Tennessee Valley Authority Kingston Fossil Plant Harriman, Roane County, Tennessee	**Perimeter Containment** **North Dredge Cell (Dike C) Segment 1** **Sta. A161+50 to A179+50**
Document Control Number RDP-0113-E *Calculation Package* FPGKIFFESCDX00030020100006	

Exhibit 15
Limit Equilibrium Stability Analyses

Purpose:

- Evaluate the stability of the closed dredge cell outslopes for static and post-seismic (post-liquefaction) load conditions.

Methods:

- Conventional, two-dimensional, limit-equilibrium slope stability analyses.
- Use Slope/W software, from GEO-SLOPE International, Ltd., of Calgary, Alberta, Canada (www.geo-slope.com).

Results:

- Four cross sections were analyzed; graphical results for the various load conditions are included.
- The design cross section was found to meet the design criteria for factors of safety.

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Revisions: 28-Jan-11	

Limit Equilibrium Slope Stability Analyses

1. Design Criteria for Stability

The design criteria for the Kingston dredge cell closure are detailed in Exhibit 2. For this design package, three criteria for slope stability apply:

- For long-term conditions following construction, the factor of safety for slope stability shall be no less than 1.5.
- The post-earthquake factor of safety for slope stability shall be greater than 1.0.
- Following the design seismic event, ash from the closed facility shall not displace beyond the permitted boundary of the facility.

The deformation criteria probably cannot be met if the perimeter cross section exhibits a factor of safety for slope stability (*FS*) close to 1.0 in the post-earthquake conditions (with expected liquefaction in the ash and foundation sands). Hence, a minimum factor of safety of 1.1 was targeted for the post-earthquake stability analyses reported here. This decision does not alter the design criteria for the project; the seismic performance will be judged on the basis of predicted deformations. Slope deformations during the design earthquake were modeled using dynamic *FLAC* simulations (Exhibit 23).

The perimeter design was thus advanced with a geometry having $FS \geq 1.5$ for the long-term, static condition, and $FS \geq 1.1$ for the post-earthquake (liquefied) condition.

2. Slope Stability Analyses

2.1. Limit Equilibrium Methods in *SLOPE/W*

Limit equilibrium, slope stability analyses were carried out using the computer program *SLOPE/W,* part of the *GeoStudio 2007* suite (Version 7.14) available from Geo-Slope International Ltd. (Calgary, Alberta, www.geo-slope.com). The stability of four cross sections within the North Dredge Cell Perimeter Segment was evaluated for static and post-earthquake conditions. The results were used to select design dimensions, verify conformance with the design criteria, and identify the critical cross section for modeling in the *FLAC* analyses.

Limit equilibrium methods for slope stability consider the static equilibrium of a soil mass above a potential failure surface. In conventional, two-dimensional methods of analysis, the slide mass above an assumed slip surface is split into vertical slices (the default slice number in *SLOPE/W* is 30) and stresses are evaluated along the sides and base of each slice. The factor of safety against a slope failure (*FS*) is defined as the ratio of soil shear strength over equilibrium shear stress:

$$FS = \frac{Shear\ Strength\ of\ Soil}{Shear\ Stress\ required\ for\ Equilibrium}$$

where the strength and stresses are computed along a defined slip surface, on the base of each vertical slices. The shearing resistance at locations along the potential slip surface is computed based on appropriate soil strength parameters as a function of the total or effective normal stress.

A number of limit equilibrium methods have been implemented in *SLOPE/W*. Different assumptions for the inter-slice forces are employed in these methods. Some methods only satisfy one equilibrium equation (moment equilibrium or force equilibrium), while some methods satisfy both. Spencer's method was used in the analyses presented here. This method is considered mathematically rigorous, because its formulation includes all inter-slice forces and satisfies all equations of equilibrium.

A slope stability analysis must include a search for the most critical slip surface, corresponding to the lowest *FS*. First, circular potential failure surfaces were generated using the "Entry and Exit" method, where a wide variation of trial slip surfaces can be assessed with defined ranges of possible entries and exits. After the most critical circular failure surface was obtained, the optimization scheme available in *SLOPE/W* was used to alter portions of the failure surface and check for a potentially lower factor of safety.

2.2. Cross Sections

Stability analyses were carried out for four representative cross sections within the North Dredge Cell Segment. The cross sections were selected to represent the range of subsurface conditions and ground surface geometries expected within this design segment. The analyzed cross sections are spaced 400 to 600 feet apart, and are located at Stations A162+00, A168+00, A172+00, and A178+00.

2.3. Failure Modes

Numerous parametric stability analyses completed during the conceptual design phase demonstrated that the dredge cell perimeter is vulnerable to two distinct failure modes:

- Deep failure, which involves a slip surface that cuts through the stabilized foundation near the top of bedrock.

- Shallow failure, which tends to occur on a slip surface in the outslope of the landfilled ash embankment, behind the perimeter berm.

The shallow failure mechanism usually has a lower *FS* under both the long-term, static condition and the post-earthquake condition. The established project stability criteria must be met for both mechanisms.

2.4. Material Properties

Materials in the analyzed cross sections include landfilled ash, hydraulically placed ash, lean clay foundation soil, sandy silt to silty sand, earthen berm, coarse stone, shot rock, shale bedrock, stabilized ash, stabilized lean clay, and stabilized silt/sand. For the post-earthquake conditions, liquefaction is predicted in the landfilled ash within a zone of about eight feet above the phreatic surface (Exhibit 12), the hydraulically placed ash, and the sandy silt to silty sand (Exhibit 11).

Material properties used in the stability analyses are summarized in Table 1. Details on these design properties are discussed in Exhibits 3 and 13. Composite strength parameters for the

stabilized ash, stabilized lean clay, and stabilized silt/sand were computed based on the required mean soil-cement strength (f'_{sc} = 200 psi) and area replacement ratio (0.26), using the weighted average approach (Exhibit 14).

Table 1 – Material Parameters used in Stability Analyses

Material Name	Unit Weights		Static Drained Strengths		Post-Earthquake, Undrained Strengths		
	γ_m (pcf)	γ_{sat} (pcf)	ϕ' (deg.)	c' (psf)	ϕ (deg.)	c (psf)	c/p
Unliquefied Landfilled Ash	109	111	30	0	30	0	--
Liquefied Landfilled Ash	--	111	30	0	--	--	0.06
Hydraulically Placed Ash	100	107	25	0	--	--	0.06
Lean Clay Foundation Soil	--	130	32	0	20	0	--
Sandy Silt to Silty Sand	--	128	30	0	--	--	0.06
Earthen Berm	125	128	28	0	0	1,500	--
Coarse Stone	115	128	38	0	32	0	--
Shot Rock	115	128	38	0	38	0	--
Shale	--	140	20	3,000	20	3,000	--
Stabilized Ash*	100	107	19	2,995	2.5	2,995	--
Stabilized Lean Clay*	--	130	25	2,995	15.1	2,995	--
Stabilized Silt/Sand*	--	128	23	2,995	2.5	2,995	--

* Computed for ARR = 0.26 and f'_{sc} = 200 psi

2.5. Groundwater Pressures

Long-term groundwater levels were predicted with the three-dimensional groundwater model discussed in Exhibit 5. For the long-term stability calculations, pore water pressures were computed directly using the depth below this predicted phreatic surface on each cross section. In the post-earthquake stability analyses, the long-term pore pressures were used to compute consolidation pressures, consistent with the parameters for the shearing resistance of each soil layer.

2.6. Area Replacement Ratio and Soil-Cement Strength

During the conceptual phase of the design for the project, preliminary stability analyses were used to estimate what soil-cement strength and area replacement ratio would be needed to

achieve perimeter stability. The conceptual-level analyses indicated that stability could be achieved with a stabilized width of about 150 feet, an area replacement ratio of about 0.25, and an unconfined strength of f'_{sc} = 150 psi in the soil-cement. These preliminary parameters were further refined in the design process.

Structural analyses of the three-dimensional soil-cement walls were accomplished in *FLAC3D* (Exhibit 21). To meet the stability criteria without overstressing the soil-cement elements, those calculations indicated the need for a mean, unconfined compressive strength in the soil-cement of 200 psi, with an area replacement ratio of 0.26. These values were adopted for the design and included in the slope stability analyses presented here.

3. Stability under Seismic Conditions

3.1. Capillary Break Layer in the Ash Landfill

Based on the analyses in Exhibit 12, about eight feet of saturated to nearly saturated ash landfill above the water table in the closed dredge cell should be expected to liquefy in the design earthquake. If these conditions develop too near the ground surface, the landfill outslopes would be seismically unstable with respect to the shallow failure mode.

Hence, to meet the stability criteria, a zone of unsaturated, unliquefiable ash must be maintained around the dredge cell perimeter. A capillary break (layer of coarse aggregate) will be constructed within the ash landfill, to impede the accumulation of water from capillary rise above the water table. The landfilled ash above the capillary break can then be assumed to remain unsaturated and not subject to liquefaction.

Parametric calculations were carried out in *SLOPE/W* to determine the minimum lateral extents of the capillary break that are needed to maintain a stable slope (target minimum post-earthquake *FS* = 1.1 for the shallow failure mode). The results indicated that the capillary break can be built on a slope fairly close to the perimeter berm, and does not need to extend across the footprint of the ash landfill. This means the capillary break can be built within the ash infill zone, in the area between the perimeter berm and ash stacking within the dredge cell.

Design details for the capillary break layer (material specifications, thickness, slope, location, etc.) will be developed later, as part of the final cover design package. For the present design of the stabilized perimeter, the capillary break is assumed to start at the top of the inboard soil cement wall, and rise on a gentle slope to an elevation eight feet above the phreatic surface. The capillary break layer can be built on the sloping face of the stacked ash within the dredge cell, so a 6H:1V slope was assumed.

3.2. Seismic Performance of the Outer Rock Berm

The North Dredge Cell Segment of the perimeter includes a 2H:1V rock berm against the outboard wall of the stabilized foundation at cross sections A162+00, A168+00, and A172+00. As shown on the drawings, the surface of the existing ash will be excavated down to the summer pool level in Watts Bar Lake (EL. 741), and then at a 2H:1V slope down to the top of the lean clay soil. The rock berm will extend from an elevation four feet above the top of the deep mixed wall out to the top of the lean clay in the embayment.

Substantial deformations are anticipated in the rock berm during and after the design earthquake, due to liquefaction of the underlying alluvial sands. Note that the outer rock berm

will need to be re-built following the earthquake, to provide long-term protection of the exposed outboard deep mixed wall. The post-earthquake global stability assessment of the ash landfill requires an estimate of the final geometry of the deformed rock berm.

Deformation of the rock berm was predicted as documented in Exhibit 26. Static *FLAC* analyses on the cross section at Station A162+00 indicated that the rock berm would settle about 10 feet, resulting in six feet of exposed outboard deep mixed wall. These settlements will be associated with compression and lateral squeezing of the underlying soils. A post-earthquake rock berm surface slope of 13 percent was also estimated based on the *FLAC* results. These results were then applied, using some engineering judgment, to predict the post-earthquake geometries of the rock berms at Stations A168+00 and A172+00.

The cross section at Station A178+00 is in an area where the perimeter converges toward Swan Pond Road. A sediment control pond is proposed for this general location. Existing ash will be left in place in this area, and a large rock berm will not be constructed against the outboard deep mixed wall. As described in Exhibit 26, the estimated ground deformations might result in about 2.2 feet of exposed outboard deep mixed wall. The ash surface was estimated to have a post-earthquake slope of about 2 percent. This surface slope was judged to be a reasonable, rational assumption for the post-earthquake geometry at Station A178+00.

3.3. Stability under Post-Earthquake Conditions with Liquefaction

Based on the liquefaction triggering analyses (Exhibit 11), extensive liquefaction is expected within the saturated ash deposits and the alluvial sands. Hence, for the evaluation of post-earthquake stability, all of the hydraulically placed ash and alluvial sands, plus the landfilled ash not underlain by an capillary break and less than eight feet above the phreatic surface, were assumed to be liquefied and at their residual or steady state shearing resistances

Parametric calculations were carried out in *SLOPE/W* to determine the minimum stabilized foundation width needed along the North Dredge Cell Segment of the perimeter. These calculations targeted a minimum post-earthquake *FS* = 1.1 for slope stability, with liquefaction. Assuming f'_{sc} = 200 psi in the soil cement and an area replacement ratio of 0.26, the results indicated a minimum foundation treatment width of 100 feet.

Since completing these parametric evaluations, the design slopes for the landfill have been revised and additional soil borings have been advanced. The most recent borings indicated an area near Sta. A178+00 where the top of bedrock is about 10 to 15 feet lower than elsewhere in this design segment. Previously, the stability sections were drawn assuming a level final cover at an elevation of 790 feet. The current design for the cover reflects the surface slopes needed for drainage, which effectively reduces the height of the outslopes just behind the perimeter berm. The updated closure geometry results in less lateral pressure on the perimeter, resulting in post-earthquake factors of safety greater than 1.1 for slope stability. The reserve capacity is needed, however, to maintain internal structural performance (see Exhibits 18 and 21). The updated cross section geometries and the newly obtained subsurface information have been incorporated into the stability analyses presented here.

The calculated factors of safety with liquefaction and a deformed outer berm are summarized in Table 2. The computer output plots are presented in Appendix A (Figures A.1 through A.8). These results indicate that the shallow failure mode is more critical than the deep failure mode for all four cross sections evaluated.

Table 2 – Results of Stability Analyses for Post-Earthquake Conditions

Cross Section	Factor of Safety Shallow Failure	Factor of Safety Deep Failure
A162+00	1.58	2.18
A168+00	1.55	2.01
A172+00	1.50	2.36
A178+00	1.51	2.24

3.4. Critical Cross Section in the North Dredge Cell Segment

Another objective of the post-earthquake, limit equilibrium stability analyses is to identify the critical cross section for numerical modeling in *FLAC*. The results shown in Table 2 indicate that the shallow failure factors of safety are similar for all four evaluated cross sections (around 1.5).

As shown in the computer output plots in Appendix A, the shallow failure surfaces do not penetrate into the stabilized foundation. Hence, the shallow failure factors of safety are not affected by the properties of the stabilized foundation. In the *FLAC* analysis, emphasis is placed on the structural integrity and performance of the deep mixed panels; the critical loading condition is represented by the lowest deep failure factor of safety. Therefore, the cross section at Station A168+00 is the most critical among the four evaluated cross sections.

It is noted that A162+00 was identified as the most critical cross section in the previous parametric evaluations. With the reduced landfilled ash embankment heights and the additional subsurface information obtained in the newly drilled borings, A168+00 has become more critical; and was selected for further analyses in *FLAC*.

4. Stability under Long-Term, Static Conditions

The above four representative cross sections (Stations A162+00, A168+00, A172+00, and A178+00) within the limits of the first segment of the perimeter berm were also evaluated for slope stability under long-term, drained conditions. The analyses used the methods, assumptions, and material parameters outlined in Section 2.

Where the surface of the slope is composed of cohesionless (c' = 0) materials, an infinite slope failure (shallow sliding parallel to the slope surface) will be critical. The shallow, surficial failures pose little risk to the overall stability of the slopes. Suction pressures in unsaturated surface soils will often create enough apparent cohesion to prevent this type of failure. Hence, to force the *SLOPE/W* search routine to evaluate only the deeper potential failure surfaces, a minimum slip surface depth of 10 feet was specified in the analyses.

The calculated factors of safety are summarized in Table 3, and the computer output plots are presented in Appendix B (Figures B.1 through B.8). These results indicate that the critical slip surface occurs in the landfilled ash outslope for all four cross sections evaluated. Due to the high composite strengths in the stabilized foundation, the critical failure surface is not expected to cut through the stabilized foundation beneath the earthen berm.

The computed factors of safety for all four cross sections are greater than the required FS ≥ 1.5, indicating that the slopes will perform satisfactorily under static, long-term, drained conditions. This conclusion is anticipated, because the more critical (lower stability) design condition is for the post-earthquake period with liquefied ash and alluvial sands.

Table 3 – Results of Stability Analyses for Long-Term Drained Conditions

Cross Section	Factor of Safety Shallow Failure	Factor of Safety Deep Failure
A162+00	3.51	4.59
A168+00	2.62	3.98
A172+00	2.71	4.27
A178+00	2.74	7.11

Appendix A

Stability Analysis for Post-Earthquake Conditions with Liquefaction

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 1.58
Center = (-127.026, 869.323)
Radius = 80.5

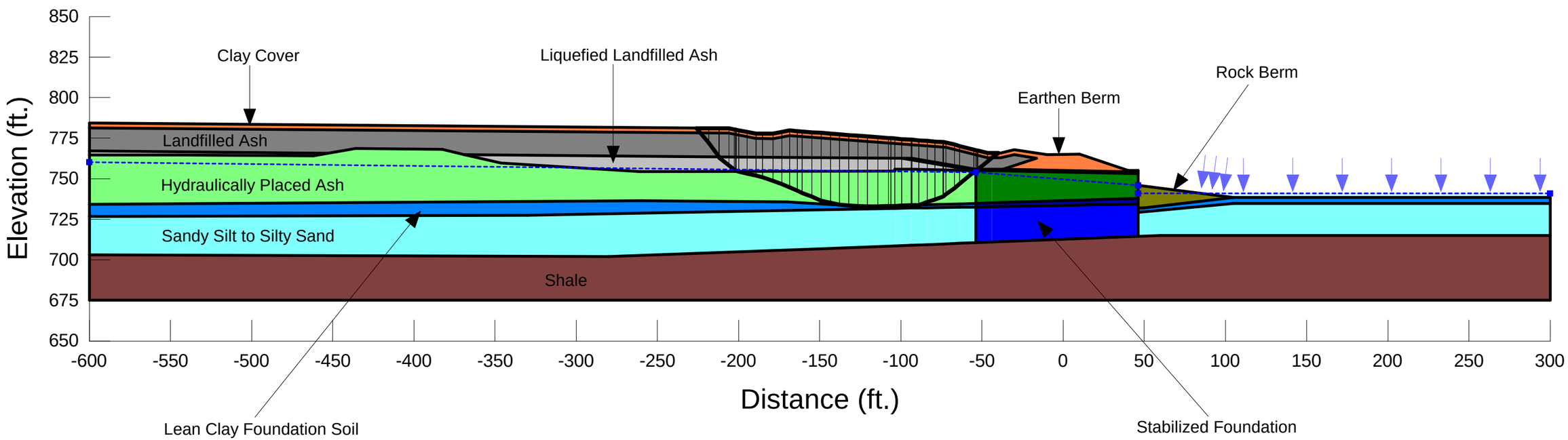

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Figure A.1 -- Post-Earthquake Stability, A162+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

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Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.18
Center = (-10.141, 1441.53)
Radius = 171.0471

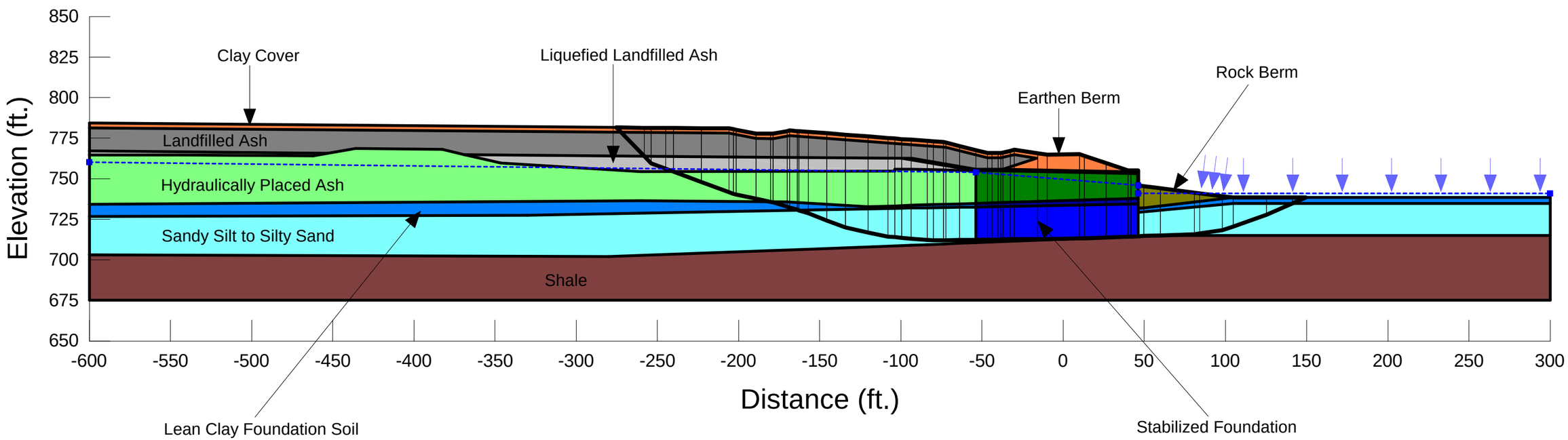

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Figure A.2 -- Post-Earthquake Stability, A162+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 1.55
Center = (-101.687, 825.088)
Radius = 59.48399

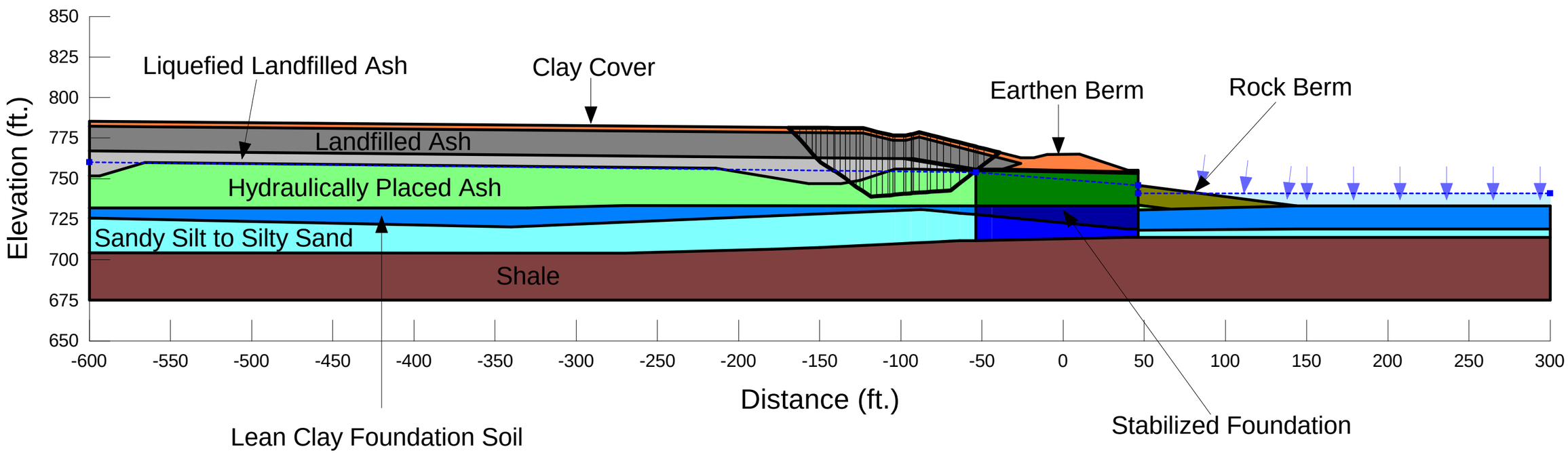

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Figure A.3 -- Post-Earthquake Stability, A168+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.01
Center = (16.201, 1403.81)
Radius = 174.2673

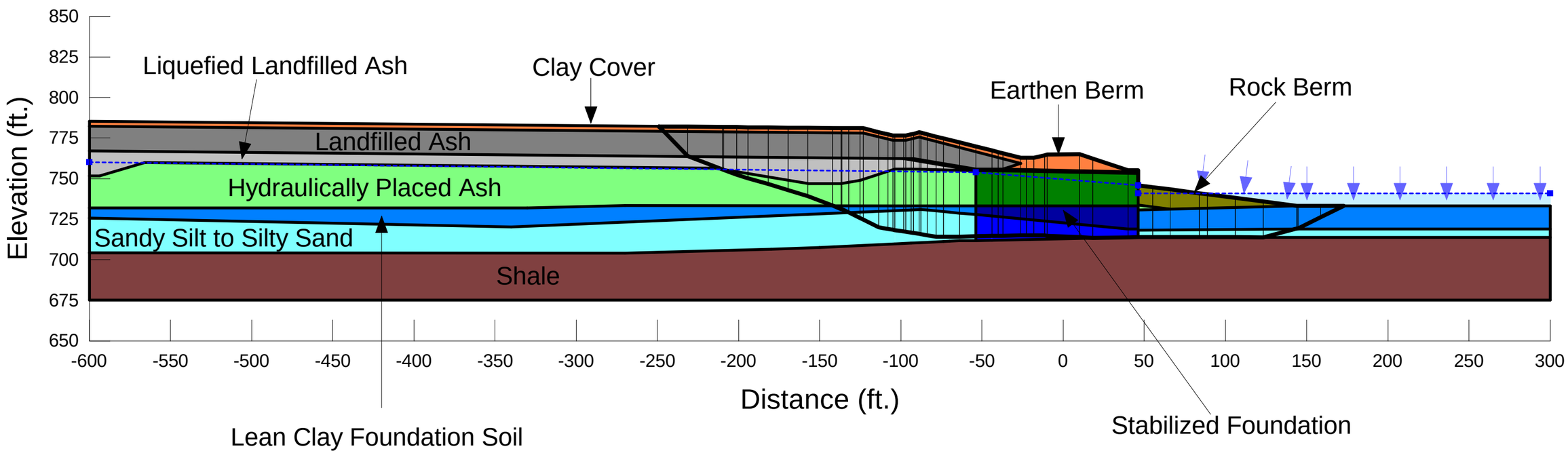

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Figure A.4 -- Post-Earthquake Stability, A168+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 1.50
Center = (-101.727, 824.922)
Radius = 60.44276

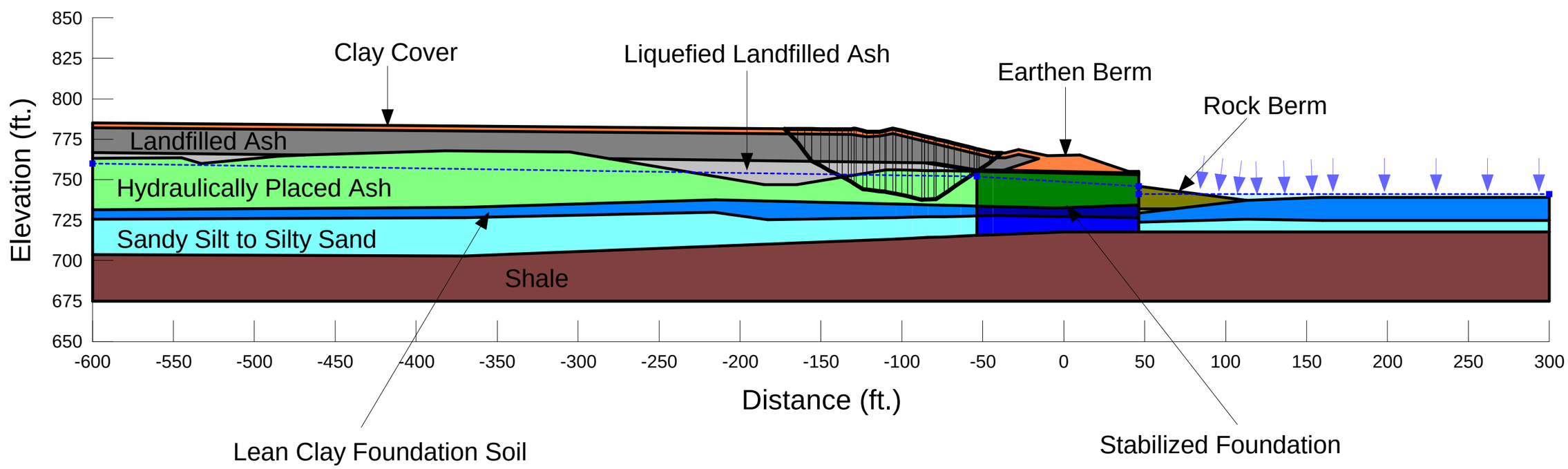

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Figure A.5 -- Post-Earthquake Stability, A172+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.36
Center = (12.567, 1207.59)
Radius = 148.0043

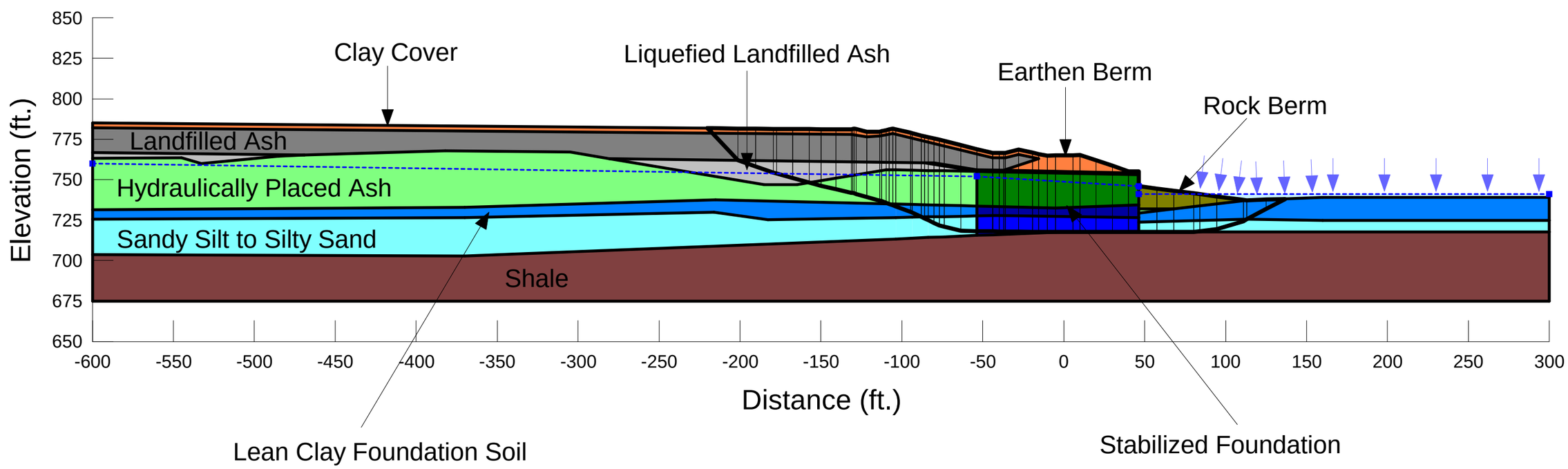

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Figure A.6 -- Post-Earthquake Stability, A172+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 1.51
Center = (-116.126, 816.385)
Radius = 64.61251

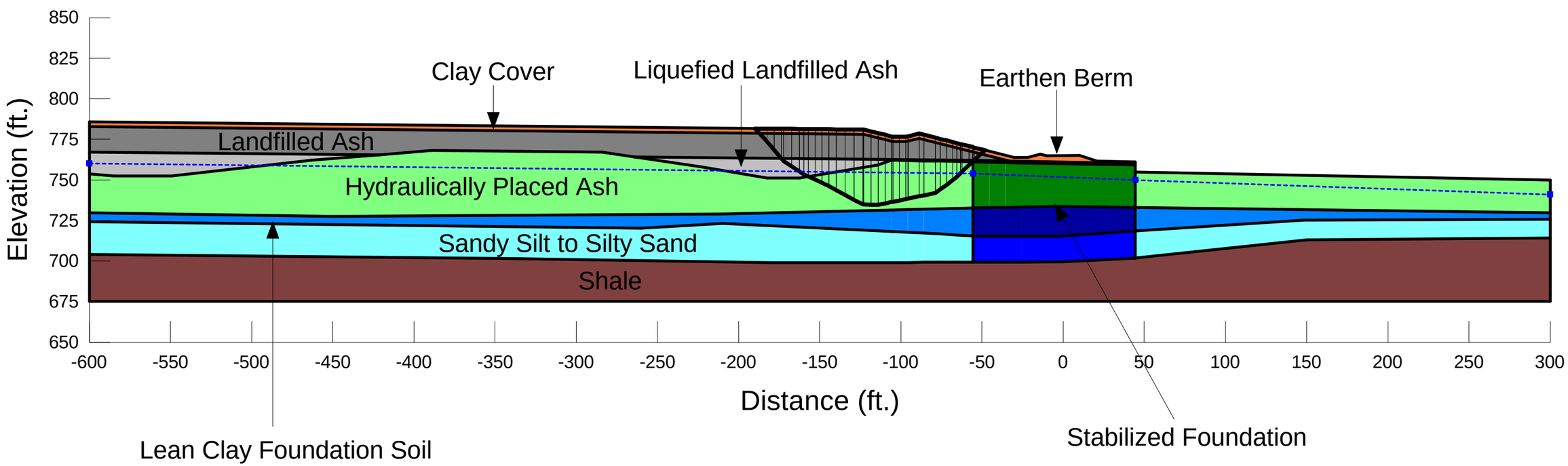

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Figure A.7 -- Post-Earthquake Stability, A178+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Undrained (Phi=0)	128; 125	c=1500; phi=0
Coarse Stone	Mohr-Coulomb	128; 115	c=0; phi=32
Landfilled Ash	Mohr-Coulomb	111; 109	c=0; phi=30
Liq. Landfilled Ash	S=f(overburden)	111; 111	Tau/Sigma=0.06
Hydraulically Placed Ash	S=f(overburden)	107; 100	Tau/Sigma=0.06
Lean Clay	Mohr-Coulomb	130; N/A	c=0; phi=20
Sandy Silt to Silty Sand	S=f(overburden)	128; N/A	Tau/Sigma=0.06
Shale	Mohr-Coulomb	140; N/A	c=3000; phi=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c=2995; phi=2.5
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c=2995; phi=15.1
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c=2995; phi=2.5
Shot Rock	Mohr-Coulomb	128; 115	c=0; phi=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.24
Center = (-20.069, 1431.94)
Radius = 226.1361

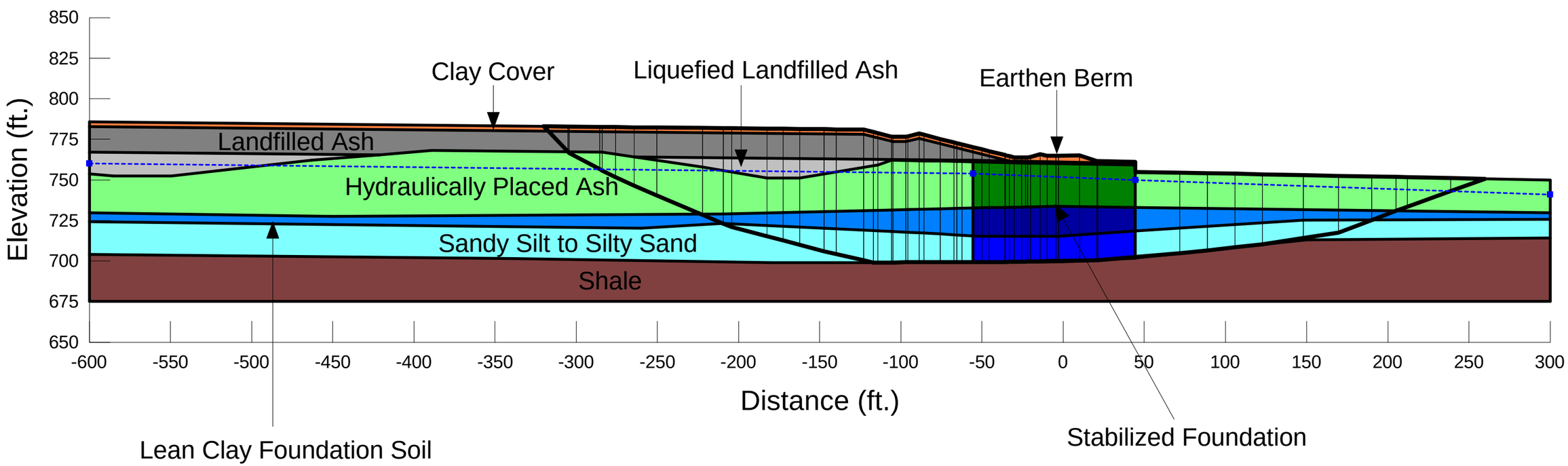

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Figure A.8 -- Post-Earthquake Stability, A178+00, Deep Failure

Appendix B

Stability Analyses for Long-Term, Drained Condition

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 3.51
Center = (-59.516, 796.601)
Radius = 20.87113

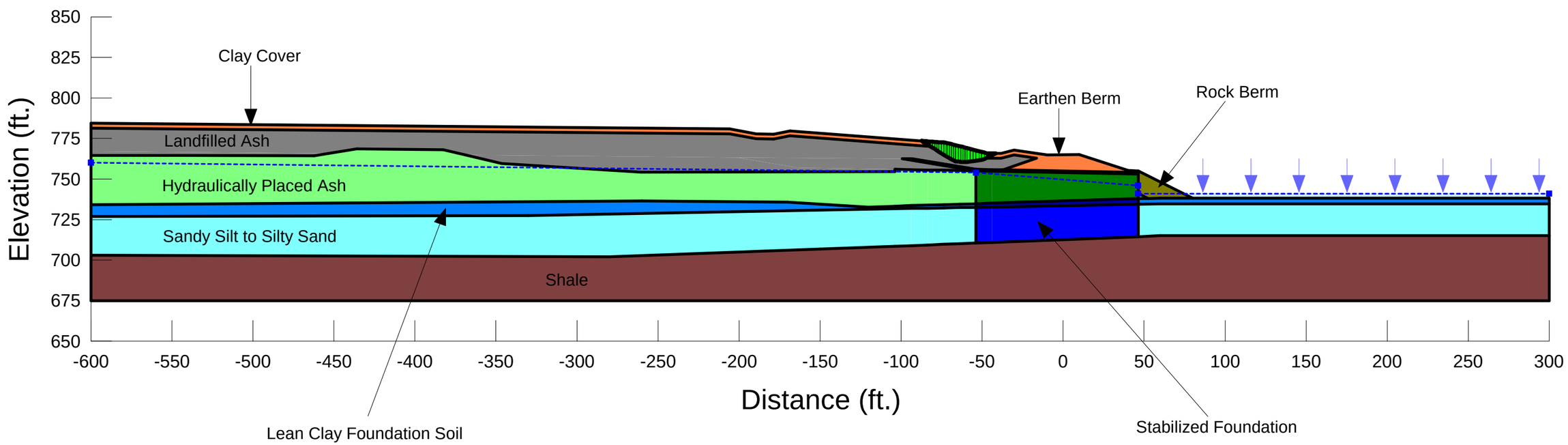

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Figure B.1 -- Long-Term, Drained Stability, A162+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 4.59
Center = (6.002, 989.695)
Radius = 124.0921

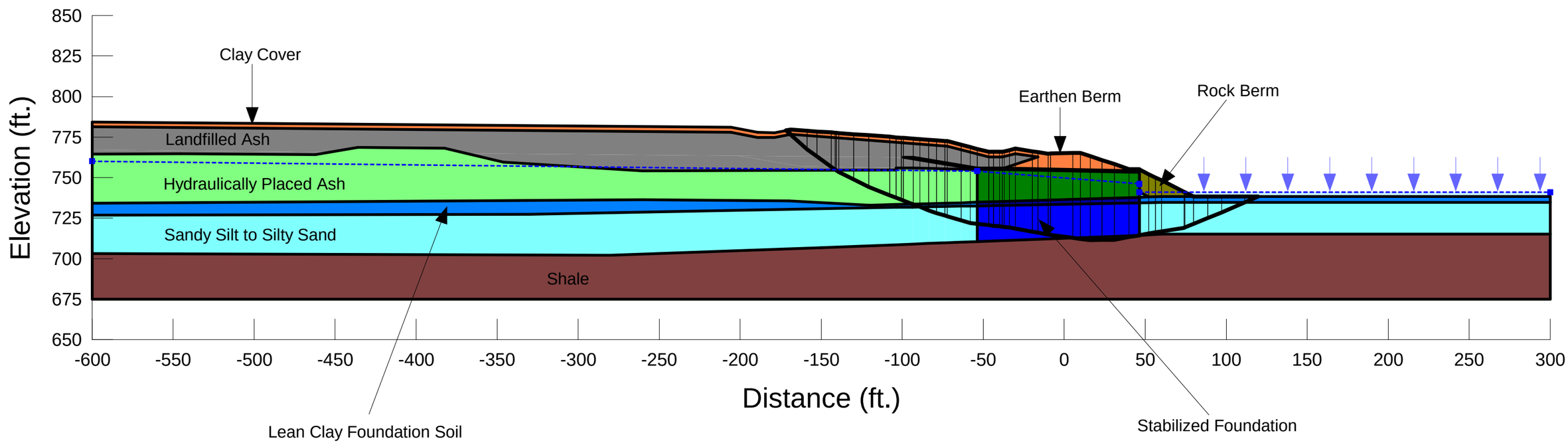

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Figure B.2 -- Long-Term, Drained Stability, A162+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.62
Center = (-45.019, 827.942)
Radius = 31.00167

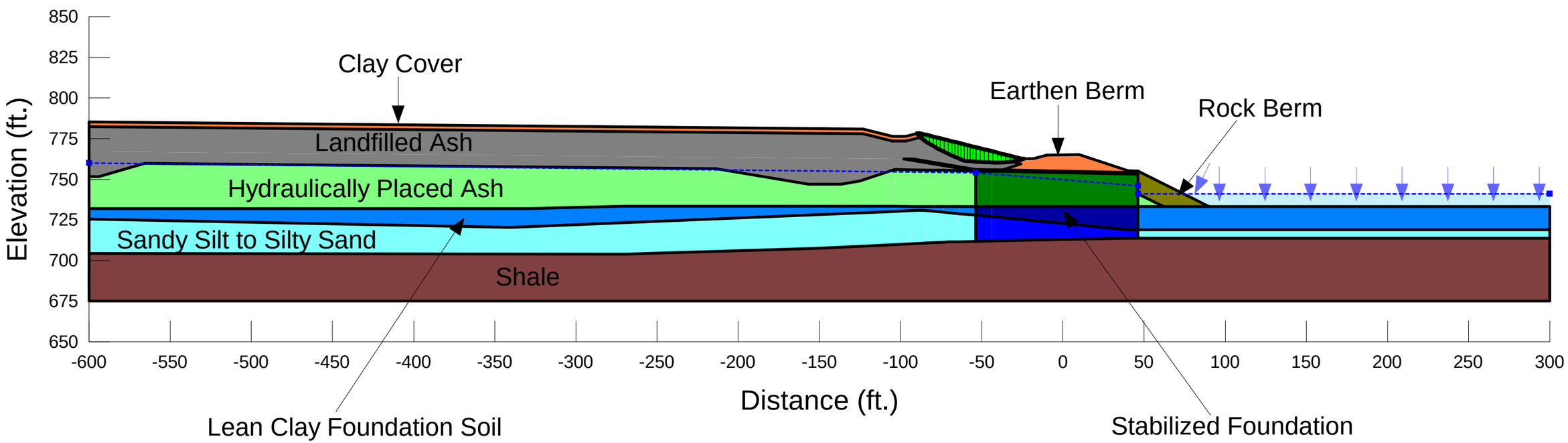

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Figure B.3 -- Long-Term, Drained Stability, A168+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 3.98
Center = (21.351, 986.078)
Radius = 125.8996

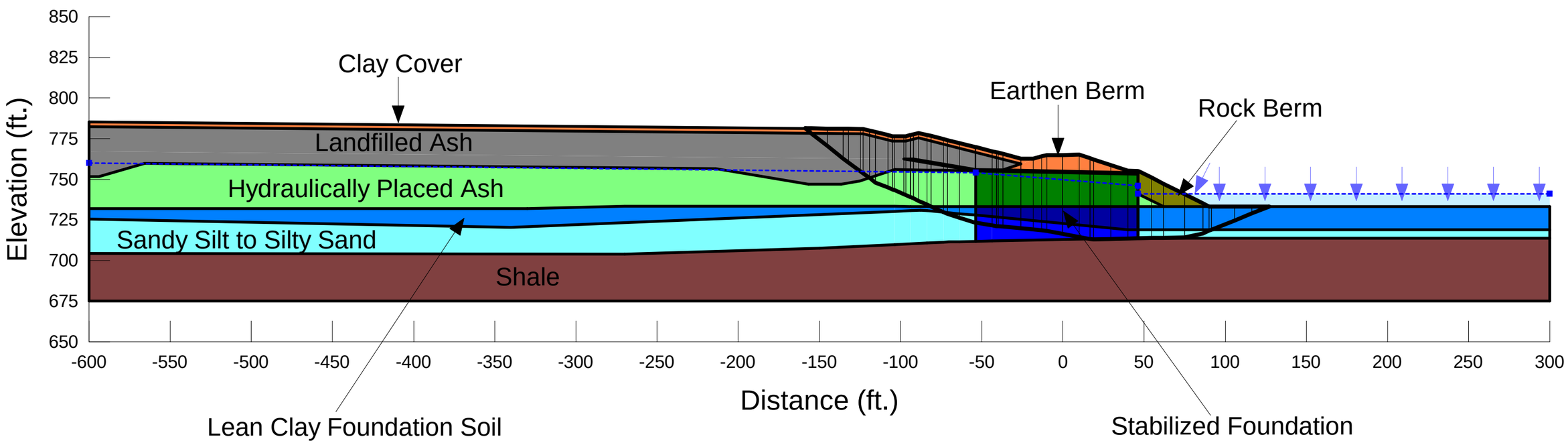

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Figure B.4 -- Long-Term, Drained Stability, A168+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.71
Center = (-63.777, 823.478)
Radius = 30.38333

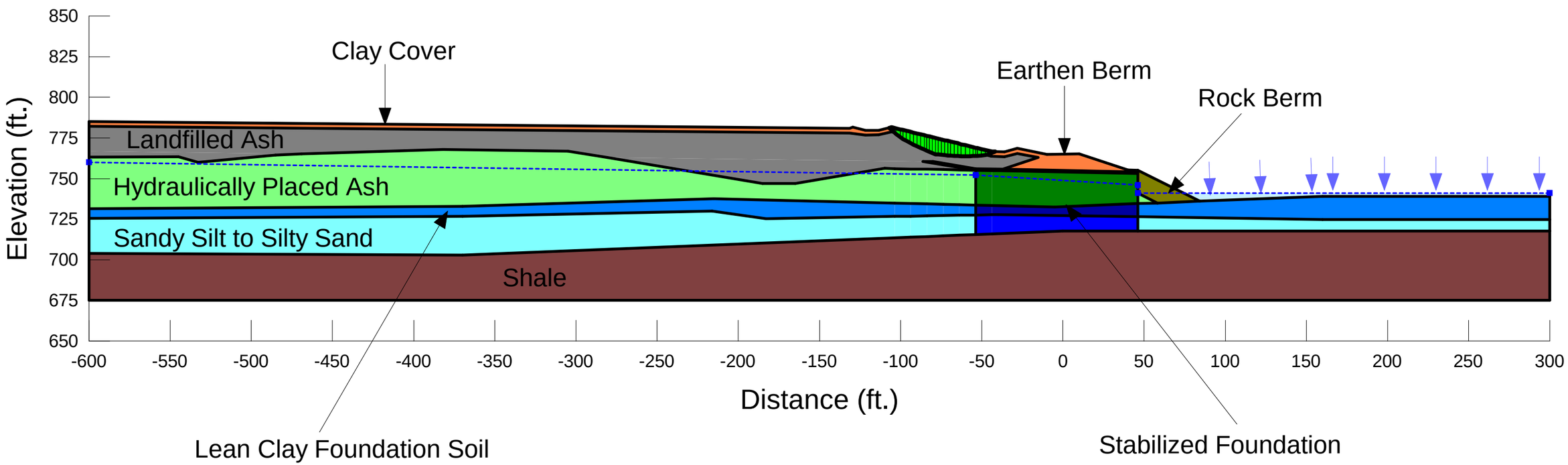

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Figure B.5 -- Long-Term, Drained Stability, A172+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 4.27
Center = (14.859, 980.788)
Radius = 117.3768

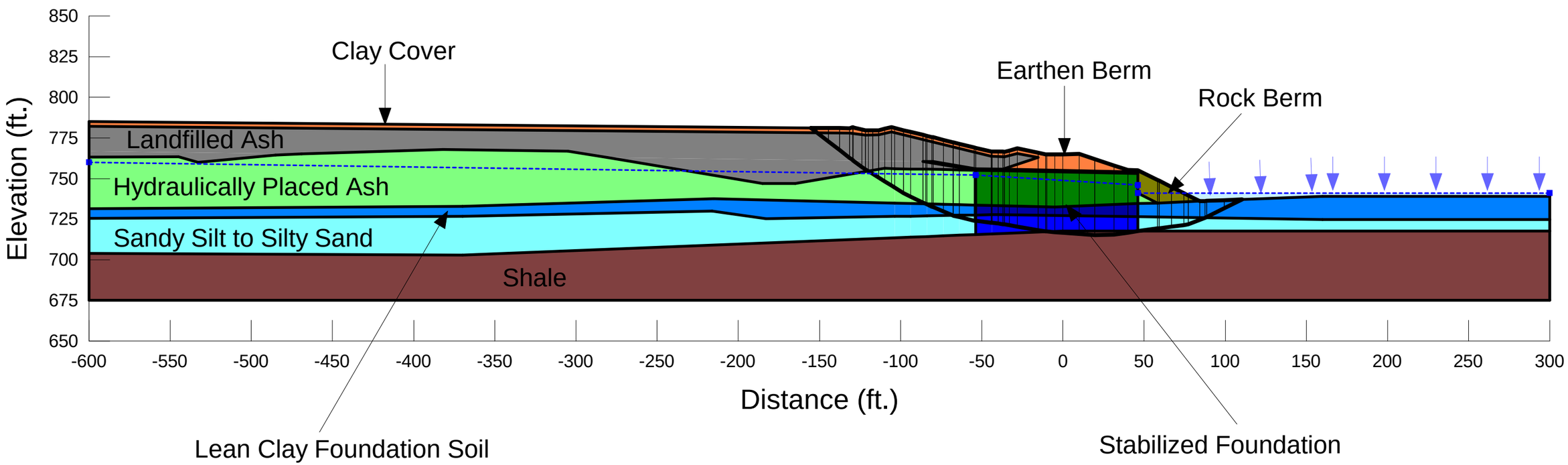

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Figure B.6 -- Long-Term, Drained Stability, A172+00, Deep Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 2.74
Center = (-60.108, 802.485)
Radius = 27.10533

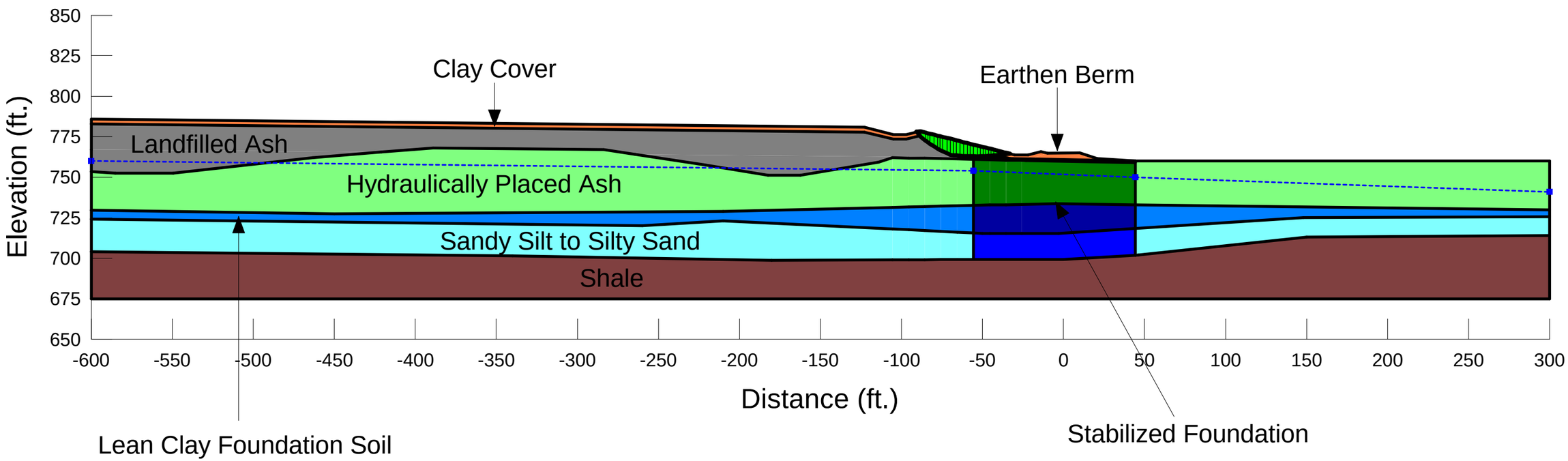

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Figure B.7 -- Long-Term, Drained Stability, A178+00, Shallow Failure

Material Name	Model	Unit Weight (Below/Above W.T.)	Strength Parameters
Earthen Berm	Mohr-Coulomb	128; 125	c'=0; phi'=28
Coarse Stone	Mohr-Coulomb	128; 115	c'=0; phi'=38
Landfilled Ash	Mohr-Coulomb	111; 109	c'=0; phi'=30
Hydraulically Placed Ash	Mohr-Coulomb	107; 100	c'=0; phi'=25
Lean Clay	Mohr-Coulomb	130; N/A	c'=0; phi'=32
Sandy Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=0; phi'=30
Shale	Mohr-Coulomb	140; N/A	c'=3000; phi'=20
Stab. Hyd. Ash	Mohr-Coulomb	107; 100	c'=2995; phi'=19
Stab. Lean Clay	Mohr-Coulomb	130; N/A	c'=2995; phi'=25
Stab. Silt to Silty Sand	Mohr-Coulomb	128; N/A	c'=2995; phi'=23
Shot Rock	Mohr-Coulomb	128; 115	c'=0; phi'=38

DSM Zone Width = 100 feet
Area Replacement Ratio = 26%

Factor of Safety (Opt.) = 7.11
Center = (-33.803, 1021.29)
Radius = 163.8568

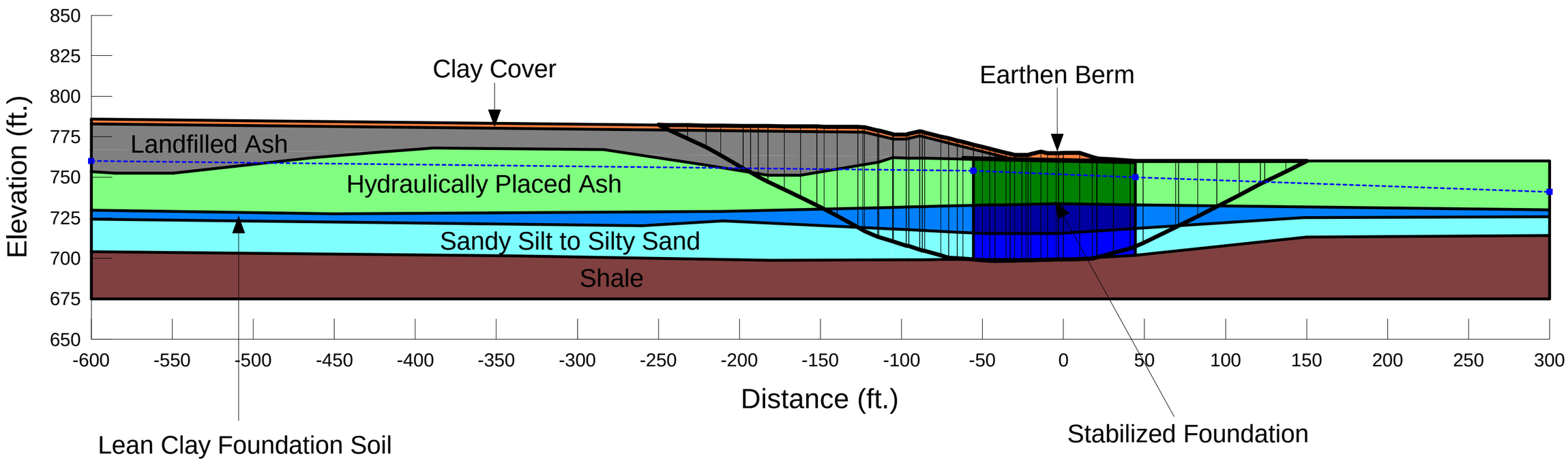

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Figure B.8 -- Long-Term, Drained Stability, A178+00, Deep Failure