detail in Woodruff, addressed reducing the length of MSE reinforcements for MSE walls located adjacent to a rigid shoring wall, as well as other variables.[49]

The centrifuge testing program was conducted in two phases:

- Phase I – Parametric study of an SMSE system.

- Phase II – Modeling of the field-scale prototype.

B.1 CENTRIFUGE MODELING

Because small-scale models do not exhibit the same stress conditions as the full-scale or prototype model, centrifuge model tests are conducted at an increased acceleration level to simulate the actual field conditions. Modeling of a prototype involves predicting the behavior of a full-scale project to be constructed in the field. The laboratory model is constructed using the same materials and is geometrically similar to the prototype.

In order to use centrifuge modeling for the prediction of prototype behavior, knowledge of scaling laws is required. Increasing the acceleration level during centrifuge modeling (to *N* times that of natural gravity) leads to the relations summarized in table 6, assuming that the material in the model is the same as the material in the prototype.

B.2 MODELING PARAMETERS

B.2.1 Materials

Two different types of materials were used for the laboratory testing presented in this appendix: reinforcement and soil. This section discusses the types of reinforcement materials and soil materials used in the centrifuge testing program.

Reinforcement

The reinforcements used in the centrifuge modeling included two commercially-available non-woven interfacing fabrics manufactured by Pellon Division of Freudenberg Non-wovens. The stronger fabric, Pellon True-Grid, consisted of 60 percent polyester and 40 percent rayon having a unit weight of 28 grams per square meter (g/m^2). The weaker fabric, Pellon Sew-In, consisted of 100 percent polyester fabric with a unit weight of 24.5 g/m^2. Characterization of the reinforcement material used in the study is provided in Zornberg et al.[56]

Table 6. Centrifuge scaling relations.[57,58]

Parameter	Prototype[1]	Model[1]
Length	N	1
Area	N^2	1
Volume	N^3	1
Velocity	1	1
Acceleration	1	N
Mass	N^3	1
Force	N^2	1
Energy	N^3	1
Stress	1	1
Strain	1	1
Mass Density	1	1
Energy Density	1	1
Time (Dynamic)	N	1
Time (Diffusion)	N^2	1
Time (Creep)	1	1
Frequency	1	N
Reinforcement Stiffness	N	1
Reinforcement Ultimate Tensile Strength	N	1

[1] The value, *N*, refers to the gravitational acceleration during centrifuge modeling with the acceleration level equal to *N* times gravity (*g*). Where indicated, the value of *N* is squared or cubed to evaluate the parameter.

The tensile strength of the reinforcement fabric is anisotropic, with the lower strength along the machine direction. Both orientations of the reinforcements (parallel and transverse to the machine direction) were used in the centrifuge modeling. The unconfined tensile strength of the reinforcement is presented in table 7.

Table 7. Unconfined tensile strengths of the reinforcement.

Geotextile	Direction	Unconfined Tensile Strength (kN/m)	Reinforcement Designation[1]
Pellon Sew-In	Weak	0.03	R1
	Strong	0.10	R3
Pellon True-Grid	Weak	0.09	R2
	Strong	1.12	R4

[1] Reinforcement designation indicates type and orientation of reinforcement for centrifuge models.

Soil

The soil used for development of the centrifuge models differed between Phases I and II of the testing program. Monterey No. 30 sand was used for the Phase I testing, and mortar sand obtained from Turner Fairbanks Highway Research Center (TFHRC) was used for Phase II testing.

The soil used for Phase I of the laboratory study was Monterey No. 30 sand having a uniform gradation and classified as poorly-graded sand (SP) according to the Unified Soil Classification System (USCS). The material gradation for Monterey No. 30 sand is presented in figure 34. For sample preparation, the Monterey No. 30 sand was pluviated to reach a target relative density, D_r, of 70 percent (16.05 kN/m^3). Results of triaxial testing conducted on Monterey No. 30 sand indicate that the peak friction angle of the sand increases with increasing relative density. Assuming a relative density of 70 percent, which was used in the centrifuge models, the peak triaxial shear friction angle (ϕ_{TX}) for Monterey No. 30 sand was estimated to be 36.7 degrees.[49] Correlation from triaxial friction angle to plane strain friction angle (ϕ_{PS}) resulted in a plane strain friction angle of 42.2 degrees for the Monterey No. 30 sand at 70 percent relative density.[49]

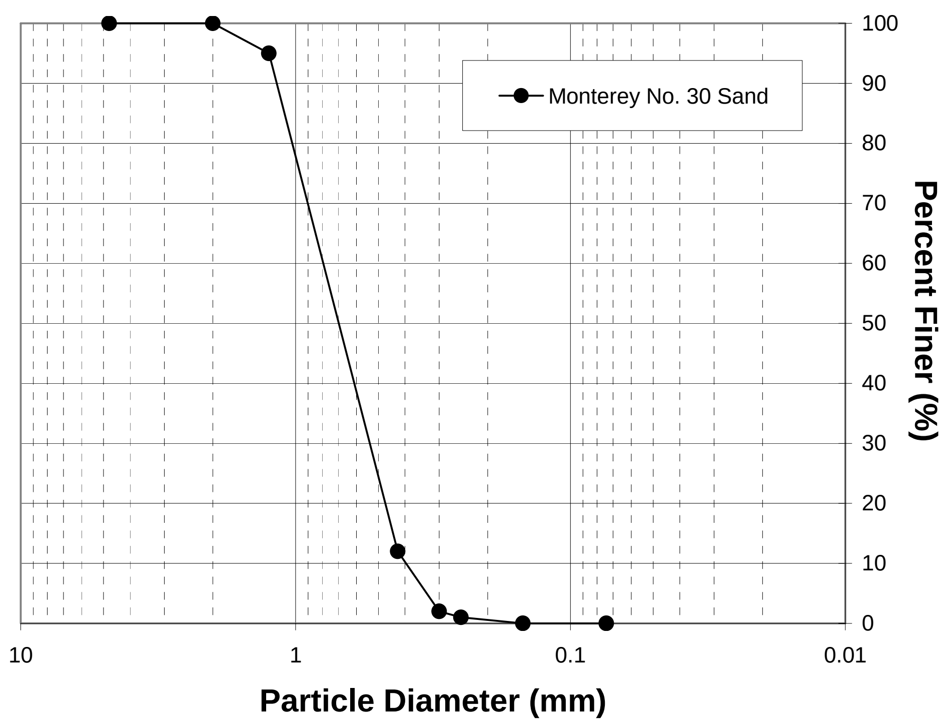


Figure 34. Graph. Particle size distribution for Monterey No. 30 sand used for Phase I centrifuge modeling.[49]

Phase II of the centrifuge program used mortar sand obtained from TFHRC, which is the same material used for construction of the reinforced fill portion of the field-scale test wall (appendix C). Laboratory test results for the sand were provided by TFHRC, including particle-size analyses, maximum and minimum density tests, standard and modified Proctor tests, and direct shear tests.(59) Results of particle-size analyses on the mortar sand are presented in figure 35. The mortar sand classifies as poorly-graded sand (SP) according to USCS and as A-3 material according to the AASHTO classification system.

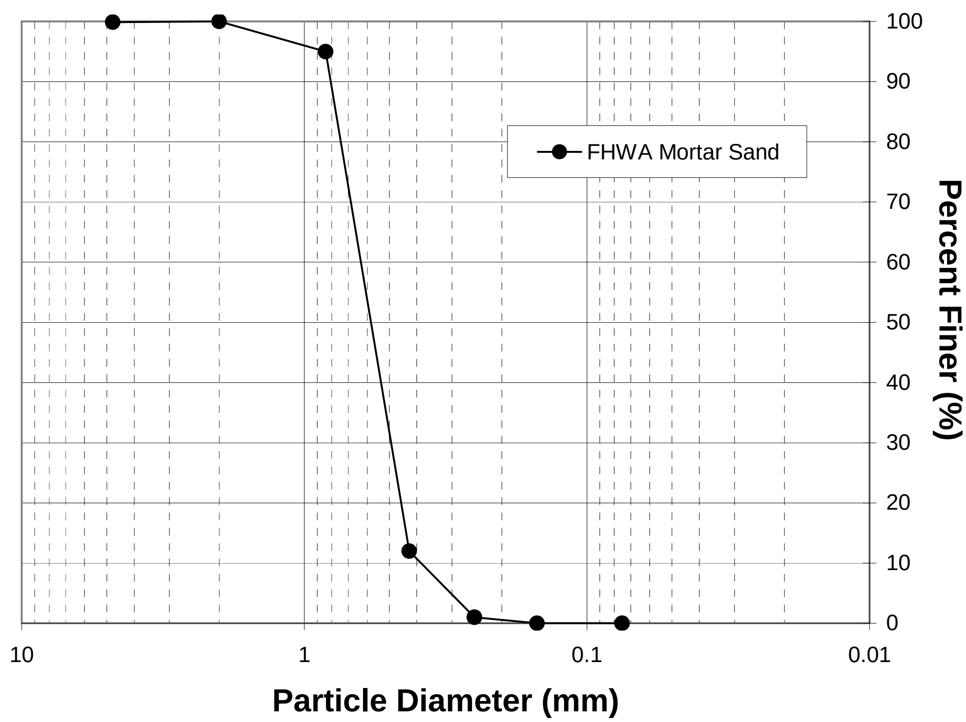


Figure 35. Graph. Gradation of mortar sand used for Phase II centrifuge testing.

The mortar sand was determined to have a maximum dry density of 15.4 kN/m^3 at an optimum water content of 7 percent. Nuclear density gauge results provided by TFHRC indicated that the average placement dry density of the mortar sand is 14.8 kN/m^3 with an average water content of 6 percent.(59) Accordingly, the centrifuge models were constructed at a dry density of 14.8 kN/m^3 at the optimum water content of 7 percent. The placement density corresponds to 96 percent compaction.

B.2.2 Testing Apparatus

Centrifuge

The laboratory centrifuge models presented in Woodruff were tested in the 400 g-ton centrifuge located at the University of Colorado at Boulder.(49) This centrifuge has a 5.5 m radius and is capable of carrying a 1.22 m square package with a height of 0.91 m weighing up to 1.8 tonnes (2 tons). The centrifuge is capable of accelerating the payload to 200 times the force of gravity (i.e., 200g).

Strong Box

The strong box used to contain the models consisted of an aluminum box with dimensions of 1.1 m wide by 1.2 m long by 0.4 m tall. Two sides of the box were replaced with plexi-glass to enable viewing of the model profiles during testing, and aluminum dividers were added to allow up to four wall profiles to be tested simultaneously. Figure 36 presents a diagram of the strong box used for centrifuge modeling.

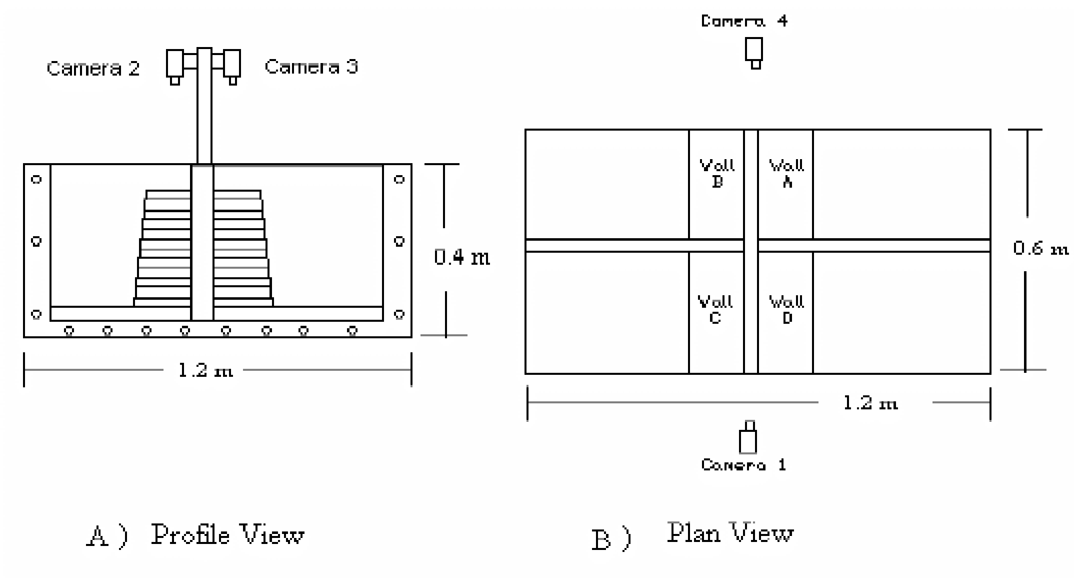


Figure 36. Schematic. Schematic of centrifuge model test set-up.[(49)]

A rigid aluminum plate was used in the centrifuge models to represent the shoring system, assuming that the MSE wall is constructed in front of a completely rigid shoring system subjected to earth pressures developed by the MSE mass alone. It should be noted that this may not be completely representative in the field since the shoring system may deflect behind the MSE wall subjecting the MSE wall to outside lateral earth pressures. The sidewalls of the model container were lined with Mylar sheets in an attempt to minimize boundary effects and restrain the wall behavior to plane strain.

B.3 TESTING PROGRAM

The centrifuge testing program was conducted in two phases: Phase I and Phase II. Phase I of the centrifuge program was conducted to test various hypotheses with regard to SMSE systems, focusing on reduction of the MSE reinforcement lengths. The objective of Phase II of the testing program was to evaluate and model the field-scale prototype, discussed further in appendix C.

B.3.1 Phase I

Phase I of the centrifuge testing program was a parametric study that addressed the following variables:

- Aspect ratio of the wall (i.e., reinforcement length divided by wall height).
- Reinforcement strength.
- Shoring interface (i.e., roughness).
- Reinforcement configuration at the shoring wall interface (i.e., attached, wrapped or unconnected).
- Reinforcement vertical spacing.
- Shoring wall inclination.

A total of 24 models were tested as part of the Phase I investigation, summarized in table 8. All of the models were constructed with an MSE face batter of 1 horizontal to 11 vertical (1:11V).

Test model 1a verified modeling techniques with known results from other centrifuge research. Test models 1b, 2a, and 2b were conducted to evaluate the internal failure mechanism of an SMSE wall system. Test series 3 was conducted to investigate the effects of varying the shoring wall interface, using materials that were smooth to rough and a retained fill. Test series 4 and 5 were conducted to evaluate the minimum reinforcement length (aspect ratio) suitable for SMSE wall construction. The detail of the reinforcement connection at the shoring wall interface was also varied in test series 5 to investigate the benefits of wrapping the reinforcement around the back of the reinforced fill. Other design considerations were investigated in test series 6, including connection of the uppermost reinforcement layer, wrapping of the uppermost reinforcement layer, inclination of the shoring system, and a conventional MSE wall having retained fill with an aspect ratio of 0.3. Test series 7 investigated the effects of varying the reinforcement vertical spacing for a wall aspect ratio of 0.25.

B.3.2 Phase II

Phase II of the centrifuge testing program was conducted to predict behavior of the field-scale prototype wall scheduled for construction at TFHRC (appendix C). The field-scale wall modeled both reinforcements connected to the shoring system and unconnected reinforcements. Phase II centrifuge modeling only considered the unconnected system due to difficulties inherent in attempting to model the connected wall system.

The model that was tested in the centrifuge was a duplication of the proposed field-scale prototype wall reduced by N, where N is the gravitational acceleration coefficient. The centrifuge model geometry versus the prototype geometry is presented in table 9, corresponding to a test acceleration of 16g.

Table 8. Summary of Phase I centrifuge test models.

Test Designation		Reinforcement Length	Reinforcement Strength[1]	Reinforcement Configuration at Shoring Interface	Shoring Interface Material	Reinforcement Vertical Spacing (mm)
1	a[2] (Control)	0.9*H*	R1	Unconnected	Retained fill	20
	b	0.6*H*	R1	Unconnected	Aluminum	20
2	a	0.6*H*	R2	Unconnected	Aluminum	20
	b	0.4*H*	R2	Unconnected	Aluminum	20
3	a	0.7*H*	R2	Unconnected	Aluminum	20
	b	0.7*H*	R2	Unconnected	Retained fill	20
	c	0.7*H*	R2	Unconnected	Smooth	20
	d	0.7*H*	R2	Unconnected	Rough	20
4	a	0.7*H*	R4	Unconnected	Aluminum	20
	b	0.5*H*	R4	Unconnected	Aluminum	20
	c	0.3*H*	R4	Unconnected	Aluminum	20
	d	0.3*H*	R4	Unconnected	Aluminum	20
5	a	0.17*H*	R4	Unconnected	Aluminum	20
	b	0.2*H*	R4	Wrapped	Aluminum	20
	c	0.25*H*	R4	Unconnected	Aluminum	20
	d	0.2*H*	R4	Wrapped	Aluminum	20
6	a	0.3*H*	R4	Top layer attached	Aluminum	20
	b	0.3*H*	R4	Top layer wrapped	Aluminum	20
	c	0.2*H*-0.3*H*	R4	Unconnected	Inclined	20
	d	0.3*H*	R4	Unconnected	Retained fill	20
7	a	0.25*H*	R4	Unconnected	Aluminum	10
	b	0.25*H*	R4	Unconnected	Aluminum	30
	c	0.25*H*	R4	Unconnected	Aluminum	40
	d	0.25*H*	R4	Unconnected	Aluminum	50

[1] Reinforcement strengths: R1=Pellon Sew-In weak direction, R2=Pellon True-Grid weak direction, R3=Pellon Sew-In strong direction, and R4=Pellon True-Grid strong direction.

[2] This test was conducted as a duplication test on a standard MSE configuration to ensure that model preparation methods are acceptable.

Table 9. Centrifuge model parameters compared to prototype parameters.

Variable	Centrifuge model	Prototype (Preliminary Design)	Prototype (Final Design)
Height, H	0.34 m	5.49 m	5.5 m
Aspect ratio, α	0.25	0.25	0.25 to 0.39
Reinforcement vertical spacing, s_v	0.029 m	0.457 m	0.457 m
Width of load footing, W_f	0.089 m	1.422 m	1.0 m
Length of load footing, L_f	0.425 m	6.81 m	2.5 m
Area of load footing, A_f	0.038 m^2	9.68 m^2	2.5 m^2
Wall length, L_w	0.43 m	6.90 m	7.0 m
Wall width (top), L_T	0.143 m	2.29 m	2.3 m
Wall width (bottom), L_B	0.086 m	1.37 m	1.4 m
Reinforcement Tensile Strength, T	1.12 kN/m	18 kN/m	52 kN/m

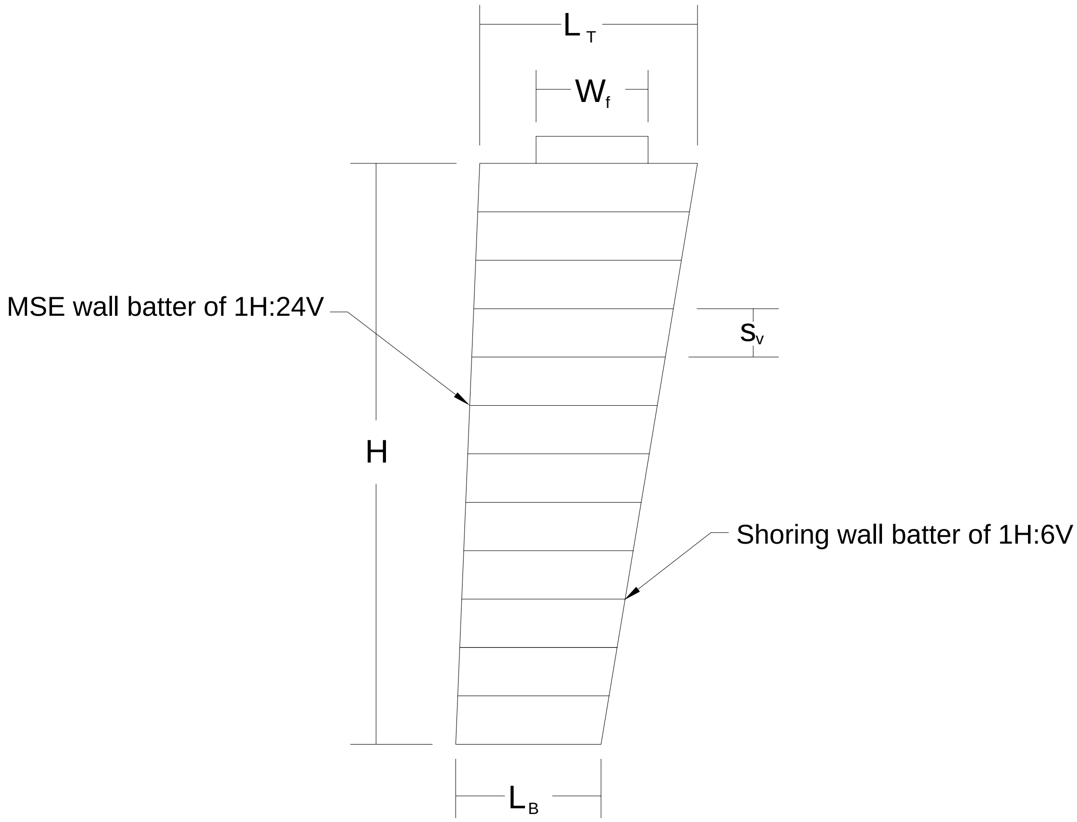
Pellon True-grid fabric placed in the strong direction was used as the reinforcement for construction of the Phase II centrifuge model. The ultimate tensile strength of the geotextile determined using the wide width tensile test (ASTM D4595 modified using 300 mm per minute displacement rate) was 1.12 kN/m.[60, 61] Scaling of the reinforcement strength for an acceleration level of 16*g* results in an ultimate tensile strength of 18 kN/m.

The field-scale test wall was loaded with a jack and footing, and the centrifuge model was designed accordingly. The capacity of the hydraulic jacks at TFHRC is 890 kN. Two air actuators were used to apply load to the centrifuge model footing, as illustrated in figure 37. The model and prototype applied footing pressures are summarized in table 10.

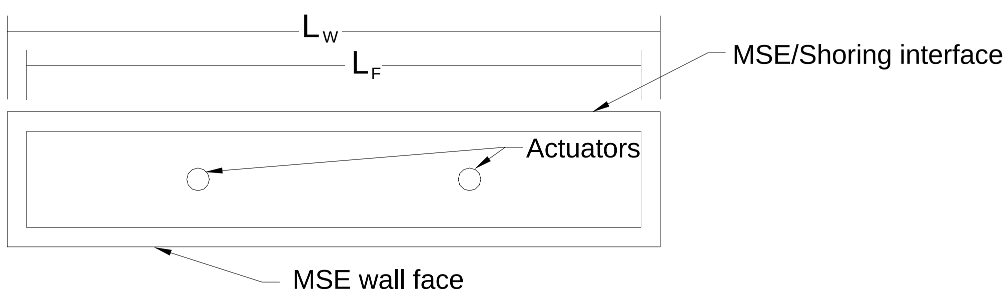
Table 10. Comparison of centrifuge model and prototype footing pressures.

Loads	Model		Prototype	
	Force (kN)	Pressure (kPa)	Force (kN)	Pressure (kPa)
Service Load	0.90	23.9	231.6	23.9
Maximum Load	9.05	239.2	2316.1	239.2

The centrifuge model was tested in two phases. First, the model was spun at a constant acceleration of 16*g* and loaded to the service load of 23.9 kPa, followed by loading to failure of the model or capacity of the actuators. Secondly, after the actuator capacity was reached and the wall had not failed, the acceleration level was increased while keeping the actuator load constant until wall failure.



A. Profile view of the model.



B. Plan view of the model.

Figure 37. Illustration. Phase II centrifuge model configuration.

B.4 RESULTS

B.4.1 Phase I

Results of the Phase I centrifuge modeling program are summarized in table 11. The table presents the wall aspect ratio, gravitational acceleration level at failure (*g*-level), type of failure, and the *g*-level at "pull away." "Pull away" is defined as the point where a trench develops along the MSE-shoring interface.

Table 11. Summary of Phase I centrifuge test results.

Test Designation		Aspect Ratio	g-Level at Failure	Failure Type[1,2]	g-Level at Pull Away
1	a[3] (Control)	0.9*H*	18	Internal (1)	N/A
	b	0.6*H*	17	Compound (1)	17
2	a	0.6*H*	38	Compound (1)	27
	b	0.4*H*	41	Compound (2)	39
3	a	0.7*H*	38	Internal (1)	N/A
	b	0.7*H*	49	Internal (1)	N/A
	c	0.7*H*	47	Internal (1)	N/A
	d	0.7*H*	44	Internal (1)	N/A
4	a	0.7*H*	N/A	N/A	N/A
	b	0.5*H*	N/A	N/A	N/A
	c	0.3*H*	N/A	N/A	22
	d	0.3*H*	N/A	N/A	32
5	a	0.17*H*	7	Overturning (2)	5
	b	0.2*H*	N/A	N/A	N/A
	c	0.25*H*	32	Overturning (2)	13
	d	0.2*H*	N/A	N/A	N/A
6	a	0.3*H*	N/A	N/A	27
	b	0.3*H*	N/A	N/A	30
	c	0.2*H*-0.3*H*	78	Overturning	25
	d	0.3*H*	N/A	N/A	N/A
7	a	0.25*H*	38	Overturning (2)	31
	b	0.25*H*	2.5	Overturning (2)	1
	c	0.25*H*	1	Overlap pullout	N/A
	d	0.25*H*	1	Overlap pullout	N/A

[1] Compound failure implies that a portion of the failure surface followed the shoring interface.
[2] Deformation modes (1) and (2) designate different types of deformation leading to failure, discussed in the text.
[3] This test was conducted as a duplication test on a standard MSE configuration to ensure that model preparation methods are acceptable.

Figure 38 is a photo of centrifuge test series 2 at a *g*-level of approximately 37*g*, which shows trench development at the top of the model on the left (model 2b), and surface settlement of the model on the right (model 2a). Figure 39 is a photo of the same test at an acceleration of 38*g*, marked by failure of the model on the right having an aspect ratio of 0.6. Failure of the model with an aspect ratio of 0.4 (on the left) is shown in figure 40 at an acceleration of 41*g*.

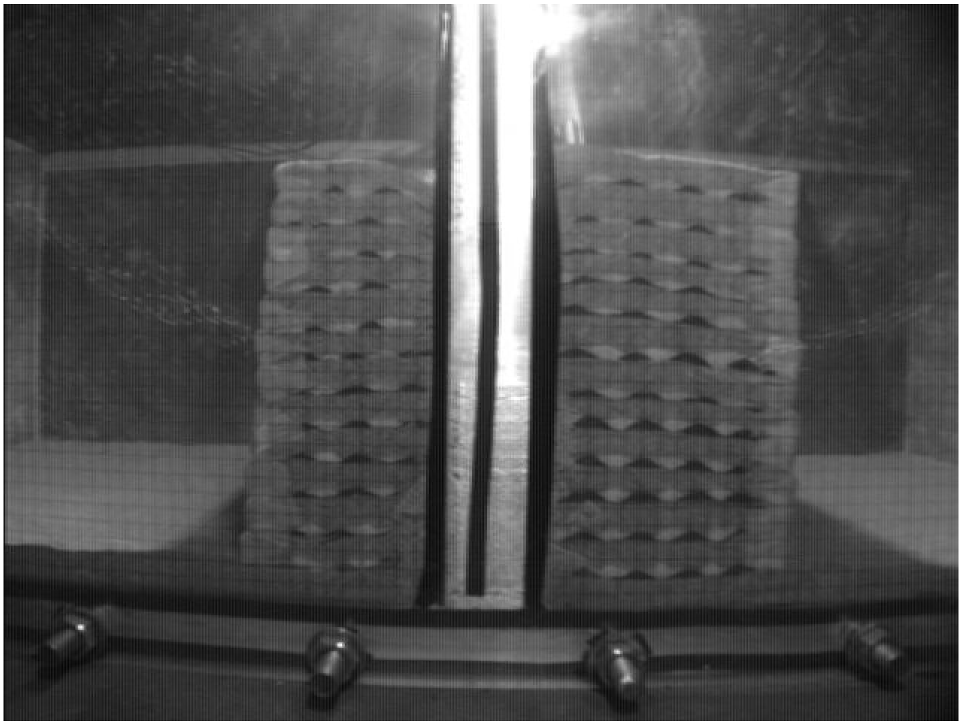


Figure 38. Photo. Centrifuge test series 2 at 37*g* acceleration.

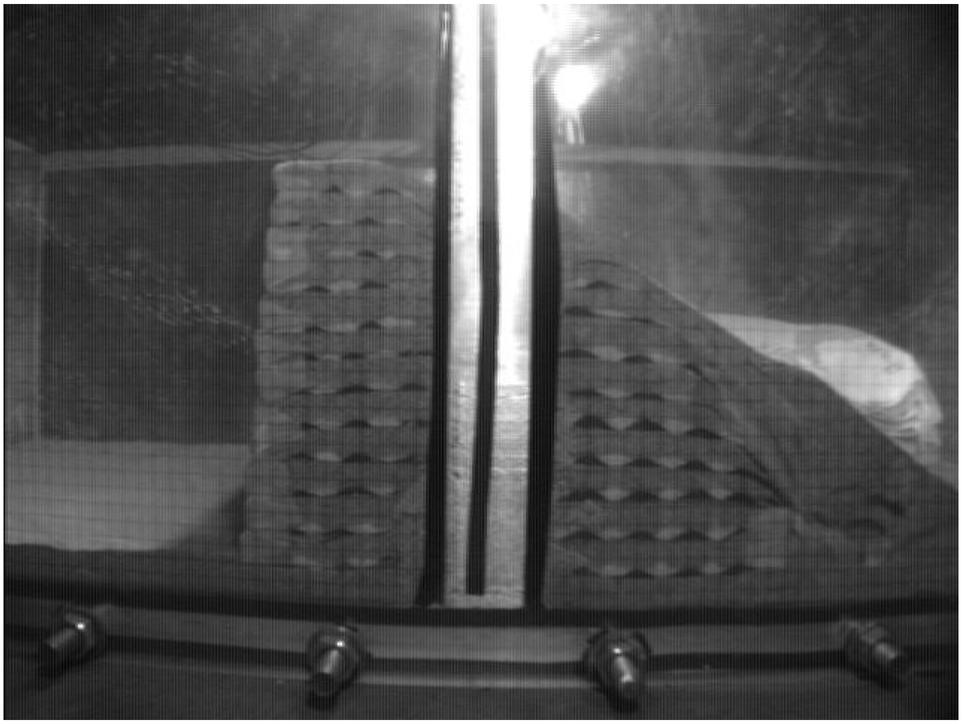


Figure 39. Photo. Centrifuge test series 2 at 38*g* acceleration.

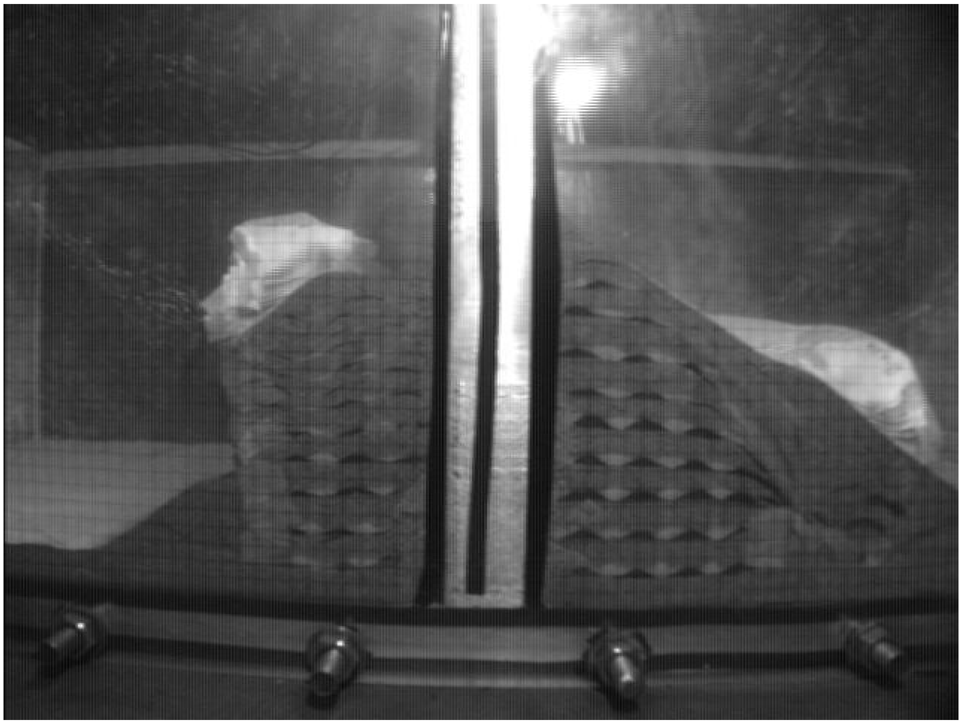


Figure 40. Photo. Centrifuge test series 2 at 41*g* acceleration.

The centrifuge test results are summarized as follows:

- Test series 1 (models 1a and 1b) – Model 1a was a control model constructed to verify modeling techniques. Model 1b was an MSE wall with sample reinforcements of length 0.6*H* using low strength reinforcements oriented with weak direction perpendicular to wall face. Reinforcing layers were butted against a vertical wall to resemble shoring by an unconnected system. Model 1b exhibited compound failure at a gravitational acceleration of 17*g*.

- Test series 2 (models 2a and 2b) – MSE wall with sample reinforcements of lengths of 0.6*H* and 0.4*H* using high strength reinforcements oriented with weak direction perpendicular to wall face. Reinforcing layers were butted against a vertical wall to resemble shoring by an unconnected system. The models exhibited compound failure at gravitational accelerations of 38*g* and 41*g* for aspect ratios of 0.6 and 0.4, respectively. It should be noted that these models exhibited pull-away from the shoring wall at lower accelerations of 27*g* and 39*g*, respectively.

- Test series 3 (models 3a through 3d) – MSE walls with sample reinforcement lengths of 0.7*H* using strong fabric reinforcements in the weak direction to investigate shoring interface roughness. Shoring interfaces tested included aluminum, retained fill, smooth surface, and rough surface. All of these models exhibited internal failure at gravitational accelerations ranging from 38*g* to 49*g*. The results were not as expected, as model 3b did not employ shoring and failed at the highest acceleration level, and the model with a smooth shoring interface (3c) appeared to be slightly more robust than, but otherwise very similar to, the model with a rough shoring interface (3a).

- Test series 4 (models 4a through 4d) – MSE walls with sample reinforcement lengths ranging from 0.3*H* to 0.7*H* using strong fabric reinforcements in the strong direction to investigate reinforcement length. The models with reinforcement length of 0.3*H* began to pull away from the shoring at 22*g* to 32*g*, but did not fail at the test acceleration. Models with reinforcements of 0.5*H* and 0.7*H* did not even pull away at the test acceleration.

- Test series 5 (models 5a through 5d) – For this test, two (5b and 5d) of the four models were duplicate tests, each constructed with 0.2*H* reinforcement lengths and MSE wrap-around at the shoring face. These models (5b and 5d) did not fail at the test acceleration. Models 5a and 5c were tested with reinforcement lengths (unconnected at the shoring wall) of 0.17*H* and 0.25*H*, respectively. These models exhibited overturning failure at *g*-levels of 7*g* and 32*g*, respectively.

- Test series 6 (models 6a through 6d) – In general, these models had MSE reinforcement lengths on the order of 0.3*H*. Model 6a had the top reinforcements tied, while model 6b had the top reinforcements wrapped at the back. Model 6c was a standard test with a shoring wall, and model 6d had retained fill at the shoring interface. Models 6a, 6b, and 6d did not fail at the test acceleration, while model 6c exhibited overturning failure at 78*g*.

- Test series 7 (models 7a through 7d) – MSE walls with sample reinforcement lengths of 0.25*H* using strong fabric reinforcements in the strong direction to investigate reinforcement vertical spacing (ranging from 10 mm to 50 mm). Models 7a and 7b with vertical reinforcement spacings of 10 and 30 mm, respectively, exhibited overturning failure of38*g* and 2.5*g*, respectively. Models 7c and 7d, with vertical reinforcement spacings in excess of 30 mm, exhibited pullout failure at 1*g*.

The main conclusions that can be drawn from this study with regard to each of the variables evaluated are:

- Aspect ratio – Walls with an aspect ratio larger than 0.6 failed completely internally with all reinforcement layers intersecting the failure plane. Walls with aspect ratios equal to or less than 0.6 failed in a compound mode with the failure plane following the shoring interface near the top of the wall and intersecting the reinforcement layers near the bottom of the wall. In general, models constructed with aspect ratios of 0.3 or greater did not exhibit failure. However, failure due to overturning typically resulted when the wall aspect ratio was reduced to 0.25 or less.

- Reinforcement strength – Test series 1 through 3 failed internally due to the comparatively low tensile strength of the reinforcement fabric used in the models. Stronger reinforcement materials, such as those used for test series 4 through 7, effectively prevented internal failure due to breakage of the reinforcement layers.

- Shoring interface – The roughness of the shoring interface was studied. However, the results were not as expected because the smooth shoring wall was found to be as effective, if not more effective, than the rough shoring wall.

- Reinforcement configuration – Wrapping around the back reinforcement layers at the shoring interface produced a wall configuration that was stable to very high acceleration levels, suggesting that earth pressures are effectively reduced.

- Reinforcement vertical spacing – Decreasing the spacing of the reinforcements was observed to increase the stability of the walls with very short aspect ratios, suggesting that close reinforcement spacings reduce lateral earth pressures.

- Shoring wall batter – Shoring inclination was observed to add stability to the wall when moderately inclined, as noted by test 6c which employed a shoring batter of 1H:14V.

Other important observations were made from the Phase I centrifuge modeling. The failure planes have a tendency to be at an inclination slightly flatter than the theoretical Rankine failure plane where a shoring wall is employed. However, the presence of a retained fill produces a failure plane which closely approximates the theoretical Rankine failure plane. At aspect ratios on the order of 0.3, the models exhibited excessive deformation along the shoring interface in the form of a trench, though the walls did not exhibit collapse. This observation supports use of longer reinforcements at the top of the wall, on the order of 0.6*H*.

B.4.2 Phase II

General

Results from the Phase I centrifuge program indicated that models with a small aspect ratio (0.25 or less) would fail through overturning if the reinforcement layers were sufficiently strong to resist breakage, as is the case with the centrifuge model tested during the Phase II program. The Phase II test model had an aspect ratio ranging from 0.25 to 0.39 and employed the strongest reinforcement type and direction. However, the prototype modeled in the centrifuge was subjected to vertical surcharge loading, which results in increased resistance to overturning, but decreased resistance to other modes of failure.

The centrifuge model was tested at a constant acceleration of 16*g*, corresponding to the height of the prototype, and loaded to the capacity of the actuators. The centrifuge model did not exhibit failure during the first phase of the test, and so was then subjected to increasing acceleration levels until the model failed at an acceleration level of 32*g*.

Due to the high surcharge load applied to the top of the centrifuge model, the model exhibited boundary effects with deformations the largest at the center, decreasing toward the edge of the container. Nine layers of the reinforcement tore during loading, causing ultimate failure of the model.

Prediction of Field-Scale Test Wall Behavior

The field-scale test wall is discussed in detail in appendix C. The field-scale test wall consisted of two different wall cross sections, one with MSE reinforcements connected to the shoring wall, and the other as an unconnected system. Due to difficulties inherent in modeling the connected system, the centrifuge modeling was only conducted to model the unconnected portion of the field-scale test wall.

The Phase II program further investigated the affects of shoring wall batter. The shoring wall was modeled with a batter of 1H:6V, further supporting the conclusion that moderate batter appears to increase wall stability.

The centrifuge model was stable under the full capacity loading available, exceeding the prototype loading available at TFHRC. Results of the Phase II centrifuge modeling indicate that the field-scale prototype, as designed, would likely not exhibit significant failure under the maximum test load attainable at TFHRC.(59)