Dataset: Strength parameter selection framework for evaluating the design life of clay cut slopes

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Summary

This document contains the read me and metadata relating to the dataset used in the following publication: Postill, H; Helm, PR; Dixon, N; El-Hamalawi, A; Glendinning, S & Take, WA (2021). Strength parameter selection framework for evaluating the design life of clay cut slopes. Proc Inst Civ Eng - Geotechnical Engineering. Published online ahead of print.

The linked repository contains the dataset used to produce the figures in the related publication and consists of material strain softening data, assumed *in-situ* initial stress profiles, modelled time series of slope surface displacements, derived values for inverse velocity of the modelled slopes, residual factor change with time, the failure geometry and modelled time to failure along with data on design life for differing slope geometries.

Keywords: Slope Stability Analysis; Seasonal Ratcheting; Progressive Failure; Numerical Modelling and Analysis; Design Life; Infrastructure Deterioration.

The final published work in which this dataset was used is available from the Institution of Civil Engineers: https://doi.org/10.1680/jgeen.21.00125.

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Contents

Notation List

A_Λ	Inverse velocity fitting parameter ($years^{-1}$). Eqn. [2] & Eqn. [6].
B_Λ	Inverse velocity fitting parameter (–). Eqn. [2] & Eqn. [6].
d_h	Total horizontal displacement (mm). Eqn. [3].
d_v	Total vertical displacement (mm). Eqn. [3].
Δd	Displacement increment (mm). Eqn. [1].
Δd_{hv}	Annual displacement increment derived from d_h and d_v (mm). Eqn. [3].
R	Residual factor (–). Eqn. [5].
Δt	Time increment (years). Eqn. [1].
v	Velocity (mm / year). Eqn. [1].
Λ	Inverse velocity (years / mm). Eqn. [2].
Λ_{Fit}	Fitted inverse velocity (years / mm). Eqn. [2] & Eqn. [6].
Λ_{max}	Maximum fitted inverse velocity (years / mm). Eqn. [2] & Eqn. [6].
τ	Current shear strength on ultimate failure surface (kPa). Eqn. [5].
τ_{p}	Peak shear strength on ultimate failure surface (kPa). Eqn. [5].
τ_{r}	Residual shear strength on ultimate failure surface (kPa). Eqn. [5].
$\phi_m^{'}$	Mobilised friction angle (°).
$\phi_{m_{\text{Fit}}}^{'}$	Fitted mobilised friction angle (°).

1 Introduction

This document summarises the data relating to the Proc Inst Civ Eng - Geotechnical Engineering paper "Strength parameter selection framework for evaluating the design life of clay cut slopes". It contains information relating to the processed data used to produce the figures contained within the paper.

For more information on the research on which this publication was based, see Postill (2018). For information on the research program undertaking related work and which supported writing of the publication, see the ACHILLES project (EPSRC programme grant EP/R034575/1) web page (https://www.achilles-grant.org.uk). The validation of the numerical model used in this work is published in Postill et al. (2020). See Section 4 for more information.

2 Data Format

- Data is stored as comma separated values in .csv files.
- Normally, the first row of the .csv files contains a dataset reference and a link, the 2nd row (where necessary) contains additional metadata about a given column and row 3 contains the column headers. The 1st line of the data starts on row 4.
- The units of measurement are summarised within this document and are often (but not always) included in the header row (row 3) of the .csv and also on the figure axes in the body of the paper.
- Missing data may be marked with the use of some form of NaN / nan / NAN value.

Where there has been significant post processing from raw data, that process is described in this document.

3 Data

3.1 Figure 1

Caption: Figure 1: Typical mesh and boundary conditions.

General Notes:

- The x and y-coordinates of the FLAC model gridpoints are included as separate .csv files (Fig_1_X.csv and Fig_1_Y.csv). These are the coordinates used to generate the CAD style drawing in the published paper.
- The model used for this figure was of an 8.65 m high, 16 m long slope. The adopted slope height was used for compatibility with the validation modelling undertaken in Postill et al. (2020).
- The datum point adopted was the slope toe which has coordinates X, Y (0, 0).
- All coordinates have units of length in metres.

Notes on the Data:

The layout of the data in the .csv files relating to Fig. 1 differs from the norm for this dataset due to the form the data takes (an array of x or y-coordinates). In summary, the coordinate data starts in row 4, column 3 and extends to row 29, column 67. Assorted information including grid point ID numbers are in columns 1 and 2 and rows 2 and 3.

Data file: Fig_1_X.csv
Contains the X-coordinate data for Fig. 1.

Data file: Fig_1_Y.csv
Contains the Y-coordinate data for Fig. 1.

3.2 Figure 2

Caption: Figure 2: Strain-softening relationships (Cekerevac and Laloui, 2004).

Data file: Fig_2.csv

Column headers:
Axial_Strain_A_Perc, Dev_Stress_A_kPa, Axial_Strain_B_Perc, Dev_Stress_B_KPa, Axial_Strain_C_Perc, Dev_Stress_C_kPa, Axial_Strain_Perc, Dev_Stress_kPa

Column header description:
Axial_Strain_A_Perc: Axial strain for softening curve A from the model (strain, %).
Dev_Stress_A_kPa: Deviator stress for softening curve A from the model (stress, kPa).
Axial_Strain_B_Perc: Axial strain for softening curve B from the model (strain, %).
Dev_Stress_B_kPa: Deviator stress for softening curve B from the model (stress, kPa).
Axial_Strain_C_Perc: Axial strain for softening curve C from the model (strain, %).
Dev_Stress_C_kPa: Deviator stress for softening curve C from the model (stress, kPa).
Axial_Strain_Perc: Axial strain laboratory data (Cekerevac and Laloui, 2004), (strain, %).
Dev_Stress_kPa: Deviator stress laboratory data (Cekerevac and Laloui, 2004), (stress, kPa).

3.3 Figure 3

Caption: Figure 3: Initial stress conditions prior to application of seasonal boundary conditions (after Postill et al., 2020); a) overconsolidation ratio; b) K0; c) vertical and horizontal stresses.

Data file: Fig_3.csv

Column headers:
Depth_m, OCR, K_0, Sigma_v_kPa, Sigma_h_kPa

Column header description:
Depth_m: Depth below ground surface (length, m).
OCR: Overconsolidation ratio (–).
K_0: Coefficient of earth pressure at rest (–).
Sigma_v_kPa: Vertical effective stress (stress, kPa).
Sigma_h_kPa: Horizontal effective stress (stress, kPa).

3.4 Figure 4

Caption: Figure 4: Schematic plot showing seasonal ratcheting and progressive failure movement characteristics for an 8.65 m high 28.4° slope; a) target pore water pressure cycles at mid-slope surface; b) slope surface displacements corresponding to mid-point of final failure surface, see Figure 6 for quantitative model data; c) reciprocal of velocity of net annual displacement at slope surface corresponding to mid-point of final failure surface when net movement is outward and downwards.

Notes:

- The plot is schematic however parts b) and c) used real model data for the model described in the figure caption but removed the axis ticks and numbering from the plots. Fig. 6a (the pore pressure data) is wholly schematic as it is showing target pore pressure cycles which are driven by a fluid discharge boundary within the model.
- The initial 19 years of inverse velocity (Λ) data were not included in the published plot as small changes in velocity in this range cause very large fluctuations in Λ.

Data file: Fig_4.csv

Column headers:
4a_X_Time_Yrs, 4a_Y_PWP_kPa, 4b_X_Disp_mm , 4b_Y_Disp_mm, 4c_X_Time_Yrs, 4c_Y_Velocity_mm_per_Yr, 4c_Y_Inv_Velocity_Yrs_per_mm

Column header description:
4a_X_Time_Yrs: Time (years).
4a_Y_PWP_kPa: Target Pore pressure cycles at mid-slope surface (stress, kPa).
4b_X_Disp_mm: Mid-slope horizontal displacement (length, mm).*
4b_Y_Disp_mm: Mid-slope vertical displacement (length, mm).*
4c_X_Time_Yrs: Time (years).
4c_Y_Velocity_mm_per_Yr: Velocity, v (mm / year).
4c_Y_Inv_Velocity_Yrs_per_mm: 1 / v = 1 / (mm / year) = (years / mm).

*NB these are ratcheting displacements so are cumulative with time, they exclude displacements as a result of slope excavation. The values are normalised from the end of the first year.

3.5 Figure 5

Caption: Figure 5: Schematic deterioration curve and point of operational failure: a) reciprocal of velocity of net annual displacement at the slope surface corresponding to the centre of the failed region when net movement is outward and downwards and fitted curve; b) slope surface net displacements in an annual cycle corresponding to mid-point of final failure surface; c) slope surface net cumulative displacements in an annual cycle corresponding to mid-point of final failure surface d) residual factor calculated along final failure surface.

Notes:

- This data required derivation / processing. The processed data as used in the figures in the paper is stored in Fig_5.csv, the raw data to derive Fig_5b is found in Fig_6.csv.
- The plot is schematic however all parts (a to d) used model data (the model is described in the Figure 4 caption) but as per Fig. 4, removed the axis ticks and numbering.
- The y-axes in the paper for Fig. 5b and Fig. 5c are inverted.

Data file: Fig_5.csv

Column headers (Fig. 5a):
5a_X_Time_Yrs, 5a_Y_Inv_Vel, 5a_Y_Fitted_Inv_Vel, 5a_X_Fitted_Inv_Vel_Inf_Pnt_Yrs, 5a_Y_Fitted_Inv_Vel_Inf_Pnt

Column header description (Fig. 5a):
5a_X_Time_Yrs: Time (years).
5a_Y_Inv_Vel: Inverse velocity, Λ (years / mm) calculated from annual displacement increment (Δd) stored in 5b_Y_An_Disp_Inc_mm.

$$\Lambda = \frac{\Delta t}{\Delta d} \tag{1}$$

Where Δt is the increment duration (time, years).
5a_Y_Fitted_Inv_Vel: Fitting curve (Λ_{Fit}) to 5a_Y_Inv_Vel (years / mm). Fitting as follows:

$$\Lambda_{\text{Fit}} = \frac{\Lambda_{\text{max}}}{\left[1 + (\,\text{A}_\Lambda * \text{T}_{\text{yr}}\,)^{\text{B}_\Lambda}\right]^{\,(1-1/\text{B}_\Lambda)}} \tag{2}$$

Where $\text{A}_\Lambda = \frac{1}{48.94}$ (years^{-1}), B_Λ = 10.73 (–), Λ_{max} = 0.065 years / mm and T_{yr} is time (ranging from 20 to 68 years).

5a_X_Fitted_Inv_Vel_Inf_Pnt_Yrs: X-axis value of inflection point on the curve, used to approximate failure time. Inflection point (x-axis) = 48.937 years: derived from fitting for 5a_Y_Fitted_Inv_Vel.
5a_Y_Fitted_Inv_Vel_Inf_Pnt: Y-val of inflection point on the curve, used to approximate failure time. Inflection Point (y-axis) = 0.03467 years / mm. Derived from fitting for 5a_Y_Fitted_Inv_Vel using x-val = 48.937 years.

Column headers (Fig. 5b):
5b_X_Time_Yrs, 5b_Y_An_Disp_Inc_mm, 5b_xfitted_Time_Yrs, 5b_Y_Fitted_An_Disp_Inc_mm, 5b_X_Fitted_An_Disp_Inc_Inf_Pnt_Yrs, 5b_Y_Fitted_An_Disp_Inc_Inf_Pnt_mm

Column header description (Fig. 5b):
5b_X_Time_Yrs: Time (years).
5b_Y_An_Disp_Inc_mm: Annual displacement increment, Δd_{hv} (length, mm). Calculated from the values of total horizontal (d_h) and total vertical displacement (d_v) at the end of each year from Fig_6.csv (A16_Horizontal & A16_Vertical) as follows:

$$d_{hv} = \sqrt{(\,[\,d_v(\,n\,) - d_v(\,n-1\,)\,]^2\,) + (\,[\,d_h(\,n\,) - d_h(\,n-1\,)\,]^2\,)} \quad (3)$$

Where $d_v(\,n\,)$ and $d_v(\,n-1\,)$ are d_v at year n and $n-1$ respectively. $d_h(\,n\,)$ is derived as per $d_v(\,n\,)$ but using horizontal displacement data.

Column headers (Fig. 5c):
5c_X_Time_Yrs, 5c_Y_Cu_Disp_mm, 5c_X_Fitted_Cu_Disp_Inf_Pnt_Yrs, 5c_Y_Fitted_Cu_Disp_Inc_Inf_Pnt_mm

Column header description (Fig. 5c):
5c_X_Time_Yrs: Time (years).
5c_Y_Cu_Disp_mm: Cumulative displacements (calculated from 5b_Y_An_Dis_Inc_mm, d_{hv} with a starting value of 183.023 mm).

$$\text{5c\_Y\_Cu\_Disp\_mm}(\,n\,) = \text{5c\_Y\_Cu\_Disp\_mm}(\,n-1\,) + \text{5b\_Y\_An\_Disp\_Inc\_mm}(\,n\,) \quad (4)$$

Where n are the corresponding years in columns 5b_X_Time_Yrs and 5c_X_Time_Yrs.
5c_X_Fitted_Cu_Disp_Inf_Pnt_Yrs: The location of the inflection point on the x-axis (time, years).
5c_Y_Fitted_Cu_Disp_Inf_Pnt_mm: The location of the inflection point on the y-axis (displacement, mm).

Column headers (Fig. 5d):
5d_X_Time_Yrs , 5d_Y_Res_Fac, 5d_X_Fitted_Res_Fac_Inf_Pnt_Yrs, 5d_Y_Fitted_Res_Fac_Inf_Pnt

Column header description (Fig. 5d):
5d_X_Time_Yrs: Time (years) for residual factor plot.
5d_Y_Res_Fac: Residual factor values (R) calculated from the current (τ), peak (τ_p) and residual (τ_r) shear strength on the ultimate failure surface respectively.

$$R = \frac{\tau_p - \tau}{\tau_p - \tau_r} \quad (5)$$

5d_X_Fitted_Res_Fac_Inf_Pnt_Yrs: The location of the inflection point on the x-axis (time, years).
5d_Y_Fitted_Res_Fac_Inf_Pnt: The location of the inflection point on the y-axis (–).

3.6 Figure 6

Caption: Figure 6: Slope surface displacements corresponding to the mid-point of the final failure surface against number of annual cycles for different slope angles, strain-softening curve (A); a) horizontal displacements; b) vertical displacements.

Data file: Fig_6.csv

Column headers:
A10_Time_Yrs, A10_Horizontal_Disp_m, A10_Vertical_Disp_m . . . A20_Time_Yrs, A20_Horizontal_Disp_m, A20_Vertical_Disp_m

Notes:

- The column headers summarise the softening model adopted (A), the number represents the horizontal slope length from crest to toe in m (range from 10 to 20, all slopes in Fig. 6 are 8.65 m high).
- Note in the published version of this figure, the displacements are in mm.

Column header description:
A10_Time_Yrs to A20_Time_Yrs: Time in years for specified model (time, years).
A10_Horizontal_Disp_m to A20_Horizontal_Disp_m: Mid-shear surface horizontal displacement (displacement, m) for specified model.
A10_Vertical_Disp_m to A20_Vertical_Disp_m: Mid-shear surface horizontal displacement (displacement, m) for specified model.

3.7 Figure 7

Caption: Figure 7: a) to e) Failure surfaces for different slope angles - strain-softening curve (A).

Data file: Fig_7.csv

Column headers:
A_X_Coord, A_Y_Coord . . . E_X_Coord, E_Y_Coord, A_X_Slope_Coord . . . E_X_Slope_Coord, Y_Slope_Coord

Notes:

- The column headers summarise the sub figure letter as in the paper (A to E), at a constant height of 8.65 m and varying angles (40.9°, 35.8°, 31.7°, 28.4°, 25.7°).
- The datum is the slope toe at X, Y (0, 0).

Column header description:
A_X_Coord to E_X_Coord: Models A to E, shear surface x-coordinates (length, m).
A_Y_Coord to E_Y_Coord: Models A to E, shear surface y-coordinates (length, m).
A_X_Slope_Coord to E_X_Slope_Coord: Models A to E, slope surface x-coordinates (length, m).
Y_Slope_Coord: Models A to E, slope surface y-coordinates (length, m).

3.8 Figure 8

Caption: Figure 8: Deterioration curves and points of operational failure for different slope geometries - strain-softening curve (A); a) reciprocal of velocity of net annual displacement at slope surface corresponding to mid-point of final failure surface when net movement is outward and downwards; b) fitted deterioration curve and point of operational failure.

Data file: Fig_8.csv

Notes:
The following letter codes relate to the slope angles as below:
A = 40.9°, B = 38.2°, C = 35.8°, D = 33.6°, E = 31.7°
F = 30.0°, G = 28.4°, H = 27.0°, I = 25.7°, J = 24.5°

NB: Blank values are denoted with "NaN". This does not represent missing / unrecorded data in this specific case, but is intended to aid data alignment on the shared time column.

Column headers:
Time_Yrs, A . . . J, A_Fitted . . . J_Fitted

Column header description:
Time_Yrs: Time (years).
A to J: Inv. velocity, Λ for the respective modelled slope angles ($1 / \text{velocity} = \text{years} / \text{mm}$).
A_Fitted to J_Fitted: Fitted Inv. velocity curves for A to J above. The fitting curves for inverse velocity (Λ_{Fit}) are derived as follows:

$$\Lambda_{\text{Fit}} = \frac{\Lambda_{\text{max}}}{1 + \left(\text{T}_{\text{yr}} * \text{A}_{\Lambda} \right)^{\text{B}_{\Lambda}}} \tag{6}$$

Where T_{yr} is the time in years and the additional inverse velocity curve fitting parameters are summarised in Table 1.

Table 1: Fitting parameters for the differing deterioration curves in Fig. 8.

Model	$\boldsymbol{\Lambda}_{\text{max}}$	$\mathbf{1 / A_{\Lambda}}$	$\mathbf{B_{\Lambda}}$
A	0.015	3.1	15.0
B	0.120	15.0	10.0
C	0.135	17.0	10.0
D	0.135	23.0	10.0
E	0.050	29.0	10.0
F	0.060	37.0	10.0
G	0.070	49.0	10.0
H	0.085	59.0	10.0
I	0.100	73.0	10.0
J	0.110	88.0	8.0

The x-axis (time, years) location of the inflection point of the curve which defines the failure time is specified by the value of $\mathbf{1} / \text{A}_{\boldsymbol{\Lambda}}$ in each case.

The y-axis value (Inv. velocity) of the inflection point can be derived by setting $(\text{T}_{\text{yr}} * \text{A}_{\Lambda}) = 1$ in Eqn. 6.

3.9 Figure 9

Caption: Figure 9: Results for different slope geometries and strain-softening relationships; a) number of seasonal cycles to operational failure for different slope angles; b) number of seasonal cycles to operational failure for different slope angles; c) residual factor at operational failure against slope angle; d) residual factor at operational failure against number of seasonal cycles to operational failure.

Data file: Fig_9a.csv

Column headers:
Length_m, Failure_Time, Slope_Angle

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Failure_Time: Time to slope failure (time, years). Defined as the inflection point on fitting curves of inverse velocity.
Slope_Angle: Slope angle (angle, degrees).

The above repeats for each of the three adopted softening relationships: (A), (B) & (C).

Data file: Fig_9b.csv

Column headers:
Length_m, Res_Factor, Slope_Angle, Slope_Angle_Fitted, Fitted_Res_Factor

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Res_Factor: Residual factor values (R) calculated from the current (τ), peak (τ_p) and residual (τ_r) shear strength on the ultimate failure surface respectively.

$$R = \frac{\tau_p - \tau}{\tau_p - \tau_r} \tag{7}$$

Slope_Angle: Slope angle (angle, degrees).
Slope_Angle_Fitted: Slope angles used for the fitted curve (angle, degrees).
Fitted_Res_Factor: Fitted residual factor values.

The above repeats for each of the three adopted softening relationships: (A), (B) & (C).

Data file: Fig_9c.csv

Column headers:
Length_m, Slope_Angle, Failure_Time, Res_Factor, Time_Yrs, Fitted_Res_Factor

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Slope_Angle: Slope angle (angle, degrees).
Failure_Time: Time to slope failure (time, years). Defined as the inflection point on fitting curves of inverse velocity.
Res_Factor: Residual factor values (R) calculated from the current (τ), peak (τ_p) and residual (τ_r) shear strength on the ultimate failure surface respectively.

$$R = \frac{\tau_p - \tau}{\tau_p - \tau_r} \tag{8}$$

Time_Yrs: Time used for the fitted residual factor curves (time, years).
Fitted_Res_Factor: Fitted residual factor values.

The fitting for the residual factor (R_{fit}) curves in Fig. 9c is as follows:

$$R_{\text{fit}} = c_0 + x^m * c \tag{9}$$

Where x is the time (years) and the other variables are fitting parameters.

For softening curve (A):
$c_0 = 0.183\,452\,05$
$m = 0.701\,436\,61$
$c = -0.732\,889\,27$

For softening curves (B) & (C):
$c_0 = 0.164\,432\,33$
$m = 0.509\,391\,07$
$c = -0.377\,209\,52$

3.10 Figure 10

Caption: Figure 10: Residual factor on a critical shear surface at operational failure - 8.65m high 28.4° slopes; a) strain-softening curve (A); b) strain-softening curve (B); c) strain-softening curve (C).

Data file: Fig_10.csv

Column headers:
Fig_10_A_X, Fig_10_A_Y, Fig_10_A_RF . . . Fig_10_C_X, Fig_10_C_Y, Fig_10_C_RF

Column header description:
Fig_10_A_X, Fig_10_B_X, Fig_10_C_X: X-coordinates of the failure surface for slope with softening curves (A), (B) & (C), (length, m).
Fig_10_A_Y, Fig_10_B_Y, Fig_10_C_Y: Y-coordinates of the failure surface for slope with softening curves (A), (B) & (C), (length, m).
Fig_10_A_RF, Fig_10_B_RF, Fig_10_C_RF: Average residual factor along the respective segment.

NB: For coordinates, datum is slope toe at X, Y (0, 0).

3.11 Figure 11

Caption: Figure 11: Results for different slope geometries and heights; a) number of annual cycles to operational failure for different slope geometries; b) residual factor at operational failure against slope angle; c) residual factor at operational failure against number of annual cycles to failure.

Data file: Fig_11a.csv

Column headers:
Length_m, Height_m, Cot_Angle, Failure_Time, Slope_Angle

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Failure_Time: Time to slope failure (time, years). Defined as inflection point on fitting curves of inverse velocity.
Slope_Angle: Slope angle (angle, degrees).

The above repeats for each of the three adopted softening slope heights: 5 m, 8.65 m & 12 m.

Data file: Fig_11b.csv

Column headers:
Length_m, Height_m, Cot_Angle, Res_Factor, Slope_Angle, Slope_Angle_Fitted, Fitted_Res_Factor

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Res_Factor: Residual factor values (R) calculated from the current (τ), peak (τ_p) and residual (τ_r) shear strength on the ultimate failure surface respectively.

$$R = \frac{\tau_p - \tau}{\tau_p - \tau_r} \quad (10)$$

Slope_Angle: Slope angle (angle, degrees).
Slope_Angle_Fitted: Slope angles used for the fitted curve (angle, degrees).
Fitted_Res_Factor: Fitted residual factor values.

The above repeats for each of the three adopted slope heights: 5 m, 8.65 m & 12 m.

Data file: Fig_11c.csv

Column headers:
Length_m, Height_m, Cot_Angle, Slope_Angle, Failure_Time, Res_Factor, Time_Yrs_Fitted, Fitted_Res_Factor

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Slope_Angle: Slope angle (angle, degrees).
Failure_Time: Time to slope failure (time, years). Defined as inflection point on fitting curves of inverse velocity.
Res_Factor: Residual factor values (R) calculated from the current (τ), peak (τ_p) and residual (τ_r) shear strength on the ultimate failure surface respectively.

$$R = \frac{\tau_p - \tau}{\tau_p - \tau_r} \tag{11}$$

Time_Yrs_Fitted: Time used for the fitted residual factor curves (time, years).
Fitted_Res_Factor: Fitted residual factor values.

The above repeats for each of the three adopted slope heights: 5 m, 8.65 m & 12 m.

The fitting for the residual factor (R_{fit}) curves in Fig. 11c is as follows:

$$R_{\text{fit}} = c_0 + x^m * c \tag{12}$$

Where x is the time (years) and the other variables are fitting parameters.

For softening curve (A):
$c_0 = 0.103\,028\,47$
$m = 0.701\,711\,21$
$c = -0.674\,501\,96$

For softening curves (B) & (C):
$c_0 = 0.164\,432\,33$
$m = 0.509\,391\,07$
$c = -0.377\,209\,52$

3.12 Figure 12

Caption: Figure 12: Mobilised internal angle of friction at operational failure for different strain-softening relationships, slope geometries, and heights; a) mobilised internal angle of friction at operational failure against slope angle; b) mobilised internal angle of friction at operational failure against number of seasonal cycles to failure.

Data file: Fig_12a.csv

Column headers:
Length_m, Height_m, Cot_Angle, Slope_Angle, Friction_Angle, Fitted_Slope_Angle, Fitted_Friction_Angle

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Slope_Angle: Slope angle (angle, degrees).
Friction_Angle: Mobilised friction angle (ϕ'_m) on the shear surface at failure (angle, degrees).
Fitted_Slope_Angle: Slope angles used for the fitted curve (angle, degrees).
Fitted_Friction_Angle: Fitted mobilised friction angle ($\phi'_{m_{\text{Fit}}}$).

The above repeats for each of the three adopted slope heights: 5 m, 8.65 m & 12 m for material (B) and then once more for a slope height of 8.65 m with material (C).

Data file: Fig_12b.csv

Column headers:
Length_m, Height_m, Cot_Angle, Failure_Time, Friction_Angle, Fitted_Time, Fitted_Friction_Angle

Column header description:
Length_m: The horizontal slope length from crest to toe (length, m).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Failure_Time: Time to slope failure (time, years). Defined as inflection point on fitting curves of inverse velocity.
Friction_Angle: Mobilised friction angle (ϕ'_m) on the shear surface at failure (angle, degrees).
Fitted_Time: Time used for the fitted curve (time, years).
Fitted_Friction_Angle: Fitted mobilised friction angle ($\phi'_{m_{\text{Fit}}}$).

The above repeats for each of the three adopted slope heights: 5 m, 8.65 m & 12 m for material (B) and then once more for a slope height of 8.65 m with material (C).

The fitting for the mobilised friction ($\phi'_{m_{\text{Fit}}}$) curves in Fig. 12b is as follows:

$$\phi'_{m_{\text{Fit}}} = a + \log(x)^n * b \tag{13}$$

Where x is the time (years) and the other variables are fitting parameters.

For a slope height of 5 m and material (B):
$a = -0.068\,880\,88$

$n = 2.458\,976\,93$
$b = 24$

For slope heights of 8.65 m & 12 m and material (B):
$a = -0.136\,614\,15$
$n = 2.326\,056\,76$
$b = 24$

For a slope height of 8.65 m and material (C):
$a = -0.045\,067\,22$
$n = 3.016\,516\,32$
$b = 24$

3.13 Figure 13

Caption: Figure 13: Slope geometry, number of seasonal cycles to failure and mobilised friction angle at failure for strain-softening curve (B).

Data file: Fig_13.csv

Columns A to F (when viewed in EXCEL).

Column headers:
FT_Bracket, Height_m, Cot_Angle, Description, Failure_Time, Slope_Angle

Column header description:
FT_Bracket: The failure time (FT) bracket into which the model fits ($60 > FT$, $90 > FT \geq 60$, $120 > FT \geq 90$, $FT \geq 120$), (time, years).
Height_m: The vertical slope height from the toe to the crest (length, m).
Cot_Angle: Cotangent of the slope angle = $1/\tan$ (slope angle).
Description: Text descriptor of slope.
Failure_Time: Time to slope failure (time, years). Defined as the inflection point on the fitting curves of inverse velocity.
Slope_Angle: Slope angle (angle, degrees).

Columns G to L (when viewed in EXCEL).
Delineates slope geometries that fail at defined mobilised friction angles.

Column headers:
Slope_Angle, Slope_Height

Column header description:
Slope_Angle: Slope angle (angle, degrees).
Slope_Height: The vertical slope height from the toe to the crest (length, m)

The above repeats two more times giving a total of three pairs of x, y-coordinates for lines delineating failure with $\boldsymbol{\phi'_m < 18°}$, $\boldsymbol{\phi'_m = 19.5°}$ and $\boldsymbol{\phi'_m > 21°}$.

Columns M to R (when viewed in EXCEL).
Delineates slope geometries that fail at defined times.

Column headers:
Slope_Angle, Slope_Height

Column header description:
Slope_Angle: Slope angle (angle, degrees).
Slope_Height: The vertical slope height from the toe to the crest (length, m).

The above repeats two more times giving a total of three pairs of x, y-coordinates for lines delineating time to failure of 60 years, 90 years and 120 years.

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4 References Cited / Further Reading

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