Paper No. LVR8-1095

Simplified Methods for Evaluating Road Prism Stability

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Mass failure is one of the most common failures of low-volume roads in mountainous terrain. Current methods for evaluating stability of these roads require a geotechnical specialist. A stability analysis program, XSTABL, was used to estimate the stability of 3,696 combinations of road geometry, soil, and groundwater conditions. A sensitivity analysis was carried out to find the most important site-specific variables in estimating slope stability, and two regression equations were developed to predict the factor of safety (*FS*) for a given road, one with the groundwater below the road fill and one with the groundwater in the road fill. The resulting equations predicted failures on road segments where failures were observed to have occurred. A comparison of the predicted *FS*s from the regression equations with the *FS* values predicted by the infinite slope equation showed that both methods predicted similar *FS*s.

The National Forest System's roads consist of 560,000 km (350,000 mi) of road, often over steep mountainous terrain. Numerous studies completed by the U.S. Department of Agriculture (USDA) Forest Service and university research scientists have found that roads within these steep, mountainous regions are a significant source of sediment to stream channels (*1, 2*). In February 1996, after weeks of heavy snowfall followed by warm weather and intense rainfall, the Clearwater National Forest, Orofino, Idaho, experienced a significant number of landslides (more than 900 cataloged), more than half of which were road-related (*3*). In another analysis of the Clearwater data, Gorsevski (*4*) found that the factors that influenced road-related landslides were not the same as those associated with non-road-related landslides. During the same year, a large number of landslide events were also studied in the Oregon Coast Range (*5*). The Oregon study found that although there appeared to be no increase in landslides associated with roads, road-related landslides generated greater amounts of sediment than did non-road-related landslides. There have been many similar events throughout the western mountain ranges.

In response to legal pressure to meet statutory requirements of the Endangered Species Act of 1973 and a decrease in forest operations, many National Forest managers are beginning to address the sedimentation problems associated with the existing road system. One method to reduce sedimentation is to close roads. Road closure can range from simply preventing access to a road, to seeding, reshaping, and complete prism removal (*6, 7*). Decommissioning roads can be an expensive operation. Typically, road removal costs average between $10,000 and $40,000 per mi.

One of the main reasons for complete prism removal is that the prism may be unstable (*6, 7*). USDA Forest Service researchers have developed computer models to aid in predicting whether a given road prism is likely to fail (*8*). The model most suited to road prism stability analysis is XSTABL (*9*). XSTABL was cooperatively developed by the USDA Forest Service and Interactive Software Designs. It is available for USDA Forest Service users at regional offices and for any user from Interactive Software Designs.

The inputs required to run XSTABL are presented in Table 1. Some of these input variables are not readily available, and frequently, the individual charged with road management does not have the time or experience to use a sophisticated model such as XSTABL to analyze a road prism. Consequently, prisms that are likely to be stable are removed, whereas unstable segments of the road may be left in place because the funds were insufficient to remove the entire length of road. To aid in determining which segments of a given road are likely to fail, a study was carried out with XSTABL over a wide range of road prism conditions and regression equations were developed to aid in rapidly identifying road prisms at risk of failure. These equations will allow a manager with a limited background in slope stability to determine which sections of road are likely to fail, which are marginal and require more sophisticated analysis, and which are unlikely to fail.

ANALYSIS PARAMETERS

The parameters of the road profiles analyzed by XSTABL in this study are presented in Table 2. Selected were a range of road parameter values typical of conditions encountered in the forest. If the road under consideration falls outside of the range presented, then the site-specific conditions can be analyzed with XSTABL.

Two groundwater conditions were considered: groundwater below the fill in undisturbed soil and groundwater in the fill. For groundwater profiles within the undisturbed soil below the fill (Figure 1*a*), a groundwater ratio was defined as the ratio of the depth of the water table in the soil profile, divided by the depth of the soil layer. For groundwater in the fill (Figure 1*b*), the groundwater ratio was defined as the depth of groundwater in the fill divided by the depth of the fill. The ratio from 0 to 1 was varied to represent the water table location from below the soil profile to the intersection of the soil below the fill with the bottom of the fill. For groundwater profiles within the fill, 0 to 1 indicates the magnitude of a hyperbolic function (whose asymptotes are the road and fill slope surfaces) as shown in Figure 1*b*, with 0 indicating a condition with no water in the road prism, and 1 a saturated prism.

Estimates of soil properties are approximate and reflect an effort to consider the range of values found in the literature. Soils are highly variable within a given category, and users are encouraged to be conservative when selecting the soil. Some estimates of soil properties for SM and SP engineering soil types are based on field measurements in the Payette National Forest in central Idaho. These estimates were used to check and calibrate estimates obtained from literature searches.

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TABLE 1 Input Variables for Road Stability Analysis with XSTABL (*9*)

Variables	Typical Values	Units
Moist unit weight	100 – 150 1600 – 2400	lbs ft^{-3} kNm^{-3}
Saturated unit weight	120 – 160 1900 – 2600	lbs ft^{-3} kNm^{-3}
Soil cohesion	0 – 500 0 – 24	lbs ft^{-2} kNm^{-2}
Soil angle of internal shear friction	20 – 45	Degrees
Surface, subsurface, groundwater and bedrock profiles		x-y coordinates in ft

A value of 65% for relative density of undisturbed soils was obtained from Hammond et al. (*10*) and researcher experience. The subgrade and compacted road fill relative densities were estimated at 80% and 95%, respectively. The subgrade road fill value (80%) was arbitrarily set as a median value between the road surface and undisturbed relative density values and is probably a low, conservative estimate. Estimates for compacted road fill were based on USDA Forest Service specifications (*11*). Friction angles for soils at each relative density were calculated using Equation 1 (*12*):

$$\cot \phi' = k_{\phi 1} - k_{\phi 2} Dr \quad (1)$$

where

ϕ' = friction angle,
$k_{\phi 1}$ and $k_{\phi 2}$ = coefficients from Hammond et al. (*10*) presented in Table 3, and
Dr = relative density from Table 4 (*10, 12*).

The assumed moist (10% moisture content) and saturated (100% moisture content) unit weights and relative densities for each soil are shown in Table 4.

The amount of road surface was varied that was supported by fill as opposed to undisturbed material. A fill ratio was defined as the projected road structure that lies on subgrade road fill divided by the total width of the projected road structure (Figure 1*a*). XSTABL requires the user to define the surface where the toe of the slide is likely to occur, or the initiation area, and the upper end of the failure, or the termination area. The slide plane termination area was defined as the area between the cut slope side of the ditch and the outside edge of the road (Figure 2). The slide plane initiation area was assumed to be the area between the base of the compacted road surface and a point 120 m (400 ft) below the down slope extent of the fill (Figure 2). For XSTABL solutions with the slide plane extending beyond 120 m (400 ft), the geometry approaches an infinite slope with the minimum factors of safety remaining essentially constant. A total of 3,696 combinations of road profiles was analyzed with XSTABL version 5.106a (*9*). For each profile, XSTABL was programmed to generate 1,500 potential failure surfaces. XSTABL determines the factor of safety (*FS*) for each surface and then predicts the failure surface with the lowest *FS* for that profile. Figure 3 presents an example of an XSTABL output from a single run, which in this case was simplified to illustrate the technology.

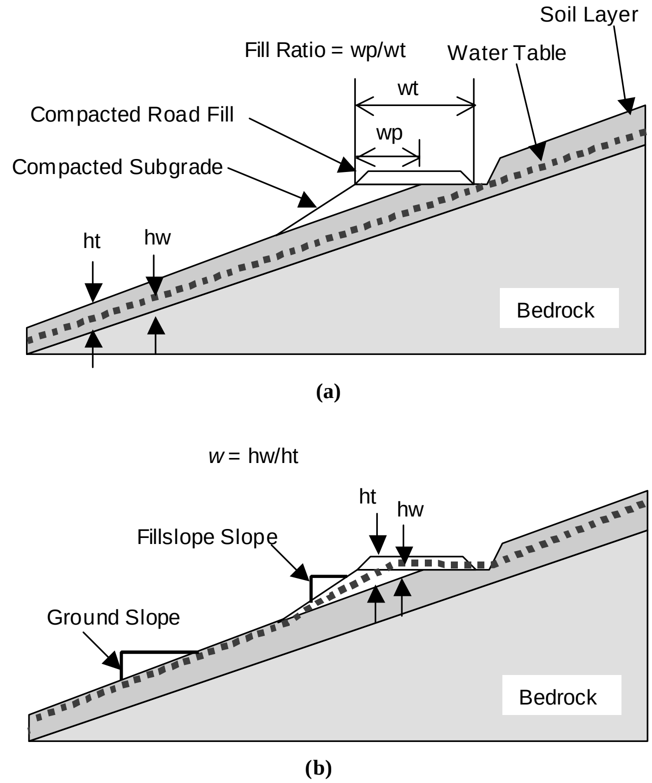

FIGURE 1 Diagrams of profiles showing methods for determining the fill ratio and the groundwater ratio *w* for (*a*) the water table located below the fill and (*b*) the water table within the fill.

ANALYSIS

A table was prepared with all 3,696 input conditions and the predicted *FS* from XSTABL. In a preliminary analysis of the results, it was found that fill ratio was not a significant factor—because the failure plane with the lowest *FS* was always near the road shoulder—so for this study, the fill ratio was fixed at 75%.

TABLE 2 Range of Input Values and Assumptions Used for 3,696 XSTABL Runs

Parameter	Values
Compacted road surface	16 ft (5 m) wide, 1 ft (0.3 m) deep
Ditch	2 ft (0.6 m) wide, 1 ft (0.3 m) deep
Ground slope	26% to 72%
Fill slope	10% to 48% greater than a given ground slope
Soil thickness	5 ft (1.5 m)
Soil types	1,2,3, and 4 types (note: only *in situ*, cohesionless soils have been considered, see Table 4)
Groundwater ratio	0 to 1

TABLE 3 Values for $k_{\phi 1}$ and $k_{\phi 2}$ for Equation 1

USCS Soil Type	$k_{\phi 1}$	$k_{\phi 2}$
GW	1.43	0.0043
GP, GM, or Coarse SW	1.54	0.0047
Med. SW, Coarse SP or SM	1.66	0.0051
Fine SW, Med. SP or SM	1.80	0.0057
Fine SP or SM	1.96	0.0064
ML	2.05	0.0067

TABLE 4 Soil Categories and Properties (*10, 12*)

Soil Cat.	Relative Density	Moist Unit Wt.		Saturated Unit Wt.		Friction Angle	USCS Soil Type
	%	lbs ft^{-3}	kNm^{-3}	lbs ft^{-3}	kNm^{-3}	degrees	
1	95	114	1824	128	2048	36.49	Fine SP or SM
	80	112	1792	126	2016	34.63	
	65	109	1744	124	1984	32.93	
2	95	125	2000	133	2128	38.47	Fine SW, Medium SP or SM
	80	122	1952	132	2112	36.65	
	65	119	1904	130	2080	34.97	
3	95	135	2160	140	2240	39.78	Medium SW, Coarse SP or SM
	80	132	2112	138	2208	38.62	
	65	129	2064	136	2176	36.97	
4	95	146	2336	146	2336	42.44	GP, GM, Coarse SW
	80	143	2288	144	2304	40.67	
	65	140	2240	142	2272	39.01	

To develop a relationship between the predicted *FS* and the remaining input variables, a stepwise linear regression analysis (*13*) was used with unsatisfactory results (coefficient of regression $r^2 < 90\%$). The runs were divided into two conditions: those with groundwater in the fill, and those with groundwater only in the undisturbed soil beneath the fill. From these results the following equations for the relationship between the *FS* and road prism properties were derived for groundwater below the road fill:

$$FS = 8.76 + \frac{f}{8.308} - 1.753\sqrt{f} - \frac{(f - 40.4w)(f - 0.88g)}{3370} - \frac{(g + 61)^2}{11{,}000} - \frac{w^2}{2.3} - \frac{\sqrt{w}}{10} + \frac{s}{6} - \frac{sf}{900} \quad (2)$$

and groundwater in the fill:

$$FS = 3.777 - \frac{\sqrt{f}}{2.147} + \frac{f}{34.44} - \frac{[f(w + 1)]^2}{110{,}000} - \frac{\sqrt{g}}{7.32} - \frac{g}{129} + \frac{[g(w + 1)]^2}{28{,}150} + \frac{s}{6.135} - \frac{sf}{1{,}053} - \frac{[s(w + 1)]^2}{1{,}000} - \frac{(w + 0.236)^2}{4.02} \quad (3)$$

where

FS = factor of safety,
f = fill slope (%),
g = ground slope (%),
w = the groundwater ratio between 0 to 1 (Figure 1), and
s = soil category (Table 4).

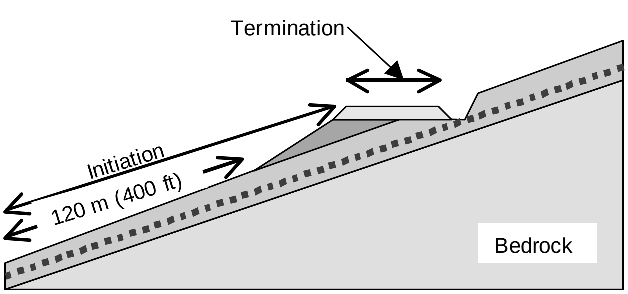

FIGURE 2 Limits for slide plane initiation and termination.

Equation 2 has an r^2 value of 0.987 and a standard error of 0.035; Equation 3 has an r^2 value of 0.983 and a standard error of 0.032. The probability that any of the coefficients in Equations 2 or 3 is zero is less than 0.0005.

Equations 2 and 3 are complex functions with multiple interactions between the groundwater, the slopes, and the soil. On steep slopes, the groundwater ratio is low and has no effect on the *FS*, because the slide plane does not intersect the water table. However, when the groundwater is in the road prism, *w* has a strong influence on *FS*, which explains the source of more interactions between *w* and the other factors in Equation 3. Road designers are well aware that saturated fills are generally unstable, which has led to the development since the 1980s of numerous methods to drain road fills in unstable areas (*8*).

COMPARISON TO INFINITE SLOPE EQUATION

The XSTABL program provides a graphical output that shows the possible failures (Figure 3). Inspection of a number of these outputs showed that most of the predicted failures tended to be on the outside shoulder of the road. The shape of the displaced material has a failure plane parallel to the fill slope surface, as can be seen in the simple example in Figure 3. Such a failure can be predicted by the infinite slope equation

$$FS = \frac{C_s + (\cos\alpha)^2[\gamma(D - D_w) + (\gamma_{sat} - \gamma_w)D_w]\tan\phi}{\sin\alpha\cos\alpha[\gamma(D - D_w) + \gamma_{sat}D_w]} \quad (4)$$

where

C_s = the soil cohesion (N m^{-2}),
α = the slope of the road fill slope,
D = the soil thickness (m),
D_w = the saturated soil thickness (m),
ϕ = the effective internal angle of friction (degrees),
γ = the moist soil unit weight (N m^{-3}),
γ_{sat} = the saturated soil unit weight (N m^{-3}), and
γ_w = the water unit weight (N m^{-3}).

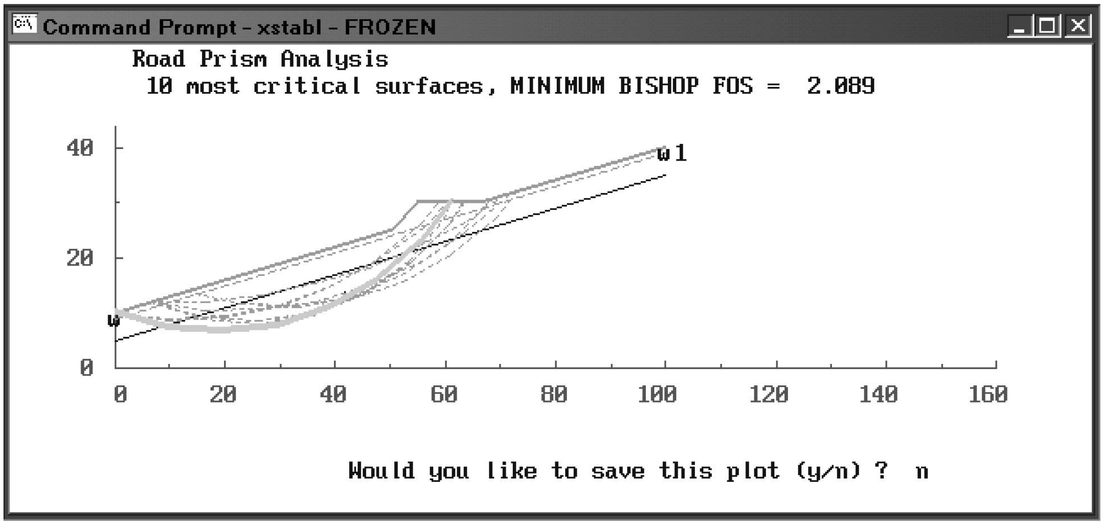

FIGURE 3 Simplified output screen from a single XSTABL run showing the ground surface (top solid line), specified water surface (*w*1) as the dotted line immediately below the surface line, 10 most likely failure surfaces (dotted lines), and surface with lowest factor of safety (wide curved line). The bottom line shows the boundary between the first and second soil layers.

Sometimes the effects of tree surcharge and root cohesion are included in Equation 4 (*10*), but these effects were assumed to be negligible on road fill slopes.

Table 5 shows a comparison of the *FS* predicted for a number of fill slope steepnesses for similar soils using the regression method (Equation 3) and the infinite slope equation (Equation 4). Computations reflect ground slopes as observed in the Clearwater National Forest in 1996 (*14*). For the soil properties and groundwater ratio specified, it appears that both equations predict similar *FS*s.

FIELD COMPARISON

In 1996, more than 500 road-related landslides occurred in Clearwater National Forest, Idaho (*14*). Table 5 also shows the distributions of road stability failures by slope. It is apparent that both Equations 3 and 4 did a reasonable job of predicting slopes on which failures were likely, assuming that the road fill had a groundwater ratio of 0.5. Data were also provided on the distribution of landslide by land type. Table 6 shows that if a 40% slope is assumed for all categories, the Border and Batholith land types (Categories 2 and 3), are predicted to be less stable than the Belt land type (Category 4), similar to the observed failure distribution. Soil Category 1 is predicted to be the least stable, but it is unlikely that alluvium would be found on a 40% slope beneath a road. (Landslides pertain to the Cleanwater National Forest in 1996.)

For another evaluation of Equations 2 and 3, data was obtained on cross sections of roads that failed within the Payette National Forest, Idaho. All failures occurred within the road fill. In these failures, it appeared that surface runoff from the out-sloping portion of the road surface may have saturated the near-surface road fill, resulting in shallow fill failures. To model this effect, *w* was set to 1.0 (i.e., saturated), with the presumption that the soil was saturated where the slide plane occurred. The soils were approximated as a Category 2 or 3. The *FS* estimates using Equation 3 with soil Categories 2 and 3 are given in Table 7. Had this analysis been used in a road survey, it was found, all of the failed roads would have been considered unstable and warranted a more detailed analysis.

TABLE 5 *FS* Computed with Equation 3 Versus *FS* Computed with Equation 4 and Percentage of Failures in 1996

Ground Slope	Factor of Safety		Percent of '96 Events
	Equation 3	Equation 4	
10	1.83	1.97	0%
20	1.45	1.48	1%
30	1.17	1.18	6%
40	0.96	0.98	21%
50	0.80	0.84	19%
60	0.68	0.74	52%

TABLE 6 Comparison of *FS* on a 40% Slope (Equation 3) for Different Soils with Distribution of Road-Related Landslides (*14*)

USCS Soil Type	Clearwater Soil			Eq. 3 FS
	Land Type	% of Forest	% of Events	
1	Alluvium and Basalt	10	40%	0.76
2	Border	25	40%	0.86
3	Batholith	39	43%	0.96
4	Belt	14	12%	1.05

TABLE 7 *FS* **Estimates from Equation 3 with Field Data from Failed Roads in Payette National Forest**

Site No.	Ground %	Fill %	Water	FS Soil 2	FS Soil 3
3d	44	85	1.0	0.49	0.55
7	29	75	1.0	0.67	0.74
12	39	71	1.0	0.59	0.66
14	28	75	1.0	0.68	0.75

TABLE 8 Estimates of ***w*** **Necessary in Fill to Reach Critical** ***FS*** **(1.0) with Equation 3, Assuming Soil Category 2**

Site No.	*w*	Fill %	Soil	FS	Water	Equation
3d	44	85	2	1.0	*	*
7	29	75	2	1.0	0.39	3
12	39	71	2	1.0	0.84	2
14	28	75	2	1.0	0.43	3

If a saturated prism is not assumed, Equations 2 and 3 can be employed to iteratively estimate *w* necessary for the road to become unstable. This analysis was performed for soil Category 2. The results are shown in Table 8. The equation column in Table 8 records which condition, water in or beneath the fill, reduced the factor of safety to <1. Site 3d is unstable regardless of *w* (i.e., *FS* is <1.0 for all values of *w*). That the road had existed for some time before failing indicates that the soil must have had properties more like those of soil Category 4, or it was a soil with some cohesive strength.

Figure 4 shows how the *FS* varied for two sites—3d and 12—as *w* gradually increased from 0 in the original soil to 1.0 in the fill. The figure shows the instability of Site 3d at all water contents, and the instability of Site 12 at groundwater ratios greater than about 0.85 below the fill. The figure also shows that Equations 2 and 3 provide a continuous function as *w* changes from 1.0 beneath the fill to 0.0 in the fill.

APPLICATIONS FOR THE MODEL

The results of this investigation suggest that it is possible for a manager with a limited geotechnical background to estimate the stability of a road prism. The number of variables has been limited to four with an accuracy in *FS* prediction of ±0.2 for groundwater below the road fill and ±0.1 for groundwater in the road fill. With an inclinometer, a field technician can measure ground slope and fill slope. Soil categories can be determined in the field, or a specialist can provide a soils map or a road plan with the pertinent information. The most difficult variable to measure is *w*. The field technician either may assume the worst case (saturated fill) or set the *FS* to 1.0 and solve for *w*. All these observations can be entered into a spreadsheet or other computer solution to quickly determine the *FS*. Later, a geotechnical engineer or hydrologist can assess the likelihood that *w* would achieve that critical value, or water level monitoring instrumentation can be installed (*8*).

It is also possible to link Equations 2 and 3 with a dynamic hydrologic model to determine the stability of a given road as the groundwater ratio varies from day to day, over a number of years (*4*, *15*).

SUMMARY AND CONCLUSIONS

We modeled a generic side cast road prism and carried out 3,696 runs with the XSTABL site-specific slope stability program, varying natural ground slope, fill slope slope, road fill ratio, groundwater ratio, and soil properties. We found that road fill ratio was not an important predictor of road stability. From the other factors in these runs, we developed regression relationships to readily predict the stability of a given road prism. Comparisons with observed field conditions showed that observed failures would have been predicted with our technology. Further study is needed if more comprehensive and accurate models are desired. Additional factors that may be included are soils with cohesion and a variable for depth of soil. Future work may also focus on an improved interface to XSTABL specifically for road prisms and on modeling a dynamic groundwater ratio.

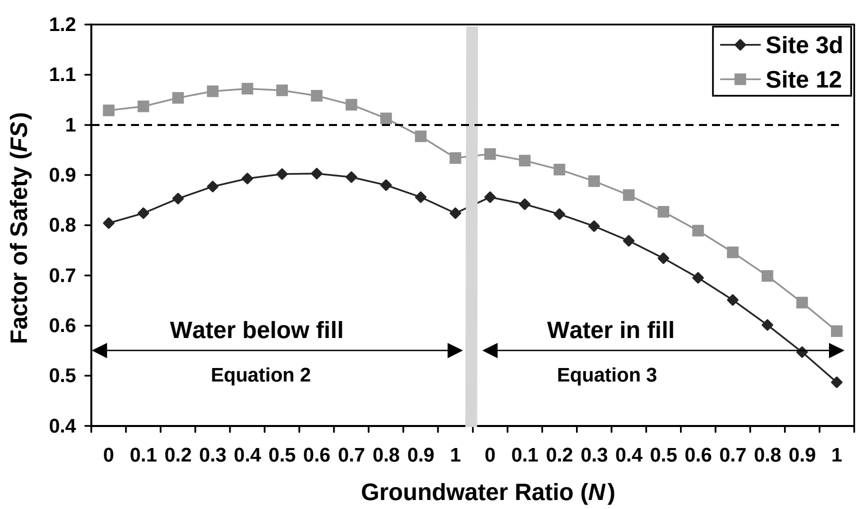

FIGURE 4 *FS* **versus** ***w*** **for Payette Sites 3d and 12 (Table 7) for soil Category 2.**

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