Rapid Drawdown – Multi-Stage Method

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Introduction

Stability analysis during rapid drawdown is an important consideration in the design of embankment dams. The stabilizing effect of the water on the upstream face is lost during rapid drawdown, but the pore-water pressures within the embankment may remain high. As a result, the stability of the upstream face of the dam can be greatly reduced. The dissipation of pore-water pressure in the embankment is largely influenced by the permeability and storage characteristics of the embankment materials. Highly permeable materials drain quickly during rapid drawdown, but low permeability materials take a long time to drain.

Stability during rapid drawdown can be analyzed using two approaches; namely the "effective strength" approach and the "staged undrained strength" approach. The purpose of this illustrative example is to show how to conduct a rapid drawdown analysis using the stage undrained strength approach.

Background

Duncan, Wright and Wong (1990) proposed a three-stage approach for modeling staged rapid drawdown. The first stage involves the stability analysis of the embankment before drawdown. The pore-water pressures are at their maximum values (piezometric line before drawdown) and the effective strength parameters for all materials are used to determine the effective normal and shear stresses at the base of each slice. At the end of the first stage, the effective normal stress and effective shear stress along the slip surface are used to determine the undrained shear strength for materials that do not drain freely.

The second stage involves the stability analysis of the embankment after drawdown when the water level is low and the pore-water pressure in the materials is at a steady state condition (piezometric line after drawdown). In this second stage, the effective strength parameters for the freely drained materials are used, and the undrained shear strengths determined from the result of Stage 1 are used for materials that do not drain freely.

In the third stage, the effective normal stress obtained from stage two, together with the effective strength parameters, are used to compute the drained strength for *all* slices along the slip surface. For materials that do not drain freely, the drained strength at the base of each slice is compared with the undrained strength, and the smaller strength is chosen. In other words, it is possible that the effective strength is used if it is smaller than the undrained strength for materials that do not drain freely. This is needed in order to avoid using undrained strengths that are higher than drained strengths, which cannot be mobilized if cavitation or drainage occurs (Duncan, Wright and Wong (1990). The computed factor of safety from the first and second stages are ignored, and only the factor of safety computed from the third stage analysis is used to represent the stability after rapid drawdown.

It is important to note that for a freely drained material, the input of Total cohesion and Total phi values are not necessary. In SLOPE/W, having a defaulted Total cohesion = 0 and defaulted Total phi = 0 signify that the material is free draining and only effective strength is considered. For materials that do not drain freely, an appropriate set of Total cohesion and Total phi must be defined. SLOPE/W will verify that Total cohesion must be larger than Effective cohesion and Total phi must be smaller than Effective phi. This appropriate set of Total cohesion and Total phi are required to ensure stability in the undrained strength computation in the staged rapid drawdown procedure.

The following parameters must be specified to conduct a staged rapid drawdown analysis in SLOPE/W:

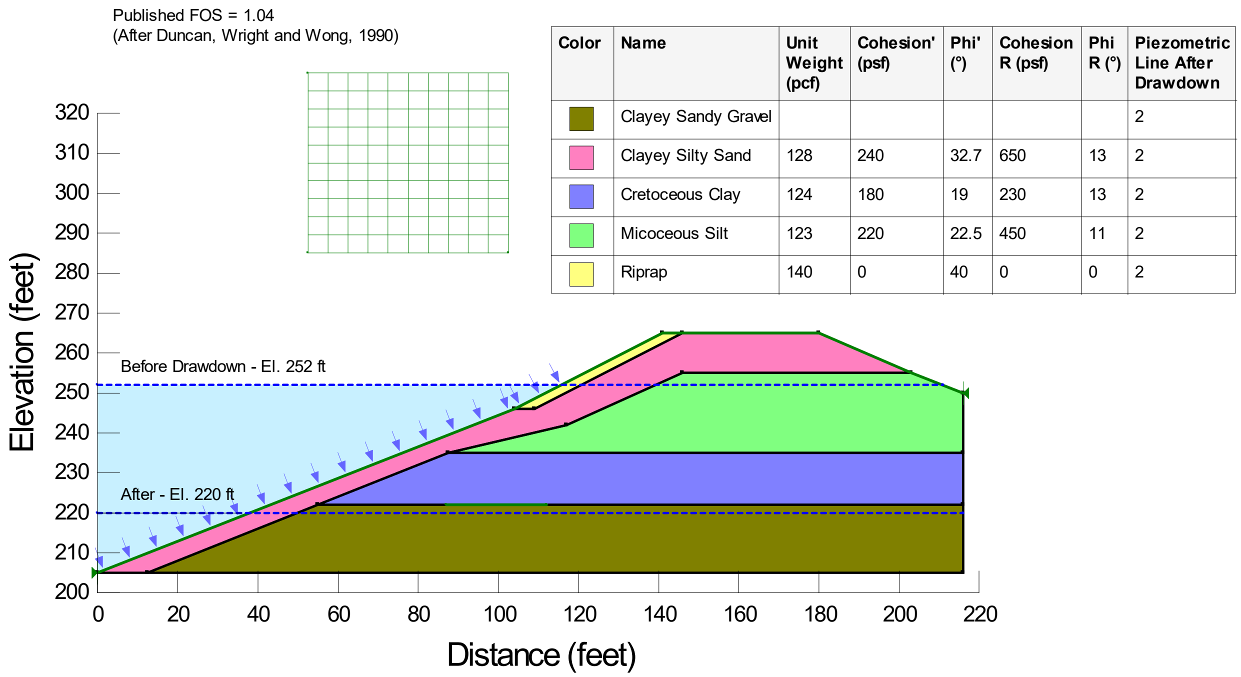
- A Mohr-Coulomb soil strength model;
- Effective c' and ϕ' parameters;
- Total c and ϕ parameters for non-freely drained material;
- The piezometric line before rapid drawdown; and
- The piezometric line after rapid drawdown.

Numerical Simulations

A total of four examples are presented in the following sections. The first three examples are analyses by Duncan, Wright and Wong (1990) and the fourth example is the Corps of Engineers benchmark example documented in the USACE Engineering Manual, EM1110-2-1902 (2003).

Example 1 – The Walter Bouldin Dam

The Walter Bouldin dam failed on February 10, 1975 during an extremely rapid drawdown of 32 feet in 5.5 hours that occurred as a result of a piping failure in another section of the dam. The dam is a rolled earth fill embankment. As shown in Figure 1, the dam is approximately 60 feet high. The lower portion of the dam is clayey sandy gravel that was not involved in the slide. Overlaying the gravel are a layer of clay, a zone of silt and a clayey silty sand layer that blankets the slope. The upper portion of the upstream slope is blanketed with riprap. The upstream slope is 2H:1V above Elevation 245 and 2.5H:1V below.



Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line After Drawdown
	Clayey Sandy Gravel						2
	Clayey Silty Sand	128	240	32.7	650	13	2
	Cretoceous Clay	124	180	19	230	13	2
	Micoceous Silt	123	220	22.5	450	11	2
	Riprap	140	0	40	0	0	2

Figure 1. The Geometry of the Walter Bouldin Dam.

Example 2 – The Pumped Storage Project Dam

The geometry of the Pumped Storage Project Dam is shown in Figure 2. The dam is about 300 feet high. The embankment has a densely compacted silty clay core. The lower portion of the upstream slope is a random zone with the same strength properties as the core. The upper portion of the upstream slope and the downstream slope is free draining rockfill.

The before drawdown water level is at 545, and the after drawdown water level is at 380, which is the elevation of the bench at the mid-height of the embankment. The drawdown results in complete dewatering of the upstream rockfill shell and a portion of the filter layer beneath the shell.

Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	Compacted Rockfill	142	0	37	0	0	0	1	2
	Silty Clay Core	140	0	36	0	2,000	18	1	2
	Silty Clay Random Zone	140	0	36	0	2,000	18	1	2

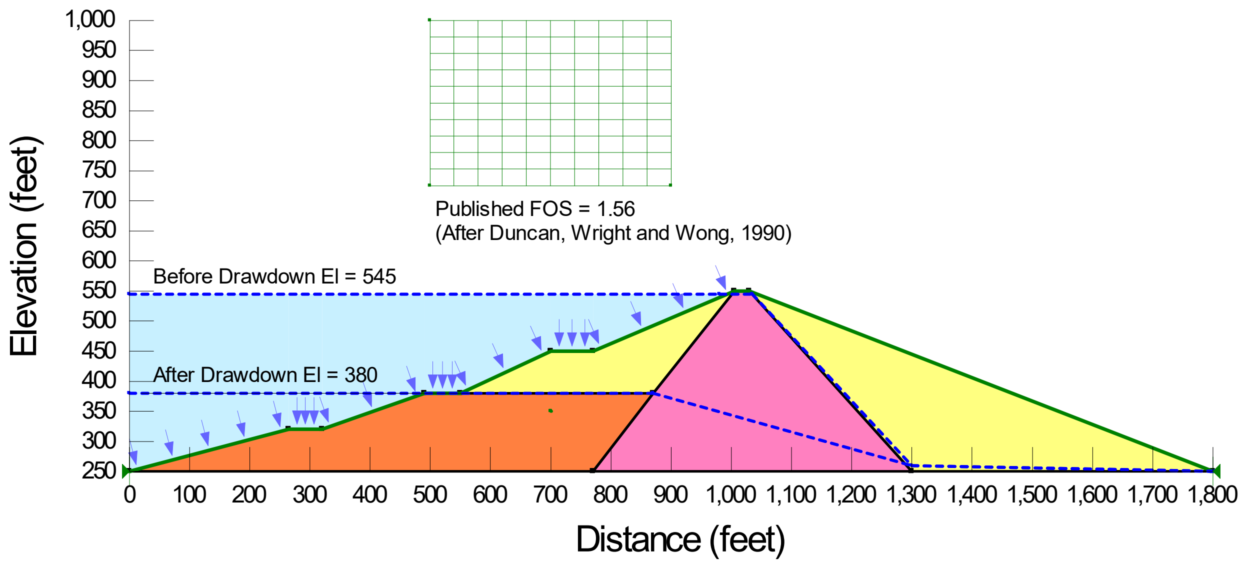
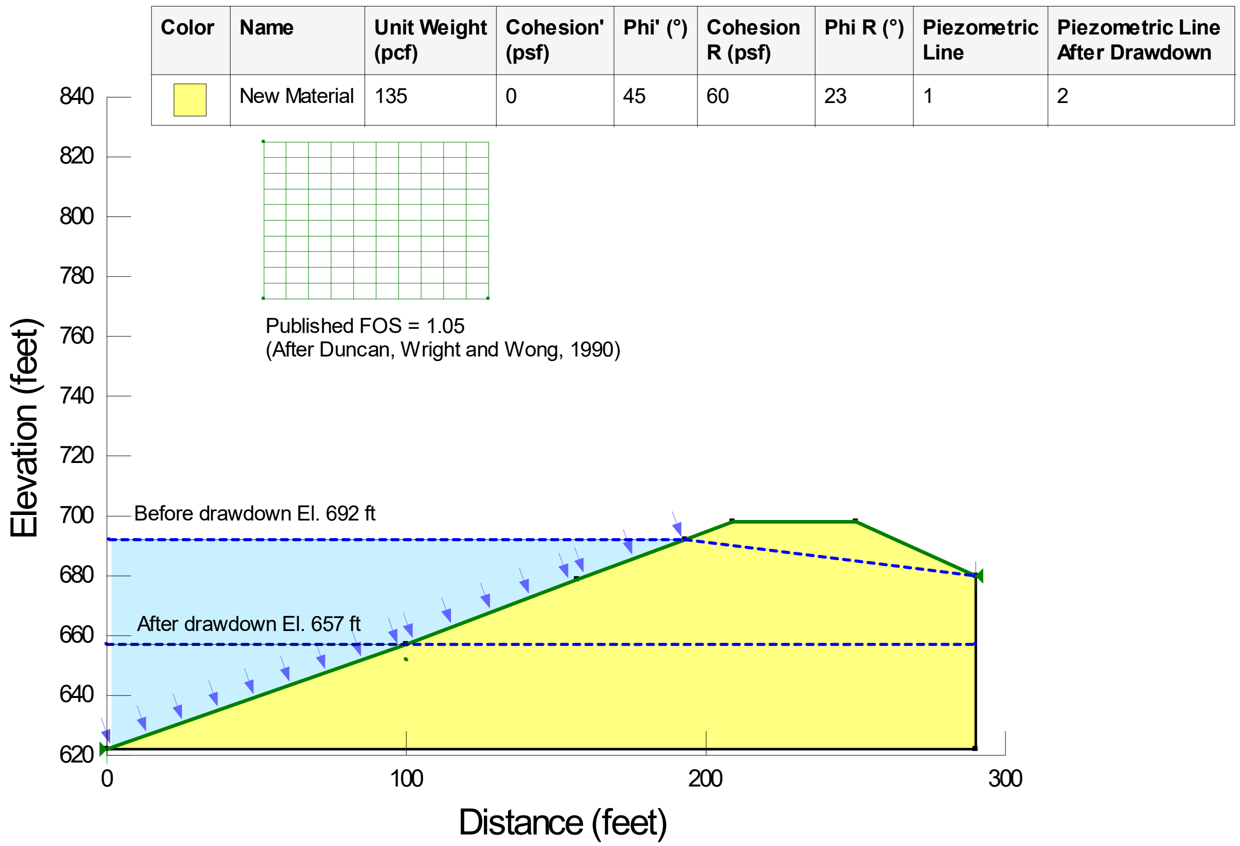


Figure 2. The Geometry of the Pumped Storage Project Dam.

Example 3 – The Pilarcitos Dam

The Pilarcitos Dam is a homogeneous rolled earth fill embankment. The crest of the dam is about 78 feet above the upstream toe, as shown in Figure 3. The embankment failed when the water level was lowered from elevation 692 to 657 between Oct 7 and November 19, 1969.



Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	New Material	135	0	45	60	23	1	2

Figure 3. The Geometry of the Pilarcitos Dam.

Example 4 – The USACE Benchmark Example

Example 4 is the benchmark example used by the U.S. Army Corps of Engineers (2003) in Appendix G of the Engineering Manual – EM 1110-2-1902. It is a simple homogenous embankment (Figure 4). Drawdown is from a maximum water level of 103 feet to a minimum level of 24 feet. The upstream slope is 3 to 1 up to elevation 74 and 2.5 to 1 above elevation 74.

Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	New Material	135	0	30	0	1,200	16	1	2

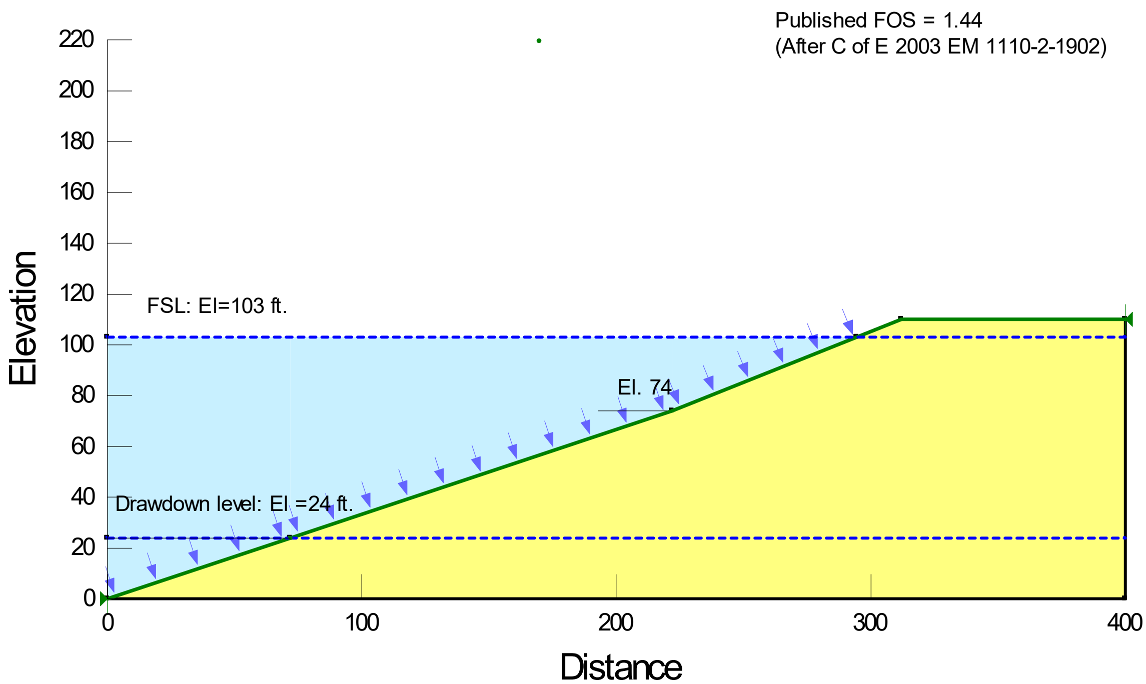


Figure 4. The Geometry of the USACE Bench Mark Example.

Results and Discussion

Example 1 – The Walter Bouldin Dam

Figure 5 shows the slip surface and the SLOPE/W computed factor of safety using the 3-stage undrained strength method. The factor of safety is 1.03, which is essentially the same as the factor of safety obtained by Duncan, Wright and Wong (1990).

Color	Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line After Drawdown
	Clayey Sandy Gravel	Bedrock (Impenetrable)						2
	Clayey Silty Sand	Mohr-Coulomb	128	240	32.7	650	13	2
	Cretoceous Clay	Mohr-Coulomb	124	180	19	230	13	2
	Micoceous Silt	Mohr-Coulomb	123	220	22.5	450	11	2
	Riprap	Mohr-Coulomb	140	0	40	0	0	2

Published FOS = 1.04
(After Duncan, Wright and Wong, 1990)

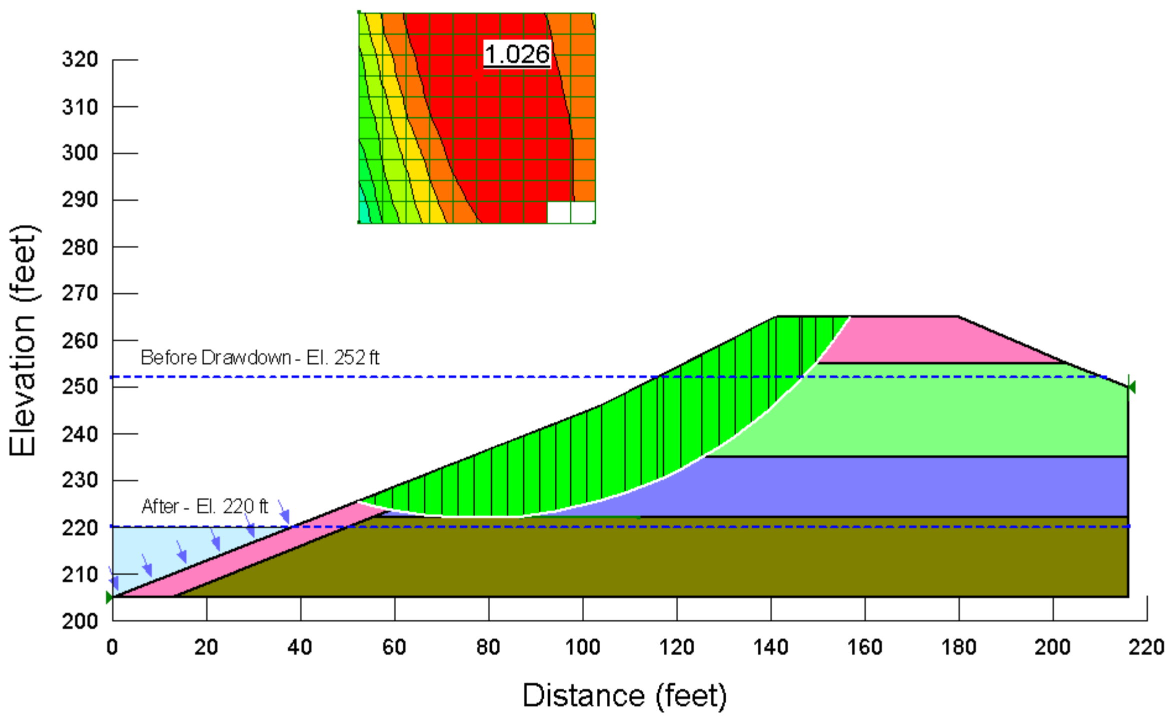


Figure 5. SLOPE/W Computed Factor of Safety Using the 3-Stage Undrained Strength Method.

Example 2 – The Pumped Storage Project Dam

Figure 6 shows the slip surface and the SLOPE/W computed factor of safety using the 3-stage undrained strength method. The factor of safety is 1.550, which is almost identical to the factor of safety obtained by Duncan, Wright and Wong (1990).

Color	Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	Compacted Rockfill	Mohr-Coulomb	142	0	37	0	0	0	1	2
	Silty Clay Core	Mohr-Coulomb	140	0	36	0	2,000	18	1	2
	Silty Clay Random Zone	Mohr-Coulomb	140	0	36	0	2,000	18	1	2

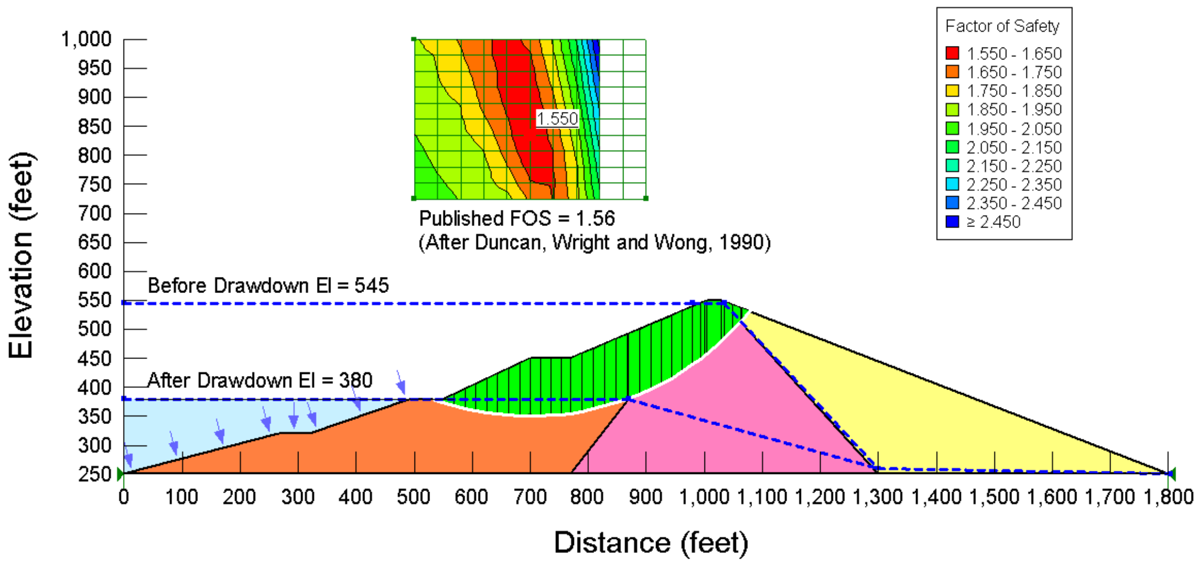
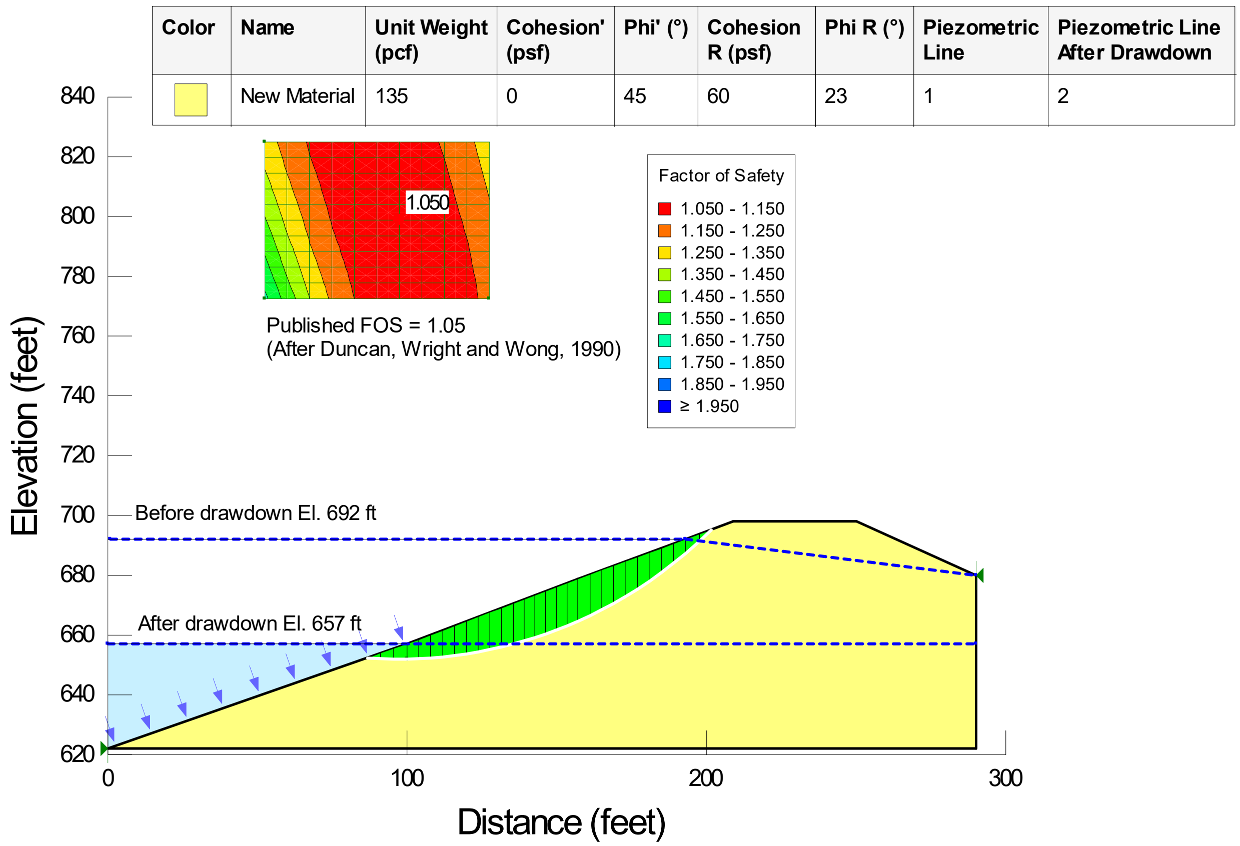


Figure 6. SLOPE/W Computed Factor of Safety Using the 3 Stage Undrained Strength Method.

Example 3 – The Pilarcitos Dam

Figure 7 shows the slip surface and the SLOPE/W computed factor of safety using the 3-stage undrained strength method. The factor of safety is 1.050, which is the same as the factor of safety obtained by Duncan, Wright and Wong (1990).



Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	New Material	135	0	45	60	23	1	2

Figure 7. SLOPE/W Computed Factor of Safety Using the 3 Stage Undrained Strength Method.

Example 4 – The USACE Benchmark Example

Figure 8 shows the results for the USACE benchmark. The slip surface is established by a center located at x=169.5 feet, y =210 feet and a radius of 210 feet. The factor of safety is 1.461, which is almost identical to the factor of safety as presented in the Corps of Engineers (2003) engineering manual.

Color	Name	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
	New Material	135	0	30	0	1,200	16	1	2

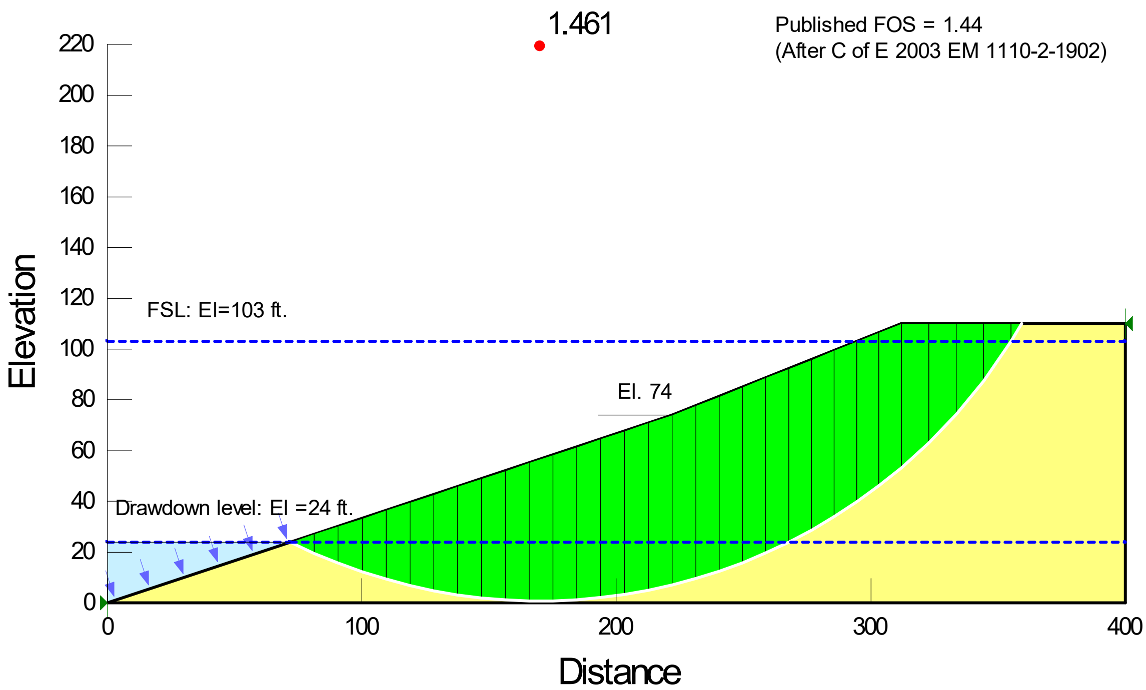


Figure 8. SLOPE/W Computed Factor of Safety Using the 3 Stage Undrained Strength Method.

Table 1 shows a comparison of the computed rapid drawdown factor of safety between SLOPE/W and the published results.

Table 1. Comparison of computed rapid drawdown factor of safety.

Example	SLOPE/W FOS	Publication FOS	Reference
Walter Bouldin Dam	1.030	1.04	**Duncan, Wright and Wong (1990)**
Pumped storage project dam	1.550	1.56	**Duncan, Wright and Wong (1990)**
Pilarcitos Dam	1.050	1.05	**Duncan, Wright and Wong (1990)**
USACE bench mark	1.461	1.44	Corps of Engineers (2003) EM 1110-2-1902

Summary and Conclusions

As illustrated in the examples, it is evident that the Duncan, Wright and Wong's 3-Stage has been implemented correctly in SLOPE/W. The computed factors of safety in all four cases are similar to those presented by Duncan, Wright and Wong (1990) and the USACE Engineering Manual (2003).

The 3-Stage method seems to provide a reasonable evaluation of the stability during rapid drawdown. The approach avoids the extra work of evaluating the pore-water pressure conditions in the embankment dam by using the undrained strengths. However, the hydraulic properties of the materials, such as permeability, cannot be considered, the element of time is missing, and the total strength parameters are used.

References

Corps of Engineers (1970) "Engineering and Design – Stability of Earth and Rock Fill Dams". Engineering Manual, EM 1110-2-1902. Department of the U.S Army Corps of Engineers.

Corps of Engineers (2003) "Appendix G - Procedures and Examples for Rapid Drawdown". Engineering Manual, EM 1110-2-1902. Department of the U.S Army Corps of Engineers.

Duncan, J.M.,Wright S.G. and Wong, K.S. (1990). "Slope Stability during Rapid Drawdown". Proceedings of H. Bolton Seed Memorial Symposium. Vol. 2.

Lowe, J and Karafiath, L., (1960) "Stability of Earth Dams Upon Drawdown". Proceedings of 1st PanAm Conference on Soil Mechanic and Foundation Engineering. Mexico City, Vol 2.