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Linking the WEPP Model to Stability Models

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Abstract:

This paper presents an initial study to determine whether the hydrology in WEPP can aid in the prediction of instability of roads constructed on steep hillsides. The WEPP model predicted soil water content for forest roads. This water content provided input to a road stability regression model developed from the XSTABL model. It appears that WEPP may be over-predicting water content of deeper soils, and that the regression model may be under-predicting the factor of safety.

Keywords:
Forest roads, Stability, Forest hydrology, Erosion models, WEPP

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Linking the WEPP Model to Stability Models

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Sedimentation from forest roads is a major concern in forested watersheds. In some areas most of the soil comes from surface erosion of the forest road or the adjacent fill slopes. In other areas, however, mass failure dominates the sediment delivery budget from roads. This is particularly true in the northern Rocky Mountains, the Sierras, the Cascades, and the Coast Range in Washington and Oregon. Surface erosion of roads occurs every year, but landslides are less frequent. However, the severity of the landslides paired with the importance of minimizing sediment delivery makes this an important topic. Landslides are most common on steeper slopes, on slopes that have lost vegetation due to fire or timber harvest, on soils that are low in cohesion, and in wetter years. Trying to understand the relationships between these factors is complex and often times confusing.

The Water Erosion Project (WEPP) model was developed to model surface erosion processes (Flanagan and Livingston 1995). Those processes include infiltration, evapotranspiration, and water movement out of the soil column. WEPP predicts a number of daily soil conditions, including soil water content. If this capability of WEPP to predict water content could be linked to a road stability model, then it may be possible to determine how frequently a slope failure can be expected on a given terrain for a specific climate.

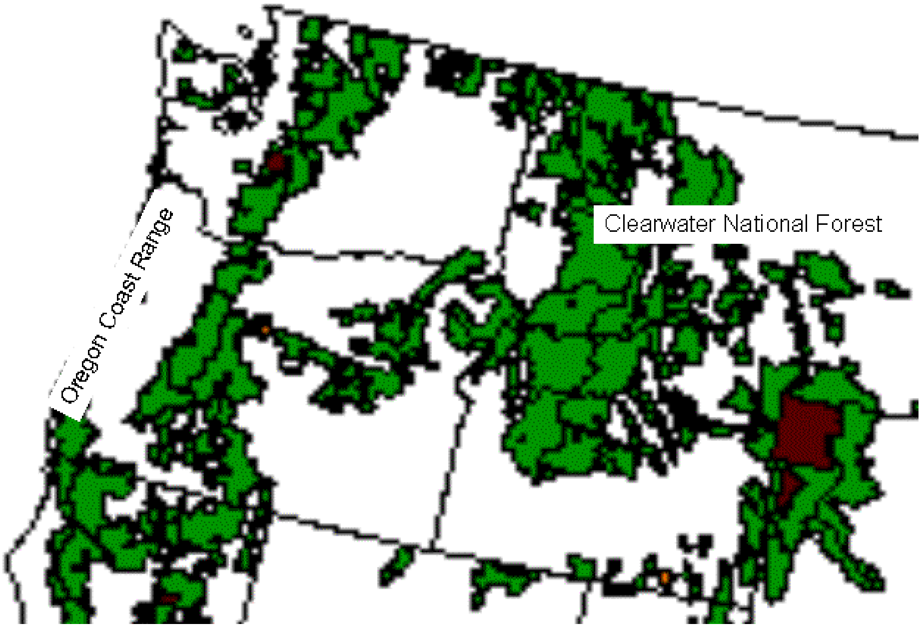
Numerous slope stability models have been developed. One of them is XSTABL, a generic stability model that allows combining very complex slopes with soil properties and soil water content to estimate the factor of safety of a given slope using the method of slices (Sharma 1994). A recent study using the XSTABL model for a range of topographies and soils common in forested conditions was carried out, and a set of regression equations developed to predict the factor of safety for a given set of road conditions.

The purpose of this paper is to report on an initial investigation to determine the suitability of combining the WEPP soil water prediction capabilities with a road stability model to better understand some of the complex interactions that cause slope instability on roads on steep hill sides.

Background

Two locations with well-documented landslide histories were picked to provide a context for our investigation, one in the Oregon Coast Range, and the other in the Clearwater National Forest in Idaho (Figure 1). Above average precipitation events in November and December of 1995 and in February of 1996 had caused of major landslides throughout the Pacific Northwest. Studies relating landslides to roads were conducted on several sites in Oregon as well as the Clearwater National Forest in north-central Idaho

Figure 1. Location of two the study areas.



(McClelland et al., 1997; Robison et al., 1999). These two locations had high occurrences of road related landslides during this period. Both reports detail the site conditions and the severity of the storms that were recorded in the months prior to the landslides.

In Tillamook, Oregon storms were high-intensity, delivering 140-180% of the average precipitation for the area (Robinson et al., 1999). Tillamook is at 12 m elevation and receives 2200 mm of annual precipitation on average. The size of the study area around Tillamook was 1200 ha, with hill slopes ranging between 60-100%. In the spring of 1996, there were 62 failures, 10 of which were road related landslides. Tillamook had a relatively low ratio of road related slides to non-road slides; however, the density of landslides or washouts in the study area is very high. There were 1.6 failures per km of road on the Tillamook watershed and 57,000 cubic meters of displaced soil.

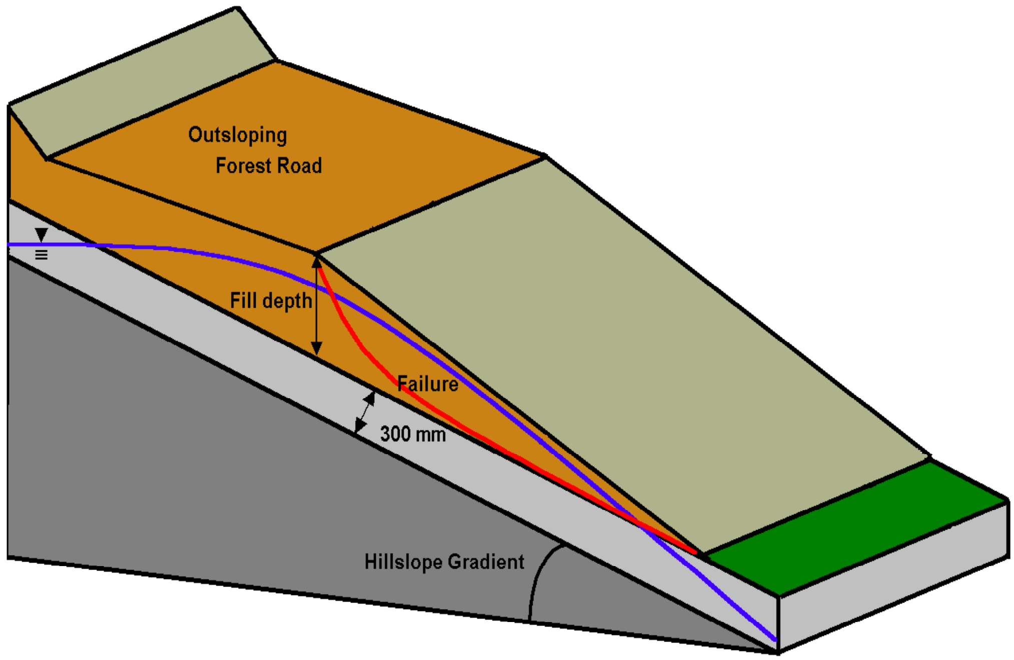
The November storms in Powell, Idaho delivered 314% of the average rainfall (Conner et al., 2000). The Squaw Creek drainage is approximately 15 km from Powell, Idaho and was the location of a large number of landslides. Squaw Creek drains into the Clearwater River at 1100 m elevation and receives 890 mm of annual precipitation. Squaw Creek basin is 4400 ha and has average hill slopes of 20-60%. There were over 900 landslides on the entire Clearwater National Forest and 58% were attributed to road failures (Conner et al., 2000). In the Squaw Creek drainage alone, there were 6000 cubic meters of sediment delivery to streams (McClelland et al., 1997).

Methods
The general approach to this study was to generate one hundred years of climate typical for each of the sites. This climate was used to drive the WEPP model with a typical forest road soil and topography (Elliot and Hall, 1997). The WEPP water balance output file was analyzed to determine the distribution of the road water contents throughout the period of simulation. This distribution was used as an input to stability regression equations to determine how many days in 100 years the road was likely to fail from instability.

CLIMATE. A weather generator, Cligen, is distributed with the WEPP model (Flanagan and Livingston, 1995). Cligen is a stochastic weather generator, which uses station climate statistics to predict weather records, including daily precipitation amounts and intensities, and temperatures. Cligen formats weather files for the WEPP model. Cligen has a database of over 1200 stations, including Tillamoock, OR. The data for Tillamook were considered adequate for the study. For the Squaw Creek site, the nearest station was the Fenn Ranger Station, which was located at a lower elevation, and in the shelter of the Clearwater River Valley. The Fenn climate is warmer and wetter than the location of concern, so the station data were modified using a newly developed program called Rock:Clime (Elliot et al., 2000). The Rock:Clime generator accesses the PRISM monthly precipitation database with interpolated values on a 4-km grid, to generate climate data for a given latitude, longitude and elevation (Oregon State University, 2000). These data are then used by CLIGEN to generate a climate file for the WEPP model. Fenn was modified from 46.10^{o}N, 115.55^{o}W and 488 m elevation to 46.52^{o}N, 114.87^{o}W and 1070 m elevation. The average annual rainfall at Fenn is 940 mm, which was adjusted for location and elevation to a value of 890 mm for the nearby Powell Ranger Station according to the PRISM data base. The Powell Ranger Station is about 19 km from the study location, and the PRISM value is similar to the precipitation observed at the station. The largest storms in the 100 years generated by CLIGEN were similar to the storms prior to the landslide events for both climates. Once it was determined the climates were acceptable, CLIGEN generated 100 years of climate data for both sites.

TOPOGRAPHY. The road was modeled as a 12 percent outsloping road, 4.3 m wide. The length of the road did not matter because we were only interested in the daily soil water content and not the surface erosion. The depth of fill soil at the shoulder of the road is dependent on the hill slope on which the road is built on. There is a linear relationship between the steepness of the hill and the depth of fill. As the hill increases in steepness, the depth of fill also increases. For every 5% increase in steepness, there is a corresponding increase of fill depth of approximately 200 mm. Under all conditions we assumed a 300 mm base of native forest soil beneath the fill (Figures 2 and 3).

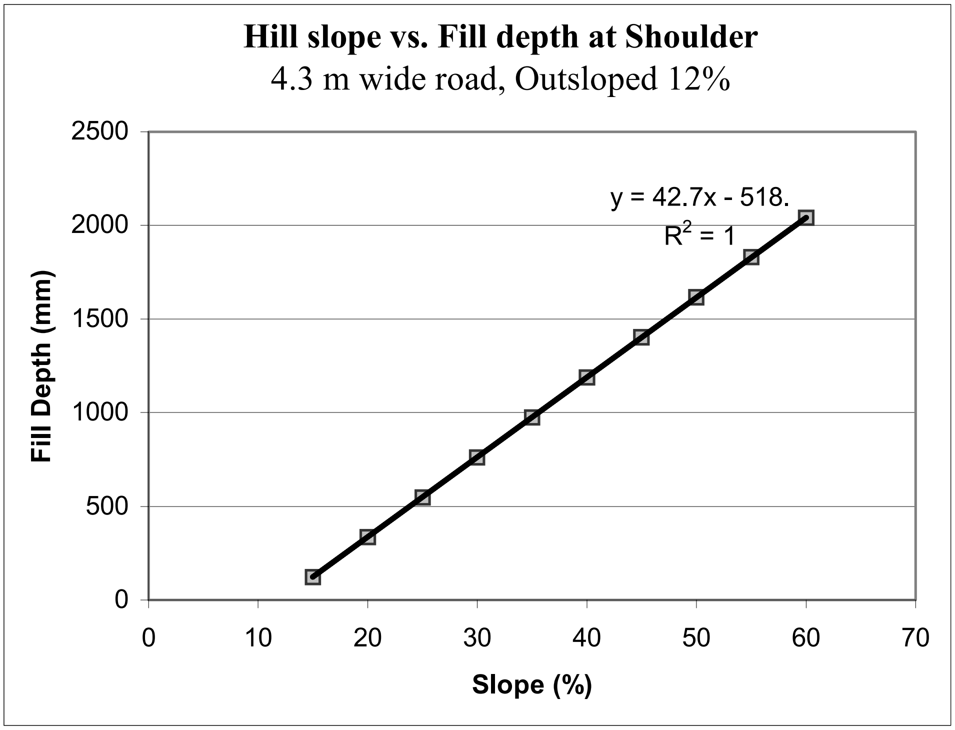
Figure 2. Topographic relationships of road to the water table and the hillside on steep terrain.



SOIL PROPERTIES. The soil files in WEPP described a native surface road under forest conditions (Elliot and Hall, 1997). Soil types were picked that are appropriate for each location. In Oregon, a silt loam soil is a common native soil. The silt loam has a hydraulic conductivity of 1 mm/hr and a porosity of 30 percent for a native surface road. In Idaho, a sandy loam was used, with a hydraulic conductivity of 4 mm/hr and a porosity of 40 percent for the road. Depths of the road subgrade varied with the steepness of the hillside on which the road was located (Figure 3). The road vegetation was described as fallow so there were no vegetation influences on the results. The initial condition for the road scenario was a bladed road, and the road is bladed once a year to remove ruts.

SOIL WATER. The WEPP model was run for 100 years for each site. The "Water output " run option was selected. This file contains the daily water content of the top 1.8 m of soil. The file was opened with a spreadsheet, and the saturation calculated from the water content, the depth of soil, and the soil water holding properties.

Figure 3. Relationship between steepness of hillside and depth of fill on a road.



ROAD PRISM STABILITY. The XSTABL generic soil stability model (Sharma 1994) was run for approximately 3000 permutations of road prisms to determine the factor of safety for different slopes, different soils, and different degrees of saturation. From the results, two regression equations were developed, one for conditions when only the soil beneath the road prism has some level of saturation, and the other equation for conditions when the road prism itself has a level of saturation.

<u>Groundwater below the road fill:</u>

$$FS = 8.76 + \frac{f}{8.308} - 1.753\sqrt{f} - \frac{(f - 40.4w)(f - 0.88g)}{3370} - \frac{(g+61)^2}{11{,}000} - \frac{w^2}{2.3} - \frac{\sqrt{w}}{10} + \frac{s}{6} - \frac{f\,s}{900} \qquad (1)$$

<u>Groundwater in the road fill:</u>

$$FS = 3.777 - \frac{\sqrt{f}}{2.147} + \frac{f}{34.44} - \frac{(f(w+1))^2}{110{,}000} - \frac{\sqrt{g}}{7.32} - \frac{g}{129} + \frac{(g(w+1))^2}{28{,}150} + \frac{s}{6.315} - \frac{f\,s}{1053} - \frac{(s(w+1))^2}{1000} - \frac{(w+0.236)^2}{4.02} \qquad (2)$$

Where *FS* is factor of safety, *f* is fill slope steepness (percent), *g* is ground slope steepness (percent), *w* is depth of saturated soil as a fraction of the total soil depth between 0 and 1, and *s* is the soil category (Fine SP or SM = 1; Fine SW, Medium SP or SM = 2; Medium SW, Coarse SP or SM = 3; and GP, GM, and Coarse SW = 4). The Oregon silt loam soil was best described as a category 2 soil, and the Idaho sandy loam as a category 3 soil.

Figure 4 shows the water contents that resulted in a factor of safety of 1 from the equations for the two soils in this study.

Results and Discussion

The results are presented in Figures 5 and 6. Figure 5 shows a typical cyclical distribution of water content for a ten-year period of simulation for the Idaho climate and soil. Helvey and Kochenderfer (1989) noted a similar, but smaller in magnitude, annual cycle of water content in roads they monitored in the Central Appalachians. Figures 4 and 6 show that according to the regression equation, roads on hillslopes of 15 percent (or less) are stable for both sites. Figure 6 also shows that roads built on side slopes over about 40 percent steepness are unstable, regardless of soil conditions. In the range of 20 to 35 percent steepness, there will be some periods of time when the water content of the road is sufficiently high that failure results. The figure also shows that the silt loam soil with the Oregon climate tends to be less stable than the sandy loam soil with the Idaho climate. These results support the observation that generally, Idaho experiences fewer years with major landslides than Oregon. McClelland et al. (1997) indicated that major landslide events occur about once every 20 years in this area. Years with major landslide events in the wetter Oregon coast range are more frequent, although the 1996 storms were considered as 20 to 30 year events (Robison et al., 1999).

When running the WEPP model, WEPP was predicting greater amounts of water in deeper soils. WEPP divides the soil column into 200-mm deep layers for predicting the soil water balance. We noted that WEPP predicted the same water content in each soil layer, and that the total number of layers then determined the soil water content, rather than the difference between infiltration and seepage and evapotranspiration. This observation requires further investigation into the WEPP soil water balance predictions.

Figure 4. Degree of saturation necessary for a factor of safety of 1 as predicted by the equations 1 and 2.

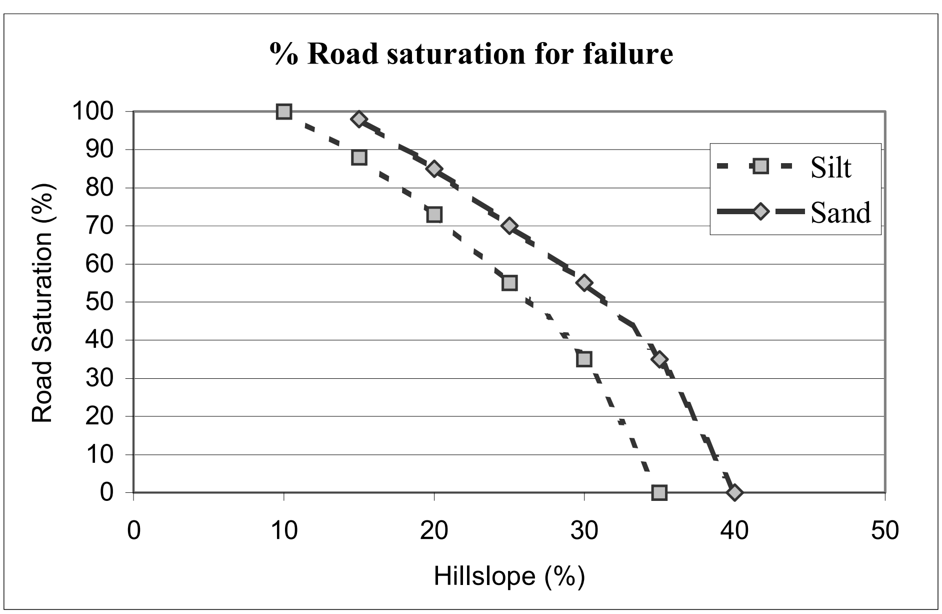
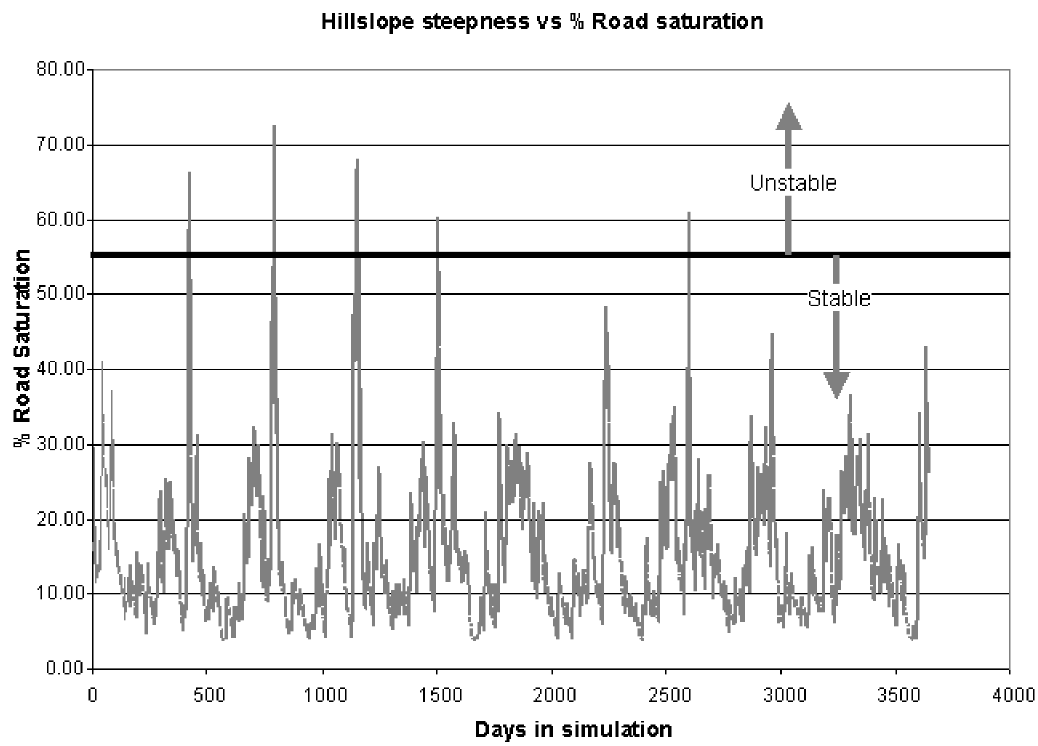


Figure 5. Variation in soil water content of road prism for a 30 percent hill slope, a sandy loam soil, and an Idaho climate during 10 years of WEPP simulations.

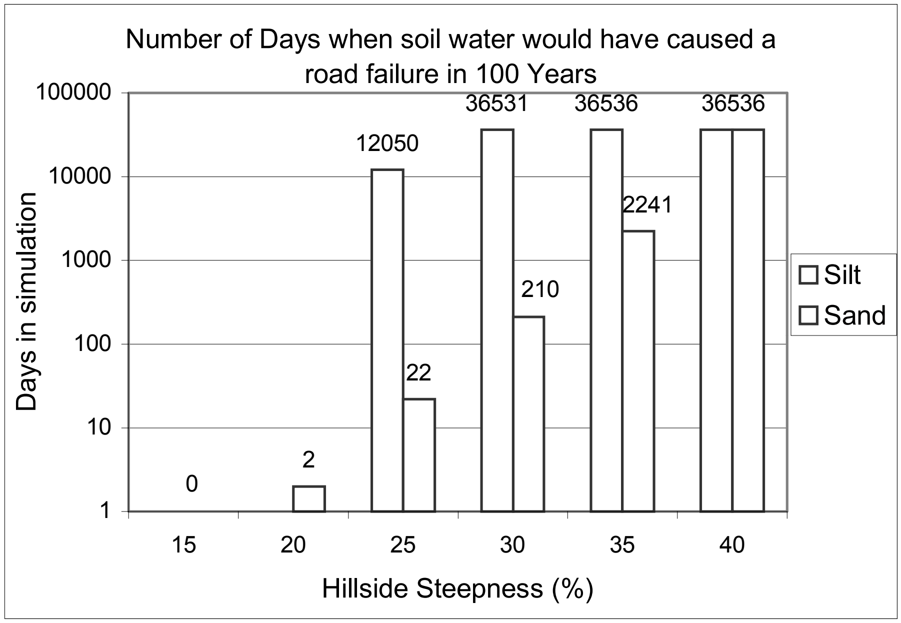


It appears from figure 6 that the regression equation is likely under-predicting the factor of safety. Generally, roads on slopes up to about 50 percent are stable in most years, but will fail only in unusally wet years. For example, McLelland et al. (1997) reported that 40 percent of road failures in a wet year occurred on slopes over 40 percent steepness, but some road failures did occur on roads at below 20 percent hillslope steepness. Robison et al. (1999), however, did not show a direct relationship between road failure and slope steepness, suggesting that steepness alone is not adequate to predict the probability of failure. One of the assumptions of the stability regression model was that the cohesion of the soil was zero. This assumption is likely one of the reasons for the predictions of unstable conditions on the steeper slopes every year, and not just in the wet years. Cohesion is frequently due to moisture tension in fine-grained soils, and only approaches zero when the soil becomes saturated (Lambe and Whitman, 1969).

Summary

The WEPP model was used to predict soil water content for forest roads. This water content provided input to a road stability regression model developed from the XSTABL model. It appears that WEPP may be over-predicting water content in deeper soils, and that the regression model may be under-predicting the factor of safety.

Figure 6. Number of days in 100 years that a road on the given hillside steepness is likely to fail, based on WEPP-predicted road soil water content and the road stability regression equation for a silt loam soil and an Oregon climate, or a sandy loam soil and an Idaho climate.



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