Risk Quantification for Design

Roger A. Failmezger, P.E., F. ASCE
In-Situ Soil Testing, L.C.

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Overview

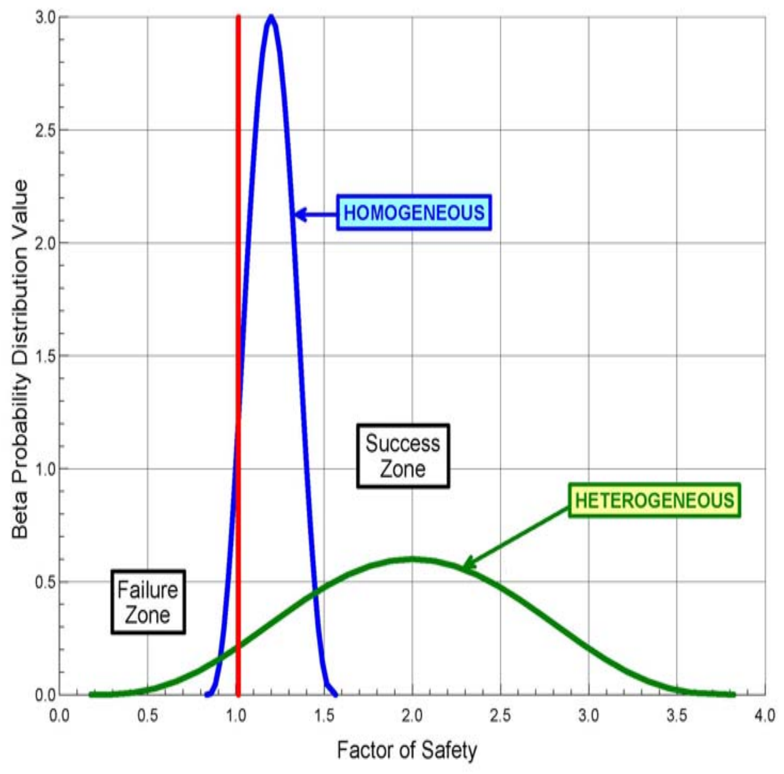
- Uncertainty is what makes geotechnical engineering both interesting and challenging
  - Site Variability
  - How well we can predict
- The more you know, the better your design will be and the lower construction costs will be
- Our goal is to educate the Owner so that he will understand our risk analyses and will ask “what if” questions and we tell him the risk impact to those scenarios
- Design will serve the owner’s needs

Design Approaches

- Traditional factor of safety design assesses uncertainty QUALITATIVELY
  - Based on engineering judgment and codes
  - If owner doesn't like the solution, he doubts your judgment
- Probability design assesses uncertainty QUANTITATIVELY
  - Previously probability approaches have been too mathematical for practical use by geotechnical engineers
  - Approach presented today is technically sound, yet easy to apply

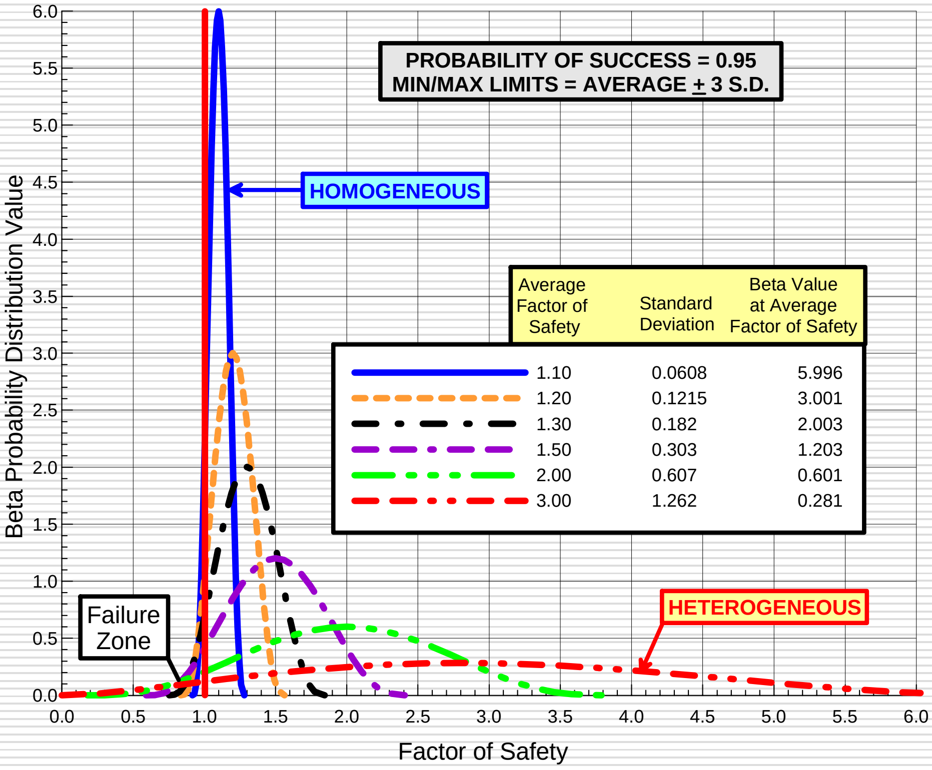
Probability Rules

- Probability distribution curves tend to be “bell” shaped for civil engineering applications
- The total area underneath a probability distribution curve must equal exactly 1.0
- Probability of success + probability of failure = 1.0
  - Use term “Probability of Success” with owner

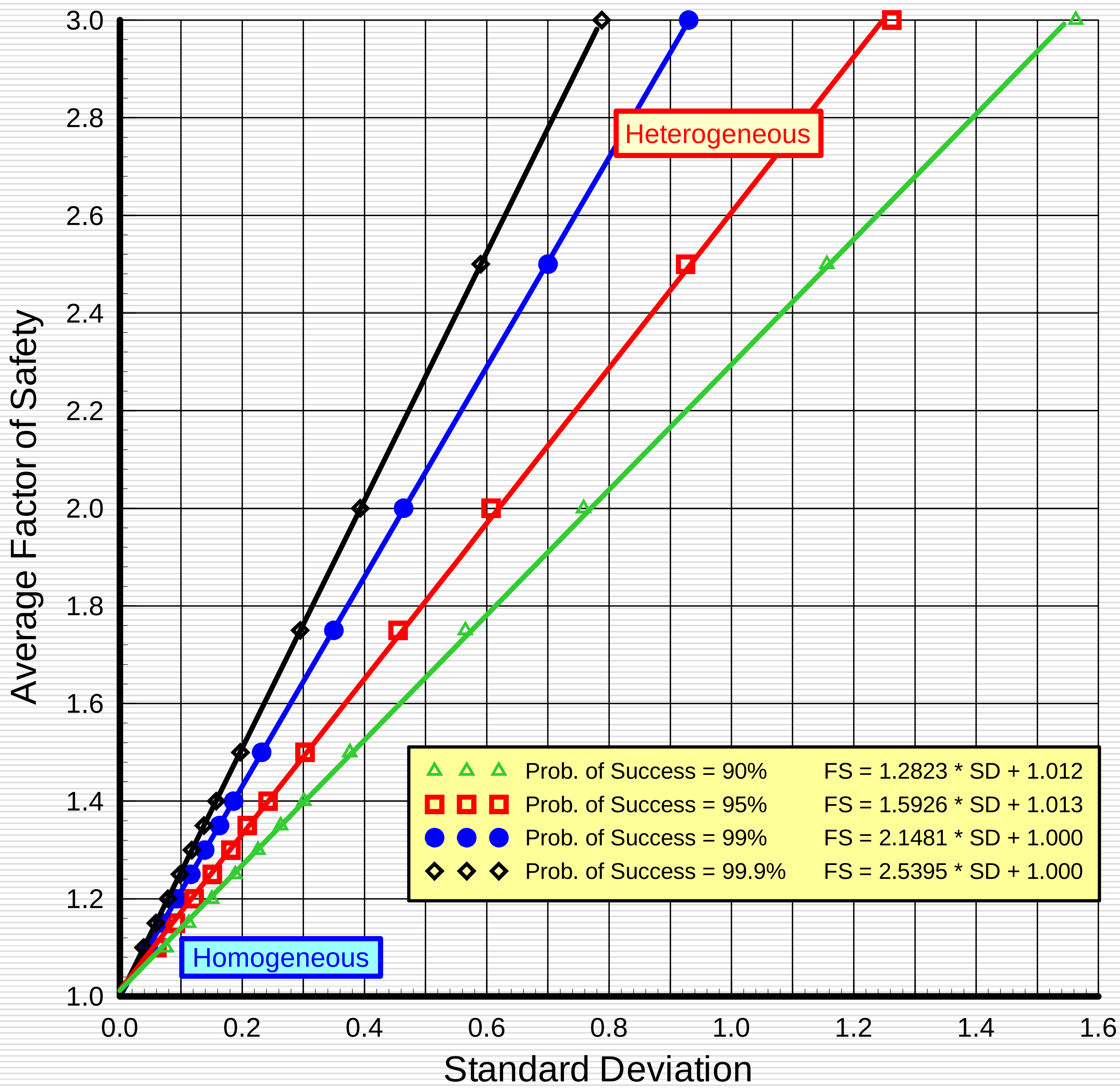


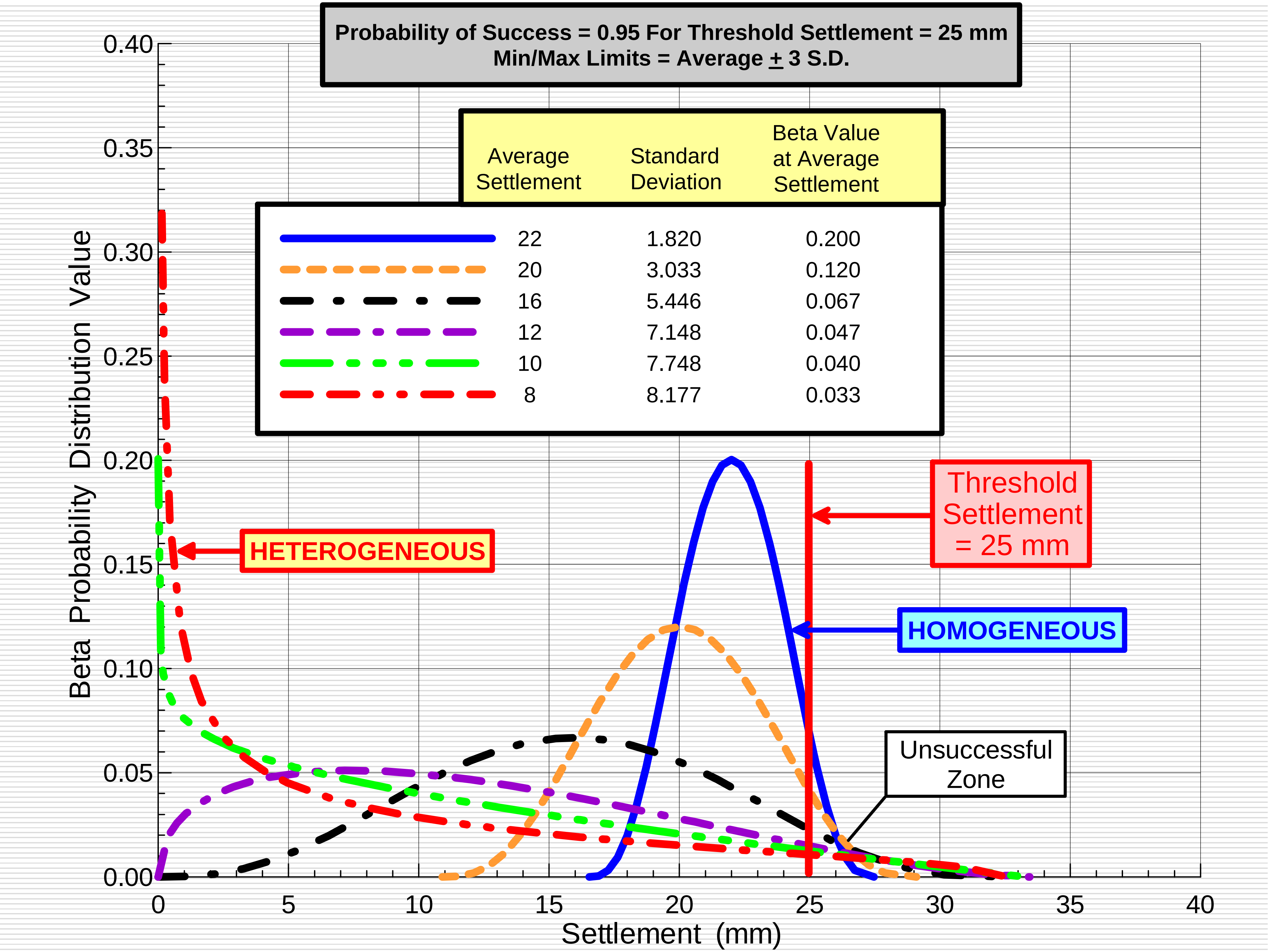
Technical Approach

- Assume an average factor of safety
- Use trial and error convergence approach with standard deviation values until get the one that gives the desired probability of success

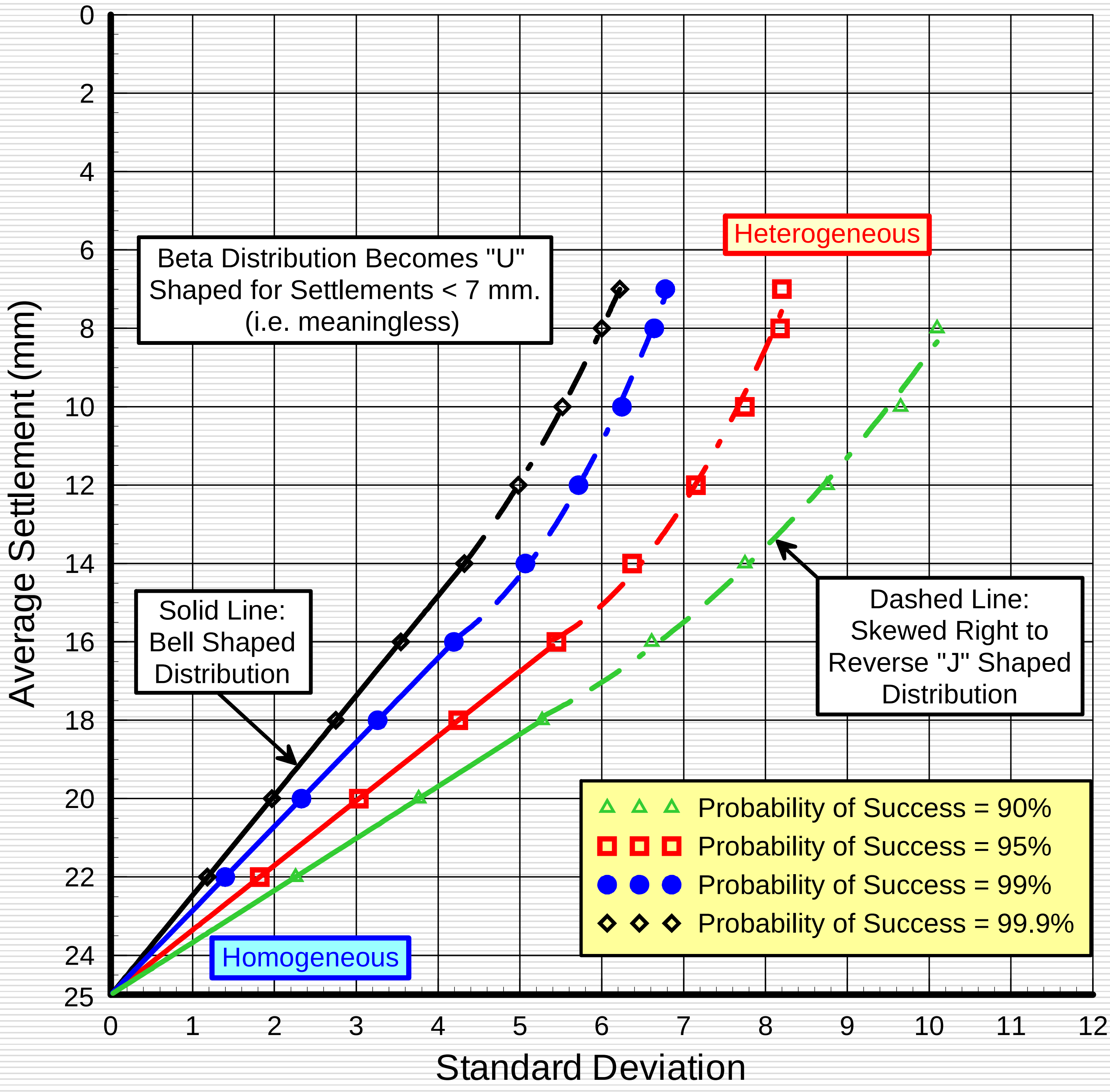


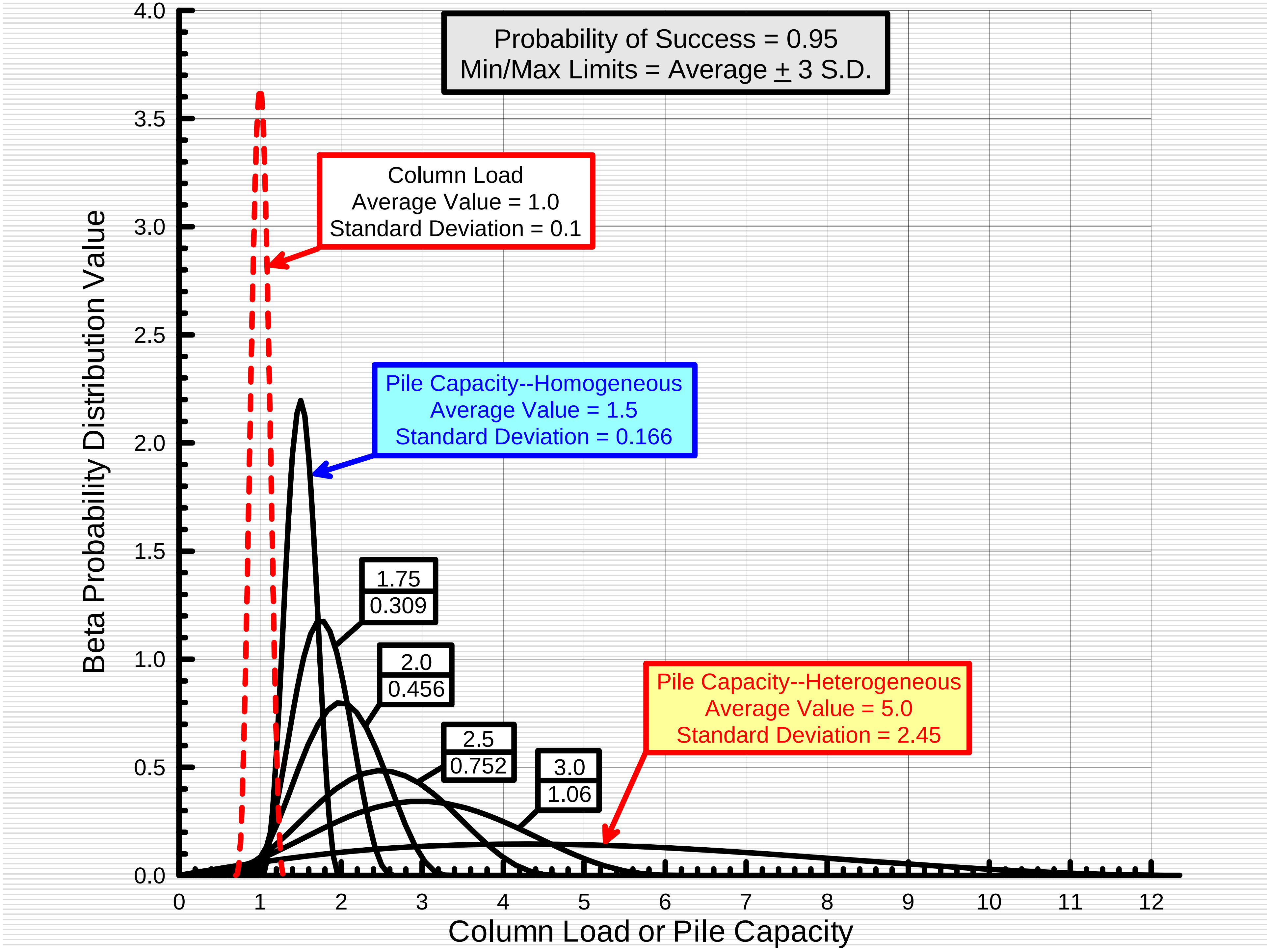
	Average Factor of Safety	Standard Deviation	Beta Value at Average Factor of Safety
━━	1.10	0.0608	5.996
╍╍	1.20	0.1215	3.001
━·━	1.30	0.182	2.003
━·━	1.50	0.303	1.203
━·━	2.00	0.607	0.601
━··━	3.00	1.262	0.281


Average Factor of Safety
Standard Deviation
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Heterogeneous
Homogeneous
△ △ △ Prob. of Success = 90% FS = 1.2823 * SD + 1.012
□ □ □ Prob. of Success = 95% FS = 1.5926 * SD + 1.013
● ● ● Prob. of Success = 99% FS = 2.1481 * SD + 1.000
◇ ◇ ◇ Prob. of Success = 99.9% FS = 2.5395 * SD + 1.000



Probability of Success = 0.95 For Threshold Settlement = 25 mm
Min/Max Limits = Average ± 3 S.D.
Average Settlement
Standard Deviation
Beta Value at Average Settlement
22 1.820 0.200
20 3.033 0.120
16 5.446 0.067
12 7.148 0.047
10 7.748 0.040
8 8.177 0.033
HETEROGENEOUS
HOMOGENEOUS
Threshold Settlement = 25 mm
Unsuccessful Zone
Beta Probability Distribution Value
Settlement (mm)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
5
10
15
20
25
30
35
40


Heterogeneous
Beta Distribution Becomes "U" Shaped for Settlements < 7 mm. (i.e. meaningless)
Solid Line: Bell Shaped Distribution
Dashed Line: Skewed Right to Reverse "J" Shaped Distribution
△ △ △ Probability of Success = 90%
□ □ □ Probability of Success = 95%
● ● ● Probability of Success = 99%
◇ ◇ ◇ Probability of Success = 99.9%
Homogeneous
Average Settlement (mm)
0
2
4
6
8
10
12
14
16
18
20
22
24
25
Standard Deviation
0
1
2
3
4
5
6
7
8
9
10
11
12

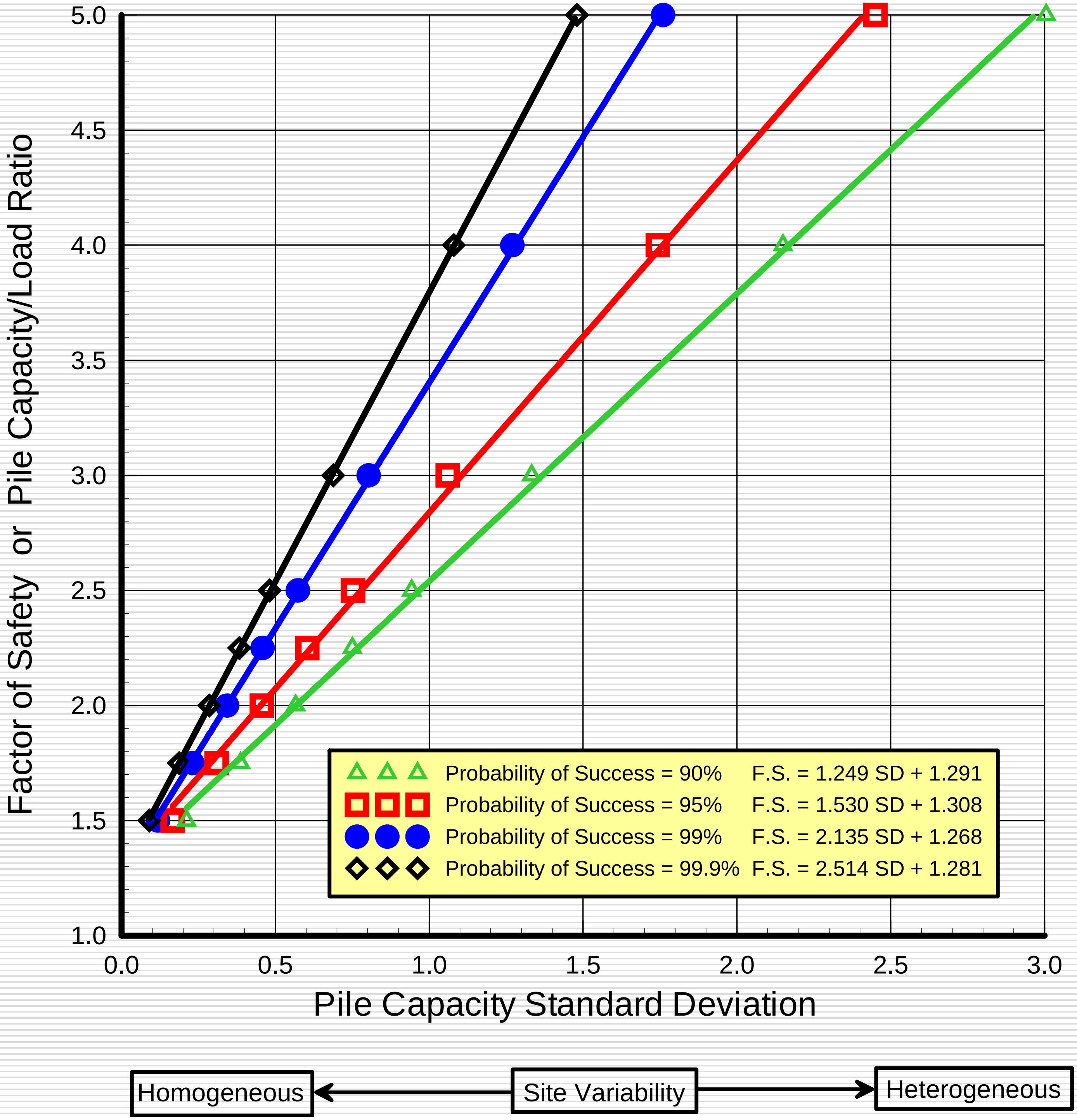


Probability of Success = 0.95
Min/Max Limits = Average ± 3 S.D.

Column Load
Average Value = 1.0
Standard Deviation = 0.1

Pile Capacity--Homogeneous
Average Value = 1.5
Standard Deviation = 0.166

Pile Capacity--Heterogeneous
Average Value = 5.0
Standard Deviation = 2.45


Factor of Safety or Pile Capacity/Load Ratio
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Pile Capacity Standard Deviation
△ △ △ Probability of Success = 90% F.S. = 1.249 SD + 1.291
□ □ □ Probability of Success = 95% F.S. = 1.530 SD + 1.308
● ● ● Probability of Success = 99% F.S. = 2.135 SD + 1.268
◇ ◇ ◇ Probability of Success = 99.9% F.S. = 2.514 SD + 1.281
Homogeneous
Site Variability
Heterogeneous

Summarizing

- Simply plot the average and standard deviation values on the appropriate design chart and see what the probability of success is!
- Non-technical owner understands his risk

Risk Considerations

- Probability of success = 0.95 is historically typical for civil engineering projects (Harr)
- Sensitivity of facility
- Foundation redundancy
  - Pile group numerically needs 8.2 piles—install 9 piles
- Cost to repair
- Monitoring Instrumentation?
- Quality of contractor/engineering inspection
  - Contractor pre-qualified?
  - Will your firm do the inspection?

Sources of Standard Deviation

1. Natural variability of the soil or rock
2. Man-created variability
   - How well does the test/design method predict what will occur—case study database to quantify
   - Goal is to minimize this source of variability through sufficient number of accurate tests
3. Intangible variability
   - Another firm doing inspection/low bid contractor/not enough tests/no performance monitoring

- Overall standard deviation equals square root of the sum of individual standard deviations squared

Geotechnical Design Example Problems

- Slope stability
- Liquefaction analyses
- Pile capacity
- Settlement

Slope Stability

- Local and national codes arbitrarily specify a minimum factor of safety
  - Do not consider subsurface variability or consequences of failure
  - Owner does not want to buy excess land to have overly conservative slopes

Example Slope Stability Problem

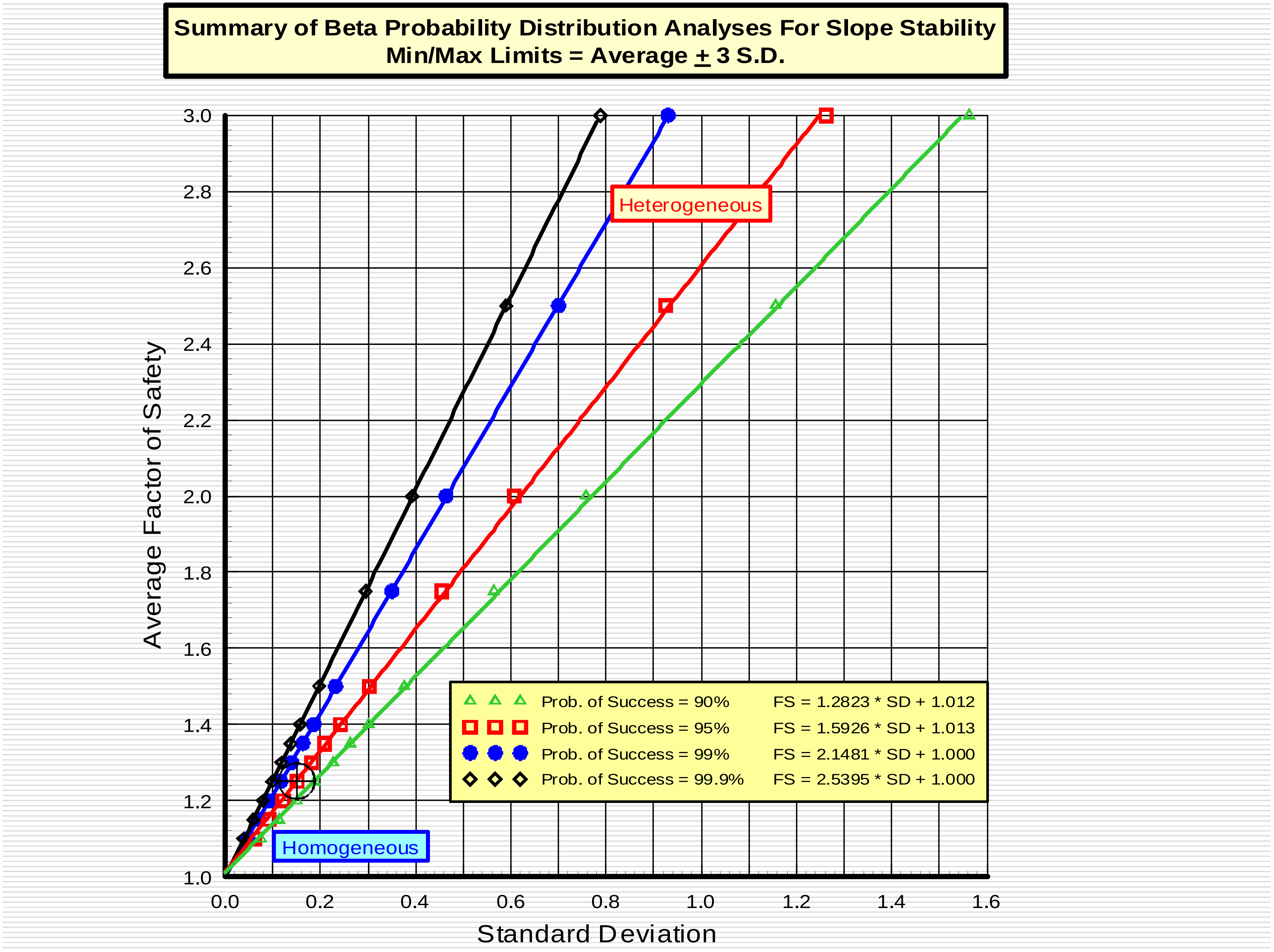
- Initial investigation phase with CPT delineated three geological strata
- Second phase: 5 borehole shear tests were performed in each stratum
- Calculated average factor of safety and its standard deviation from point estimate method (Christian, 1997)

Example (cont.)

- Multiple slope stability analyses performed using either the average plus one standard deviation or average minus one standard deviation for each variable
- Variables were shear strength of each stratum and groundwater level
- Total number of computations = 2^n, where n is number of variables => 16

Example (cont.)

- Summary of the 16 Analyses
  - Average factor of safety = 1.25
  - Standard deviation = 0.15

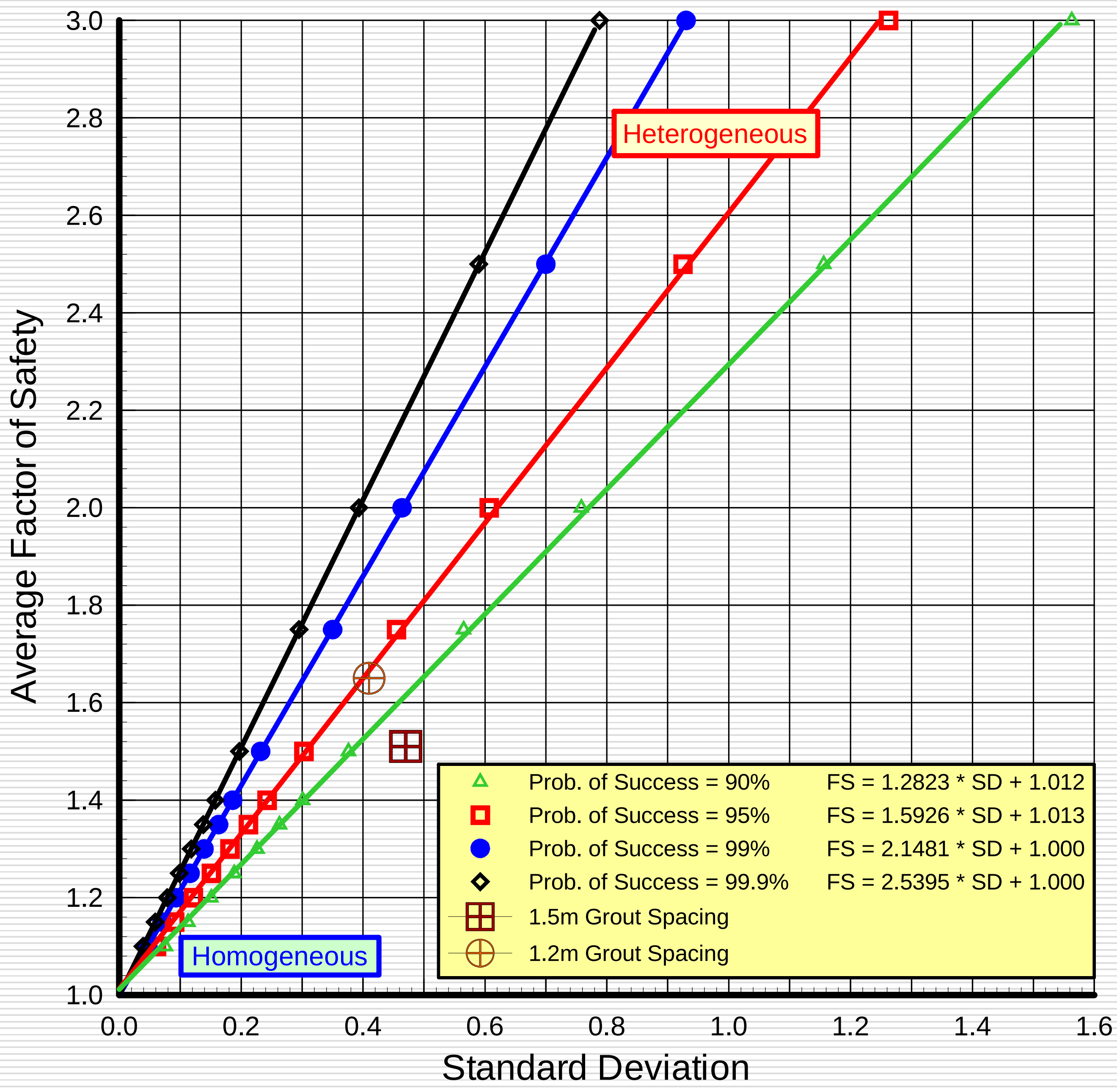


Summary of Beta Probability Distribution Analyses For Slope Stability
Min/Max Limits = Average ± 3 S.D.

Liquefaction Analyses

- Miller and Roycroft (ASCE Geot. April 2004) analyzed compaction grout spacing based on CPT data using Seed and De Alba method
- For 1.5 meter spacing (220 F.S. Computations):
  - Average F.S. = 1.51
  - Standard Deviation = 0.47
- For 1.2 meter spacing (107 F.S. Computations):
  - Average F.S. = 1.65
  - Standard Deviation = 0.41
- They overlooked S.D. and used local F.S.=1.2 as safe—thought 1.5 m spacing was adequate based on their engineering judgment

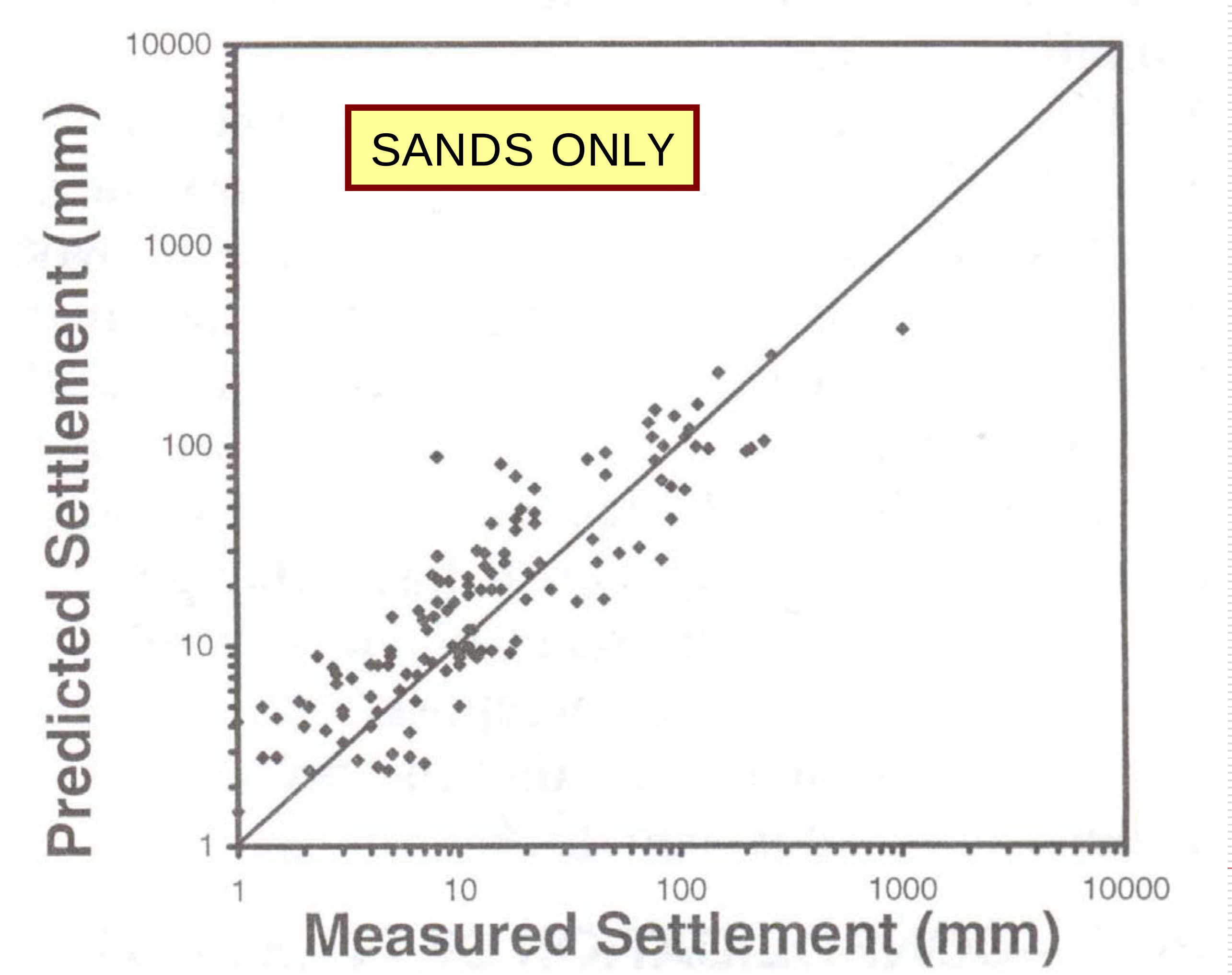
Summary of Beta Probability Distribution Analyses
Min/Max Limits = Average ± 3 S.D.



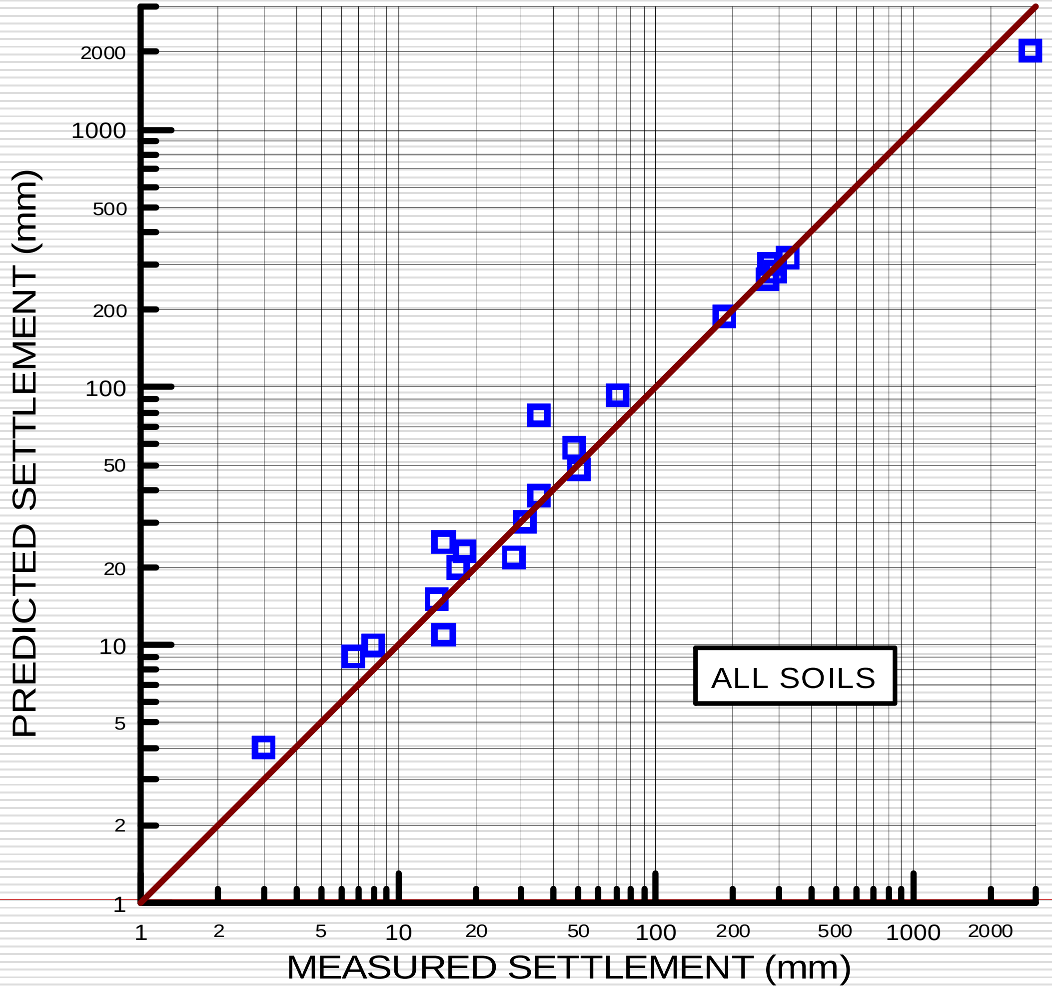
Settlement

- Considered total settlement exceeding 25 mm (1 inch) as unacceptable
- From case study database, coefficient of variation:
  - Dilatometer [all soils, except quick silts] = 0.18
  - SPT [sands] = 0.67 (Burland and Burbridge)

SPT Predicted Settlements after Burland and Burbridge (1985)



Dilatometer Predicted Settlements after Schmertmann (1986) and Hayes (1986)



Maximum value of average settlement with zero site variability for a threshold settlement of 25 mm

	Maximum Average Settlement (mm)	
	DMT Method	SPT Method
	in all soils	in only sands using N_{60}
	with Coeff.	with Coeff.
Probability	of Variation	of Variation
of Success	= 0.18	= 0.67
90%	20.17	12.5
95%	19.28	11.1
99%	18.03	9.5
99.9%	17.15	8.7

Example Settlement Problem—White Flint WMATA Site

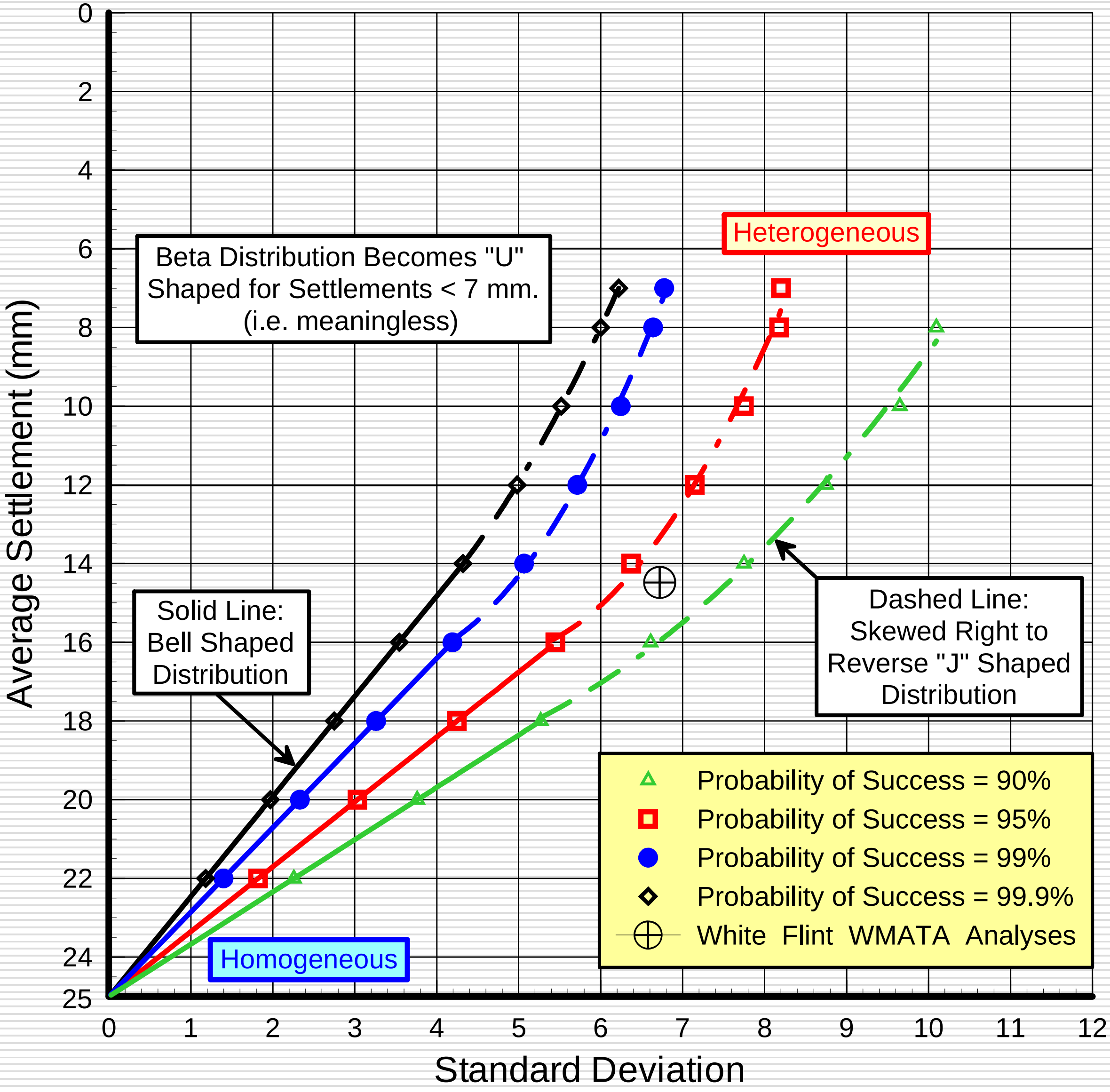
- 6 dilatometer soundings were performed to top of decomposed rock
- Schmertmann's (1986) method was used to predict settlement at each sounding
- DMT were performed at 20-cm depth intervals and each test was considered a layer for the analyses

Column Load (kips / kN)	Footing Width (ft / m)	Applied Bearing Pressure (ksf / kPa)	Sounding	Predicted Settlement (inch / mm)
850 / 3780	10.5 / 3.2	7.71 / 369	D-5	0.24 / 6.1
850 / 3780	10.5 / 3.2	7.71 / 369	D-6	0.37 / 9.4
1000 / 4448	13 / 4	5.92 / 283	D-1	0.70 / 17.8
1000 / 4448	11 / 3.4	8.26 / 396	D-2	0.33 / 8.4
1400 / 6227	15 / 4.6	6.22 / 298	D-1	0.84 / 21.3
1400 / 6227	13 / 4	8.28 / 397	D-2	0.38 / 9.7
1400 / 6227	13 / 4	8.28 / 397	D-3	0.57 / 14.5
1400 / 6227	13 / 4	8.28 / 397	D-4	0.82 / 20.8
1400 / 6227	13 / 4	8.28 / 397	D-5	0.40 / 10.2
1400 / 6227	13 / 4	8.28 / 397	D-6	0.51 / 13.0
1500 / 6672	16 / 4.9	5.86 / 281	D-1	0.84 / 21.3
1500 / 6672	13.5 / 4.1	8.23 / 394	D-2	0.38 / 9.7
1500 / 6672	13.5 / 4.1	8.23 / 394	D-5	0.42 / 10.7
1500 / 6672	13.5 / 4.1	8.23 / 394	D-6	0.53 / 13.5
2000 / 8896	18 / 5.5	6.17 / 296	D-1	0.98 / 24.9
2000 / 8896	16 / 4.9	7.81 / 374	D-2	0.41 / 10.4
2000 / 8896	16 / 4.9	7.81 / 374	D-3	0.72 / 18.3
2000 / 8896	16 / 4.9	7.81 / 374	D-4	0.89 / 22.6
2000 / 8896	16 / 4.9	7.81 / 374	D-5	0.50 / 12.7
2000 / 8896	16 / 4.9	7.81 / 374	D-6	0.57 / 14.5

Summary of Design Analyses

		(inch)	(mm)
Average Settlement		0.57	14.48
Spatial Standard Deviation		0.22	5.48
Method Coefficient of Variation	0.18	(Failmezger, 2004)	
Method Standard Deviation		0.10	2.61
Intangible Coefficient of Variation	0.20	(Lack of Soundings)	
Intangible Standard Deviation		0.11	2.90
Overall Standard Deviation		0.26	6.72
Probability of Success for Settlement not Exceeding 1.0 inch			93%

Summary for Beta Probability Distribution Analyses for Settlement With a Threshold Settlement = 25 mm and Min/Max Limits = Average ± 3 S.D.



Beta Distribution Becomes "U" Shaped for Settlements < 7 mm. (i.e. meaningless)

Solid Line: Bell Shaped Distribution

Dashed Line: Skewed Right to Reverse "J" Shaped Distribution

Pile Capacity

- Probability of success is where the soil capacity curve exceeds load curve
- Assign average load = 1 to make analyses conveniently unitless
- Load also has standard deviation
  - Considered 0.1 and 0.2
- Often some redundancy
- Method can also be used for tiebacks, soil nails, lateral capacity of piles

Example Pile Capacity Problem

- Column loads will require support of 200 kN per pile
- Load standard deviation = 20 kN
- For sensitive laboratory, desired probability of success = 99%
- 20 CPT soundings were performed at the site

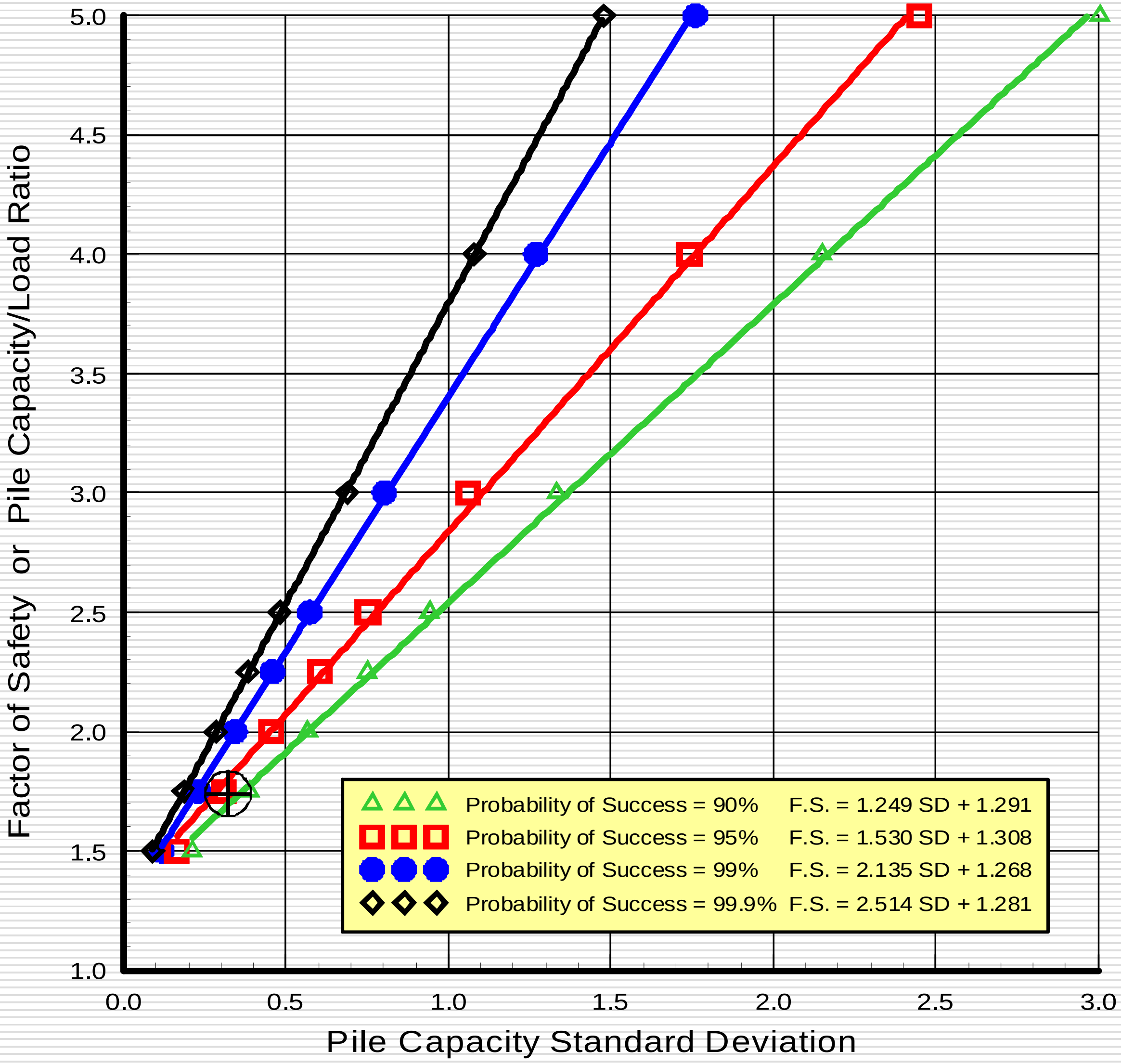
Example (cont.)

- For each sounding the LCPC pile capacity prediction method was done
  - Average capacity = 350 kN
  - Factor of Safety = 350/200 = 1.75
  - Standard deviation of site soils = 35 kN

Example (cont.)

- Campanella case study database gives coefficient of variation = 0.15
- Coefficient of variation = standard dev/average
- Method S.D. = 0.15 * 350 = 52.5 kN
- Overall S.D. = sq. rt. $\{35^2 + 52.5^2\}$ = 63.1 kN
- Unitless S.D. = 63.1/200 = .32

Summary of Beta Probability Distribution Analyses of Pile Design with Load Standard Deviation = 0.1

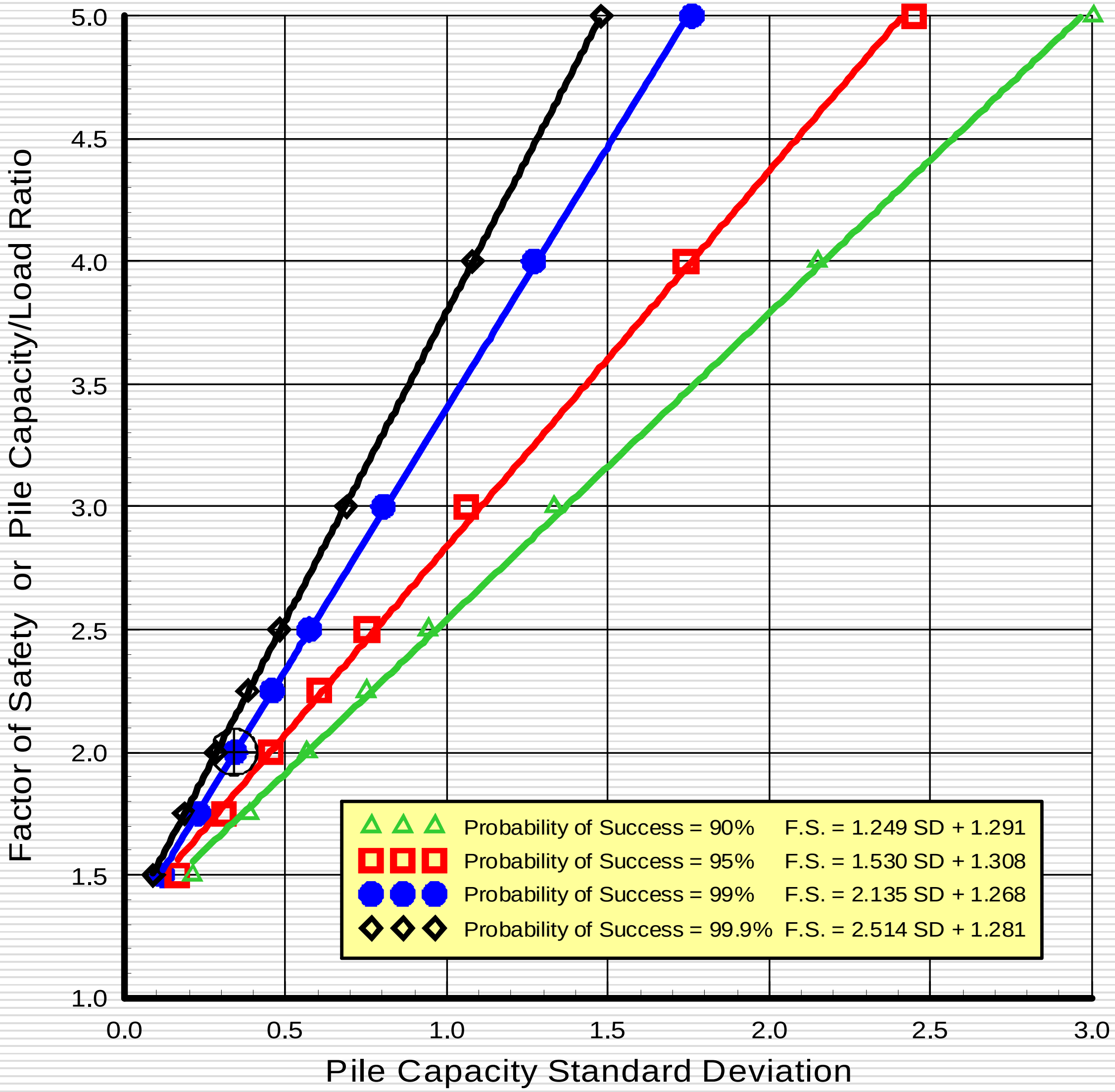


Homogeneous ← Site Variability → Heterogeneous

Example (cont.)

- Since probability of success was only 93%, pile diameter was increased so that each pile will have an average capacity of 400 kN
  - Unitless F.S. value = 2
- Recomputed overall standard deviation = 69.5 kN
  - Unitless S.D. value = 0.35

Summary of Beta Probability Distribution Analyses of Pile Design with Load Standard Deviation = 0.1



Homogeneous ← Site Variability → Heterogeneous

Conclusions

- Approach brings about a fundamental change in the engineer/owner relationship
  - Forces both parties to understand each other
- Owner views engineer as an important contributor to improving his bottom line
- Risk is easily determined and quantified
- Owner decides risk and assumes liability
- Engineer designs for that risk level

Conclusions (cont.)

- Most economical design can be chosen at an acceptable risk level to owner
- Accurate site characterization program reduces uncertainty
- Designs will be less costly for homogeneous conditions (less uncertainty) than for heterogeneous conditions