

# Software Requirements Specification for Slope Stability Analysis

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October 12, 2018

# 1 Revision History

| Date     | Version | Notes   |
|----------|---------|---|
| 09/24/18 | 1.0     | Removed RFEM  |
| 09/25/18 | 1.1     | Traceability matrix work  |
| 09/26/18 | 1.2     | Physical System Description expanded, Non-functional requirements itemized          |
| 10/01/18 | 1.3     | Various improvements throughout   |
| 10/02/18 | 1.4     | Initial revision of the solution characteristics specification                      |
| 10/03/18 | 1.5     | Completed revision of the solution characteristics specification and other sections |
| 10/04/18 | 1.6     | Minor fixes throughout  |

## 2 Reference Material

This section records information for easy reference.

### 2.1 Table of Units

The unit system used throughout is SI (Système International d'Unités). In addition to the basic units, several derived units are also used. For each unit, the table lists the symbol, a description and the SI name.

| Symbol                 | Unit     | SI     |
|------------------------|----------|--------|
| N                      | force    | Newton |
| m                      | length   | meter  |
| Pa = N m <sup>-2</sup> | pressure | Pascal |
| °                      | angle    | degree |

### 2.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units.

| Symbol     | Unit              | Description   |
|------------|-------------------|---|
| $b$        | m                 | width of the base of a slice in the $x$ direction   |
| $c'$       | Pa                | effective cohesion  |
| $C1_i$     | N                 | interslice shear force expression used to calculate the numerator of the scaling factor                     |
| $C2_i$     | N                 | interslice normal force expression used to calculate the denominator of the scaling factor                  |
| $F_x$      | N                 | $x$ -component of force   |
| $F_y$      | N                 | $y$ -component of force   |
| $f$        |                   | function describing variation of the interslice normal to shear force ratio; can be constant or a half-sine |
| $FS$       |                   | factor of safety  |
| $FS_{Min}$ |                   | minimum factor of safety associated with the critical slip surface  |
| $G$        | N m <sup>-1</sup> | interslice normal force   |
| $H$        | N m <sup>-1</sup> | interslice water force  |

|            |                   |   |
|------------|-------------------|---|
| $h$        | m                 | height in the $y$ -direction from the base of a slice to the slope surface, at the $x$ -direction midpoint on the slice |
| $i$        |                   | index representing a single slice   |
| $K_c$      |                   | horizontal seismic coefficient  |
| $M$        | N m               | moment  |
| $N$        | N m <sup>-1</sup> | normal force  |
| $N'$       | N m <sup>-1</sup> | effective normal force  |
| $N^*$      | N m <sup>-1</sup> | effective normal force without the influence of interslice forces   |
| $n$        |                   | the total number of slices  |
| $P$        | N m <sup>-1</sup> | resistive shear force   |
| $Q$        | N m <sup>-1</sup> | imposed surface load or external force  |
| $R$        | N m <sup>-1</sup> | resistive shear force without the influence of interslice forces  |
| $S$        | N m <sup>-1</sup> | mobilized shear force   |
| $T$        | N m <sup>-1</sup> | mobilized shear force without the influence of interslice forces  |
| $U_b$      | N m <sup>-1</sup> | base hydrostatic force  |
| $U_t$      | N m <sup>-1</sup> | surface hydrostatic force   |
| $W$        | N m <sup>-1</sup> | self-weight   |
| $X$        | N m <sup>-1</sup> | interslice shear force  |
| $x$        | m                 | $x$ -ordinate in the Cartesian coordinate system  |
| $x_{cs}$   | m                 | $x$ -ordinate of a point on the critical slip surface   |
| $x_{slip}$ | m                 | $x$ -ordinate of a point on a slip surface  |
| $x_{us}$   | m                 | $x$ -ordinate of a point on the slope   |
| $x_{wt}$   | m                 | $x$ -ordinate of a point on the water table   |
| $y$        | m                 | $y$ -ordinate in the Cartesian coordinate system  |
| $y_{cs}$   | m                 | $y$ -ordinate of a point on the critical slip surface   |
| $y_{slip}$ | m                 | $y$ -ordinate of a point on a slip surface  |
| $y_{us}$   | m                 | $y$ -ordinate of a point on the slope   |

|                |                   |  |
|----------------|-------------------|--|
| $y_{wt}$       | m                 | $y$ -ordinate of a point on the water table  |
| $z$            | m                 | height in the $y$ -direction from the base of a slice to the center of the slice   |
| $z_w$          | (m)               | height in the $y$ -direction from the base of a slice halfway to the water table   |
| $\alpha$       | °                 | angle between the base of a slice and the horizontal   |
| $\beta$        | °                 | angle between the surface of a slice and the horizontal  |
| $\gamma$       | N m <sup>-3</sup> | soil dry unit weight   |
| $\gamma_{Sat}$ | N m <sup>-3</sup> | soil saturated unit weight   |
| $\gamma_w$     | N m <sup>-3</sup> | unit weight of water   |
| $\Delta H$     | N m <sup>-1</sup> | difference between interslice water forces   |
| $\lambda$      |                   | proportionality constant for the interslice normal to shear force ratio  |
| $\mu$          | Pa                | pore pressure from water within the soil   |
| $\sigma$       | Pa                | the total stress a soil mass needs to maintain itself as a rigid collection of particles                                     |
| $\sigma_N$     | Pa                | normal stress  |
| $\sigma'$      | Pa                | effective stress provided by the soil skeleton   |
| $\tau$         | Pa                | shear strength   |
| $\Upsilon$     |                   | generic minimization function or algorithm   |
| $\varphi'$     | °                 | effective angle of friction  |
| $\Phi$         |                   | first constant to convert shear without the influence of interslice forces to shear with the influence of interslice forces  |
| $\Psi$         |                   | second constant to convert shear without the influence of interslice forces to shear with the influence of interslice forces |
| $\omega$       | °                 | angle between the imposed surface load acting into the surface and the vertical  |
| $\ell_b$       | m                 | base length of a slice in the direction parallel to the slope of the base  |

|          |   |   |
|----------|---|---|
| $\ell_s$ | m | surface length of a slice in the direction parallel to the slope of the surface |
|----------|---|---|

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## 2.3 Abbreviations and Acronyms

| Symbol | Description                         |
|--------|-------------------------------------|
| 2D     | Two-Dimensional                     |
| A      | Assumption                          |
| DD     | Data Definition                     |
| GD     | General Definition                  |
| GS     | Goal Statement                      |
| IM     | Instance Model                      |
| LC     | Likely Change                       |
| NFR    | Non-Functional Requirement          |
| PS     | Physical System Description         |
| R      | Requirement                         |
| SRS    | Software Requirements Specification |
| SSP    | Slope Stability Analysis Program    |
| T      | Theoretical Model                   |
| TU     | Typical Uncertainty                 |
| UC     | Unlikely Change                     |

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### 3 Introduction

A slope of geological mass, composed of soil and rock and sometimes water, is subject to the influence of gravity on the mass. This can cause instability in the form of soil or rock movement. The effects of soil or rock movement can range from inconvenient to seriously hazardous, resulting in significant life and economic losses. Slope stability is of interest both when analysing natural slopes, and when designing an excavated slope. Slope stability analysis is the assessment of the safety of a slope, identifying the surface most likely to experience slip and an index of its relative stability known as the factor of safety.

The following section provides an overview of the Software Requirements Specification (SRS) for a slope stability analysis problem. The developed program will be referred to as the Slope Stability Analysis Program (SSP). This section explains the purpose of this document, the scope of the system, the characteristics of the intended readers, and the organization of the document.

#### 3.1 Purpose of Document

The primary purpose of this document is to record the requirements of SSP and the models that will be used to meet those requirements. Goals, assumptions, theoretical models, definitions, and other model derivation information are specified, allowing the reader to fully understand and verify the purpose and scientific basis of SSP. With the exception of system constraints in Section 4.3, this SRS will remain abstract, describing *what* problem is being solved, but not *how* to solve it.

This document will be used as a starting point for subsequent development phases, including writing the design specification and the software verification and validation plan. The design document will show how the requirements are to be realized, including decisions on the numerical algorithms and programming environment. The verification and validation plan will show the steps that will be used to increase confidence in the software documentation and the implementation. Although the SRS fits in a series of documents that follow the so-called waterfall model, the actual development process is not constrained in any way. Even when the waterfall model is not followed, as Parnas and Clements point out [4], the most logical way to present the documentation is still to “fake” a rational design process.

#### 3.2 Scope of Requirements

The scope of the requirements includes stability analysis of a 2-dimensional slope, composed of homogeneous soil layers. The analysis will be at an instant in time; factors that may change the slope properties over time will not be considered.

#### 3.3 Characteristics of Intended Reader

Reviewers of this documentation should have an understanding of undergraduate Level 4 physics and should have completed a second year or higher level undergraduate course in solid mechanics. The users of SSP can have a lower level of expertise, as explained in Section 4.2.



### 3.4 Organization of Document

The organization of this document follows the template for an SRS for scientific computing software proposed by [2] and [5]. The presentation follows the standard pattern of presenting goals, theories, definitions, and assumptions. For readers that would like a more bottom up approach, they can start reading the instance models in Section 5.2.5 and trace back to find any additional information they require. The goal statements are refined to the theoretical models, and the theoretical models (Section 5.2.2) to the instance models (Section 5.2.5). The instance models provide the set of algebraic equations that must be solved.

## 4 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics, and lists the system constraints.

### 4.1 System Context

Figure 1 shows the system context. A circle represents an external entity outside the software. A rectangle represents the software system itself (SSP). Arrows are used to show the data flow between the system and its environment.

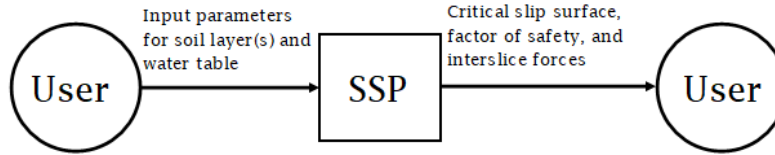


Figure 1: System Context

The responsibilities of the user and the system are as follows:

- User Responsibilities:
  - Provide the input data related to the soil layer(s) and water table (if applicable), ensuring conformation to input data format required by SSP
  - Ensure that consistent units are used for input variables
  - Ensure required software assumptions (Section 5.2.1) are appropriate for the problem to which the user is applying the software
- SSP Responsibilities:
  - Detect data type mismatch, such as a string of characters input instead of a floating point number
  - Verify that the inputs satisfy the required physical constraints
  - Identify the critical slip surface within the possible input range
  - Find the factor of safety for the slope
  - Find the interslice normal and shear forces along the critical slip surface

## 4.2 User Characteristics

The end user of SSP should have an understanding of undergraduate Level 1 Calculus and Physics, and be familiar with soil and material properties, specifically cohesion, effective angle of friction, and unit weight.

## 4.3 System Constraints

The Morgenstern-Price method, which involves dividing the slope into vertical slices, will be used to derive the equations for analysing the slope.

# 5 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, definitions and finally the instance models.

## 5.1 Problem Description

SSP is a computer program developed to evaluate the factors of safety for a slope's slip surfaces and identify the critical slip surface of the slope, as well as the interslice normal and shear forces along the critical slip surface. It is intended to be used as an educational tool for introducing slope stability issues, and to facilitate the analysis and design of a safe slope.

### 5.1.1 Terminology

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements.

- *Factor of safety*: The global stability metric of a slip surface of a slope.
- *Slip surface*: A surface within a slope that has the potential to fail or displace due to load or other forces.
- *Critical slip surface*: Slip surface of the slope that has the lowest factor of safety, and is therefore most likely to experience failure.
- *Water table*: The upper boundary of a saturated zone in the ground.
- *Stress*: Force applied over an area.
- *Strain*: A measure of deformation of a body or plane under stress.
- *Normal force*: A force applied perpendicular to the plane of the material.
- *Shear force*: A force applied parallel to the plane of the material.
- *Resistive shear force*: Shear force in the direction opposite of the direction of potential motion, thus hindering motion along the plane.

- *Mobile shear force*: Shear force in the direction of potential motion, thus encouraging motion along the plane.
- *Cohesion*: An attractive force between adjacent particles that holds the matter together.
- *Isotropic*: A condition where the value of a property is independent of the direction in which it is measured.
- *Plane strain*: A condition where the resultant stresses in one of the directions of a 3-dimensional material can be approximated as 0. Results when the length of one dimension of the body dominates the others. Stresses in the direction of the dominant dimension can be approximated as 0.

### 5.1.2 Physical System Description

The physical system of SSP, as shown in Figure 2, includes the following elements:

PS1: A slope comprised of one or more layers of soil.

PS2: A water table within the soil layers, which may or may not exist.



Figure 2: An example slope for analysis by SSP

Morgenstern-Price analysis of the slope involves representing the slope as a series of vertical slices. As shown in Figure 3, the index  $i$  is used to denote a value for a single slice, and an interslice value at a given index  $i$  refers to the value between slice  $i$  and adjacent slice  $i+1$ .

A free body diagram of the forces acting on a slice is displayed in Figure 4.

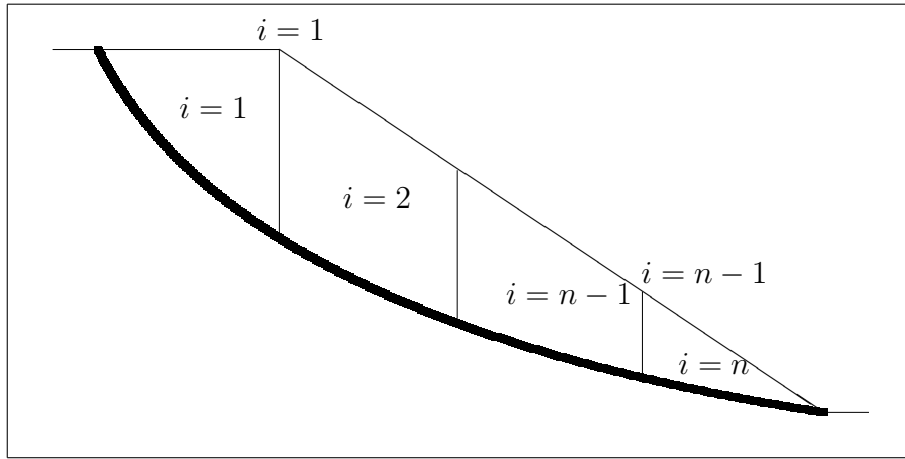


Figure 3: Index convention for slice and interslice values

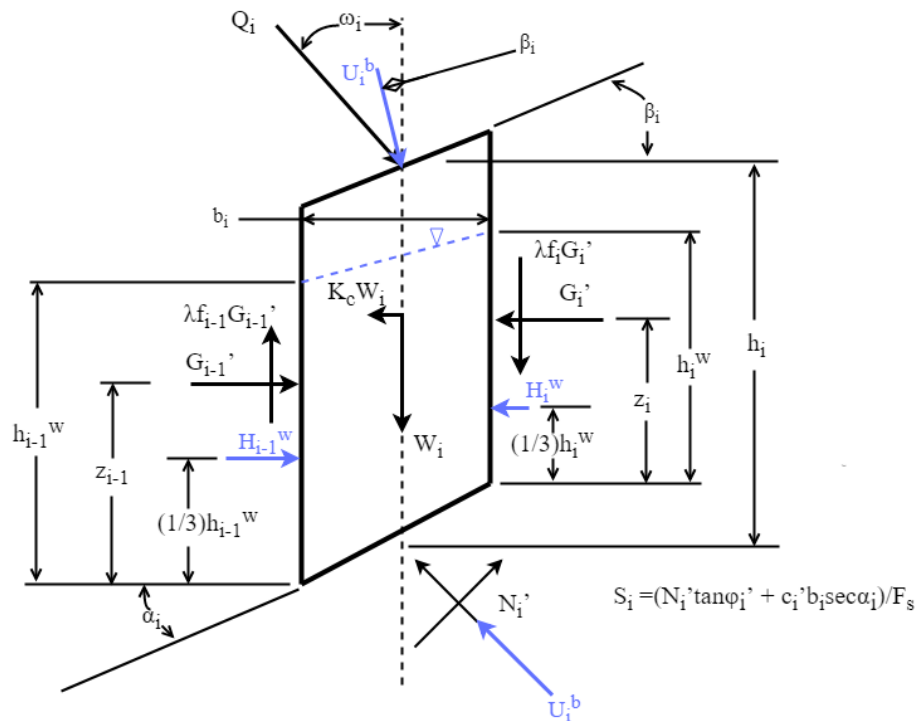


Figure 4: Free body diagram of forces acting on a slice

### 5.1.3 Goal statements

Given the geometry of the soil layers and water table composing the plane of a slope and the material properties of the layers, the goal statements are:

- GS1: Evaluate the factors of safety for possible slip surfaces along the slope.
- GS2: Identify the critical slip surface for the slope, with the lowest factor of safety.
- GS3: Determine the interslice normal force between each pair of vertical slices of the slope.

GS4: Determine the interslice shear force between each pair of vertical slices of the slope.

## 5.2 Solution Characteristics Specification

The instance models that govern SSP are presented in Section 5.2.5. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

### 5.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical models by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

- A1: The slip surface is concave with respect to the slope surface. The  $(x_{slip}, y_{slip})$  coordinates of a slip surface follow a concave up function. [IM4]
- A2: The factor of safety is assumed to be constant across a whole slip surface. [GD4, IM1, IM3]
- A3: The different layers of the soil are homogeneous, with consistent soil properties throughout. [GD3, GD4, DD10, DD11, LC1]
- A4: The soil properties are independent of dry or saturated conditions, with the exception of unit weight. [GD3, GD4, DD10, DD11]
- A5: Soil layers are treated as if they have isotropic properties. [GD3, GD4, DD10, DD11]
- A6: Interslice normal and shear forces have a proportional relationship, depending on a proportionality constant ( $\lambda$ ) and an function ( $f$ ) describing variation depending on  $x$  position. [GD6, IM1, IM2, IM3]
- A7: The slope and slip surface extends far into and out of the geometry ( $z$ -coordinate). This implies plane strain conditions, making 2D analysis appropriate. [T2]
- A8: The effective normal stress is large enough that the resistive shear to effective normal stress relationship can be approximated as a linear relationship. [T3, GD5]
- A9: The surface and base of a slice are approximated as straight lines [DD2, DD3, DD5, DD6, DD8, DD9].
- A10: There is no seismic force acting on the slope. [DD10, DD11, IM1, IM2, IM3, LC2]
- A11: There is no imposed surface load, and therefore no external force, acting on the slope. [DD10, DD11, IM1, IM2, IM3, LC3]

### 5.2.2 Theoretical Models

This section focuses on the general equations and laws that SSP is based on.

|             |  |
|-------------|--|
| Number      | T1   |
| Label       | <b>Factor of Safety</b>  |
| Equation    | $FS = \frac{P}{S}$   |
| Description | <p><math>FS</math> is the factor of safety, or stability metric of the slope.</p> <p><math>S</math> is the mobile shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>P</math> is the resistive shear force (<math>\text{N m}^{-1}</math>).</p> |
| Source      | [1]  |
| Ref. By     | IM1, GD4   |

|             |  |
|-------------|--|
| Number      | T2   |
| Label       | <b>Static Equilibrium</b>  |
| Equation    | $\sum F_x = \sum F_y = \sum M = 0$   |
| Description | <p>For a body in static equilibrium the net forces and net moments acting on the body will cancel out. This equation assumes a 2D space (A7).</p> <p><math>F_x</math> is the x-component of the net force (N).</p> <p><math>F_y</math> is the y-component of the net force (N).</p> <p><math>M</math> is the net moment (<math>\text{N m}</math>).</p> |
| Source      | [1]  |
| Ref. By     | GD1, GD2, GD7, IM2   |

|             |  |
|-------------|--|
| Number      | T3   |
| Label       | <b>Mohr-Coulomb Shear Strength</b>   |
| Equation    | $\tau = \sigma_N \cdot \tan(\varphi') + c'$  |
| Description | <p>The <math>\tau</math> versus <math>\sigma_N</math> relationship is not truly linear, but assuming the effective normal force is strong enough, it can be approximated with a linear fit (A8), where the cohesion <math>c'</math> represents the <math>\tau</math> intercept of the fitted line.</p> <p><math>\tau</math> is the shear strength (Pa).</p> <p><math>\sigma_N</math> is the normal stress (Pa).</p> <p><math>\varphi</math> is the effective angle of friction (<math>^\circ</math>).</p> <p><math>c'</math> is the effective cohesion (Pa).</p> |
| Source      | [1]  |
| Ref. By     | GD3, GD4, DD10, DD11   |

|             |  |
|-------------|--|
| Number      | T4   |
| Label       | <b>Effective Stress</b>  |
| Equation    | $\sigma' = \sigma - \mu$   |
| Description | <p><math>\sigma</math> is the total stress a soil mass needs to maintain itself as a rigid collection of particles (Pa).</p> <p><math>\sigma'</math> is the effective stress provided by the soil skeleton (Pa).</p> <p><math>\mu</math> is the pore pressure from water within the soil (Pa).</p> |
| Source      | [1]  |
| Ref. By     | GD5, DD10, IM1, IM2, IM3   |

### 5.2.3 General Definitions

This section collects the laws and equations that will be used to build the instance models.

|             |   |
|-------------|---|
| Number      | GD1   |
| Label       | <b>Normal Force Equilibrium</b>   |
| SI Units    | $\text{N m}^{-1}$   |
| Equation    | $N_i = [W_i - X_{i-1} + X_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \\ + [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \sin(\alpha_i)$   |
| Description | <p>This equation satisfies T2 in the normal direction. Force equilibrium is derived from the free body diagram of Figure 4 in section 5.1.2.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>N</math> is the normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>X</math> is the interslice shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>Q</math> is the external force (<math>\text{N m}^{-1}</math>).</p> <p><math>\omega</math> is the angle between the imposed surface load acting into the surface and the vertical (<math>^\circ</math>).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>K_c</math> is the seismic coefficient.</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>H</math> is the interslice water force (<math>\text{N m}^{-1}</math>).</p> |
| Source      | [6]   |
| Ref. By     | DD10, DD11, IM3   |



|             |  |
|-------------|--|
| Number      | GD2  |
| Label       | <b>Base Shear Force Equilibrium</b>  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $S_i = [W_i - X_{i-1} + X_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \sin(\alpha_i) - [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i)$   |
| Description | <p>This equation satisfies T2 in the shear direction. Force equilibrium is derived from the free body diagram of Figure 4 in section 5.1.2.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>S</math> is the mobile shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>X</math> is the interslice shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>Q</math> is the external force (<math>\text{N m}^{-1}</math>).</p> <p><math>\omega</math> is the angle between the imposed surface load acting into the surface and the vertical (<math>^\circ</math>).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>K_c</math> is the seismic coefficient.</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>H</math> is the interslice water force (<math>\text{N m}^{-1}</math>).</p> |
| Source      | [6]  |
| Ref. By     | DD10, DD11, IM3  |

|             |   |
|-------------|---|
| Number      | GD3   |
| Label       | <b>Resistive Shear Force</b>  |
| SI Units    | $\text{N m}^{-1}$   |
| Equation    | $P_i = N'_i \cdot \tan(\varphi'_i) + c' \cdot \ell_{b,i}$   |
| Description | <p>The Mohr-Coulomb resistive shear strength from T3 implemented with forces.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>P</math> is the resistive shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>N'</math> is the effective normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>\varphi'</math> is the effective angle of friction (<math>^\circ</math>).</p> <p><math>c'</math> is the effective cohesion (Pa).</p> <p><math>\ell_b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> |
| Source      | [6]   |
| Ref. By     | GD4, DD10, DD11   |

|             |  |
|-------------|--|
| Number      | GD4  |
| Label       | <b>Mobile Shear Force</b>  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $S_i = \frac{P_i}{FS} = \frac{N'_i \cdot \tan(\varphi'_i) + c' \cdot \ell_{b,i}}{FS}$  |
| Description | <p>Mobile shear force as derived from the definition of the factor of safety in T1, and the definition of <math>P</math> in GD3.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>S</math> is the mobile shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>P</math> is the resistive shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>N'</math> is the effective normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>\varphi'</math> is the effective angle of friction (<math>^\circ</math>).</p> <p><math>c'</math> is the effective cohesion (Pa).</p> <p><math>\ell_b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>FS</math> is the factor of safety.</p> |
| Source      | [6]  |
| Ref. By     | DD10, IM3  |

|             |  |
|-------------|--|
| Number      | GD5  |
| Label       | <b>Effective Normal Force</b>  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $N'_i = N_i - U_{b,i}$   |
| Description | <p>Effective normal force as derived from T4 and implemented with forces.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>N'</math> is the effective normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>N</math> is the normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>U_b</math> is the base hydrostatic force (<math>\text{N m}^{-1}</math>).</p> |
| Source      | [6]  |
| Ref. By     | DD10   |

|             |   |
|-------------|---|
| Number      | GD6   |
| Label       | <b>Interslice Normal and Shear Force Proportionality</b>  |
| Equation    | $X = \lambda \cdot f \cdot G$   |
| Description | <p>Mathematical representation of the primary assumption for the Morgenstern-Price method (A6).</p> <p><math>X</math> is the interslice shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>\lambda</math> is the proportionality constant.</p> <p><math>f</math> is a function describing variation of the interslice normal to shear force ratio; can be constant or a half-sine.</p> |
| Source      | [6]   |
| Ref. By     | IM1, IM2, IM3   |

|             |   |
|-------------|---|
| Number      | GD7   |
| Label       | <b>Moment Equilibrium</b>   |
| Equation    | $ \begin{aligned} 0 = & -G_i \left[ z_i + \frac{b_i}{2} \tan(\alpha_i) \right] + G_{i-1} \left[ z_{i-1} - \frac{b_i}{2} \tan(\alpha_i) \right] - H_i \left[ z_{w,i} + \frac{b_i}{2} \tan(\alpha_i) \right] \\ & + H_{i-1} \left[ z_{w,i-1} - \frac{b_i}{2} \tan(\alpha_i) \right] + \frac{b_i}{2} (X_i + X_{i-1}) - K_c W_i \frac{h_i}{2} + U_{t,i} \sin(\beta_i) h_i \\ & + Q_i \sin(\omega_i) h_i \end{aligned} $   |
| Description | <p>This equation satisfies T2 for the net moment. Force equilibrium is derived from the free body diagram of Figure 4 in section 5.1.2.</p> <p><math>i</math> is the index representing a single slice.</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>z</math> is the height in the <math>y</math>-direction from the base of a slice to the center of the slice (m).</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>H</math> is the interslice water force (<math>\text{N m}^{-1}</math>).</p> <p><math>z_w</math> is the height in the <math>y</math>-direction from the base of a slice halfway to the water table (m).</p> <p><math>X</math> is the interslice shear force (<math>\text{N m}^{-1}</math>).</p> <p><math>K_c</math> is the seismic coefficient.</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>h</math> is the height in the <math>y</math>-direction from the base of a slice to the slope surface, at the <math>x</math>-direction midpoint on the slice (m).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>Q</math> is the external force (<math>\text{N m}^{-1}</math>).</p> <p><math>\omega</math> is the angle between the imposed surface load acting into the surface and the vertical (<math>^\circ</math>).</p> |
| Source      | [6]   |
| Ref. By     | IM2   |

### 5.2.4 Data Definition

This section collects and defines all the data needed to support the general definitions of 5.2.3 or build the instance models of 5.2.5. The dimension of each quantity is also given.

|             |  |
|-------------|--|
| Number      | DD1  |
| Label       | <b>Weight</b>  |
| Symbol      | $W$  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $W_i = b_i \begin{cases} (y_{us,i} - y_{slip,i}) \gamma_{Sat}, & y_{wt,i} \geq y_{us,i} \\ (y_{us,i} - y_{wt,i}) \gamma + (y_{wt,i} - y_{slip,i}) \gamma_{Sat}, & y_{us,i} > y_{wt,i} > y_{slip,i} \\ (y_{us,i} - y_{slip,i}) \gamma, & y_{wt,i} \leq y_{slip,i} \end{cases}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>y_{us}</math> is the <math>y</math>-ordinate of a point on the slope (m).</p> <p><math>y_{slip}</math> is the <math>y</math>-ordinate of a point on a slip surface (m).</p> <p><math>\gamma_{Sat}</math> is the soil saturated unit weight (<math>\text{N m}^{-3}</math>).</p> <p><math>y_{wt}</math> is the <math>y</math>-ordinate of a point on the water table (m).</p> <p><math>\gamma</math> is the soil dry unit weight (<math>\text{N m}^{-3}</math>).</p> |
| Sources     | [1]  |
| Ref. By     | GD1, GD2, GD7, DD10, DD11, IM1, IM2, IM3   |

|             |  |
|-------------|--|
| Number      | DD2  |
| Label       | <b>Base Water Force</b>  |
| Symbol      | $U_b$  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $U_{b,i} = \ell_{b,i} \begin{cases} (y_{wt,i} - y_{slip,i}) \gamma_w, & y_{wt,i} > y_{slip,i} \\ 0, & y_{wt,i} \leq y_{slip,i} \end{cases}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>U_b</math> is the base hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\ell_b</math> is the base length of a slice in the direction parallel to the slope of the base (m).</p> <p><math>y_{wt}</math> is the <math>y</math>-ordinate of a point on the water table (m).</p> <p><math>y_{slip}</math> is the <math>y</math>-ordinate of a point on a slip surface (m).</p> <p><math>\gamma_w</math> is the unit weight of water (<math>\text{N m}^{-3}</math>).</p> |
| Sources     | [1]  |
| Ref. By     | DD10, IM1, IM2, IM3  |

|             |  |
|-------------|--|
| Number      | DD3  |
| Label       | <b>Surface Hydrostatic Force</b>   |
| Symbol      | $U_t$  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $U_{t,i} = \ell_{s,i} \begin{cases} (y_{wt,i} - y_{us,i}) \gamma_w, & y_{wt,i} > y_{us,i} \\ 0, & y_{wt,i} \leq y_{us,i} \end{cases}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\ell_s</math> is the surface length of a slice in the direction parallel to the slope of the surface (m).</p> <p><math>y_{wt}</math> is the <math>y</math>-ordinate of a point on the water table (m).</p> <p><math>y_{us}</math> is the <math>y</math>-ordinate of a point on the slope (m).</p> <p><math>\gamma_w</math> is the unit weight of water (<math>\text{N m}^{-3}</math>).</p> |
| Sources     | [1]  |
| Ref. By     | GD1, GD2, GD7, DD10, DD11, IM1, IM2, IM3   |

|             |   |
|-------------|---|
| Number      | DD4   |
| Label       | <b>Interslice Water Force</b>   |
| Symbol      | $H$   |
| SI Units    | $\text{N m}^{-1}$   |
| Equation    | $H_i = \begin{cases} \frac{[y_{us,i} - y_{slip,i}]^2}{2} \gamma_{Sat} + [y_{wt,i} - y_{us,i}]^2 \gamma_{Sat}, & y_{wt,i} \geq y_{us,i} \\ \frac{[y_{wt,i} - y_{slip,i}]^2}{2} \gamma_{Sat}, & y_{us,i} > y_{wt,i} > y_{slip,i} \\ 0, & y_{wt,i} \leq y_{slip,i} \end{cases}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>H</math> is the interslice water force (<math>\text{N m}^{-1}</math>).</p> <p><math>y_{us}</math> is the <math>y</math>-ordinate of a point on the slope (m).</p> <p><math>y_{slip}</math> is the <math>y</math>-ordinate of a point on a slip surface (m).</p> <p><math>\gamma_{Sat}</math> is the soil saturated unit weight. (<math>\text{N m}^{-3}</math>).</p> <p><math>y_{wt}</math> is the <math>y</math>-ordinate of a point on the water table (m).</p> |
| Sources     | [1]   |
| Ref. By     | GD1, GD2, GD7, DD10, DD11, IM1, IM2, IM3  |

|             |   |
|-------------|---|
| Number      | DD5   |
| Label       | <b>Base Angle</b>   |
| Symbol      | $\alpha$  |
| SI Units    | $^{\circ}$  |
| Equation    | $\alpha_i = \arctan \left( \frac{y_{slip,i} - y_{slip,i-1}}{x_{slip,i} - x_{slip,i-1}} \right)$   |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^{\circ}</math>).</p> <p><math>y_{slip}</math> is the <math>y</math>-ordinate of a point on a slip surface (m).</p> <p><math>x_{slip}</math> is the <math>x</math>-ordinate of a point on a slip surface (m).</p> |
| Sources     | [1]   |
| Ref. By     | GD1, GD2, GD7, DD8, DD10, DD11, IM1, IM2, IM3   |



|             |   |
|-------------|---|
| Number      | DD6   |
| Label       | <b>Surface Angle</b>  |
| Symbol      | $\beta$   |
| SI Units    | °   |
| Equation    | $\beta_i = \arctan \left( \frac{y_{us,i} - y_{us,i-1}}{x_{us,i} - x_{us,i-1}} \right)$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (°).</p> <p><math>y_{us}</math> is the <math>y</math>-ordinate of a point on the slope (m).</p> <p><math>x_{us}</math> is the <math>x</math>-ordinate of a point on the slope (m).</p> |
| Sources     | [1]   |
| Ref. By     | GD1, GD2, GD7, DD9, DD10, DD11, IM1, IM2, IM3   |

|             |  |
|-------------|--|
| Number      | DD7  |
| Label       | <b>Base <math>x</math>-Direction Width of a Slice</b>  |
| Symbol      | $b$  |
| SI Units    | m  |
| Equation    | $b_i = x_{slip,i} - x_{slip,i-1}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>x_{slip}</math> is the <math>x</math>-ordinate of a point on a slip surface (m).</p> |
| Sources     | [1]  |
| Ref. By     | GD7, DD1, DD8, DD9, DD10, DD11, IM1, IM2, IM3  |

|             |   |
|-------------|---|
| Number      | DD8   |
| Label       | <b>Total Base Length of a Slice</b>   |
| Symbol      | $\ell_b$  |
| SI Units    | m   |
| Equation    | $\ell_{b,i} = b_i \sec(\alpha_i)$   |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>\ell_b</math> is the base length of a slice in the direction parallel to the slope of the base (m).</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> |
| Sources     | [1]   |
| Ref. By     | GD3, GD4, DD2   |

|             |   |
|-------------|---|
| Number      | DD9   |
| Label       | <b>Total Surface Length of a Slice</b>  |
| Symbol      | $\ell_s$  |
| SI Units    | m   |
| Equation    | $\ell_{s,i} = b_i \sec(\beta_i)$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>\ell_s</math> is the surface length of a slice in the direction parallel to the slope of the surface (m).</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> |
| Sources     | [1]   |
| Ref. By     | DD3   |

|             |  |
|-------------|--|
| Number      | DD10   |
| Label       | <b>Resistive Shear, Without Interslice Normal and Shear Forces</b>   |
| Symbol      | $R$  |
| SI Units    | $\text{N m}^{-1}$  |
| Equation    | $R_i = \left( \begin{array}{l} [W_i + U_{t,i} \cos(\beta_i)] \cos(\alpha_i) \\ + [-\Delta H_i + U_{t,i} \sin(\beta_i)] \sin(\alpha_i) - U_{b,i} \end{array} \right) \cdot \tan(\varphi') + c'_i \cdot b_i \cdot \sec(\alpha_i)$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>R</math> is the resistive shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>\Delta H</math> is the difference between interslice water forces (<math>\text{N m}^{-1}</math>).</p> <p><math>U_b</math> is the base hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\varphi'</math> is the effective angle of friction (<math>^\circ</math>).</p> <p><math>c'</math> is the effective cohesion (Pa).</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> |
| Sources     | [6]  |
| Ref. By     | IM1, IM3   |

### Resistive Shear, Without Interslice Normal and Shear Forces Derivation

The resistive shear force of a slice is defined as  $P_i$  in GD3, and depends upon the effective normal force. The definition for normal force in GD1 can be substituted into the definition for effective normal force in GD5 to obtain equation (1).

$$N'_i = \begin{aligned} & [W_i - X_{i-1} + X_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \\ & + [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \sin(\alpha_i) \\ & - U_{b,i} \end{aligned} \quad (1)$$

The values of the interslice forces  $G$  and  $X$  in the equation are unknown. Thus, a force equilibrium without the effect of interslice normal and shear forces is considered, from which a value for  $N_i^*$  can be obtained, as shown in equation (2).

$$N_i^* = \begin{aligned} & [W_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \\ & + [-K_c W_i - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \sin(\alpha_i) - U_{b,i} \end{aligned} \quad (2)$$

Using  $N_i^*$ , a resistive shear force neglecting the influence of interslice normal and shear forces can be expressed in terms of only known values, as shown in equation (3).

$$R_i = N_i^* \tan(\varphi') + c'_i \cdot b'_i \sec(\alpha_{t,exti}')$$

$$R_i = \left( \begin{array}{l} [W_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \\ + [-K_c W_i - \Delta H_i + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \sin(\alpha_i) - U_{b,i} \end{array} \right) \cdot \tan(\varphi') + c'_i \cdot b_i \cdot \sec(\alpha_i) \quad (3)$$

This can be further simplified by considering assumptions A10 and A11, which state that the seismic coefficient and the external force, respectively, are 0. Removing seismic and external forces yields equation (4).

$$R_i = \left( \begin{array}{l} [W_i + U_{t,i} \cos(\beta_i)] \cos(\alpha_i) \\ + [-\Delta H_i + U_{t,i} \sin(\beta_i)] \sin(\alpha_i) - U_{b,i} \end{array} \right) \cdot \tan(\varphi') + c'_i \cdot b_i \cdot \sec(\alpha_i) \quad (4)$$

|             |   |
|-------------|---|
| Number      | DD11  |
| Label       | <b>Mobile Shear, Without Interslice Normal and Shear Forces</b>   |
| Symbol      | $T$   |
| SI Units    | $\text{N m}^{-1}$   |
| Equation    | $T_i = (W_i + U_{t,i} \cos(\beta_i)) \sin(\alpha_i) - (-\Delta H_i + U_{t,i} \sin(\beta_i)) \cos(\alpha_i)$   |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>T</math> is the mobilized shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> <p><math>W</math> is the weight (<math>\text{N m}^{-1}</math>).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>\Delta H</math> is the difference between interslice water forces (<math>\text{N m}^{-1}</math>).</p> |
| Sources     | [6]   |
| Ref. By     | IM1   |

### Mobile Shear, Without Interslice Normal and Shear Forces Derivation

The mobile shear force acting on a slice is defined as  $S_i$  from the force equilibrium in GD2, also shown in equation (5).

$$S_i = \begin{array}{l} [W_i - X_{i-1} + X_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \sin(\alpha_i) \\ - [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \end{array} \quad (5)$$

The values of the interslice forces  $G$  and  $X$  in the equation are unknown. Thus, a force equilibrium without the effect of interslice normal and shear forces is considered, from which a value for  $T_i$  can be obtained, as shown in equation (6).

$$T_i = \begin{aligned} & [W_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \sin(\alpha_i) \\ & - [-K_c W_i - \Delta H_i + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \cos(\alpha_i) \end{aligned} \quad (6)$$

The value of  $T_i$  is now defined completely in terms of known values. This can be further simplified by considering assumptions A10 and A11, which state that the seismic coefficient and the external force, respectively, are 0. Removing seismic and external forces yields equation (7).

$$T_i = [W_i + U_{t,i} \cos(\beta_i)] \sin(\alpha_i) - [-\Delta H_i + U_{t,i} \sin(\beta_i)] \cos(\alpha_i) \quad (7)$$

### 5.2.5 Instance Models

This section transforms the problem defined in the Section 5.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 5.2.4 to replace the abstract symbols in the models identified in the Sections 5.2.2 and 5.2.3.

The goals GS1, GS3, and GS4 are met by the simultaneous solution of IM1, IM2, and IM3. The goal GS2 is met by IM4.

The Morgenstern-Price Method is a vertical slice, limit equilibrium slope stability analysis method. Analysis is performed by breaking the assumed slip surface into a series of vertical slices of mass. Static equilibrium analysis is performed, using two force equations and one moment equation as in T2. The problem is statically indeterminate with only these 3 equations and one constitutive equation (the Mohr-Coulomb shear strength of T3), so the assumption A6 and corresponding equation GD6 are used. The force equilibrium equations can be modified to be expressed only in terms of known physical values, as done in DD10 and DD11.

|             |  |
|-------------|--|
| Number      | IM1  |
| Label       | <b>Factor of Safety</b>  |
| Input       | $\Psi_c, \Phi_c, T_i, R_i$   |
| Output      | $FS = \frac{\sum_{i=1}^{n-1} \left[ R_i \prod_{c=i}^{n-1} \frac{\Psi_c}{\Phi_c} \right] + R_n}{\sum_{i=1}^{n-1} \left[ T_i \prod_{c=i}^{n-1} \frac{\Psi_c}{\Phi_c} \right] + T_n}$   |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>n</math> is the total number of slices.</p> <p><math>FS</math> is the factor of safety.</p> <p><math>R</math> is the resistive shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> <p><math>\Psi</math> is the second constant used to convert shear without the influence of interslice forces to shear with the influence of interslice forces.</p> <p><math>\Phi</math> is the first constant used to convert shear without the influence of interslice forces to shear with the influence of interslice forces.</p> <p><math>T</math> is the mobile shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> |
| Sources     | [6]  |
| Ref. By     | IM2, IM3   |

### Factor of Safety Derivation

Using the boundary conditions from IM3 that  $G_0$  and  $G_n$  are equal to 0, one can derive equation (8), also seen in IM1.

$$FS = \frac{\sum_{i=1}^{n-1} \left[ R_i \prod_{c=i}^{n-1} \frac{\Psi_c}{\Phi_c} \right] + R_n}{\sum_{i=1}^{n-1} \left[ T_i \prod_{c=i}^{n-1} \frac{\Psi_c}{\Phi_c} \right] + T_n} \quad (8)$$

The constants  $\Psi$  and  $\Phi$ , described in equations 16 and 15 of the derivation for IM3, are functions of the unknowns: the interslice normal and shear force proportionality constant,  $\lambda$  (IM2), and the factor of safety,  $FS$  (IM1).

|             |  |
|-------------|--|
| Number      | IM2  |
| Label       | <b>Normal and Shear Force Proportionality Constant</b>   |
| Input       | $b_i, G_i, H_i, \alpha_i, h_i, W_i, U_{t,i}, \beta_i, f_i$   |
| Output      | $C1_i = \begin{cases} b_1 [G_1 + H_1] \tan(\alpha_1) & i = 1 \\ b_i [(G_i + G_{i-1}) + (H_i + H_{i-1})] \tan(\alpha_i) & 2 \leq i \leq n-1 \\ + h_i (-2 U_{t,i} \sin(\beta_i)) \\ b_n [G_{n-1} + H_{n-1}] \tan(\alpha_{n-1}) & i = n \end{cases}$ $C2_i = \begin{cases} b_1 G_1 f_1 & i = 1 \\ b_i (f_i G_i + f_{i-1} G_{i-1}) & 2 \leq i \leq n-1 \\ b_n G_{n-1} f_{n-1} & i = n \end{cases}$ $\lambda = \frac{\sum_{i=1}^n C1_i}{\sum_{i=1}^n C2_i}$   |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>n</math> is the total number of slices.</p> <p><math>b</math> is the width of the base of a slice in the <math>x</math> direction (m).</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>H</math> is the interslice water force (<math>\text{N m}^{-1}</math>).</p> <p><math>\alpha</math> is the angle between the base of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>h</math> is the height in the <math>y</math>-direction from the base of a slice to the slope surface, at the <math>x</math>-direction midpoint on the slice (m).</p> <p><math>U_t</math> is the surface hydrostatic force (<math>\text{N m}^{-1}</math>).</p> <p><math>\beta</math> is the angle between the surface of a slice and the horizontal (<math>^\circ</math>).</p> <p><math>f</math> is a function describing variation of the interslice normal to shear force ratio; can be constant or a half-sine.</p> <p><math>\lambda</math> is the proportionality constant.</p> |
| Sources     | [6]  |
| Ref. By     | IM1, IM3   |

## Normal/Shear Force Ratio Derivation

From the moment equilibrium of GD7, with the primary assumption for the Morgenstern-Price method of A6 and associated definition GD6, equation (9) can be derived.

$$0 = -G_i \left[ z_i - \frac{b_i}{2} \tan(\alpha_i) \right] + G_{i-1} \left[ z_{i-1} + \frac{b_i}{2} \tan(\alpha_i) \right] - H_i \left[ z_{w,i} - \frac{b_i}{2} \tan(\alpha_i) \right] \\ + H_{i-1} \left[ z_{w,i-1} + \frac{b_i}{2} \tan(\alpha_i) \right] - \lambda \frac{b_i}{2} (G_i f_i + G_{i-1} f_{i-1}) + K_c W_i \frac{h_i}{2} - U_{t,i} \sin(\beta_i) h_i - Q_i \sin(\omega_i) h_i \quad (9)$$

Rearranging the equation in terms of  $\lambda$  leads to equation (10).

$$\lambda = \frac{-G_i \left[ z_i - \frac{b_i}{2} \tan(\alpha_i) \right] + G_{i-1} \left[ z_{i-1} + \frac{b_i}{2} \tan(\alpha_i) \right] - H_i \left[ z_i - \frac{b_i}{2} \tan(\alpha_i) \right] \\ + H_{i-1} \left[ z_{i-1} + \frac{b_i}{2} \tan(\alpha_i) \right] + K_c W_i \frac{h_i}{2} - U_{t,i} \sin(\beta_i) h_i - Q_i \sin(\omega_i) h_i}{\frac{b_i}{2} [G_i f_i + G_{i-1} f_{i-1}]} \quad (10)$$

Taking the summation of all slices, considering the boundary conditions that  $G_0$  and  $G_n$  are equal to zero, and removing the seismic and external forces due to A10 and A11, respectively, a general equation for the constant  $\lambda$  is developed in equation (11), also found in IM2.

$$\lambda = \frac{\sum_{i=1}^n b_i [(G_i + G_{i-1}) + (H_i + H_{i-1})] \tan(\alpha_i) + h_i [-2 U_{t,i} \sin(\beta_i)]}{\sum_{i=1}^n b_i [f_i G_i + f_{i-1} G_{i-1}]} \quad (11)$$

Equation (11) for  $\lambda$ , is a function of the unknown interslice normal force  $G$  (IM3).



|             |   |
|-------------|---|
| Number      | IM3   |
| Label       | <b>Interslice Normal Forces</b>   |
| Input       | FS, $T_i$ , $R_i$ , $\Psi_i$ , $\Phi_i$   |
| Output      | $G_i = \begin{cases} \frac{(FS)T_1 - R_1}{\Phi_i} & i=1 \\ \frac{\Psi_{i-1} \cdot G_{i-1} + (FS) \cdot T_i - R_i}{\Phi_i} & 2 \leq i \leq n-1 \\ 0 & i=0 \vee i=n \end{cases}$  |
| Description | <p><math>i</math> is the index representing a single slice.</p> <p><math>n</math> is the total number of slices.</p> <p><math>G</math> is the interslice normal force (<math>\text{N m}^{-1}</math>).</p> <p><math>FS</math> is the factor of safety.</p> <p><math>T</math> is the mobile shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> <p><math>R</math> is the resistive shear force without the influence of interslice forces (<math>\text{N m}^{-1}</math>).</p> <p><math>\Phi</math> is the first constant used to convert shear without the influence of interslice forces to shear with the influence of interslice forces.</p> <p><math>\Psi</math> is the second constant used to convert shear without the influence of interslice forces to shear with the influence of interslice forces.</p> |
| Sources     | [6]   |
| Ref. By     | IM1, IM2  |

### Interslice Force Derivation

Substituting the normal force equilibrium of GD1 and the assumption A6 represented by GD6 into the effective normal force definition from GD5 yields equation (12).

$$N'_i = \begin{aligned} & [W_i - \lambda \cdot f_{i-1} \cdot G_{i-1} + \lambda \cdot f_i \cdot G_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \cos(\alpha_i) \\ & + [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \sin(\beta_i) + Q_i \sin(\omega_i)] \sin(\alpha_i) - U_{b,i} \end{aligned} \quad (12)$$

Next, substituting the base shear force equilibrium of GD2 and the assumption of GD6 into the definition of mobilized shear from GD4 results in equation (13).

$$\frac{N'_i \tan(\varphi'_i) + c'_i \cdot b'_i \cdot \sec(\alpha_i)}{FS} = \begin{aligned} & [W_i - \lambda \cdot f_{i-1} \cdot G_{i-1} + \lambda \cdot f_i \cdot G_i + U_{t,i} \cos(\beta_i) + Q_i \cos(\omega_i)] \sin(\alpha_i) \\ & - [-K_c W_i - G_i + G_{i-1} - H_i + H_{i-1} + U_{t,i} \cdot \sin(\beta_i) + Q_i \sin(\omega_i)] \cos(\alpha_i) \end{aligned} \quad (13)$$

Substituting equation (12), DD10, and DD11 into equation (13) and rearranging results in equation (14)

$$G_i \begin{bmatrix} [\lambda \cdot f_i \cos(\alpha_i) - \sin(\alpha_i)] \tan(\varphi'_i) \\ -[\lambda \cdot f_i \sin(\alpha_i) + \cos(\alpha_i)] (FS) \end{bmatrix} = G_{i-1} \begin{bmatrix} [\lambda \cdot f_{i-1} \cos(\alpha_i) - \sin(\alpha_i)] \tan(\varphi'_i) \\ -[\lambda \cdot f_{i-1} \sin(\alpha_i) + \cos(\alpha_i)] (FS) \end{bmatrix} + (FS) \cdot T_i - R_i \quad (14)$$

Where  $R$  and  $T$  are the resistive and mobile shear of the slice, without the influence of interslice forces  $G$  and  $X$ , as defined in DD10 and DD11. The constants  $\Phi$  and  $\Psi$  are defined below in equations (15) and (16) respectively.

$$\Phi_i = [\lambda \cdot f_i \cos(\alpha_i) - \sin(\alpha_i)] [\tan(\varphi'_i)] - [\lambda \cdot f_i \sin(\alpha_i) + \cos(\alpha_i)] (FS) \quad (15)$$

$$\Psi_i = [\lambda \cdot f_i \cos(\alpha_{i+1}) - \sin(\alpha_{i+1})] [\tan(\varphi')] - [\lambda \cdot f_i \sin(\alpha_{i+1}) + \cos(\alpha_{i+1})] (FS) \quad (16)$$

These constants can be used to simplify equation (14) to obtain equation (17), which can be found in IM3.

$$G_i = \frac{\Psi_{i-1} G_{i-1} + (FS) T_i - R_i}{\Phi_i} \quad (17)$$

The constants  $\Psi$  and  $\Phi$  in equation (17) for are functions of the unknowns: the proportionality constant,  $\lambda$  (IM2), and the factor of safety,  $FS$  (IM1).

| Number      | IM4   |
|-------------|---|
| Label       | <b>Critical Slip Surface Identification</b>   |
| Input       | $\{(x_{us}, y_{us})\}$  |
| Output      | $(FS_{Min}, \{(x_{cs}, y_{cs})\}) = \Upsilon(\{(x_{us}, y_{us})\})$   |
| Description | <p><math>FS_{Min}</math> is the minimum factor of safety associated with the critical slip surface.</p> <p><math>x_{cs}</math> is the <math>x</math>-ordinate of a point on the critical slip surface (m).</p> <p><math>y_{cs}</math> is the <math>y</math>-ordinate of a point on the critical slip surface (m).</p> <p><math>\Upsilon</math> is a minimization algorithm or function.</p> <p><math>x_{us}</math> is the <math>x</math>-ordinate of a point on the slope (m).</p> <p><math>y_{us}</math> is the <math>y</math>-ordinate of a point on the slope (m).</p> |
| Sources     | [3]   |

[Should this IM exist? It doesn't arise from any T —BM]

### 5.2.6 Data Constraints

Tables 1 and 2 show the data constraints on the input and output variables, respectively. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The uncertainty column provides an estimate of the confidence with which

the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise. The constraints are conservative, to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario.

Table 1: Input Variables

| Var   | Physical Constraints   | Typical Uncertainty Value |     |
|---|--|---------------------------|-----|
| $\{(x_{wt}, y_{wt})\}$  | Consecutive vertices $x$ values are always increasing or always decreasing. Starts and ends on the same $x$ values as soil layers. | N/A                       | 10% |
| $\{(x_{slip}, y_{slip})\}$ for potential slip surface entry and exit points | Slopes between $x$ values of consecutive vertices are always increasing.   | N/A                       | 10% |
| $\{(x_{us}, y_{us})\}$ (*)  | Consecutive vertices $x$ values are always increasing or always decreasing. All layers start and end on the same $x$ values.       | N/A                       | 10% |
| $c'$ (*)  | $c > 0$  | 10                        | 10% |
| $\varphi'$ (*)  | $0 < \varphi < 90$   | 25                        | 10% |
| $\gamma$ (*)  | $\gamma > 0$   | 20                        | 10% |
| $\gamma_{\text{Sat}}$ (*)   | $\gamma_{\text{Sat}} > 0$  | 20                        | 10% |
| $\gamma_w$  | $\gamma_w > 0$   | 9.8                       | 10% |

(\*) Input coordinates needed for each layer.

Table 2: Output Variables

| Var                | Physical Constraints                  |
|--------------------|---------------------------------------|
| $FS$               | $FS > 0$                              |
| $(x_{cs}, y_{cs})$ | Vertices are monotonically increasing |
| $G_i$              | $G_i > 0$                             |
| $X_i$              | $X_i < 0$                             |

### 5.2.7 Properties of a Correct Solution

A correct solution must exhibit conformation to the system of non-linear equations presented in IM1, IM2, and IM3. In addition, the factor of safety for the critical slip surface must be lower than the factors of safety calculated for other slip surfaces. The coordinates of the critical slip surface must form a concave up function.

## 6 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

### 6.1 Functional Requirements

R1: Read the inputs, shown in the table below, and store the data.

| symbol                | unit              | description  |
|-----------------------|-------------------|--|
| $(x, y)$              | m                 | $x$ and $y$ -coordinates for vertices of the slope layers, for the water table if one exists, and for potential entry and exit points of a slip surface. |
| $c'$                  | Pa                | Cohesion for each slope layer.   |
| $\varphi'$            | °                 | Effective angle of friction for each slope layer.  |
| $\gamma$              | $\text{N m}^{-3}$ | Unit weight of dry soil for each slope layer.  |
| $\gamma_{\text{Sat}}$ | $\text{N m}^{-3}$ | Unit weight of saturated soil for each slope layer.  |
| $\gamma_{\text{w}}$   | $\text{N m}^{-3}$ | Unit weight of water.  |
| N/A                   | N/A               | A boolean decision on which form of the interslice variation function $f$ the user desires: constant or half-sine.                                       |

R2: Verify that the input data lies within physical constraints shown in Table 1.

R3: Generate potential critical slip surfaces for the input slope (using IM4).

R4: Calculate the factors of safety for each of the potential critical slip surfaces (using IM1, IM2, and IM3).

R5: Compare the factor of safety for each potential critical slip surface to determine the minimum factor of safety, corresponding to the critical slip surface (using IM4).

R6: Verify that the factor of safety, critical slip surface, and interslice forces satisfy the physical constraints shown in Table 2 and Section 5.2.7.

R7: Display the critical slip surface of the 2D slope, as determined from IM4, graphically.

- R8: Display the value of the factor of safety for the critical slip surface, as determined from IM1, IM2, and IM3.
- R9: Using IM1, IM2, and IM3, calculate and graphically display the interslice normal forces.
- R10: Using IM1, IM2, and IM3, calculate and graphically display the interslice shear forces.

## 6.2 Nonfunctional Requirements

SSP is intended to be an educational tool, therefore accuracy and performance speed are secondary program priorities. Instead, the following non-functional requirements are prioritized:

- NFR1: Correctness, achieved if the outputs of the code have the properties described in 5.2.7.
- NFR2: Understandability, achieved if the code is modularized with complete module guide and module interface specification.
- NFR3: Reusability, achieved if the code is modularized.
- NFR4: Maintainability, achieved if the traceability between requirements, assumptions, theoretical models, general definitions, data definitions, instance models, likely changes, and modules is completely recorded in traceability matrices in the SRS and module guide.

## 7 Likely Changes

- LC1: The system currently assumes the different layers of the soil are homogeneous (A3). In the future, implementation can be added for inconsistent soil properties throughout.
- LC2: The system currently assumes no seismic force (A10). In the future, implementation can be added for the presence of seismic force.
- LC3: The system currently assumes no external force (A11). In the future, implementation can be added for an imposed surface load on the slope.

## 8 Unlikely Changes

If changes were to be made with regard to the following, a different algorithm would be needed.

- UC1: Changes related to A6 are not possible due to the dependency of the calculations on the proportional relationship between interslice normal and shear forces.
- UC2: A7 allows for 2D analysis with these models only because stress along  $z$ -direction is zero. These models do not take into account stress in the  $z$ -direction, and therefore cannot be used without manipulation to attempt 3-dimensional analysis.

[This section is not on the template, not sure if it should be kept —BM]

## 9 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an “X” may have to be modified as well. Tables 6 and 7 show the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 5 shows the dependencies of instance models, requirements, and data constraints on each other. Table 4 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions.

The purpose of the traceability graphs is also to provide easy references on what has to be additionally modified if a certain component is changed. The arrows in the graphs represent dependencies. The component at the tail of an arrow is depended on by the component at the head of that arrow. Therefore, if a component is changed, the components that it points to should also be changed. Figure 5 shows the dependencies of theoretical models, general definitions, data definitions, instance models, likely changes, and assumptions on each other. Figure 6 shows the dependencies of instance models, requirements, and data constraints on each other.

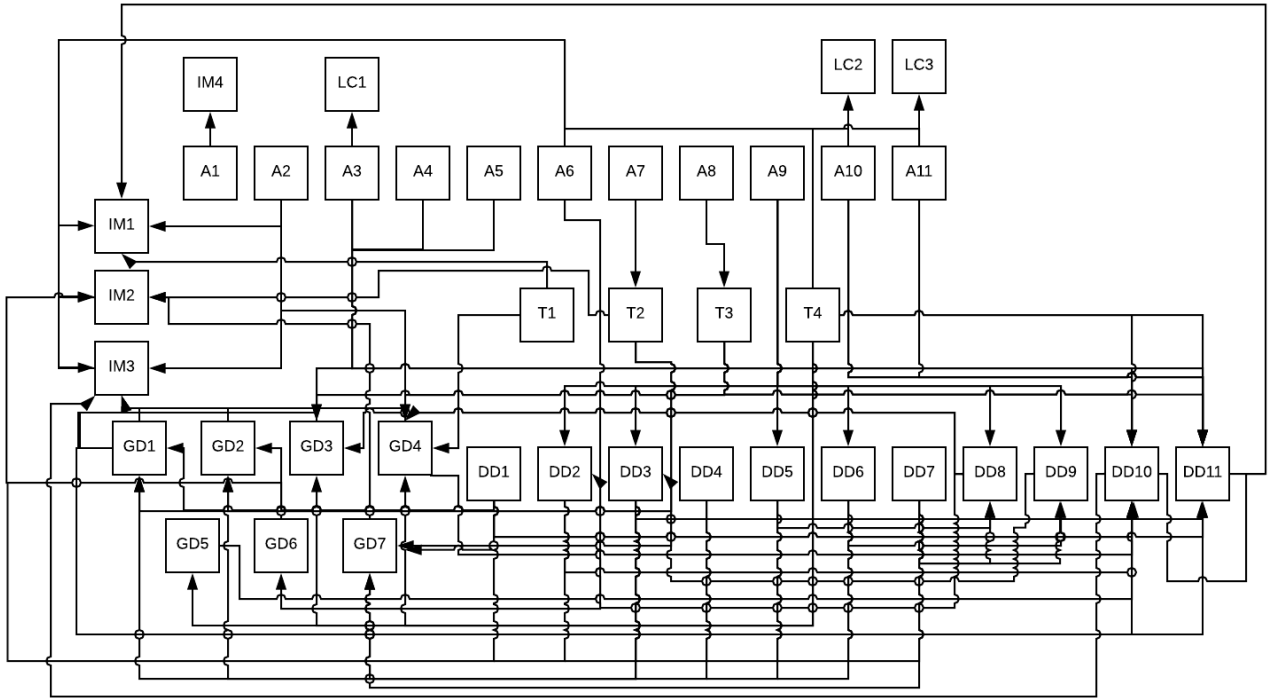


Figure 5: Traceability Matrix Showing the Connections Between Items of Different Sections

## 10 Values of Auxiliary Constants

There are no auxiliary constants.

[This section is not on the template, unless it's equivalent to symbolic constants in the appendix? —BM]

|      | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 |
|------|----|----|----|----|----|----|----|----|----|-----|-----|
| T1   |    |    |    |    |    |    |    |    |    |     |     |
| T2   |    |    |    |    |    |    | X  |    |    |     |     |
| T3   |    |    |    |    |    |    |    | X  |    |     |     |
| T4   |    |    |    |    |    |    |    |    |    |     |     |
| GD1  |    |    |    |    |    |    |    |    |    |     |     |
| GD2  |    |    |    |    |    |    |    |    |    |     |     |
| GD3  |    |    | X  | X  | X  |    |    |    |    |     |     |
| GD4  |    | X  | X  | X  | X  |    |    |    |    |     |     |
| GD5  |    |    |    |    |    |    |    | X  |    |     |     |
| GD6  |    |    |    |    |    | X  |    |    |    |     |     |
| GD7  |    |    |    |    |    |    |    |    |    |     |     |
| DD1  |    |    |    |    |    |    |    |    |    |     |     |
| DD2  |    |    |    |    |    |    |    |    | X  |     |     |
| DD3  |    |    |    |    |    |    |    |    | X  |     |     |
| DD4  |    |    |    |    |    |    |    |    |    |     |     |
| DD5  |    |    |    |    |    |    |    |    | X  |     |     |
| DD6  |    |    |    |    |    |    |    |    | X  |     |     |
| DD7  |    |    |    |    |    |    |    |    |    |     |     |
| DD8  |    |    |    |    |    |    |    |    | X  |     |     |
| DD9  |    |    |    |    |    |    |    |    | X  |     |     |
| DD10 |    |    | X  | X  | X  |    |    |    |    | X   | X   |
| DD11 |    |    | X  | X  | X  |    |    |    |    | X   | X   |
| IM1  |    | X  |    |    |    | X  |    |    |    | X   | X   |
| IM2  |    |    |    |    |    | X  |    |    |    | X   | X   |
| IM3  |    | X  |    |    |    | X  |    |    |    | X   | X   |
| IM4  | X  |    |    |    |    |    |    |    |    |     |     |
| LC1  |    |    | X  |    |    |    |    |    |    |     |     |
| LC2  |    |    |    |    |    |    |    |    |    | X   |     |
| LC3  |    |    |    |    |    |    |    |    |    |     | X   |

Table 4: Traceability Matrix Showing the Connections Between Assumptions and Other Items



|     | IM1 | IM2 | IM3 | IM4 | 5.2.6 | R1 |
|-----|-----|-----|-----|-----|-------|----|
| IM1 |     |     |     |     |       | X  |
| IM2 |     |     |     |     |       | X  |
| IM3 |     |     |     |     |       | X  |
| IM4 |     |     |     |     |       | X  |
| R1  |     |     |     |     |       |    |
| R2  |     |     |     |     | X     |    |
| R3  |     |     |     | X   |       |    |
| R4  | X   | X   | X   |     |       |    |
| R5  |     |     |     | X   |       |    |
| R6  |     |     |     |     | X     |    |
| R7  |     |     |     |     | X     |    |
| R8  | X   | X   | X   |     |       |    |
| R9  | X   | X   | X   |     |       |    |
| R10 | X   | X   | X   |     |       |    |

Table 5: Traceability Matrix Showing the Connections Between Requirements and Instance Models

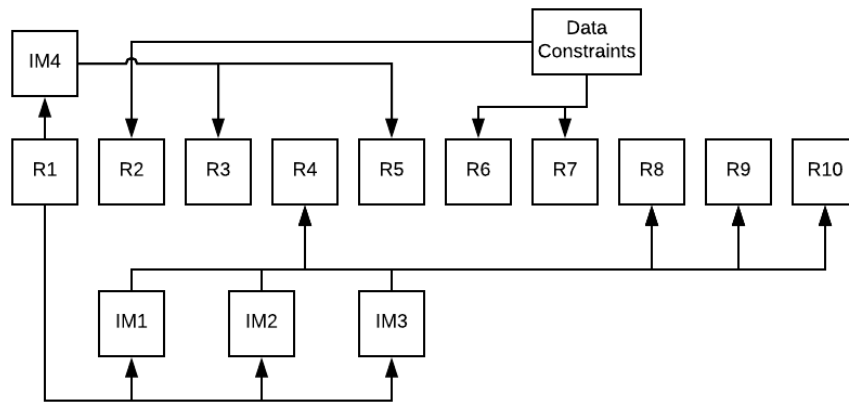


Figure 6: Traceability Matrix Showing the Connections Between Requirements, Instance Models, and Data Constraints

|      | T1 | T2 | T3 | T4 | GD1 | GD2 | GD3 | GD4 | GD5 | GD6 | GD7 |
|------|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| T1   |    |    |    |    |     |     |     |     |     |     |     |
| T2   |    |    |    |    |     |     |     |     |     |     |     |
| T3   |    |    |    |    |     |     |     |     |     |     |     |
| T4   |    |    |    |    |     |     |     |     |     |     |     |
| GD1  |    | X  |    |    |     |     |     |     |     |     |     |
| GD2  |    | X  |    |    |     |     |     |     |     |     |     |
| GD3  |    |    | X  | X  |     |     |     |     |     |     |     |
| GD4  | X  |    | X  | X  |     |     | X   |     |     |     |     |
| GD5  |    |    |    | X  |     |     |     |     |     |     |     |
| GD6  |    |    |    |    |     |     |     |     |     |     |     |
| GD7  |    | X  |    |    |     |     |     |     |     |     |     |
| DD1  |    |    |    |    |     |     |     |     |     |     |     |
| DD2  |    |    |    |    |     |     |     |     |     |     |     |
| DD3  |    |    |    |    |     |     |     |     |     |     |     |
| DD4  |    |    |    |    |     |     |     |     |     |     |     |
| DD5  |    |    |    |    |     |     |     |     |     |     |     |
| DD6  |    |    |    |    |     |     |     |     |     |     |     |
| DD7  |    |    |    |    |     |     |     |     |     |     |     |
| DD8  |    |    |    |    |     |     |     |     |     |     |     |
| DD9  |    |    |    |    |     |     |     |     |     |     |     |
| DD10 |    |    | X  | X  | X   | X   | X   | X   | X   |     |     |
| DD11 |    |    | X  | X  | X   | X   | X   |     |     |     |     |
| IM1  | X  |    |    | X  |     |     |     |     |     | X   |     |
| IM2  |    | X  |    | X  |     |     |     |     |     | X   | X   |
| IM3  |    |    |    | X  | X   | X   |     | X   |     | X   |     |
| IM4  |    |    |    |    |     |     |     |     |     |     |     |

Table 6: Traceability Matrix Showing the Connections Between Items of Different Sections With Theory Models and General Definitions

|      | DD1 | DD2 | DD3 | DD4 | DD5 | DD6 | DD7 | DD8 | DD9 | DD10 | DD11 | IM1 | IM2 | IM3 | IM4 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|-----|-----|-----|-----|
| T1   |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| T2   |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| T3   |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| T4   |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| GD1  | X   |     | X   | X   | X   | X   |     |     |     |      |      |     |     |     |     |
| GD2  | X   |     | X   | X   | X   | X   |     |     |     |      |      |     |     |     |     |
| GD3  |     |     |     |     |     |     |     | X   |     |      |      |     |     |     |     |
| GD4  |     |     |     |     |     |     |     | X   |     |      |      |     |     |     |     |
| GD5  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| GD6  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| GD7  | X   |     | X   | X   | X   | X   | X   |     |     |      |      |     |     |     |     |
| DD1  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| DD2  |     |     |     |     |     |     |     | X   |     |      |      |     |     |     |     |
| DD3  |     |     |     |     |     |     |     |     | X   |      |      |     |     |     |     |
| DD4  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| DD5  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| DD6  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| DD7  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |
| DD8  |     |     |     |     | X   |     | X   |     |     |      |      |     |     |     |     |
| DD9  |     |     |     |     |     | X   | X   |     |     |      |      |     |     |     |     |
| DD10 | X   | X   | X   | X   | X   | X   | X   |     |     |      |      |     |     |     |     |
| DD11 | X   |     | X   | X   | X   | X   | X   |     |     |      |      |     |     |     |     |
| IM1  | X   | X   | X   | X   | X   | X   | X   |     |     | X    | X    |     | X   | X   |     |
| IM2  | X   | X   | X   | X   | X   | X   | X   |     |     |      |      | X   |     | X   |     |
| IM3  | X   | X   | X   | X   | X   | X   | X   |     |     | X    |      | X   | X   |     |     |
| IM4  |     |     |     |     |     |     |     |     |     |      |      |     |     |     |     |

Table 7: Traceability Matrix Showing the Connections Between Items of Different Sections with Data Definitions and Instance Models

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