AASHTO Recommends All MSE Walls be Larger, More Expensive
Retaining Wall Global Stability & AASHTO LRFD

The implementation of the AASHTO LRFD Bridge Design Specifications includes two significant, expensive, unwarranted changes in the level of conservatism for typical retaining walls with respect to overall global stability. The first significant change is elimination of the non-critical structure option. The most recent ASD guideline (AASHTO, 2002, 17^{th} edition Standard Specification for Highway Bridges) discusses global stability (Section 4 "Foundations" Articles 4.4.9 & 4.11.4.4 and Section 5 "Retaining Walls" Articles 5.2.2.3 & 5.14.6.4). The method requires that the designer determine the "criticality" of the structure to determine the appropriate factor of safety (FOS). With the provision that an adequate site investigation was conducted and that the ground characterization was completed by in-situ or laboratory testing, a FOS of 1.3 is specified for slopes and non-critical structures. For critical structures or structures supporting bridge abutments the recommended FOS is 1.5. Although the criteria to establish whether a given structure is critical or non-critical are left to the designer, generally, unless a wall is used to support a bridge abutment, a FOS of 1.3 complies with the guideline. Note that specific site conditions notwithstanding, nearly all roadway retaining walls may classify as "non-critical" structures where the overall purpose and function, from a global stability viewpoint, is to maintain the roadway – similar, if not identical, to the function of roadway embankment slopes. Therefore, it is rational that "non-critical" retaining walls, performing the same or similar global stability function of an embankment slope, would be designed using the same global stability FOS.

In Section 11 "Abutments, Piers and Walls," Article 11.6.2.3 "Overall Stability," of the AASHTO LRFD guideline (AASHTO, 2007, 4th edition LRFD Bridge Design Specifications) the criticality test has been removed and replaced with language that recommends a resistance factor (RF) of 0.65 for structures and 0.75 for slopes applied to service limit load states. This significantly increases the size and costs for walls that formerly would have been deemed "non-critical", and which are a major portion of walls in many regions. Note that the RF as applied to overall stability is the inverse of the FOS used in ASD. Most software used to analyze the overall global stability calculates a FOS. The designer must then invert the FOS to arrive at the RF. The RF is only a reciprocal, not a number! Yet it is reported that AASHTO rounded the RF to .05 increments to avoid "looking too precise". The global geotechnical community has used 1.3 and 1.5 in their suite of choices for as long as we have had analytical models. This new AASHTO rounding increases FOS numbers to 1.333 and 1.54. This increases size and cost of every AASHTO-based MSE wall, and for no demonstrated value.

Table 1 below summarizes the desired level of design conservatism recommended by AASHTO in the two structural design guidelines using "equivalent" RF and FOS to compare the two approaches.

Design Item	ASD (17th ed)		LRFD (4th ed)		% Increase from ASD
	Factor of Safety	*Equivalent* Resistance Factor	Resistance Factor	*Equivalent* Factor of Safety	
Slopes	1.3	0.77	0.75	1.33	2.6%
Non-Critical Structures	1.3	0.77	0.65	1.54	18.3%
Critical Structures	1.5	0.67	0.65	1.54	2.6%

Table 1. Comparison between Factors of Safety and Resistance Factors from AASHTO ASD & LRFD Design Guidelines.

As shown in Table 1, the implementation of AASHTO LRFD carries an increase in FOS of nearly 20% from the ASD design methodology for "non-critical" structures. Historically, the *desired* overall global stability FOS targeted by transportation agencies for slopes and retaining walls has been 1.3. (In sloping terrain such as occurs in mountainous regions a FOS of 1.3 may be impractical.) One may wonder what impacts, in terms of materials and cost, may result by increasing the global stability FOS from 1.3 to 1.54. The accompanying analyses attempt to estimate the cost differences of this increase as applied to highway MSE retaining walls.

For this demonstration a uniform homogeneous embankment slope of 2H:1V supporting a roadway with highway loading (250 psf uniform vertical surcharge) is assumed. An MSE retaining wall with a 20 foot exposed wall face is proposed using typical design standards (eg 1:1 excavation replaced with a select granular fill). For convenience, an overall reinforcement length to wall design height ratio of 70% is maintained throughout the iterations. The software program SLOPE/w by Geoslope was used to calculate the minimum global stability factor of safety and to perform probability analyses. Two examples, A & B, are analyzed. In both examples the soil properties for the select granular fill (Class 1 Structure Backfill) are identical. The embankment soils for Example A; however, were chosen to provide an ***existing*** slope stability FOS of approximately 1.3. The embankment materials for Example B were chosen to provide an ***existing*** slope stability FOS of approximately 1.5. The material properties used in the analyses are listed below in Table 2.

Soil Type	Property	unit	min	average	max	SD
Select Granular Backfill (Class 1 Structure Backfill)	Phi	deg	32	**34**	36	***0.67***
	C	psf	0	**0**	0	***0.00***
	Gamma	pcf	119	**127**	135	***2.67***
Example A Embankment Soil	Phi	deg	25	**29**	33	***1.33***
	c	psf	25	**87.5**	150	***20.83***
	gamma	pcf	110	**119.5**	129	***3.17***
Example B Embankment Soil	phi	deg	28	**32**	36	***1.33***
	c	psf	75	**125**	175	***16.67***
	gamma	pcf	115	**126.5**	138	***3.83***

Table 2. Material Properties Used in Global Stability Analyses for Examples A & B

The standard deviations used in the probability analyses were estimated by selecting abitrary minimum and maximum values, which are thought to represent 99.7% of the range of possible values (6sigma), and dividing this range by six. Because the standard deviations listed are small, the global stability analyses was repeated for each example using the same average values and tripling the standard deviations for each soil property. The SLOPE/w program uses a normal distribution for the material properties and probability distribution functions. The size of the reinforced zone for the MSE wall was adjusted to arrive at the targeted minimum stability value and the resulting material quantities for excavation, backfill, facing & reinforced fill estimated. A summary of these quantities, unit prices and cost information is provided in Table 3 for Examples A & B.

Wall	Description	Unit	Unit Cost	FOS=1.30 (RF=0.77)		FOS=1.54 (RF=0.65)	
				Qty	Cost	Qty	Cost
Eample A	Excavation	cyd	$17	138	$2,346	359	$6,103
	Select Backfill	cyd	$19	183	$3,477	403	$7,657
	Reinforcement Zone	cyd	$23	106	$2,438	235	$5,405
	Wall Facing	sft	$15	111	$1,665	165	$2,475
	Cost per square ft of wall exposure **(above ground surface)**			**$165**		**$361**	
Example B	Excavation	cyd	$17	25	$ 425	169	$2,873
	Select Backfill	cyd	$19	69	$1,311	213	$4,047
	Reinforcement Zone	cyd	$23	40	$ 920	124	$2,852
	Wall Facing	sft	$15	68	$1,020	120	$1,800
	Cost per square ft of wall exposure **(above ground surface)**			**$61**		**$193**	

Table 3. Material Quantities and Cost Estimate for MSE Retaining Wall Examples A & B. The Soil Properties selected provide a FOS of 1.316 (Example A) and 1.507 (Example B) for the Highway Embankment without a Retaining Wall (the "existing" condition).

The quantities and costs shown in Table 3 indicate that the initial retaining wall quantities and cost for implementing RF=0.65 (LRFD) are over twice the FOS=1.3 (ASD) design. Copies of the SLOPE/w analyses for Example A & Example B are provided in Appendices A & B, respectively.

The results of a probability analyses is presented in Table 4. The reliability index and probability of failure were determined for each example using the standard deviations for material properties listed in Table 2 and calculated again with standard deviations tripled to simulate a higher degree of uncertainty. A justification for a higher factor of safety based upon risk savings appears to be baseless until the reliability index falls below 3. Even with consideration of the marginal reliability examples, the *additional* construction costs imposed by the LRFD global resistance factor will challenge underfunded transportation budgets.

Ex	SD	Probability Item	ASD	LRFD
Example A	SD (Table 2)	FOS (Bishop)	1.302	1.541
		Resistance Factor	0.768	0.649
		Reliability Index	**5.641**	**8.338**
		Standard Deviation	0.054	0.065
		Probability of Failure (Normal Distribution)	8.45E-09	0.00E+00
		Risk per sft exposed wall cost (Normal Distribution)	***$0.00***	***$0.00***
	Triple SD	FOS (Bishop)	1.303	1.541
		Resistance Factor	0.767	0.649
		Reliability Index	**1.887**	**2.792**
		Standard Deviation	0.161	0.194
		Probability of Failure (Normal Distribution)	2.96E-02	2.62E-03
		Risk per sft exposed wall cost (Normal Distribution)	***$4.90***	***$0.95***
Example B	SD (Table 2)	FOS (Bishop)	1.303	1.537
		Resistance Factor	0.767	0.651
		Reliability Index	**6.623**	**9.532**
		Standard Deviation	0.046	0.056
		Probability of Failure (Normal Distribution)	1.76E-11	0.00E+00
		Risk per sft exposed wall cost (Normal Distribution)	***$0.00***	***$0.00***
	Triple SD	FOS (Bishop)	1.303	1.537
		Resistance Factor	0.767	0.651
		Reliability Index	**2.216**	**3.176**
		Standard Deviation	0.136	0.169
		Probability of Failure (Normal Distribution)	1.33E-02	7.47E-04
		Risk per sft exposed wall cost (Normal Distribution)	***$0.82***	***$0.14***

Appendix A

Description: EXAMPLE A
Comments: Sensitivity Analyses
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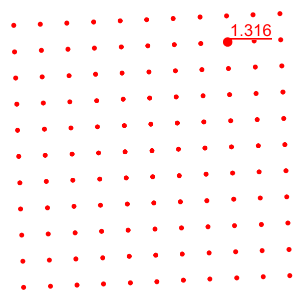
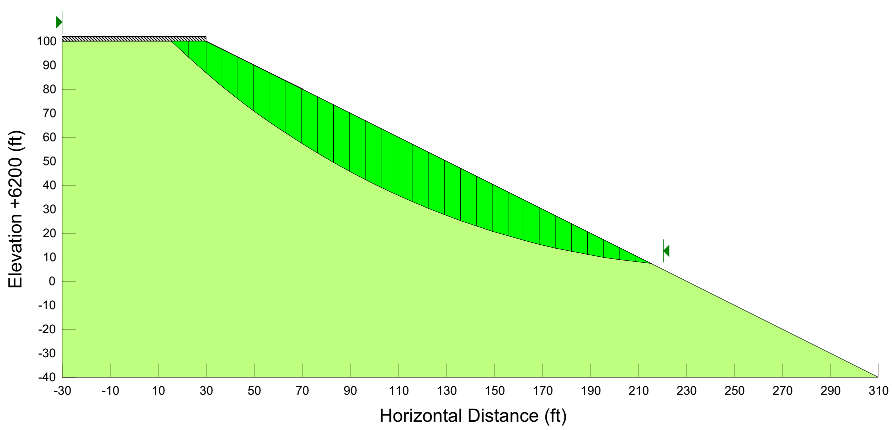
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE A
Existing Condition

Reliability Index: 5.55
P (Failure) (%): 0
Standard Dev.: 0.057
Min F of S: 1.077
Max F of S: 1.532
# of Trials: 10000



Soil: 1
Description: Embankment Sc
Soil Model: Mohr-Coulomb
Unit Weight: 119.5 (SD=3.1
Cohesion: 87.5 (SD=20.83)
Phi: 29 (SD=1.33)
Piezometric Line #: 0 (SD=0
Pore-Air Pressure: 0

Description: EXAMPLE A
Comments: Sensitivity Analyses
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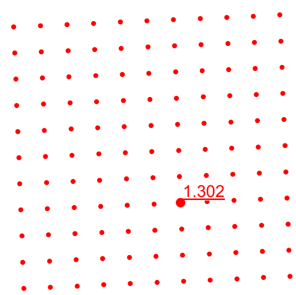
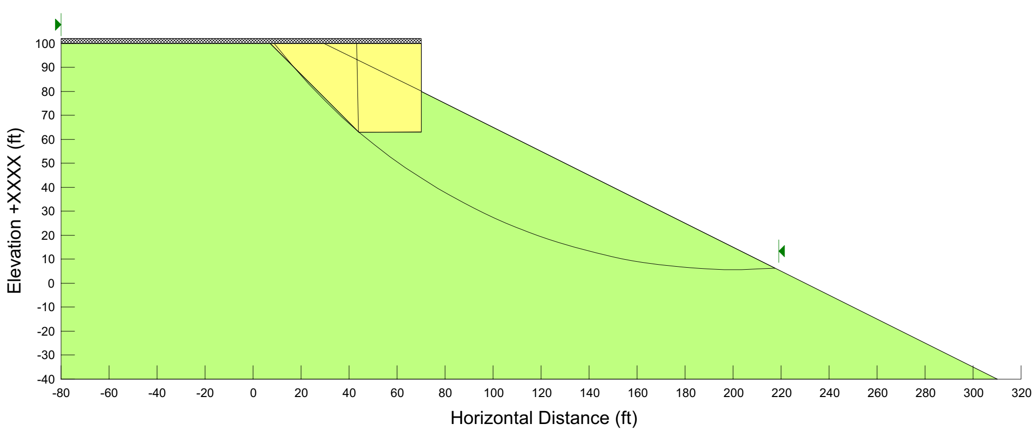
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE A
RF=0.77

Reliability Index: 5.641
P (Failure) (%): 0
Standard Dev.: 0.054
Min F of S: 1.109
Max F of S: 1.5
# of Trials: 10000



Soil: 1
Description: Class 1 Structure Back
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=2.67)
Cohesion: 0 (SD=0)
Phi: 34 (SD=0.67)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 119.5 (SD=3.17)
Cohesion: 87.5 (SD=20.83)
Phi: 29 (SD=1.33)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Description: EXAMPLE A
Comments: Sensitivity Analyses
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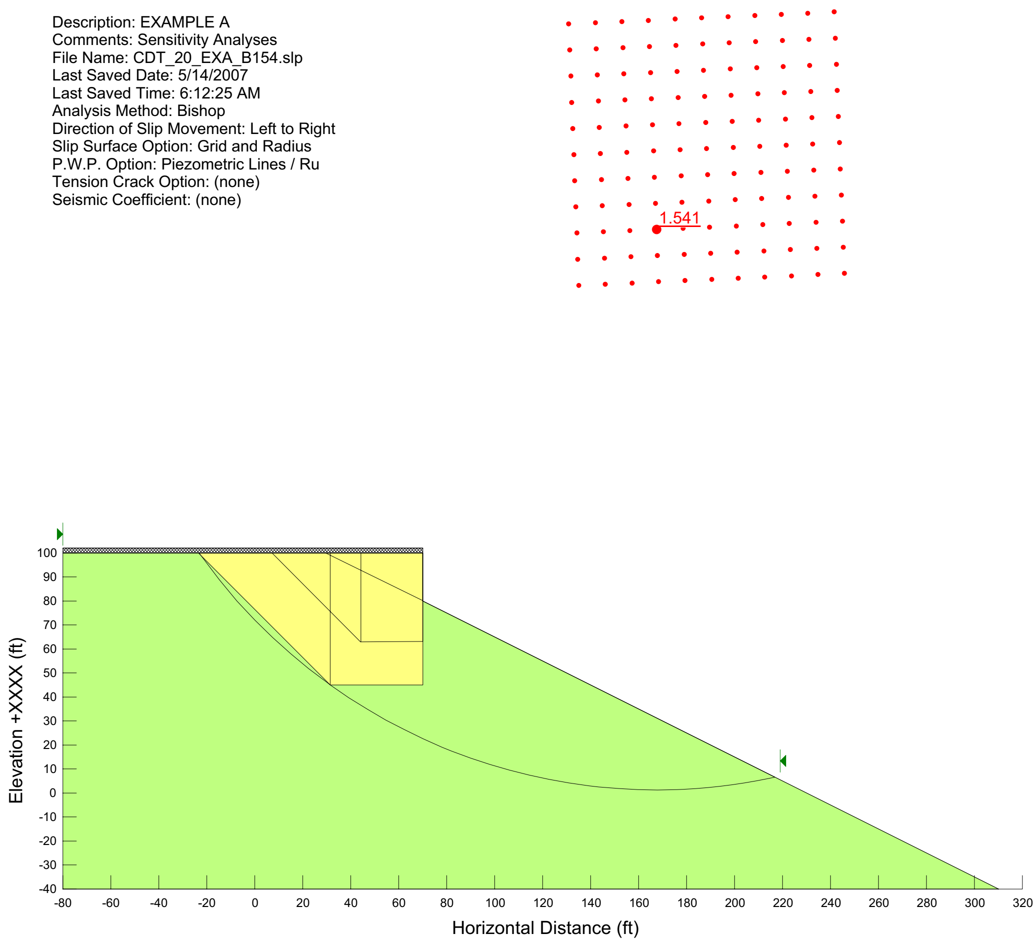
Analysis Method: Bishop
Direction of Slip Movement: Left to Right
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

EXAMPLE A
RF=0.65

Reliability Index: 8.338
P (Failure) (%): 0
Standard Dev.: 0.065
Min F of S: 1.304
Max F of S: 1.792
# of Trials: 10000



Soil: 1
Description: Class 1 Structure Back
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=2.67)
Cohesion: 0 (SD=0)
Phi: 34 (SD=0.67)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 119.5 (SD=3.17)
Cohesion: 87.5 (SD=20.83)
Phi: 29 (SD=1.33)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Description: EXAMPLE A
Comments: Sensitivity Analyses
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Analysis Method: Bishop
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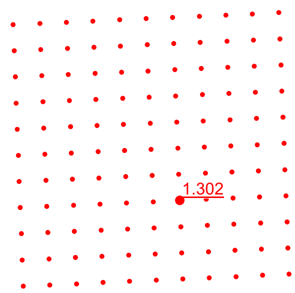
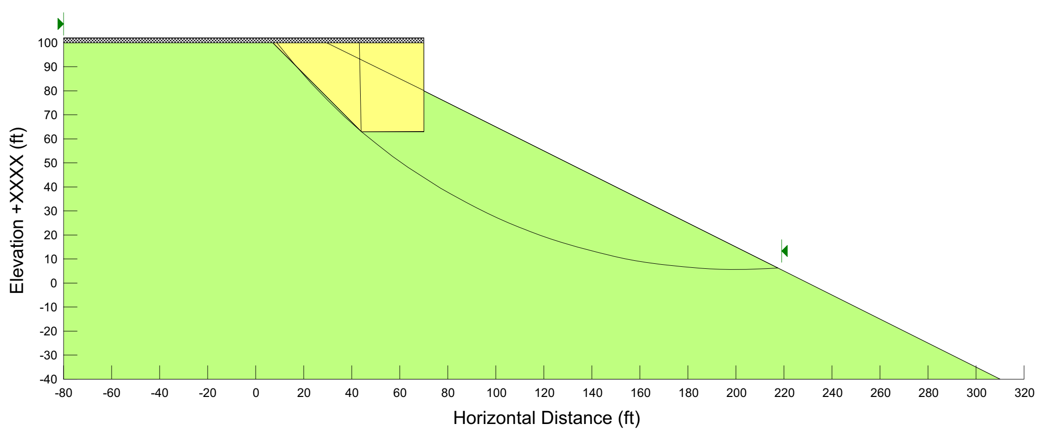
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE A
RF=0.77
Triple SD

Reliability Index: 1.887
P (Failure) (%): 2.943
Standard Dev.: 0.161
Min F of S: 0.696
Max F of S: 1.935
# of Trials: 10000



Soil: 1
Description: Class 1 Structure Back
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=2.67)
Cohesion: 0 (SD=0)
Phi: 34 (SD=0.67)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 119.5 (SD=9.51)
Cohesion: 87.5 (SD=62.49)
Phi: 29 (SD=3.99)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Description: EXAMPLE A
Comments: Sensitivity Analyses
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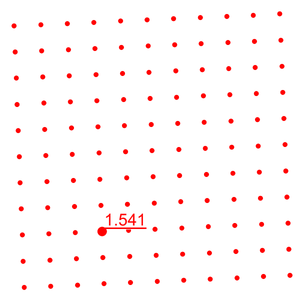
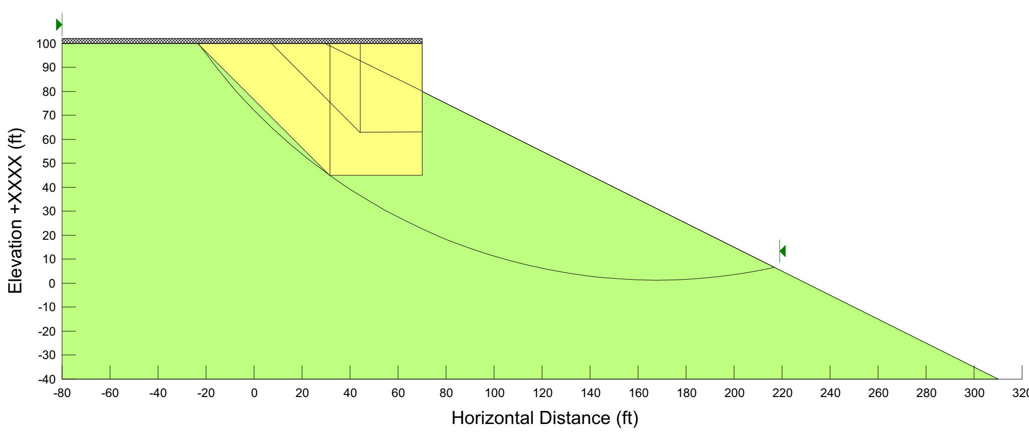
Analysis Method: Bishop
Direction of Slip Movement: Left to Right
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE A
RF=0.65
Triple SD

Reliability Index: 2.792
P (Failure) (%): 0.261
Standard Dev.: 0.194
Min F of S: 0.774
Max F of S: 2.304
# of Trials: 10000



Soil: 1
Description: Class 1 Structure Back
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=8.01)
Cohesion: 0 (SD=0)
Phi: 34 (SD=2.01)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 119.5 (SD=9.51)
Cohesion: 87.5 (SD=62.49)
Phi: 29 (SD=3.99)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Appendix B

Description: EXAMPLE B
Comments: Sensitivity Analyses
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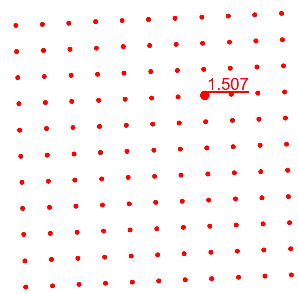
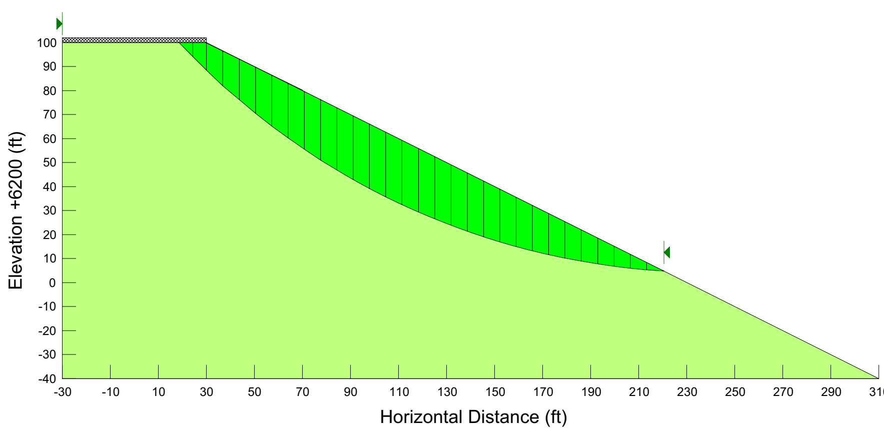
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE B
Existing Condition

Reliability Index: 9.37
P (Failure) (%): 0
Standard Dev.: 0.054
Min F of S: 1.293
Max F of S: 1.724
# of Trials: 10000



Soil: 1
Description: Embankment Sc
Soil Model: Mohr-Coulomb
Unit Weight: 126.5 (SD=3.8:
Cohesion: 125 (SD=16.67)
Phi: 32 (SD=1.33)
Piezometric Line #: 0 (SD=0
Pore-Air Pressure: 0

Description: EXAMPLE B
Comments: Sensitivity Analyses
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Last Saved Time: 6:38:43 AM
Analysis Method: Bishop
Direction of Slip Movement: Left to Right
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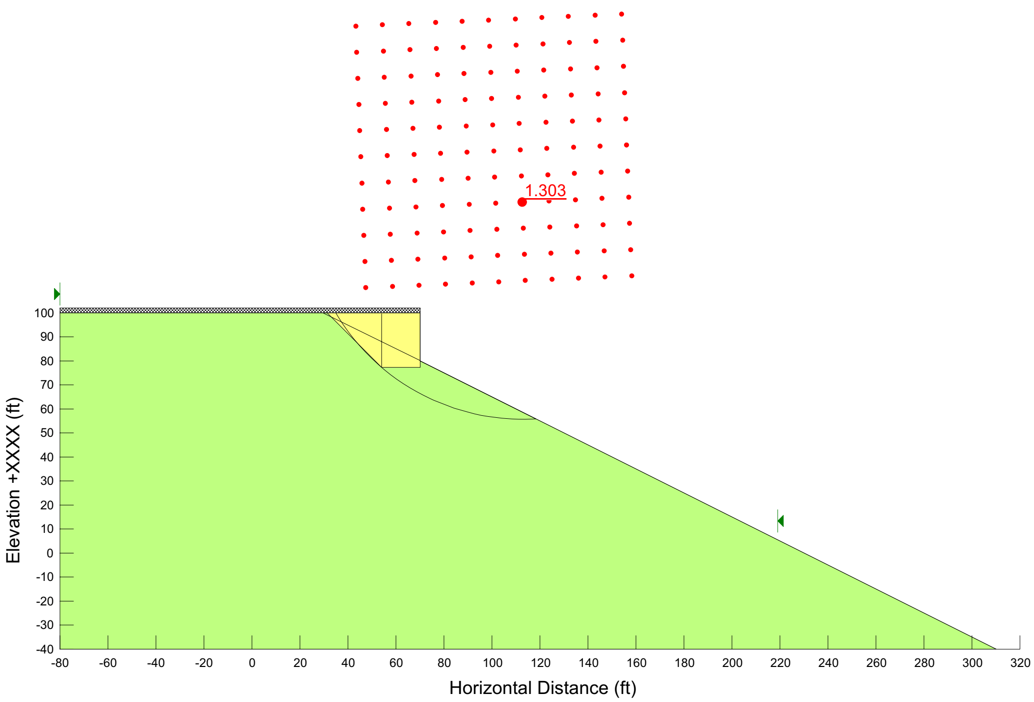
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

EXAMPLE B
RF=0.77

Reliability Index: 6.623
P (Failure) (%): 0
Standard Dev.: 0.046
Min F of S: 1.141
Max F of S: 1.504
# of Trials: 10000



Soil: 1
Description: CLASS 1 BACKFIL
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=2.67)
Cohesion: 0 (SD=0)
Phi: 34 (SD=0.67)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 126.5 (SD=3.83)
Cohesion: 125 (SD=16.67)
Phi: 32 (SD=1.33)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Description: EXAMPLE B
Comments: Sensitivity Analyses
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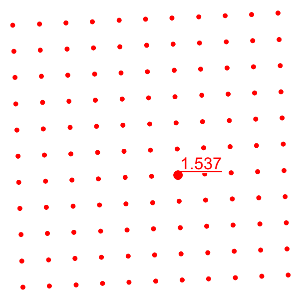
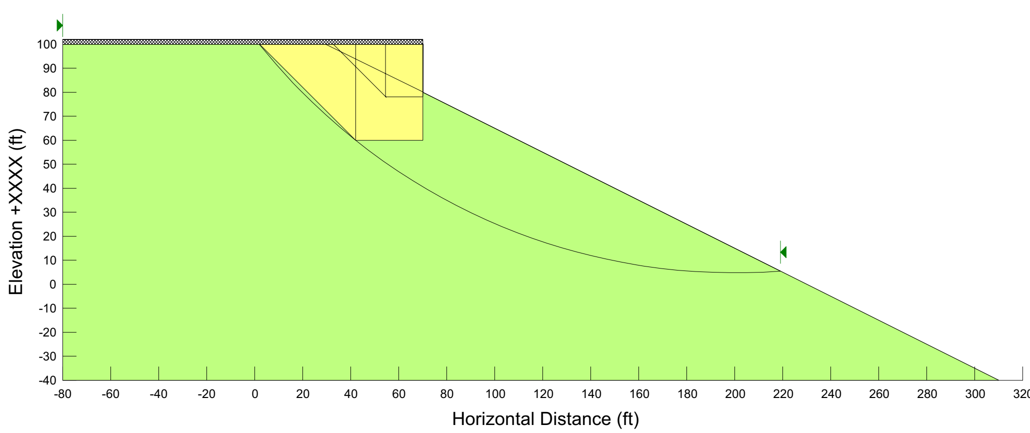
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE B
RF=0.65

Reliability Index: 9.532
P (Failure) (%): 0
Standard Dev.: 0.056
Min F of S: 1.322
Max F of S: 1.738
# of Trials: 10000



Soil: 1
Description: CLASS 1 BACKFIL
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=2.67)
Cohesion: 0 (SD=0)
Phi: 34 (SD=0.67)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 126.5 (SD=3.83)
Cohesion: 125 (SD=16.67)
Phi: 32 (SD=1.33)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

EXAMPLE B
RF=0.77
Triple SD

Description: EXAMPLE B
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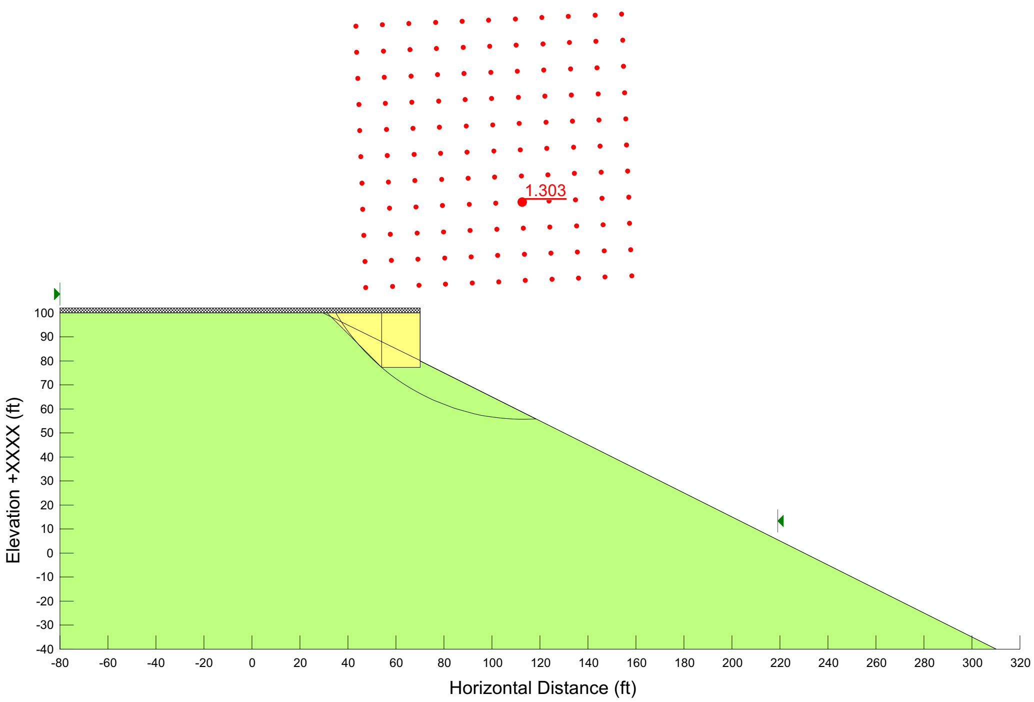
Last Saved Time: 6:35:56 AM
Analysis Method: Bishop
Direction of Slip Movement: Left to Right
Slip Surface Option: Grid and Radius
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)

Reliability Index: 2.216
P (Failure) (%): 1.33
Standard Dev.: 0.136
Min F of S: 0.753
Max F of S: 1.874
# of Trials: 10000



Soil: 1
Description: CLASS 1 BACKFIL
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=8.01)
Cohesion: 0 (SD=0)
Phi: 34 (SD=2.01)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 126.5 (SD=11.49)
Cohesion: 125 (SD=50.01)
Phi: 32 (SD=3.99)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Description: EXAMPLE B
Comments: Sensitivity Analyses
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Last Saved Time: 5:57:26 AM
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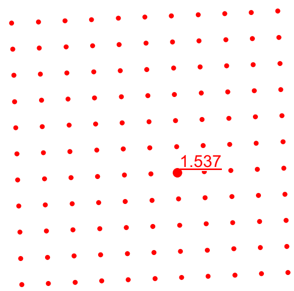
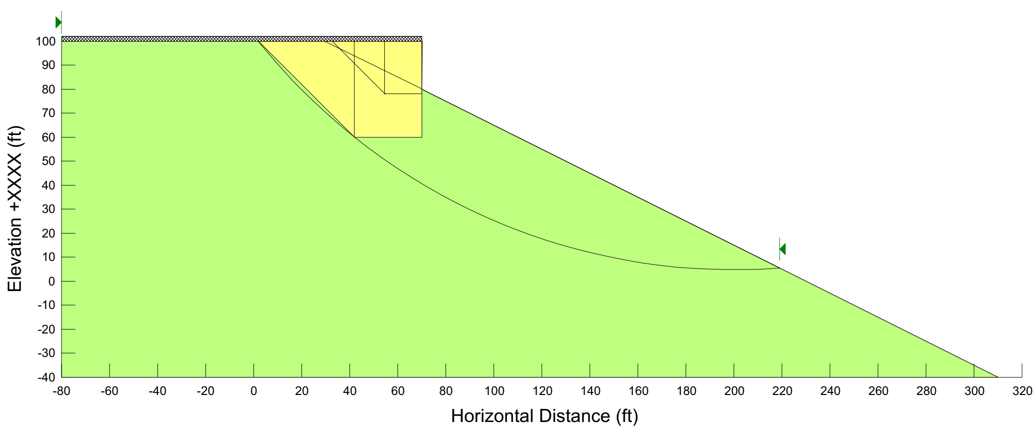
P.W.P. Option: Piezometric Lines / Ru
Tension Crack Option: (none)
Seismic Coefficient: (none)



EXAMPLE B
RF=0.65
Triple SD

Reliability Index: 3.176
P (Failure) (%): 0.074
Standard Dev.: 0.169
Min F of S: 0.953
Max F of S: 2.336
# of Trials: 10000



Soil: 1
Description: CLASS 1 BACKFIL
Soil Model: Mohr-Coulomb
Unit Weight: 127 (SD=8.01)
Cohesion: 0 (SD=0)
Phi: 34 (SD=2.01)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0

Soil: 2
Description: Embankment Soil
Soil Model: Mohr-Coulomb
Unit Weight: 126.5 (SD=11.49)
Cohesion: 125 (SD=50.01)
Phi: 32 (SD=3.99)
Piezometric Line #: 0 (SD=0)
Pore-Air Pressure: 0