Why do slopes become unstable after rainfall events?

In February of 2005, television news reports showed images of homes in California, U.S.A. and British Columbia, Canada being damaged by severe landslides after abnormally high rainfall rates over the long and short term. Between July 2004 and February 11, 2005 the Malibu, California area received over 23” cumulative precipitation. Between February 11 and February 15, a four day period, it received an intense 9” of additional rainfall.

- What caused these slides?
- Could they have been predicted?
- How does the rainfall rate affect the stability of the slopes?

GeoStudio 2004 can be used to analyze the mechanisms that keep slopes stable or, conversely, that cause them to fail. Consider the slope in the following figure. The assumed long term water table (blue line) is located well below the slope which means the pore-water pressure in the slope above this line is negative. The actual pressures that develop in the slope are a function of the soil type and net surface infiltration rate; which itself is a function of rainfall, evaporation and transpiration.

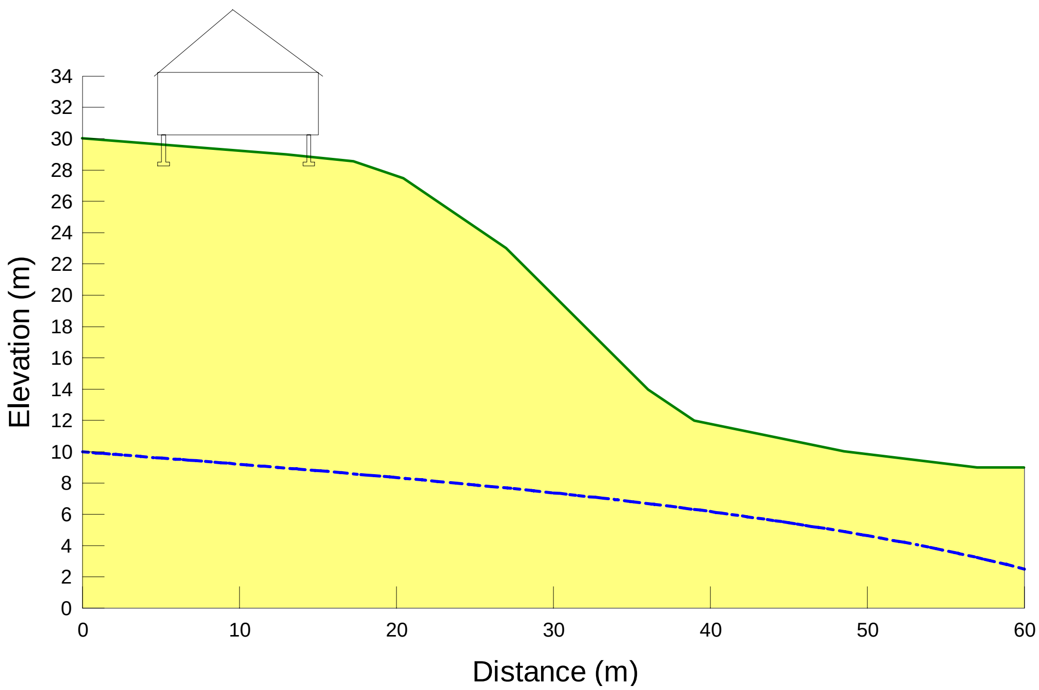

Figure 1 Assumed slope profile and initial water table used in analyses

The SEEP/W program was used to determine the changes in pore-water pressure in the slope due to the application of 23 inches of rain over a seven month period followed by an additional 9 inches in four days. The pore-water pressures were then accessed directly by the SLOPE/W program to study the factor of safety as a function of pore-water pressure and cumulative rainfall.

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The following two figures show computed near surface landslide shapes and their factors of safety following seven months of 23" cumulative rainfall and just prior to and after the intense 9" rainfall in four days. The slope appears stable after seven months of rain and then fails after only four more days of rain. Why?

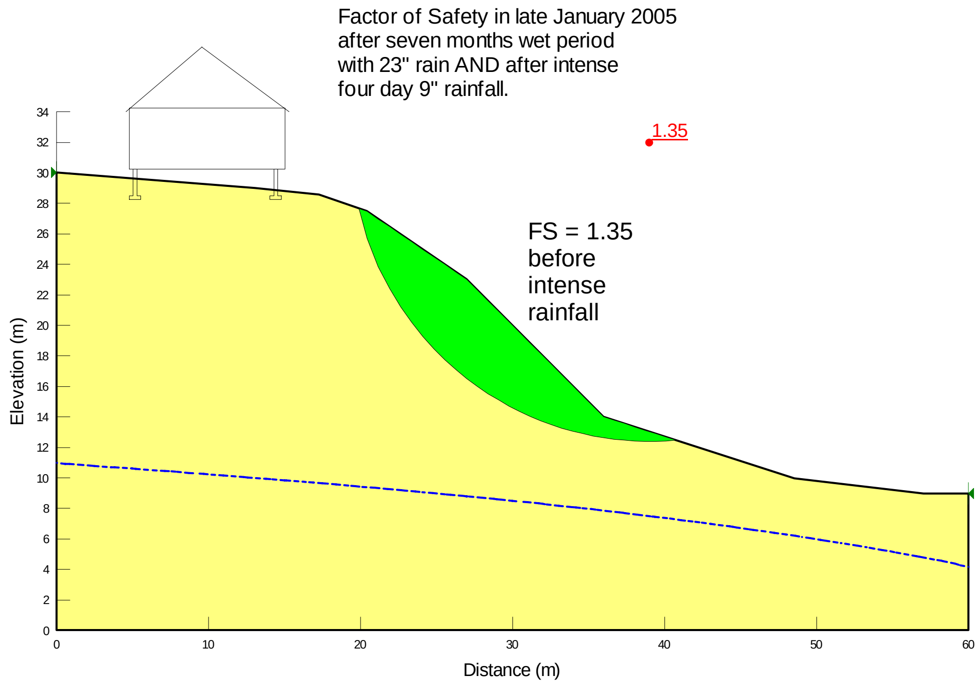

Figure 2 Computed factor of safety after seven months rainfall

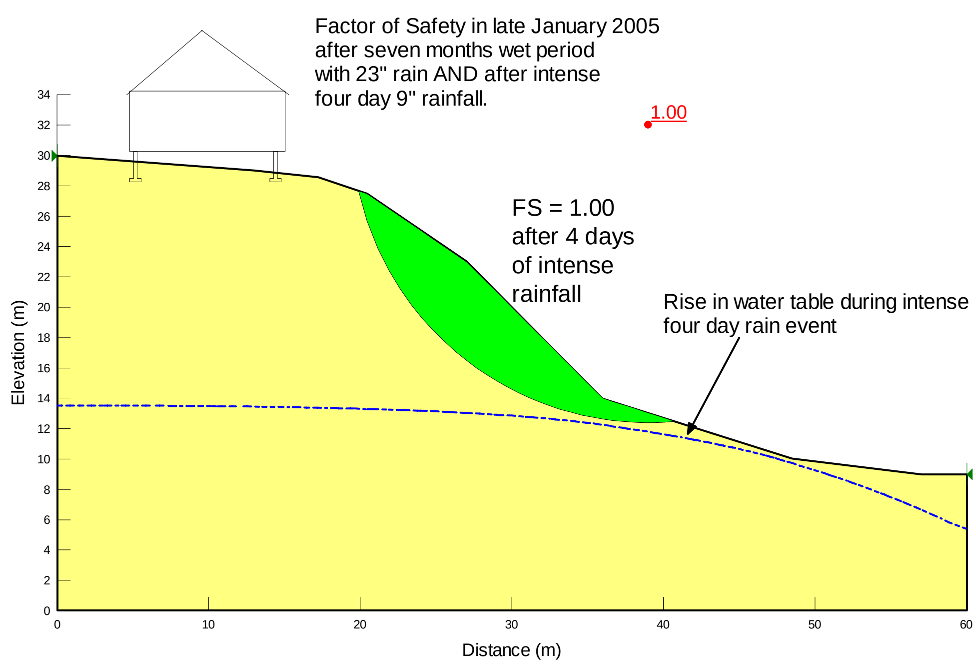

Figure 3 Computed factor of safety after four day intense rainfall

In order to understand the mechanisms that control the stability of this slope we must consider the changes in pore-water pressure within the slope at different points in time. You can see from the above images that the failure surface does not pass below the water table, so we can rule out the development of positive pore-water pressure at the base of the slip surface as the contributing factor resulting in loss of strength in the slope. We know from our observations of sand castles at the beach that there is an optimum dampness in the sand that results in the strongest shapes. If the sand is too dry, the castle falls down. If the sand is too wet, it will not take the right shape to start with. It is the water in the partially saturated sand that gives it the strength. More correctly, it is the negative pore-water pressure or suction pressures that hold the sand together. This is the exact same mechanism that is keeping the landslides from happening. If a slope gets too wet (even without becoming saturated) and looses too much strength from the suction pressures, the slope may fail.

Let’s look at the slope in this example at two instances in time: February 11th, 2005 and February 15th, 2005 – just before and just after the intense four day rainfall event. Figure 4 below shows the position of the water table after seven months of rain (lowest position) and then every half day after that during the intense four day rainfall period. Prior to the start of the intense rainfall period, a steady state seepage analysis was carried out with a surface rainfall rate equivalent to 23” of rainfall in seven months. The more intense, four day event was modeled as a transient seepage analysis that used the output from the steady state condition as its starting pressure condition.

The chart in Figure 5 shows the corresponding pore-water pressure condition for a vertical profile taken half way up the slope just before, and just after the four days of rain. In the seven months prior to February 11 ’05, the 23 inches of rain resulted in a more or less constant pressure condition without continual wetting up and loss of strength. During this time, the soil was able to transfer this rain down to the water table where it was moved away from the slope. If you look at the profile on February 15, ’05 (after four days of intense rainfall) the negative pressures in the top 5 meters (or 15 feet) have reduced significantly, because the soil cannot remove all the water at the rate it is entering and the ground is wetting up.

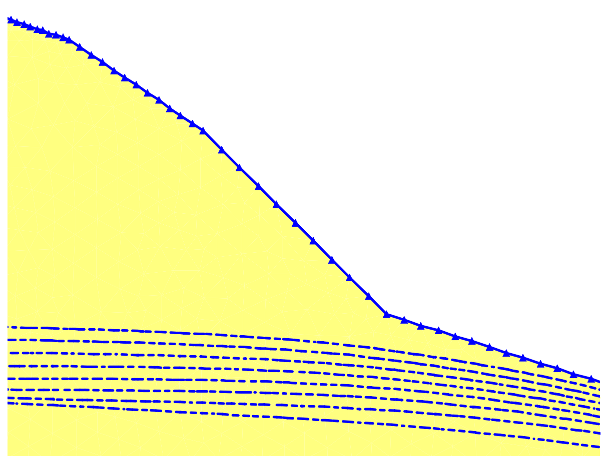

Figure 4 Rise in water table over four day intense rainfall event

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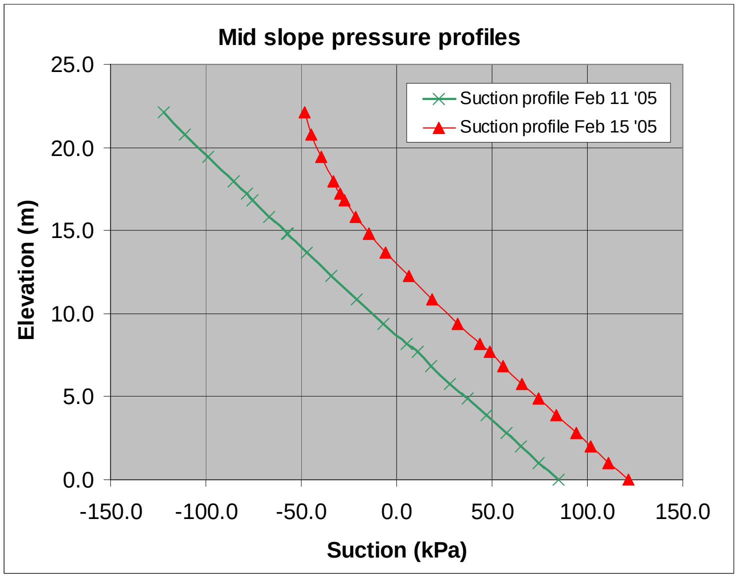

Figure 5 mid slope pressure profiles over time

Figure 6 compares the actual soil strength along the slip surface location at these two points in time. We know from unsaturated soil mechanics theory that soil gets its strength from three components: cohesion, frictional strength and suction strength. In these models the soil is assumed to be cohesionless so the slope is held in place by frictional and suction strength alone. You can see in the chart that the final four day intense rain event results in a loss of half the suction strength of the soil. The frictional component is the same regardless of the pore-water pressure condition. It is important to stress that in both cases, the pore-pressures are in the negative or unsaturated range. There is no build up of positive pressure considered in these findings. A loss of suction pressure alone has contributed to an overall loss of slope strength.

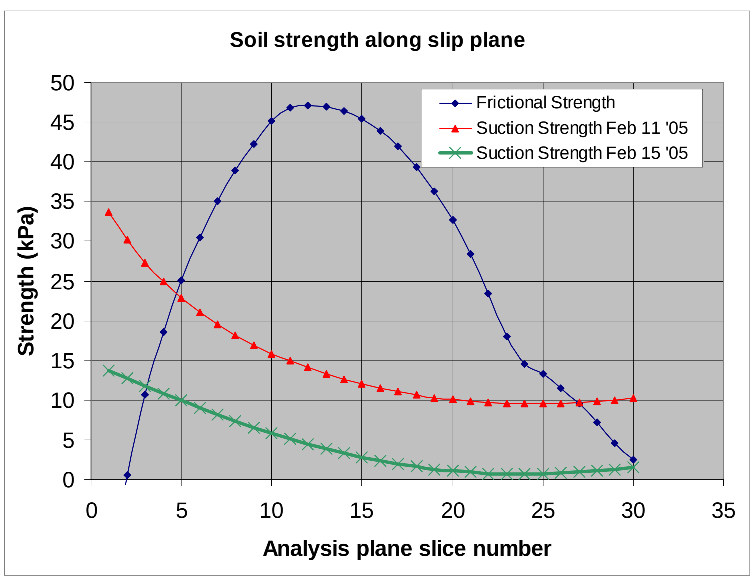

Figure 6 Failure surface soil strength components over time

One final image can be used to illustrate the mechanism that caused the instability in this example. In the figure below the minimum slope factor of safety is shown on the same plot as cumulative rainfall over time. The long term rainfall was assumed to begin cumulating seven months prior to the short term, high intensity event. It is clear that the long term, rainfall rates did not contribute to instability in this case; and that the four day intense rain event resulted in inflows to the slope that could not be accommodated without a loss in suction strength.

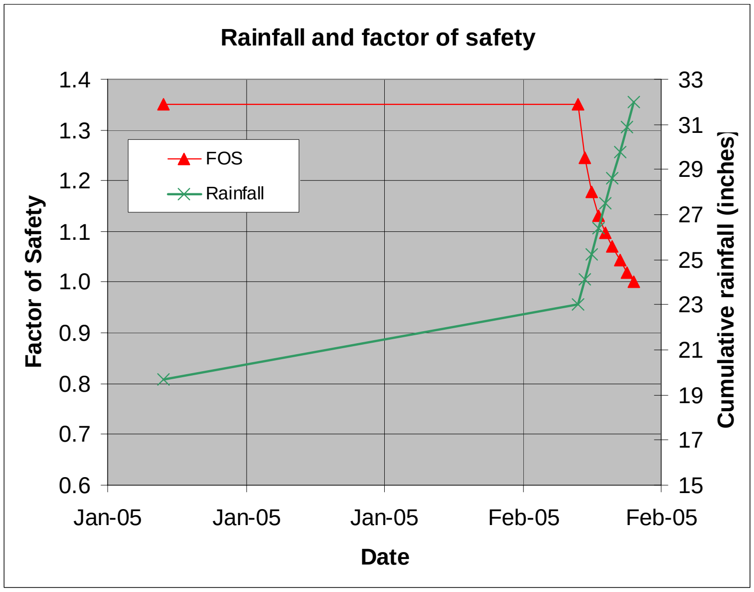

Figure 7 Factor of safety and rainfall history

Steady state and transient SEEP/W finite element analyses can be integrated with SLOPE/W within the GeoStudio 2004 environment to carry out a comprehensive analysis of failed slopes. The results of this type of analysis can be used to help predict future performance of slopes under a range of adverse climatic conditions.

NOTE: This is a purely illustrative example in the context of the Malibu rainfall rates. The surface profile and soil properties are entirely assumed. The actual site details may be significantly different from what has been assumed.
