Design of Stable Concave Slopes for Reduced Sediment Delivery during Geomorphic Reclamation

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Advances in Geomorphic Reclamation at Coal Mine Sites

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Research Focus

- Problem Statement
  - Methods exist to estimate: 1) mechanical slope stability, and 2) hillslope sediment delivery
  - However, methods have been developed for planar slopes, and existing studies would suggest concave slopes may improve stability coupled with reductions in surface erosion.
- In this presentation we:
  - Summarize field experiments quantifying the Revised Universal Soil Loss Equation (RUSLE) erodibility (K) factor for Appalachian surface coal mining reclamation sites.
  - Demonstrate that concave slopes may provide improved performance than planar slopes in terms of both mechanical and erosional resistances.
  - Demonstrate that RUSLE2 model is suitable for estimating sediment yields from reclaimed soil materials and slopes with concave geometries.

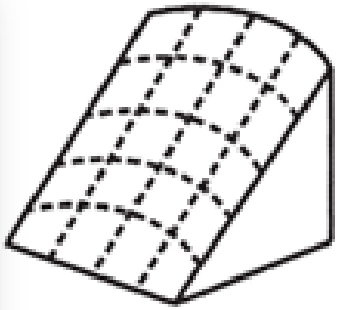
Background

- Slopes traditionally designed to be planar in cross section…
  - ✓ Easy to depict on construction plans
  - ✓ Easy for construction equipment operators to build
  - ✓ Well known methods for stability analyses (e.g., charts)
  - × In contrast to planar slopes, in nature slopes are seldom planar, but curvilinear
  - × *Concave-like slope contours like those observed in nature yield less sediment*
  - × With any reclaimed mine slope, erosion and large volumes of soil loss can occur if ground cover is not quickly established.

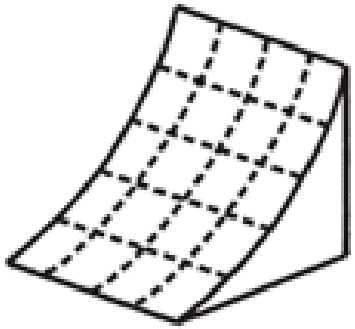
Background

- Land-forming *Geomorphic Reclamation* approaches
  - ✓ Can include the construction of concave shapes in the transversal and longitudinal (down-slope) directions
  - ✓ More natural features with improved stability and erosion resistance

Anaheim Hills (Schor and Gray 2007)



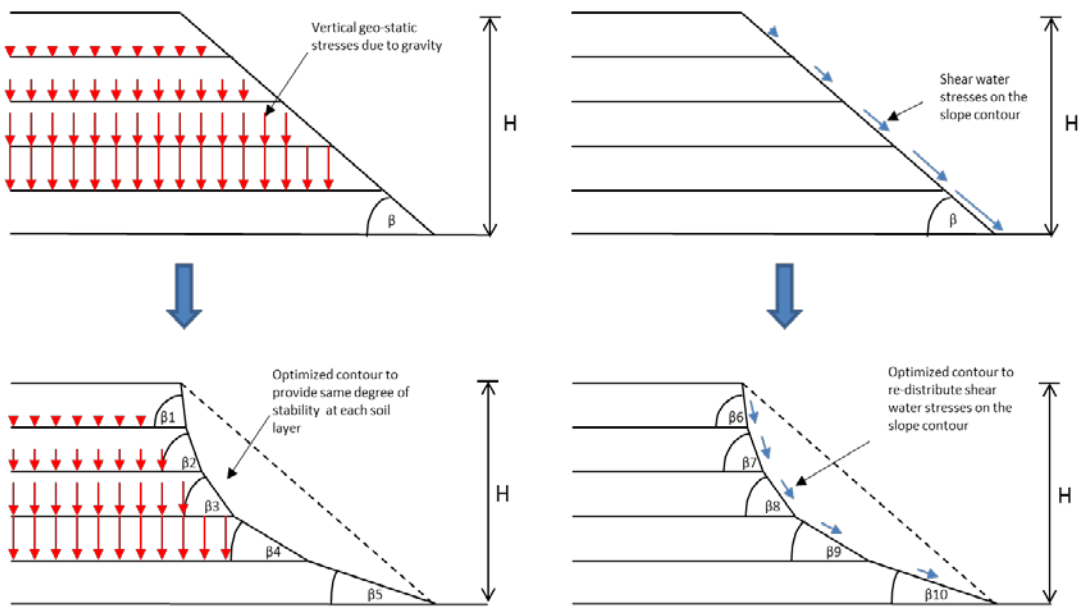
Transversely concave



Longitudinally concave (concave profile)

Background

- **Gravitational stresses** in slopes increase with depth
  - ✓ To maintain a uniform Factor of Safety (FS) the inclination must decrease downslope
- **Erosional stresses** on the surface of the slope increases with inclination and distance
  - ✓ If the slope inclination decreases as we move downslope, the erosional stresses are more uniform and lower
- For these reasons, slopes observed in nature are usually not planar

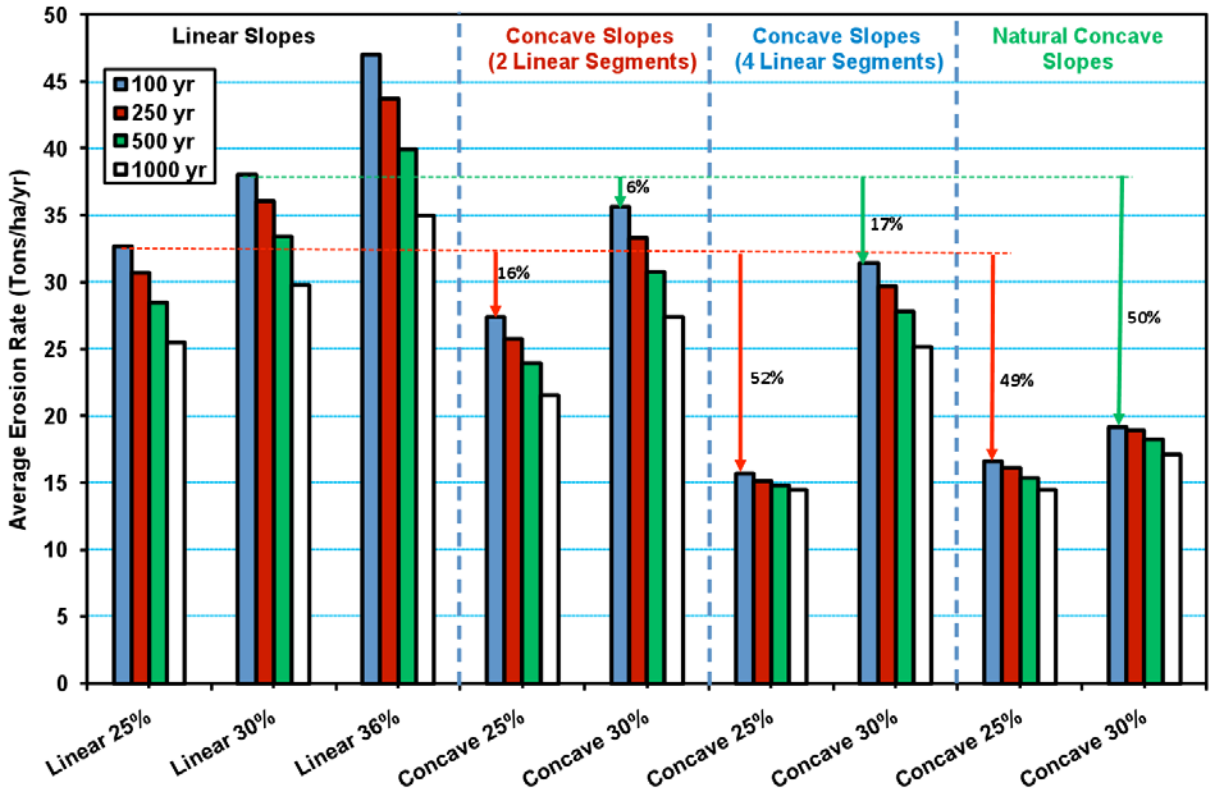


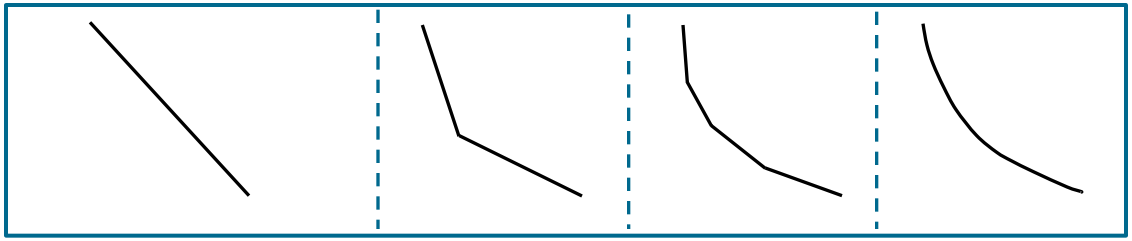
(Adapted from Schor and Gray 2007)

Background

✓ Concave slopes lead to less erosion than planar slopes

Priyashantha et al. (2009): Computational Results from the SIBERIA Model

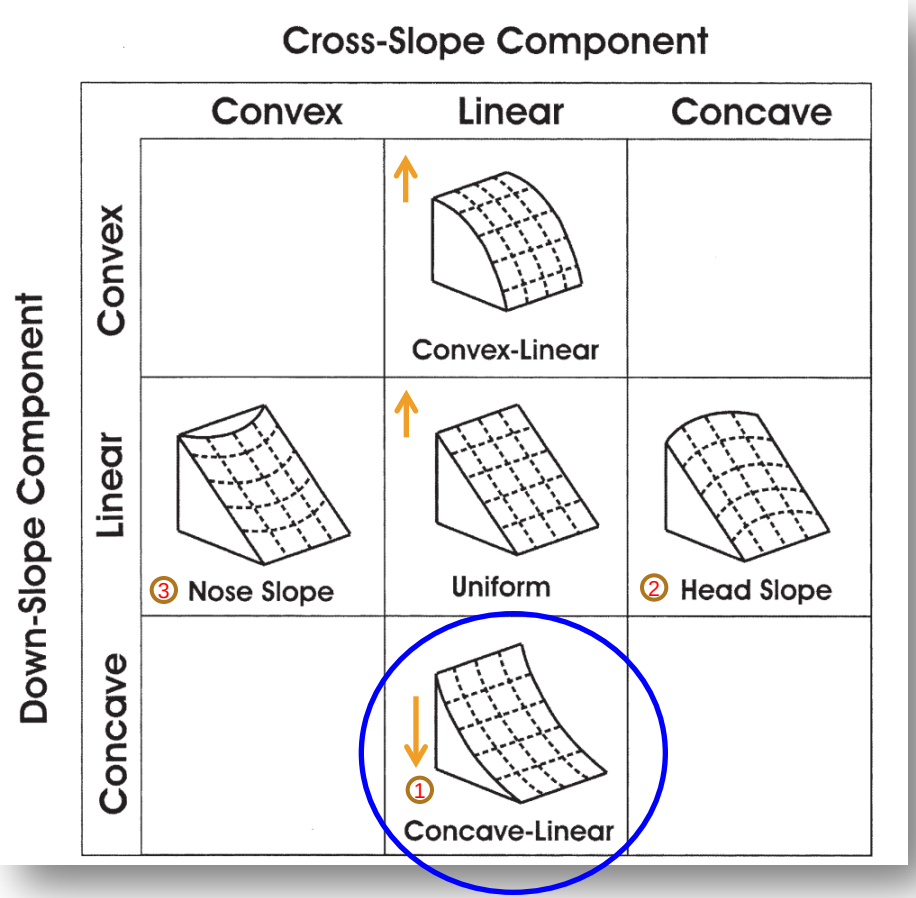




Background

✓ Concave slopes lead to less erosion than planar slopes

Rieke-Zapp and Nearing (2005): Experimental study - 3D slope shape vs erosional resistance.

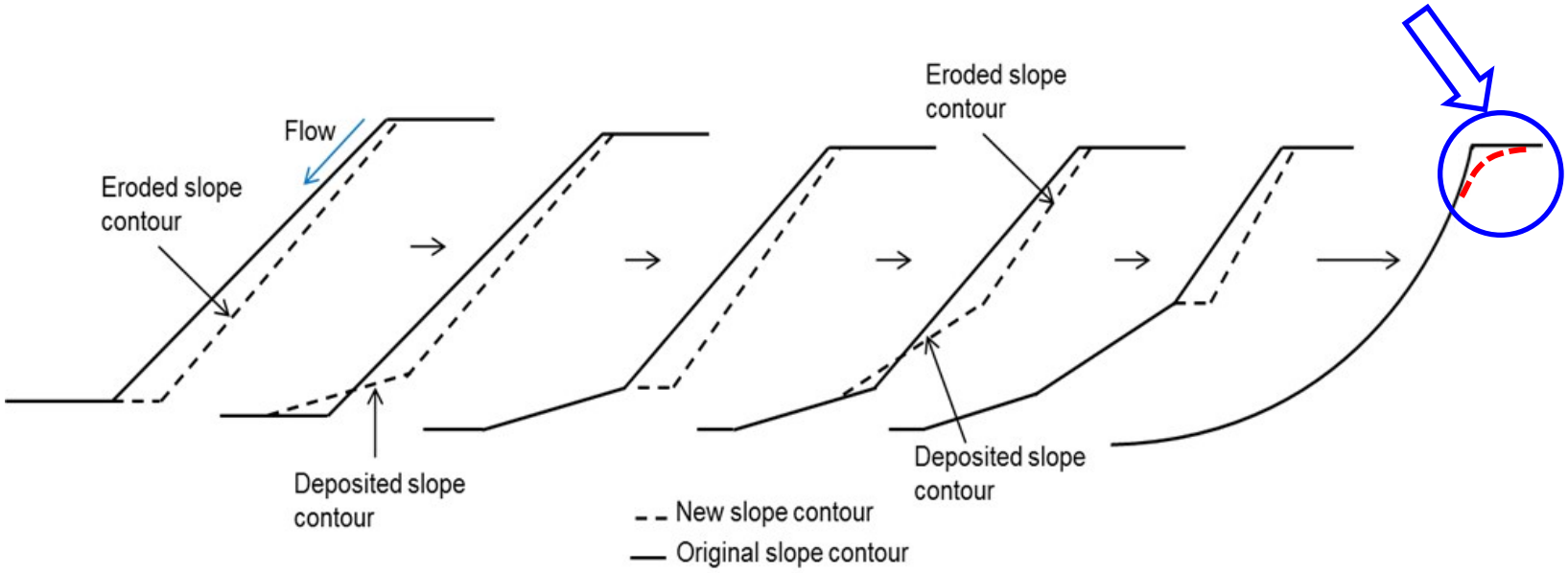


	Slope shape	Mean total runoff	Mean total sediment yield
		liter	kg
①	Concave-linear	1031[a]†	14.9[a]
②	Head	1022[a]	36.4[b]
③	Nose	1091[ab]	49.1[c]
④	Convex-linear	1026[a]	51.3[c]
⑤	Uniform	1110[b]	58.5[c]

Concave-linear slope generated less sediment than other slope types: 14.9 kg per 1031 liters runoff.

Background

- ✓ Concave slopes appear to be the result of long-term fluvial geomorphological processes leading to equilibrium conditions in slopes.
- ✓ Slopes obtain ***concave equilibrium*** after parallel retreat of the slope with spatial occurrences of erosion and deposition (Nash 1980; Twidale 2007; Pelletier and Rasmussen 2009)



Background

National Coal Mine Reclaimed Slope, Campbell TN

Current reclamation sites in the Appalachian: planar man-made slopes.

Mountainside Coal Mine Reclaimed Slope, Claiborne TN

Background

- Lessons from Australia (Howard et al. 2011)
  - Concave profiles for reduced sediment delivery on mine reclaimed slopes. It is possible to built concave slopes!
  - Replication of observed concave profiles without quantitative design can be an unpredictable practice with engineering risk.

www.landloch.com.au/technical-notes/

Background

- ✓ The growth of precision auto-guidance construction equipment allows complex shapes to be built with high level of precision.

- × NOT all concave profiles may be mechanically stable; therefore
  - × What is the optimum concave profile for stability considerations?

Supporting Research on Erosion

- Hoomehr et al. (2013, 2014) measured runoff and sediment yield from three coal mining sites in East Tennessee in order to provide accurate input parameters for the SEDCAD model.
- Computed a hydrology Curve Number (CN) and RUSLE erodibility K factor.
- Measured runoff and sediment by an unique study design using Pinson et al. (2009) collection devices.

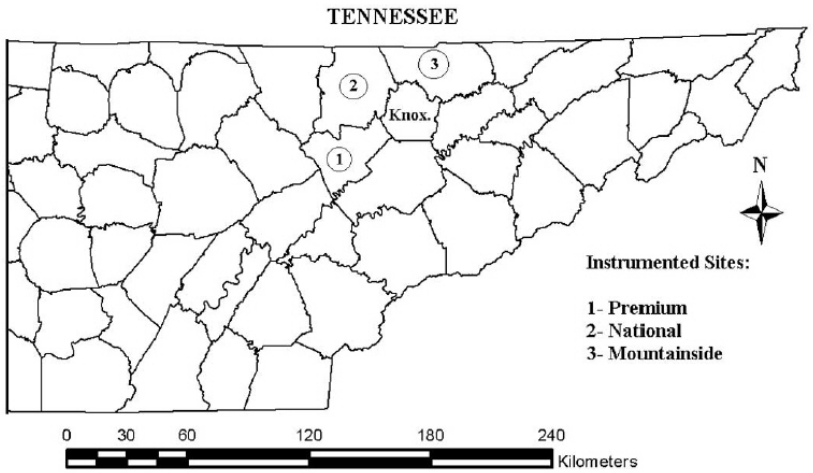
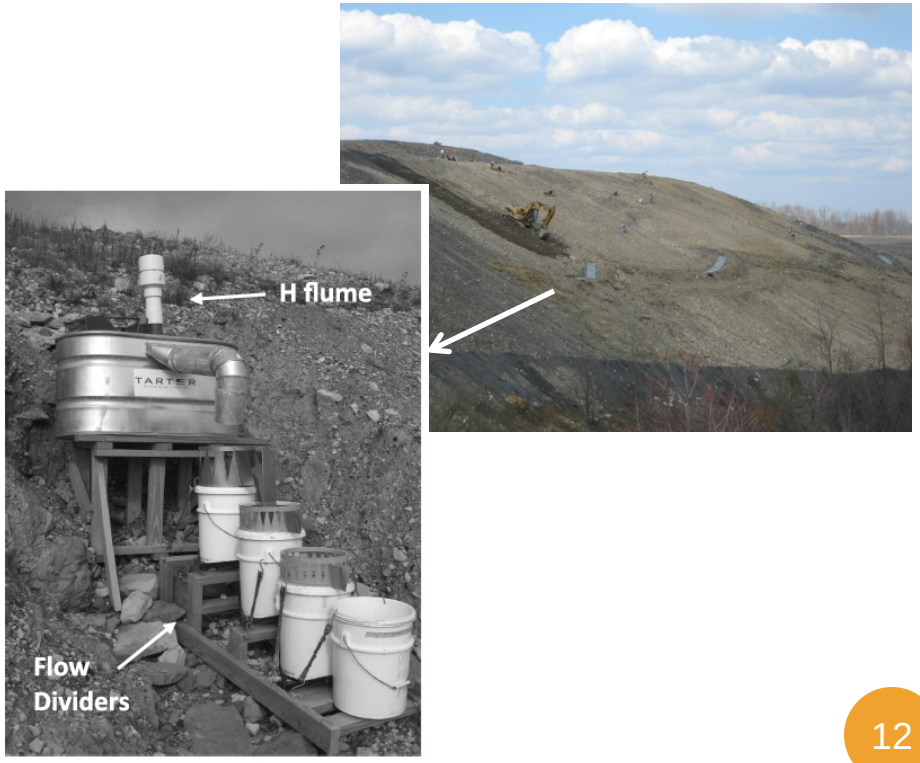


Fig. 1. Location of three study sites in east Tennessee at active coal mining operations for Premium (Anderson County), National (Campbell County), and Mountainside (Claiborne County)



Hoomehr and Schwartz (2013)

Supporting Research on Erosion

- Hydrology Curve Number for steep-sloped reclaimed mine sites determined to be: **CN = 59**

- RUSLE: **$A = R \cdot K \cdot LS \cdot C \cdot P$**
  - A = Amount of soil loss
  - R = Rainfall erosivilty
  - K = Soil erodibility
  - LS = Combined length-slope factor
  - C = cover management factor
  - P = erosion control management factor

- Measured A from collected sediment, measured R from rainfall data, measured LS from field surveys of study plots, assumed C and P = 1. Therefore, K computed per:
  - **$K = A/(R \cdot LS)$**

Supporting Research on Erosion

- Results of K computations ranged from 0.001 to 0.05 t.ha.h/(ha.MJ.mm)
- High K factors occurred during rill development, followed my slope erosional stabilty.

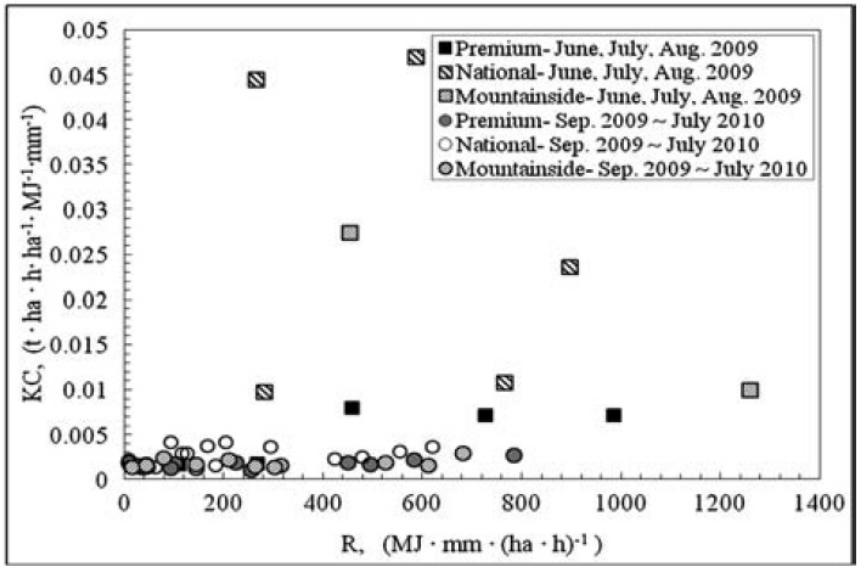


Figure 9. K_c (t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}) related to each sampling event, at each study site for pre-rill development (June, July, and August 2009) and post-rill development period (September through July 2010)

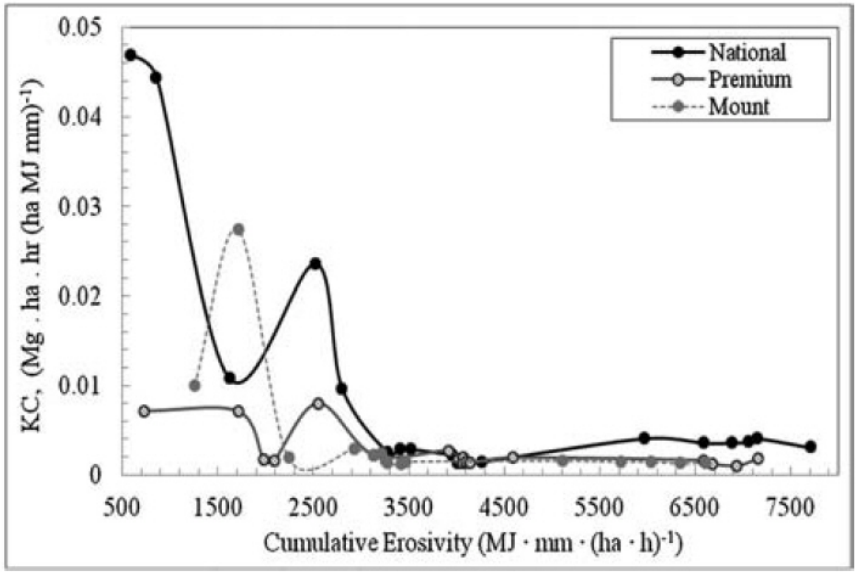


Figure 10. K_C (t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1}) related to each sampling event *versus* cumulative erosivity (MJ·mm·(ha·h)$^{-1}$) over the 14-month monitoring period from June 2009 through July 2010 for Premium, National, and Mountainside study sites

Hoomehr et al. (2013, 2014)

Supporting Research on Erosion

- SEDCAD modeling performance tended to overestimate sediment yields up to 1.6 times greater than measured, however results were variable.
- SEDCAD model was sensitive to selection of CN, for example a 40 % deviation in selection would approximately double sediment yields from the model.

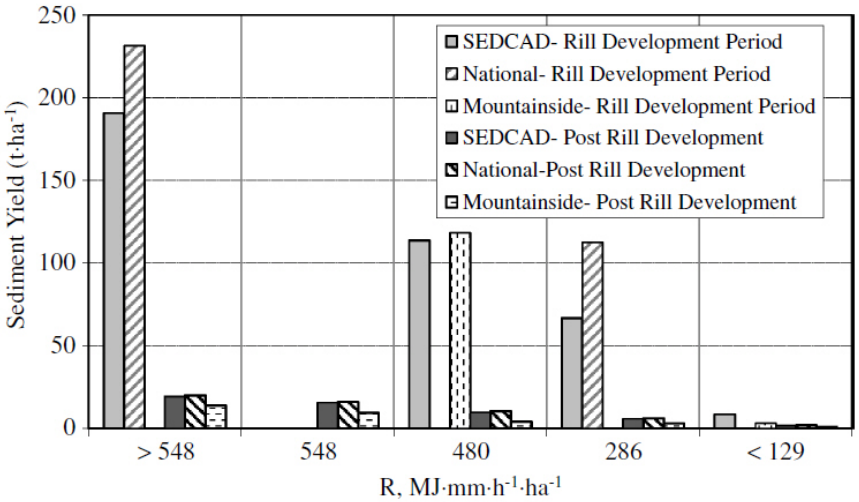


Fig. 4. Sediment yields in t · ha^{-1} from measured amounts at National and Mountainside study sites and *SEDCAD* calculated amounts, grouped by erosivity (*R*) classes: >548, 548, 480, 286, and <129 MJ · mm · h^{-1} · ha^{-1}; the *SEDCAD* simulation and comparison was made for pre- and postrill development period

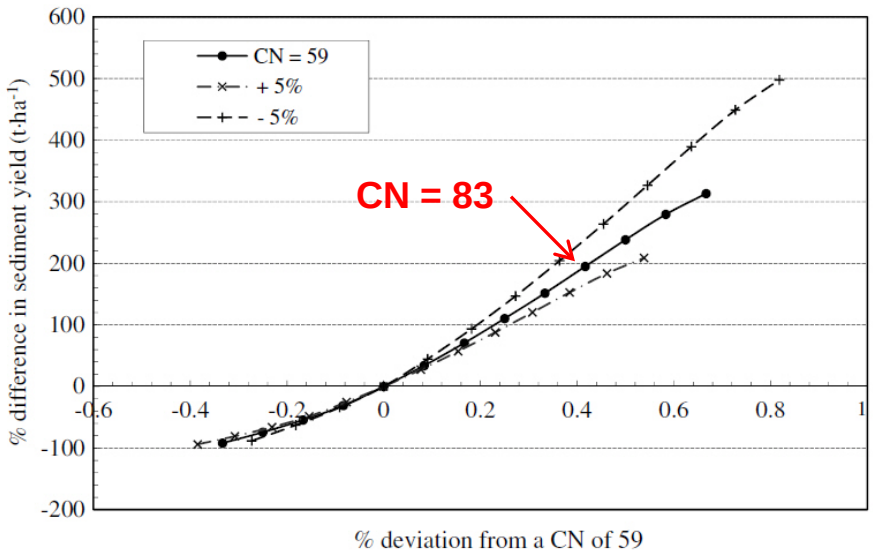
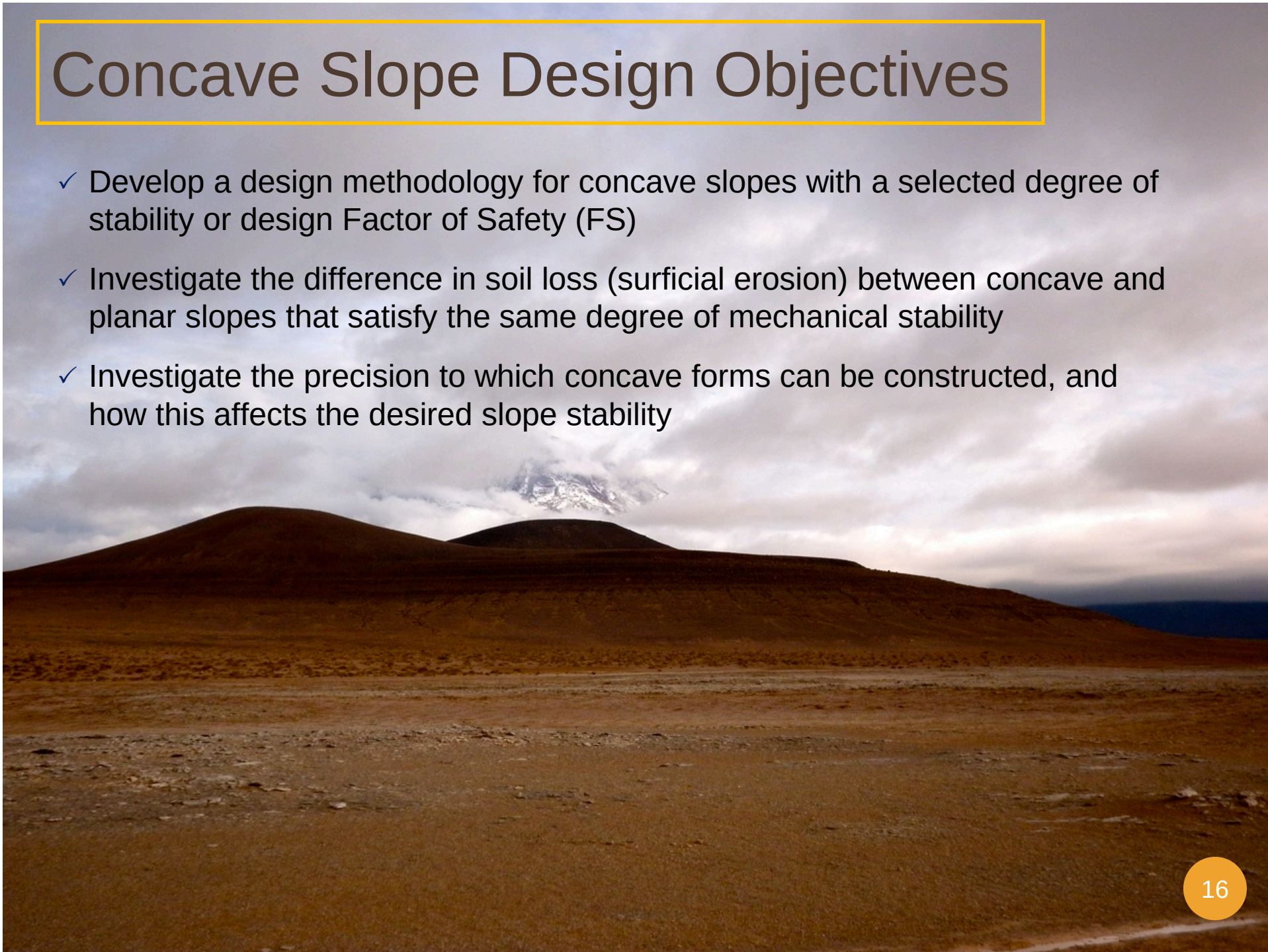


Fig. 6. Percent difference in amount of estimated sediment yields (t · ha^{-1}) relative to a percent deviation in CN selection from the measured estimate of 59 for loose compaction spoils on reclaimed surface coal mining sites (this figure relates to Table 3)

Hoomehr and Schwartz (2013)

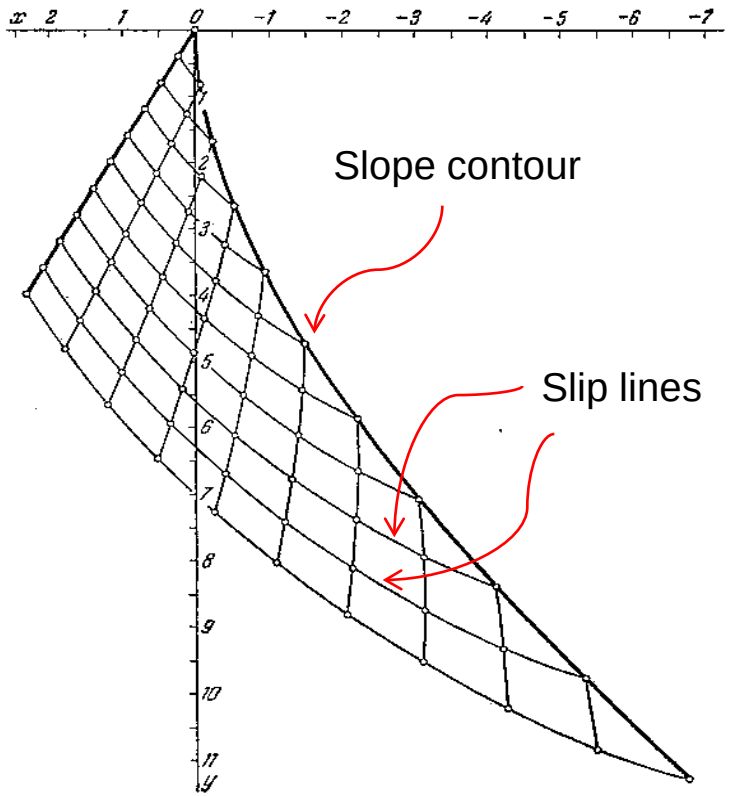
Concave Slope Design Objectives

- ✓ Develop a design methodology for concave slopes with a selected degree of stability or design Factor of Safety (FS)
- ✓ Investigate the difference in soil loss (surficial erosion) between concave and planar slopes that satisfy the same degree of mechanical stability
- ✓ Investigate the precision to which concave forms can be constructed, and how this affects the desired slope stability



Method Development

- Plasticity theory: Sokolovskiĭ (1960, 1965)
  - ✓ Equations of the characteristics that describe slip lines where the plastic deformation occurs in the soil medium



Slip lines in slope problems (Sokolovskiĭ 1960, 1965)

<u>Difficult to implement in practice, because:</u>

× No exact analytical solution (due to γ).

× Numerical solution for specific values of ϕ only

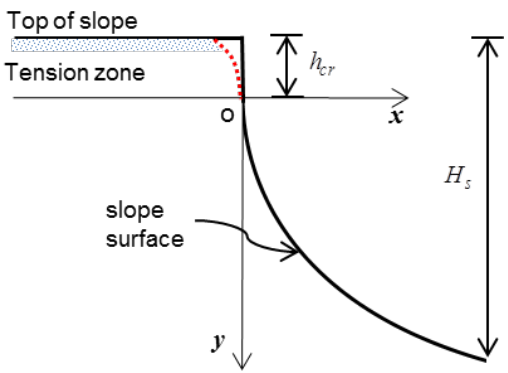
× Limited maximum height, since the reported coordinates are limited by c/γ

× **For other conditions we must reconstruct a sophisticated numerical boundary value problem (unlikely for routine design)**

Proposed Solution for the Critical Slope

- The following approximate solution for the problem of the slope at a critical state was developed (Jeldes et al., 2014)

$$x(y)=\begin{cases}0 & ,-h_{cr}\le y\le 0\\ A\left[\sigma_y\,(B-1)(cosec\phi-1)+H\;B\,(cosec\phi+1)\right], & y>0\end{cases}$$



Where:

$$A=\frac{\cos\phi}{2\gamma(1-\sin\phi)}$$

$$B=ln\left[\frac{\sigma_y}{H}\left(\frac{1-\sin\phi}{1+\sin\phi}\right)+1\right]=ln\left[\frac{\sigma_y}{H}\;K_a+1\right]$$

$$\sigma_y=\gamma y$$

$$H=c\cot\phi$$

$$h_{cr}=\frac{2c\cos\phi}{\gamma(1-\sin\phi)}=\text{Critical Height}$$

$$K_a=(1-\sin\phi)/(1+\sin\phi)=\text{Rankine's active earth pressure coefficient}$$

Required Input:

$\phi=$ Soil Internal Friction Angle
$c=$ Soil Cohesion
} **Soil Strength**

$\gamma=$ Soil Unit Weight

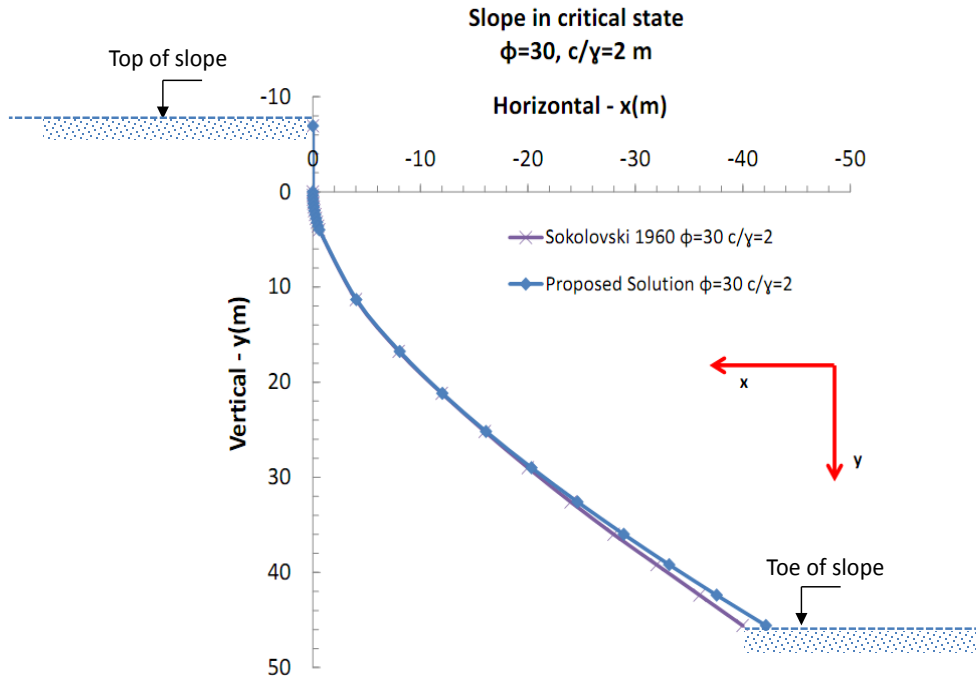
Obtained Output:

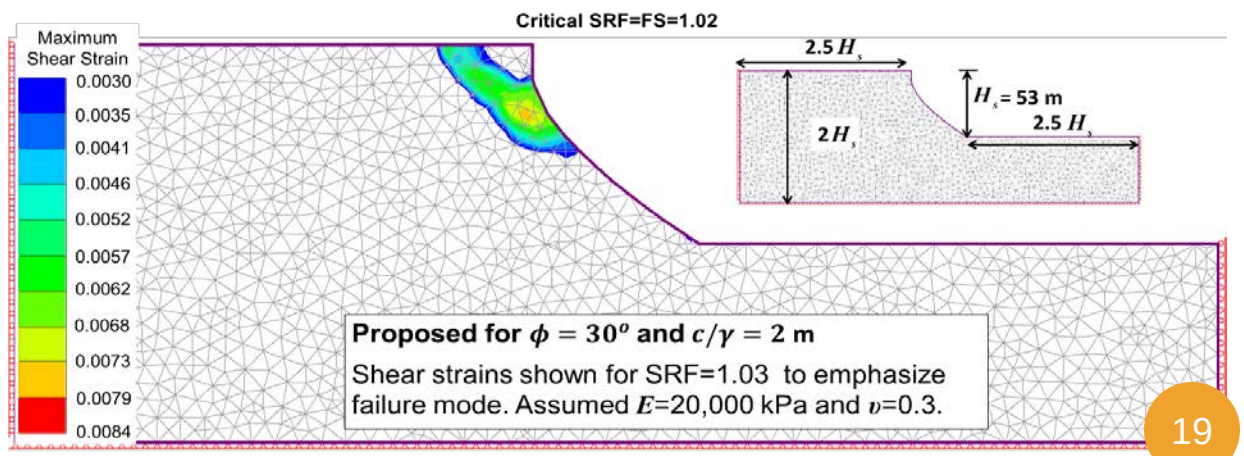
x, y coordinates of slope contour

Jeldes et al. (2014)

Proposed Solution for the Critical Slope

- Advantages of the proposed solution
  - ✓ Good agreement with Sokolovskiĭ's theoretical results
  - ✓ It is algebraic, not differential. It is analytic, no advanced numerical solution required
  - ✓ Provides coordinates of concave shapes that will perform with FS ≈ 1





Jeldes et al. (2014)

FEM Phase2 (Rocscience Inc., 2011)

Concave Profiles with Pre-selected FS

- Key: use a strength reduction factor equal to the desired factor of safety FS_0 to obtain:

$$c^* = \frac{c}{FS_o}$$

$$\phi^* = \arctan\left(\frac{\tan\phi}{FS_o}\right)$$

✓ The designer can select the performing Factor of Safety.

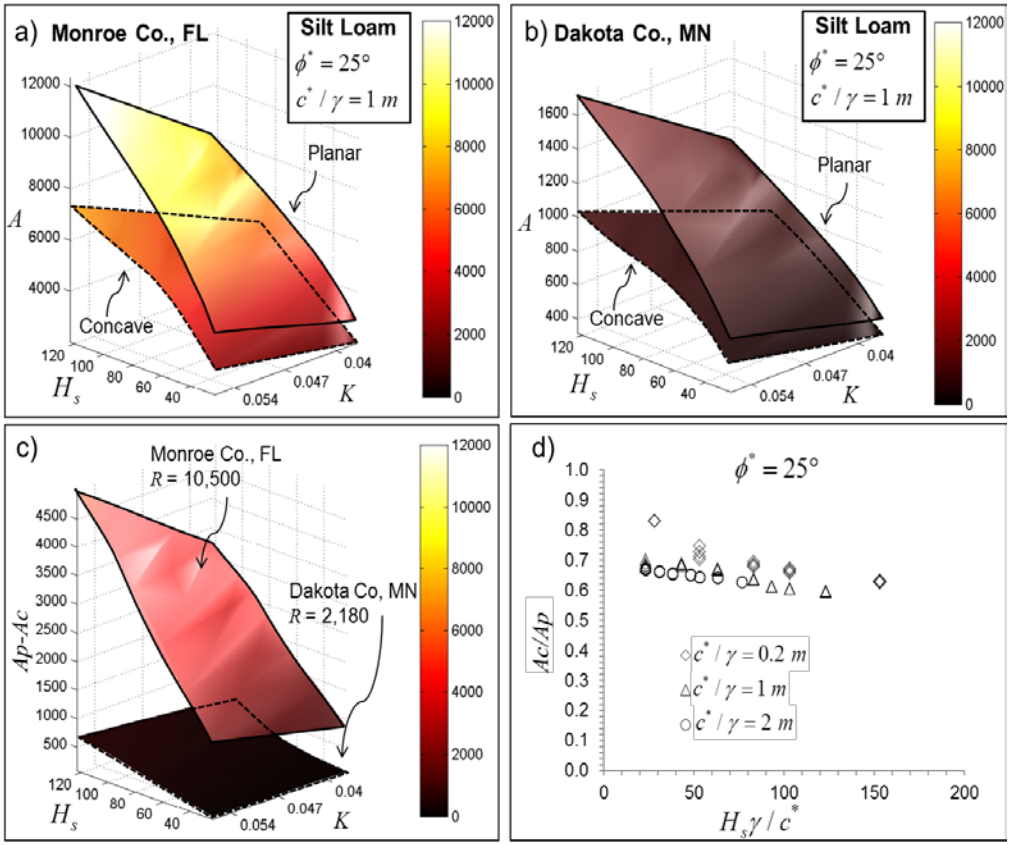
Jeldes et al. (2014)

RUSLE2 Erosion Analyses

- Sediment yield (A) determined from the widely used RUSLE2 for <u>concave and planar slopes with same FS</u>

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

  - A wide range of soil erodibility values were investigated, including those typically observed in mine reclamation (Hoomehr et al. 2014).
  - Example results for a silt soil.



A_c = Predicted erosion for concave slope

A_p = Predicted erosion for planar slope of same FS

✓Concave slopes yielded less sediment than <u>equally stable planar</u> slopes for all the erodibility values and slope heights investigated

✓For the range of values $H_s \gamma / c^*$ investigated, A_c / A_p ranges from 0.85 - 0.60 , indicating that concave slopes yield 15 - 40% less sediment than their planar counterparts

✓For TN sites RUSLE K factor = 0.001 – 0.05 t.ha.h/(ha.MJ.mm)

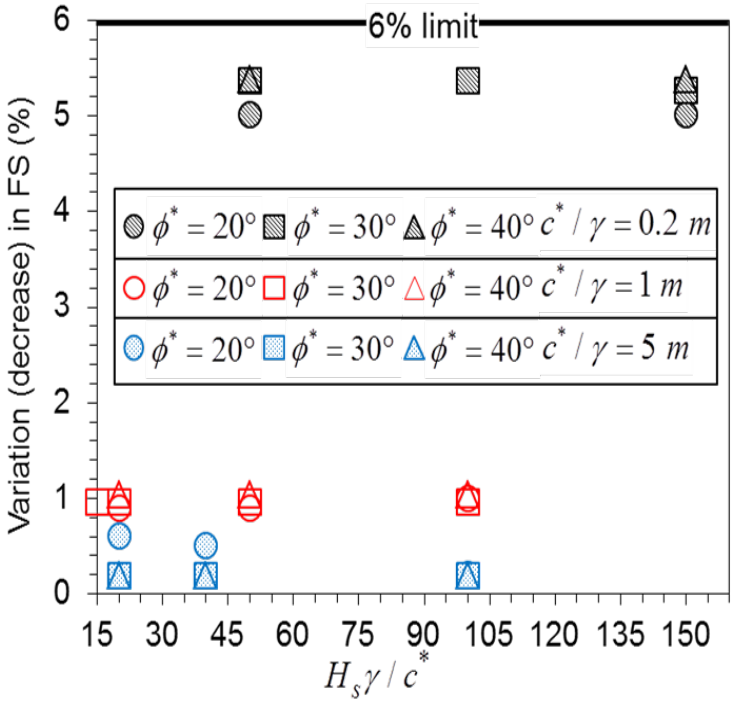
Jeldes (2014); Hoomehr et al. (2014)

Sensitivity to Construction

- The worst case scenario: the vertical component of the contour is constructed deeper than designed, resulting in a steeper slope

  - Vertical accuracy of 3D grade control systems is commonly within 30 mm (horizontal accuracy in the millimeter scale)
  - We investigated a vertical accuracy *T* = 200 mm, which may be also achieved by conventional equipment

✓ FS's are not significantly influenced by improper construction within the 200 mm of vertical accuracy



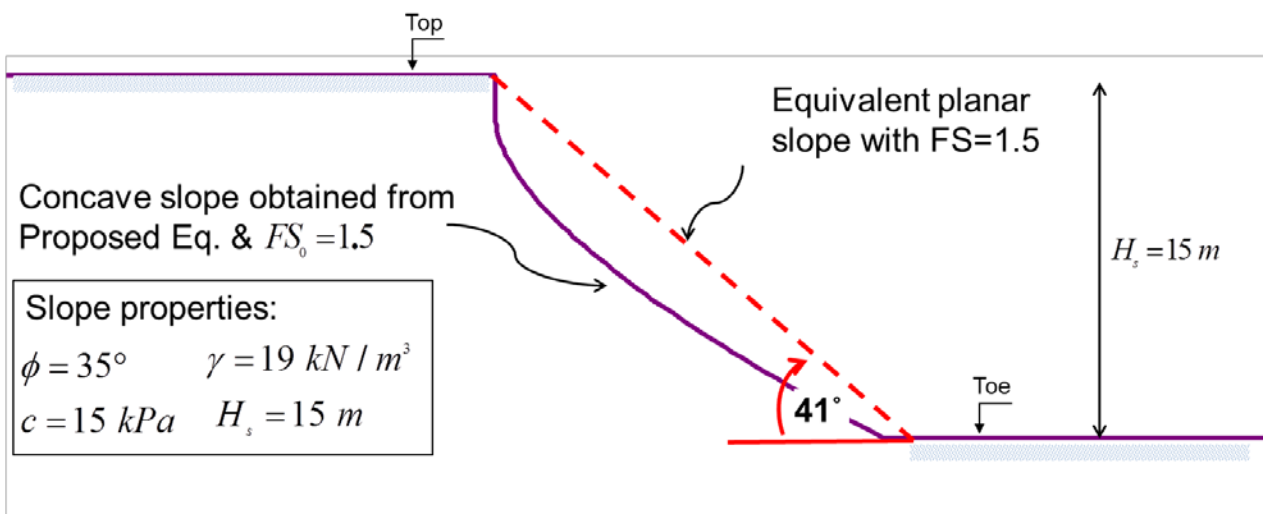
Jeldes et al. (2014)

Illustrative Example

- Find a concave profile that can provide 50% stability (FS=1.5) for a sandy slope with the following characteristics:

$$H_s = 15 \text{ m},\ \phi = 35°,\ c = 15 \text{ kPa},\ \gamma = 19 \text{ kN/m}^3,\ FS_D = 1.5$$

- Find the equivalent planar slope that satisfy the same $FS = 1.5$
- How these two slopes compare in terms of sediment delivery for Monroe county (FL) hydrological conditions?

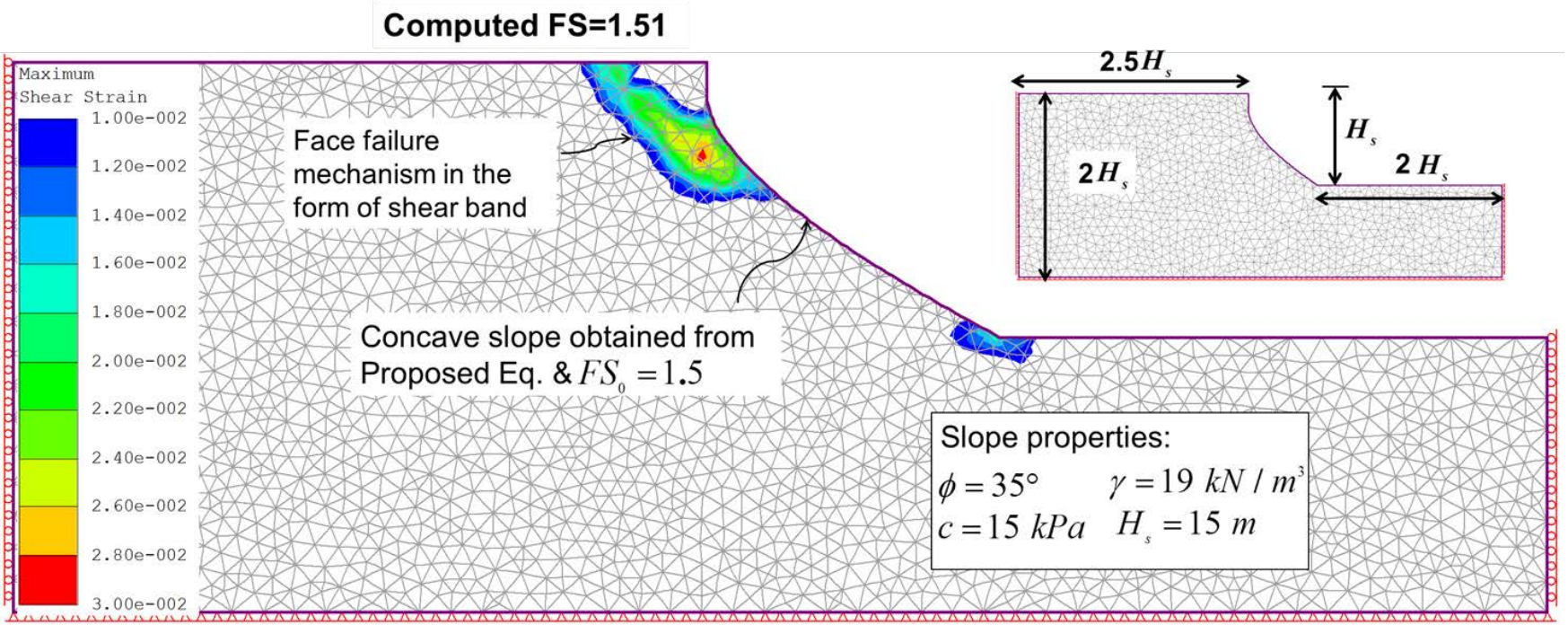


✓This particular concave slope in Monroe County (FL) delivers 24% less sediment than its equivalently stable planar slope (according to RUSLE2)

✓What about the % reduction in a dry weather e.g. Dakota Co (MN)?

Illustrative Example

- Verification of the FS for the obtained concave slope via Finite Element analyses (same obtained via Limit Equilibrium)



Results shown in terms of shear strains for the example problem with strength reduced SRF=1.52 to emphasize failure mode. (Assumed υ=0.3, E=20,000 kPa.)

Conclusions

- Slopes in nature are seldom planar in cross section.
- Concave slopes generally require less reclaimed material than planar slopes with same FS.
- Concave slope profiles produce less sediment.
- An approximate analytical solution was proposed yielding the coordinates of a concave slope at critical equilibrium or imminent failure. Concave slopes can be obtained for any FS.
- Results from RUSLE2 analyses indicate that the concave slopes proposed here yield 15-40% less sediment than planar slopes of equal FS, regardless of soil erodibility and weather conditions.
- Results from the sensitivity analyses reveal that the stability of concave slopes is not significantly influenced by errors in the constructed profile of as great as 200 mm of vertical deviation.

Questions

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