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Method for susceptibility mapping of
rock falls in Norway,
Technical report

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REPORT

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Title:
Method for susceptibility mapping of rock falls in Norway, Technical report

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Summary:

This technical report describes the method used to draw the susceptibility maps for rock falls in Norway. In order to cover the entire territory of Norway, a fully-automatic GIS-based solution was developed and applied. Input data are the gridded digital elevation model of Norway at 25 meter cell size, a bedrock geological map and a quaternary map. The potential release areas are detected applying a slope angle analysis taking into consideration the type of rock and the presence or absence of a superficial cover on the bedrock. The potential propagation zones are delimited coupling a 2D extension of the alpha-beta method with a cone propagation model. In the final product, (1) potential release areas and (2) potential propagation zones are mapped. Finally limitations and issues related to the use of these maps are discussed in the last chapter.

Keywords:	Susceptibility mapping	Rock fall
National coverage	Release areas	Propagation zones
Alpha-beta method	Shadow angle	GIS

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1 Introduction

1.1 Context and goals

In 2007, in the frame of the project "National Susceptibility Mapping of Geohazards" at NGU, it was decided to draw maps of susceptibility for rock falls for the whole Norwegian territory. These maps aim to provide a first overview (screening) of the entire country, in a relatively short time, at reduced costs, and with an automatic procedure applied homogeneously to the whole country. The main requirements for these maps are:

- To cover the entire Norwegian territory (385'000 km^2)
- To assess in a simple way the susceptibility of an area of being affected by a rock fall
- To provide maps at an indicative scale of around 1:50'000 within a short time frame (around 2 years)
- To use only data already available for the entire area

A large part of this work was achieved within the cooperation between the Geological Survey of Norway (NGU) and the Institute of Geomatics and Risk Analysis (IGAR) of the University of Lausanne, including the development of new methods and softwares.

This report describes the method used to draw these susceptibility maps. It explains the reasons of some scientific or technical choices, presents the main advantages and drawbacks of the method used, and pays a particular attention to make clear that the final maps delivered with this work have limitations that must be respected.

1.2 Some definitions

The definitions used in this report are conform to those of Fell et al (2008):

Danger: The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The characterisation of a danger does not include any forecasting.

Hazard: A condition with the potential for causing an undesirable consequence. The description of any landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Susceptibility: A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of a danger which exists or potentially may occur in an area. <u>The susceptibility does not provide any information about the probability that an event occurs (hazard), nor about the consequences of an event (risk).</u>

Risk: A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability × consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Rock fall: the definitions of Cruden & Varnes (1996) are used in this study*: "A rock fall starts with the detachment of a piece of rock from a steep slope on which little or no shear displacement takes place. The material then descends mainly through the air by falling, bouncing or rolling. Movement is very rapid to extremely rapid"*. The method presented here does not address rock "slides", "spreads" or "flows" (rock flow = rock avalanche). The term rock fall refers to blocks falling with negligible dynamic interactions between each others, as opposed to rock flow.

2 Description of the method

2.1 Principles

The method used to draw these susceptibility maps is an extension to 2D (map) of the “shadow angle” (or Fahrböschung) concept of Heim (1932). This concept states that the run-out of a rock fall can be modelled by an angle of propagation from the release area of the block. This angle of propagation is named alpha in the present document (Figure 1). In order to determine the value of alpha for each potential release area, a new method was developed based on the alpha-beta method designed initially in 1D (profile) for snow avalanches (Lied & Bakkehøi 1980 , Bakkehøi et al 1983). U Domaas at NGI has adapted this method to rock fall, but still to work on profiles. The main principles of this initial alpha-beta method for rock falls are shortly presented here (Figure 1):

1) A release point, A in Figure 1, is selected
2) The rock fall path starting from A is manually selected and its topographical profile is drawn
3) The point B is then located on the profile where the slope angle =23°
4) The angle beta is measured as the angle between the line AB and the horizontal
5) The angle alpha is then estimated using a statistical relationship between alpha and beta. The simplest relationships are of the type: alpha = m*beta -n, where m and n are empirical coefficients
6) Finally the potential propagation of the rock fall is estimated using the angle alpha as a shadow angle from A.

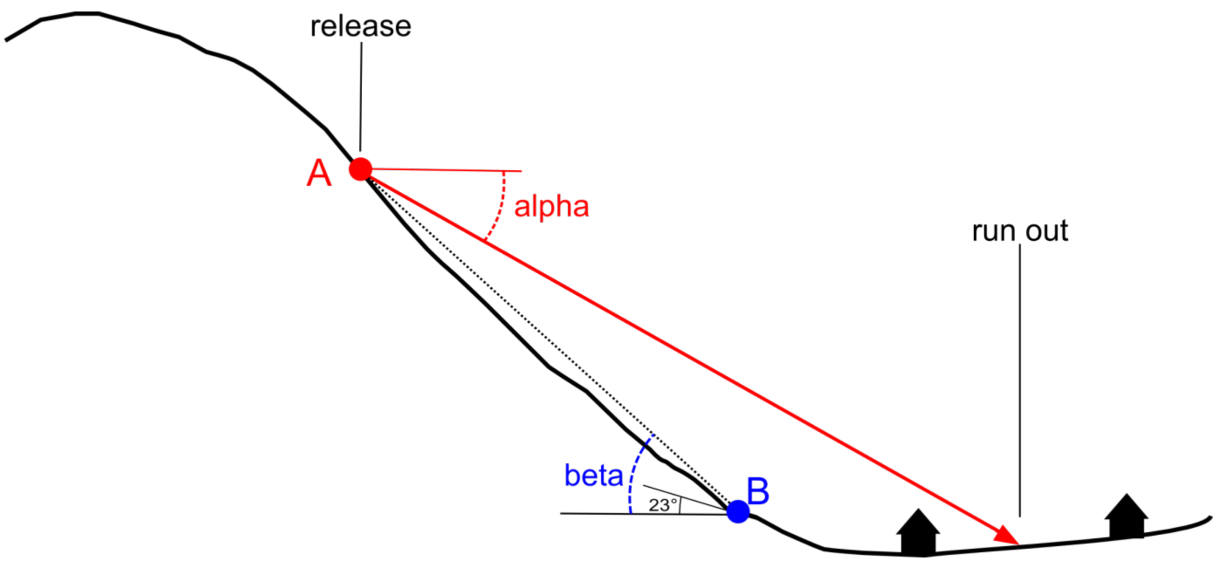


Figure 1 : Basics of the alpha-beta method adapted to rock falls by U. Domaas (NGI)

The alpha-beta method, as described above, requires to define manually the possible propagation corridors. But for the purpose of this project, to cover the entire Norway, the processing had to be fully automatized, without requiring any human interaction or interpreting.

Practically the amount of data to be processed makes it very difficult to use common GIS softwares like ArcGIS. For example, the raw digital elevation model (DEM) of Norway at 25 meters resolution is 3.5 Gigabytes, and it is distributed over three geographical UTM zones. Moreover, several required functionalities are not available in common GIS packages. Therefore an independent code was developed at NGU and IGAR specifically for this project.

In outline, the processing used for this project has two main steps: (1) the determination of release areas, i.e. the areas from which a rock fall can initiate, and (2) the estimation of the propagation zone for this rock fall.

2.2 Datasets

Input datasets:

1) The digital elevation model (DEM), provided by Statens Kartverk to the partners of the Norge Digitalt program, is an elevation grid of 25 m cell size, projected and georeferenced in UTM/WGS84 - zones 32, 33 and 35 N.

2) The geological bedrock map is the “Bergrunn kart” - N250 provided by NGU.

3) The map of superficial cover is the “Løsmasser kart” - mosaic of various scales provided by NGU

No or rock fall inventory or other dataset was used.

Output data: All the processing is done in raster mode and the results of the computations are raster files (geotiff format) in the same projection and coordinate systems than the input data (UTM 32, 33, 35 N / WGS84). At the end of the processing, all the cells of the initial DEM were classified according to three categories: 1) cell included in a release area, 2) cell included in a propagation zone, 3) cell not included in a release or propagation area. In order to make the results easier to handle in GIS environment, the release areas and propagation zones were finally vectorized in polygons (without any smoothing).

2.3 Determination of release areas

2.3.1 Slope analysis principles

The potential release areas were automatically detected by the method of slope analysis of Loye et al (2009), taking into consideration the slope angle, the DEM cell size, the type of bedrock and the outcropping conditions. The main idea of this method is that slope angle thresholds can be used to divide the relief in geomorphologic classes. In order to fix the threshold values, the slope angle distribution is decomposed in Gaussian populations **(**Figure 2**).**

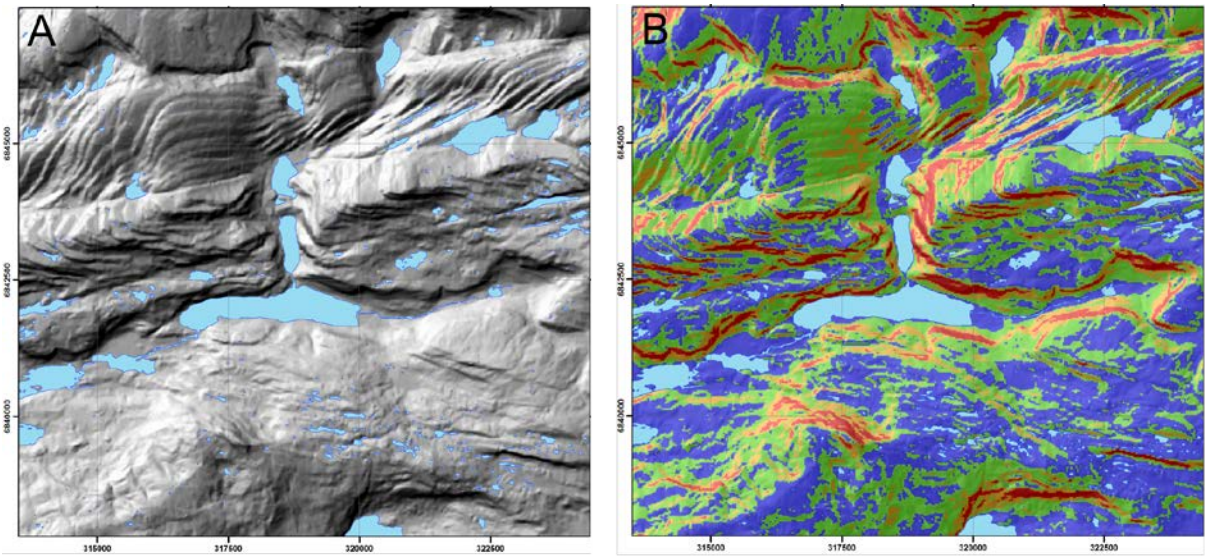
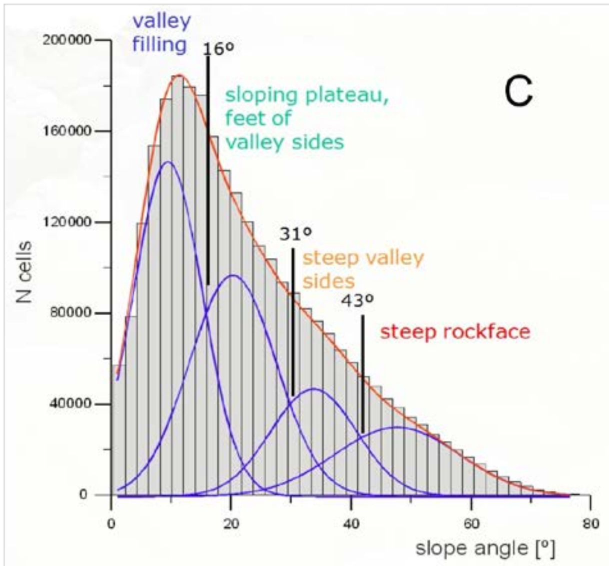
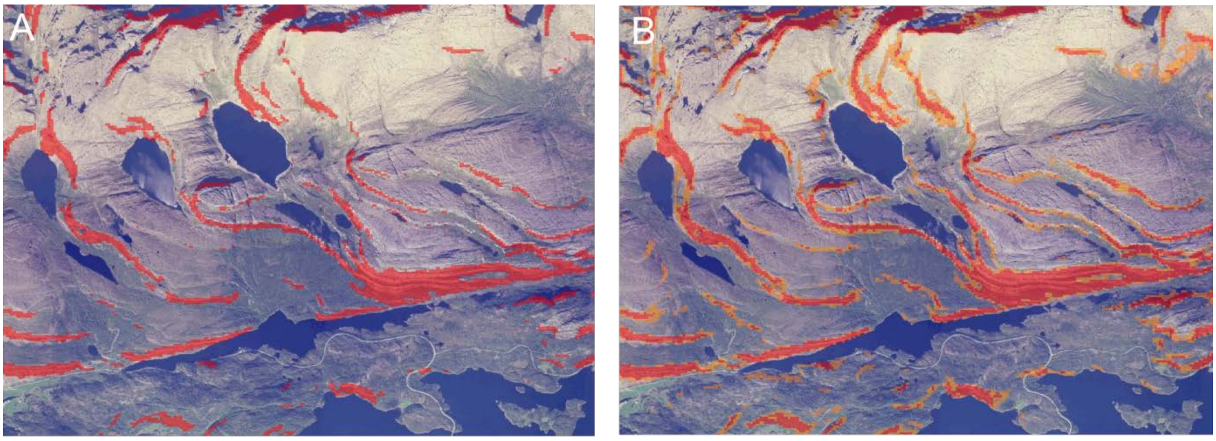


Figure 2 : A) shaded relief based on the 25m cell size DEM, B) segmentation of the relief in four classes according to the slope angle populations, C) histogram of slope angle and decomposition in four Gaussian population. Blue lines = Gaussian populations used to decompose the histogram. Red line = sum of the Gaussian populations. Black vertical lines indicating the threshold values of slope angle.



In this procedure, the threshold values of slope angle are chosen where a class overtakes the previous one. For example, in Figure 2c; the class "steep rock face" overtakes the class "steep valley side" at 43°. This value corresponds to the angle value at the intersection between the Gaussian populations of the two classes. Logically the areas in the class "steep rock face" (>43° in the example of Figure 2) will be considered as potential source areas of rock falls.

But field experience, comparisons with air photos and inventories show that rock falls can also come from less steep terrains, i.e. from the class “steep valley side” (Figure 3a). Nevertheless incorporating the entire “steep valley side” population (everything >31º in the example above) to the potential source areas, would on the other hand overestimate the potential release areas, in particular when the slopes are vegetated and/or covered by soils or quaternary sediments. In order to correct this problem, the procedure (Loye et al 2009) uses the part of the “steep valley side” population which meets the two conditions: 1) the slope angle is higher than the mode of “steep valley side” population (here 34°) and 2) the terrain is on bare rock.



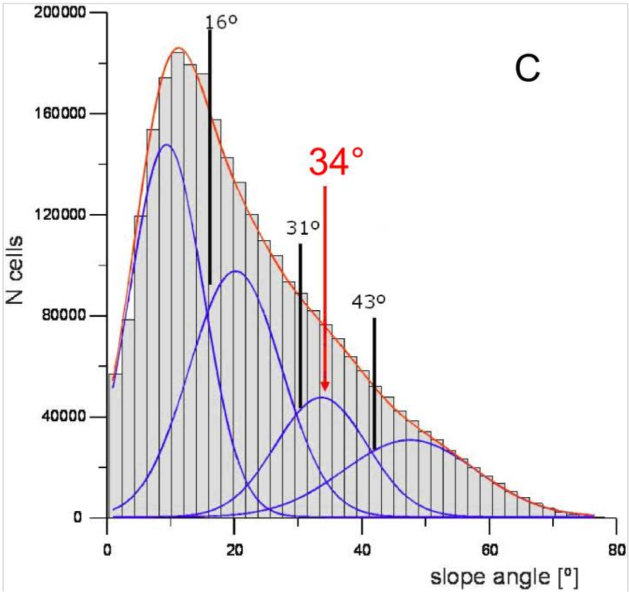


Figure 3 : A) red: the « steep rock face » class (>43°) on an airphoto; B) red: like in A, orange: part of the “steep valley side” considered as potential release areas; C) histogram of slope angle and indication of the mode of the “steep valley side” class (34°)

In conclusion the criteria to determine if a cell of the DEM is in a potential release area is:

Cell in a release area IF: (slope angle > $\delta_{rockface}$) OR
[(slope angle > δ_{side}) AND “on bare rock”]

With: $\delta_{rockface}$ = lower limit angle of the “steep rock face” class (43° in the example)

δ_{side} = mode angle of the "steep valley side" class (34° in the example)

Finally we must be aware that the slope angle thresholds defined above are strongly dependant on the resolution of the DEM and the type of rock. The larger is the cell size of the DEM, the more underestimated is the slope angle of a steep slope (Figure 4). That is why the thresholds angles must be defined using the DEM and values measured in the field cannot be directly used. The mechanical properties of the rocks will influence the values of the slope thresholds too. Consequently, this slope analysis has to be performed for the different types of rocks in order to define proper thresholds for each lithology.

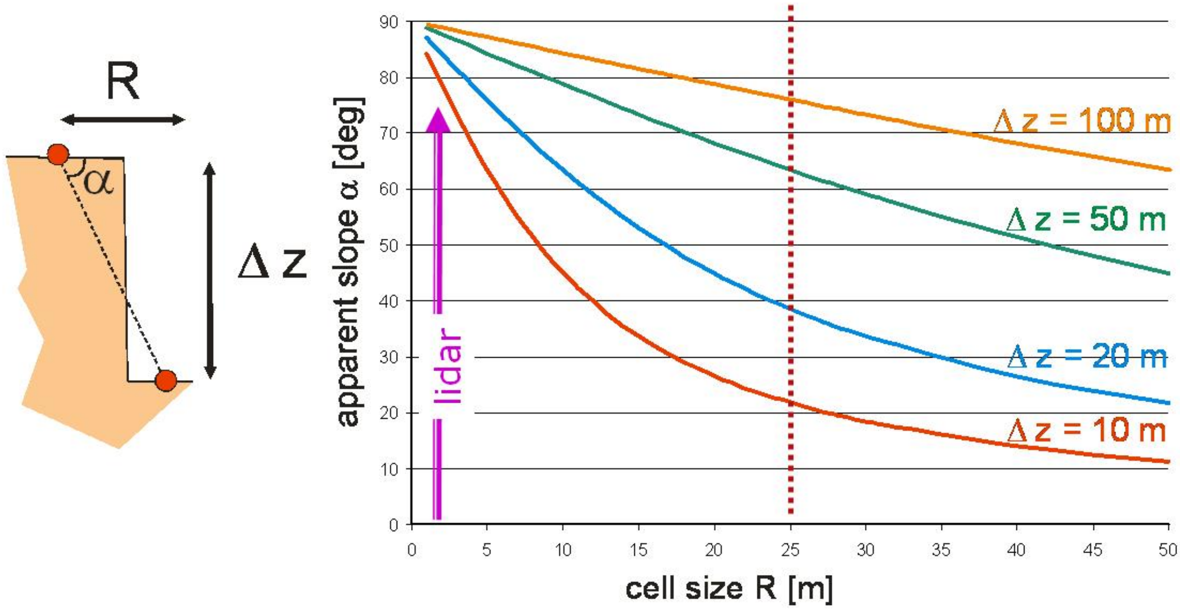


Figure 4 : Simple illustration of the effect of the cell size on the slope angle calculation. With a 25 m cell size, the apparent slope angle of a 20 m high vertical cliff would be around 40°.

2.3.2 Implementation of the slope analysis

As shown in the previous section, the goal of the slope analysis is to define slope angle thresholds that can be used to decide if a cell of the DEM is a potential release area for rock falls. These threshold values depend on (1) the type rock and (2) the presence of a cover (vegetation, soil or quaternary sediments) on the bedrock. Then three dataset are required:

a) A slope map computed from the 25 m cell size DEM. The slope angle is estimated using a 3x3 moving filter, with the algorithm of Horn (1981), exactly in the same way than for example in ArcGis.

b) A map of the main types of rock. The geological bedrock map ("Bergrunn kart" - N250 provided by NGU) map was simplified in order to distinguish five main types of rocks with relatively homogeneous rheological properties. These five types of rock (I to V) are described in Table 1. A sample of the rock-type map used is given in Figure 5.

Rock types

I) Metamorphic Archean rocks, Metamorphic rocks of Proterozoic age, autochthonous (basement) rocks of Precambrian age

(38) Quarzite,Tonalite and Trondhjemitt
(82) Diorit to granitic gneiss, migmatit
(85) Augengneiss, granit, foliert granit
(87) Bandgneis (Amphibolit, Hornblendegneiss, glimmergneiss)

II) Metamorphic rocks of Precambrian Age & Plutonic rocks of Cambro-Silur Age principally

(21) Granit, Granodiorit
(30) Mangerit to Gabbro, Gneiss and Amphibolit
(35) Gabbro, Amphibolit
(45) Anortosit

III) Volcanic and sedimentary rocks of Permo-carboniferous age & Plutonic rocks of Permian age

(22) Diorit, Monzodiorit
(23) Syenit, Quarzsyenit
(24) Monzonit, Quarzmonzonit
(25) Mangeritsyenit
(26) Ryolit, Ryodacit, dacit
(27) Romboporphyr
(28) Metabasalt
(29) Vulcanic rocks (non-specified)

IV) Metamorphic volcanic and sedimentary rocks of late Precambrian age to Silurian age:

(5) Mylonit – phylonit
(7) Sedimentary rocks (non-specified)
(8) schist, sandstone, limestone
(9) sandstone, schist
(10) limestone, schist,marl
(11) limestone, dolomite
(46) charnocklic to anorthositic rock
(50) Amphibolit and mica schist
(55) Greenstein and Amphibolit
(60) Metasandstone, schist
(61) Quarzite
(62) Mica gneiss, Mica schist
(65) Phylit, Mica schist
(66) Calc mica schist, calc silicate gneiss
(70) Marble
(71) Dolomite

V) Devonian sedimentary rocks:

(2) Sandstones
(3) Conglomerat

Table 1 : The five main types of rocks distinguished for the slope analysis. The indexes in brackets refer to the NGU BERGSDE.BE250 BergartFlate database.

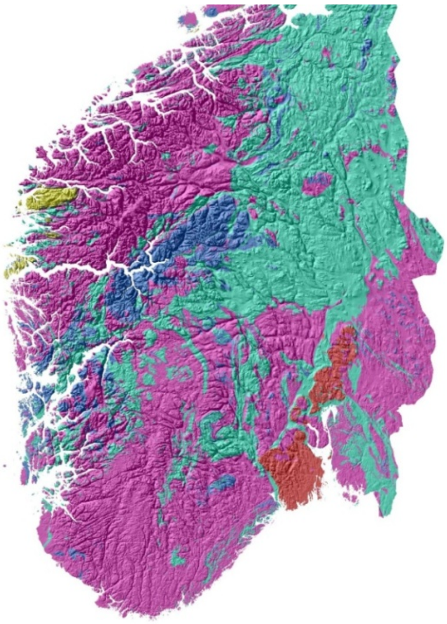


Figure 5: Simplified rock types map. Pink = class I, blue = class II, red = class III, green = class IV, yellow = class V (Table 1)

c) . A “bare rock” map was produced extracting the polygons described as “Bart fjell” in the “Løsmasser” maps database from NGU. A sample of this map is produced in Figure 6.

Figure 6: Bare rock map (pink = bare rock, grey = presence of a cover (vegetation, soil or quaternary sediments) on the bedrock

Following the procedure described in the previous section, a slope analysis was performed for each of the rock class, in order to define representative threshold angles for each type of rock (Table 2). We can notice that the differences between the rock types are small; this is mainly due to the low resolution of the DEM (25 meter cell size), which tends to homogenise the results. With a 2m resolution DEM, these thresholds would have been much more different.

	Threshold anywhere ($\delta_{rockface}$)	Threshold on bare rock (δ_{side})
Class I	≥ 43º	≥ 35º
Class II	≥ 41º	≥ 35º
Class III	≥ 39º	≥ 35º
Class IV	≥ 38º	≥ 34º
Class V	≥ 38º	≥ 35º

Table 2: Slope angle thresholds for the five classes of rocks. Threshold anywhere = any slope steeper than the angle $\delta_{rockface}$ is considered as a potential release area. Threshold on bare rock = a slope steeper than δ_{side} is considered as a potential relesase area if it is on bare rock.

Finally a map of potential release area has been drawn for the entire Norway according to the procedure defined before. A sample of this map is produced in Figure 7A.

Later we will have to estimate the propagation from each of the 25x25 meters cell included in the release areas. But the surface to cover is huge and then it is judicious to consider a reduction of the number of release cells. Some tests have shown that it is equivalent to take only the outer edges of the release areas (Figure 7B) in order to get the maximum extent of the propagation. This reduction of the number of release cells is done by removing all the cells whose eight direct neighbouring cells are "release cells". Technically, this is done very efficiently with a 3x3 convolution filtering.

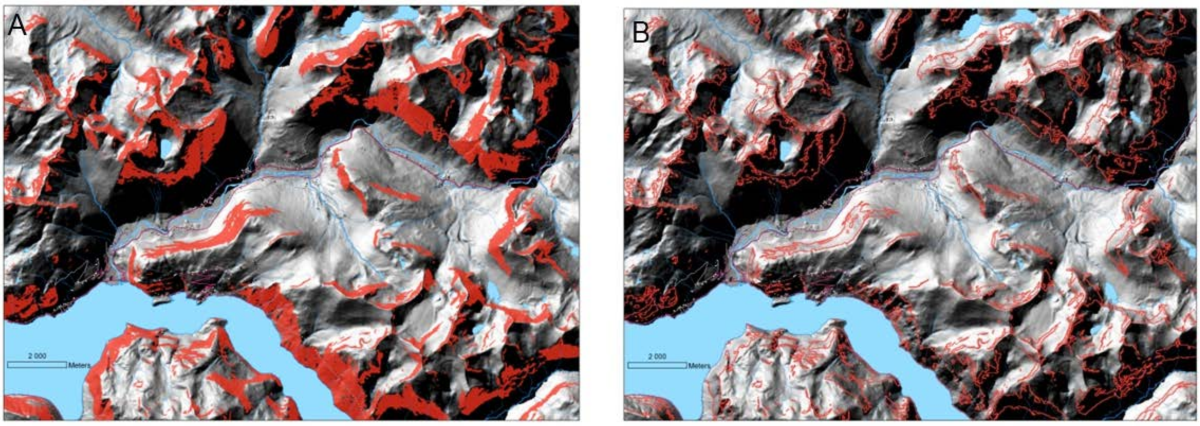


Figure 7: A) sample of the map of potential release areas for rock fall; B) edges of the release areas

2.4 Propagation zones estimation

As mentioned earlier, the estimation of rock fall propagation is based on an adaptation of the shadow angle method and more precisely of the alpha-beta method used for snow avalanches (Figure 1). For the present project, two aspects have to be improved compared to the initial shadow angle method: (1) the new method must produce maps and not only profiles, (2) the processing has to avoid any manual operation and be entirely automatic to be able to cover very large regions.

The steps of the processing used to estimate the propagation zones are illustrated in the flow chart of Figure 8:

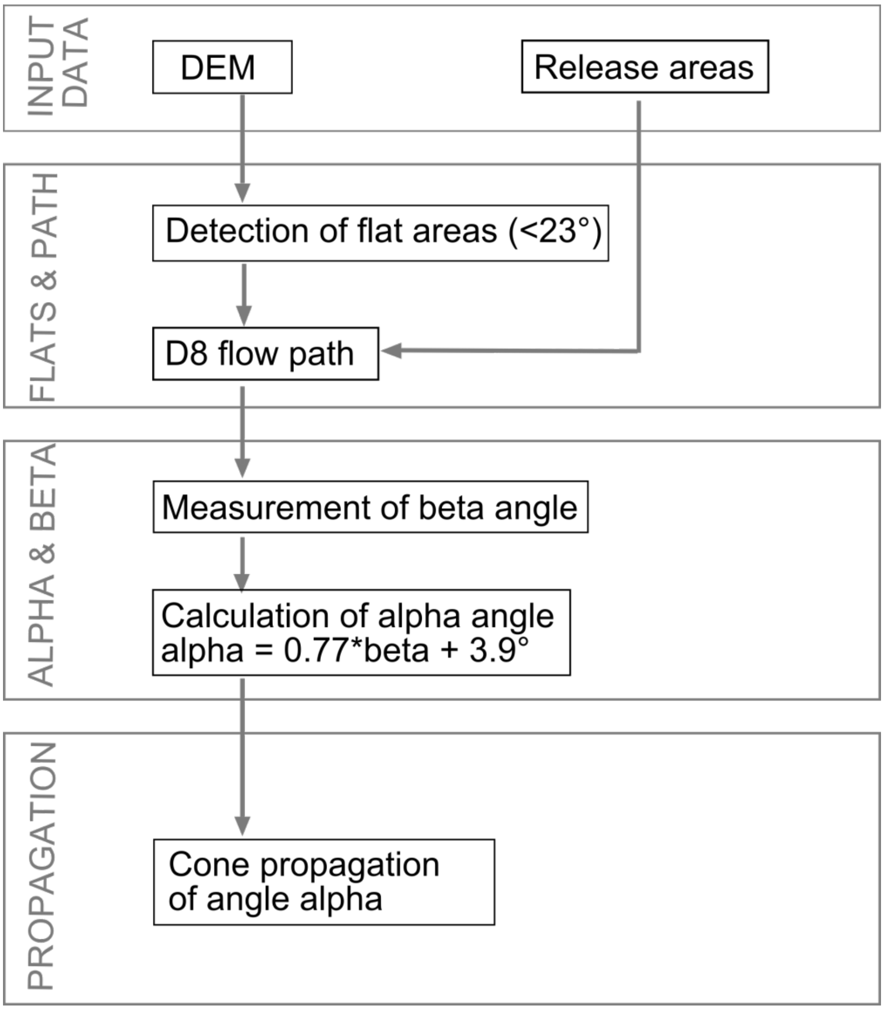


Figure 8 : Flow chart of the rock fall propagation calculation

2.4.1 Input data

The input data for the propagation estimation are: (1) the 25 m grid cells DEM and (2) the edges of the release areas defined previously. Both datasets are raster (geotiff format) projected and georeferenced in UTM/WGS84.

2.4.2 Detection of flat areas

As shown in Figure 1, a point B as to be find for each release cell A. This point B is located along the path where the slope angle gets equal or under 23° (defined by U Domaas, NGI). This point corresponds approximately to the top of the deceleration zone when the blocks reach the valley bottom. But problems occur in determining the point B, if small local flat areas are present along the flow path (Figure 9A). It would be wrong to define a point B on such a local flat, as this point does not correspond to the location where the block velocity starts to decrease.

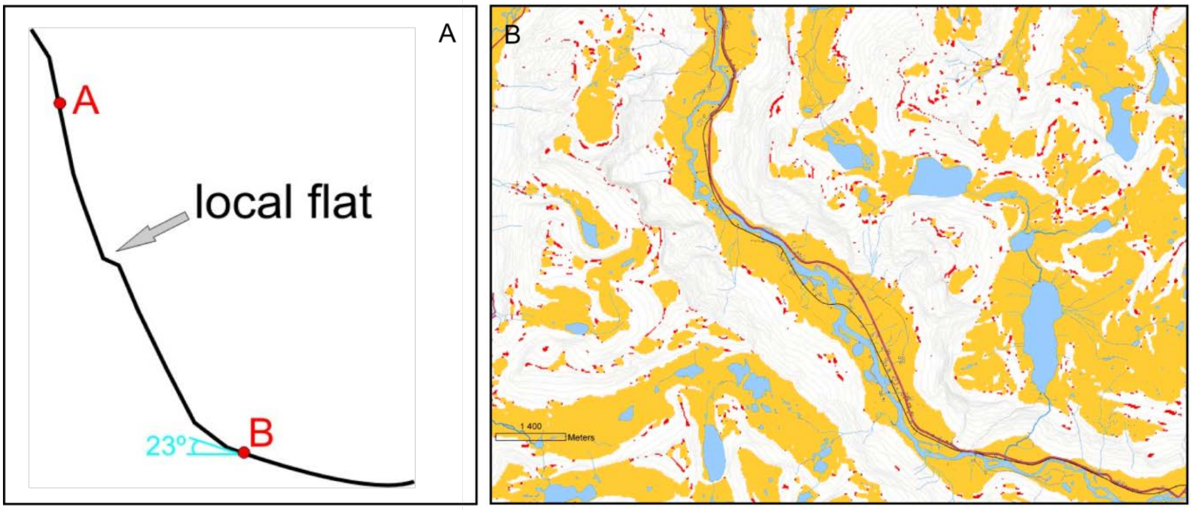


Figure 9: A) Point B determination and the problem of local small flat areas; B) orange+red= areas where the slope is ≤ 23º. Red = areas removed after filtering (morphological opening 3x3), orange= area kept after filtering.

In order to detect only major flat areas and reject small local shoulders, a two steps processing was applied: 1) selection of cells with slope ≤ 23° in a binary grid, 2) filtering of the binary grid with a morphological operator of opening (size 3x3). This procedure removes small flat areas without modifying larger flat areas (Figure 9B). In practice a map of large flat areas is produced and used in the next step of the processing.

2.4.3 Propagation path determination

A flow path is computed from each release cell of the DEM with the algorithm D8 (Jenson & Domingue 1988): the flow passes from one cell to the lowest of its 8 neighbouring cells. The flow path is stopped when the path reaches a cell that belongs to one of the large flat areas defined in the previous step (point B in Figure 1 and Figure 10). Finally, one cell B is associated to each release cell A.

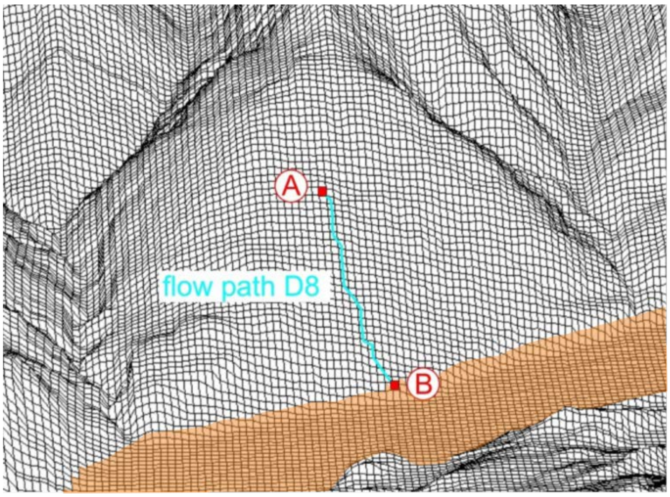


Figure 10 : D8 flow path from the release cell A to the point B where the slope angle of the DEM is ≤ 23º. Orange: large flat area

2.4.4 Estimation of alpha and beta angles

For each couple of points AB, the angle beta is measured like on the Figure 1: beta is the angle between the line AB and the horizontal. Then the alpha angle is calculated with the relationship:

$$\alpha = 0.77 * \beta + 3.9º$$

This relationship is a linear regression defined from U. Domass (NGI - unpublished), based on an inventory of 122 rock fall events (coefficient of determination = 0.80, standard deviation = 2.16°). The bigger alpha is, the shorter is the propagation.

A value of alpha is then attributed to each release cell A. In U−shape valleys the path AB are quite simple, flowing straight down the valley flanks. But in other contexts they can be tortuous and get through a long distance before to reach a locations with a slope ≤ 23°. In these cases, beta angles can be very low. That is why the value of alpha is limited to a minimum of 30º.

$$\alpha = 0.77 * \beta + 3.9º \quad \geq 30°$$

2.4.5 Cone of propagation

The cone propagation technique was developed for rock falls first by Jaboyedoff & Labiouse (2003). Once a value of alpha angle is attributed to a release cell, a vertical cone can be drawn (Figure 11A), with its apex located in the release cell. The zone of potential propagation from a release cell is delimited by the intersection of the cone with the DEM (Figure 11B).

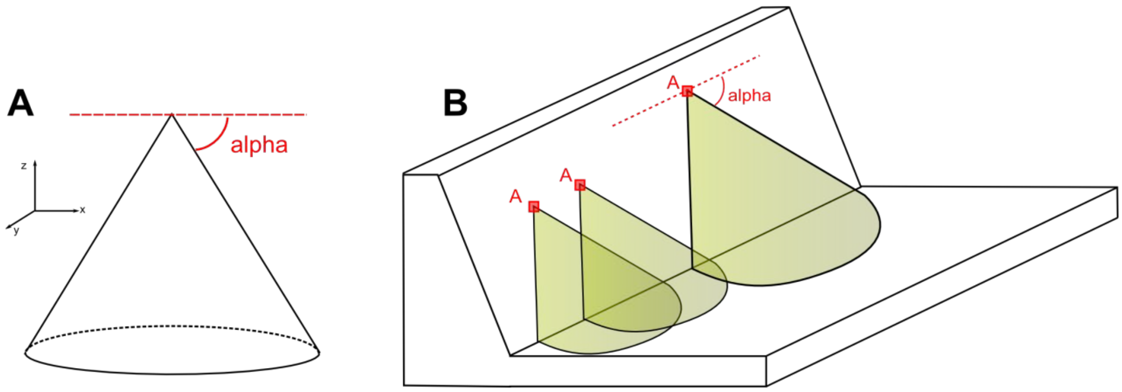


Figure 11 : A : cone of propagation with an angle of propagation alpha; B: intersection of some propagation cones on a simplified topography.

The propagation can also be constrained laterally by an opening angle δ (or dispersion angle), whereas the actual opening is 2*δ (Figure 12). The angle δ defines how far the blocks can deviate from the steepest flow path (path AB). Crosta & Agliardi (2004) propose a maximum value of 15º for δ. A very conservative value δ = 30º was selected for the final maps. Tests have shown that this parameter is by far not critical and that the results are only very slightly sensitive to its value.

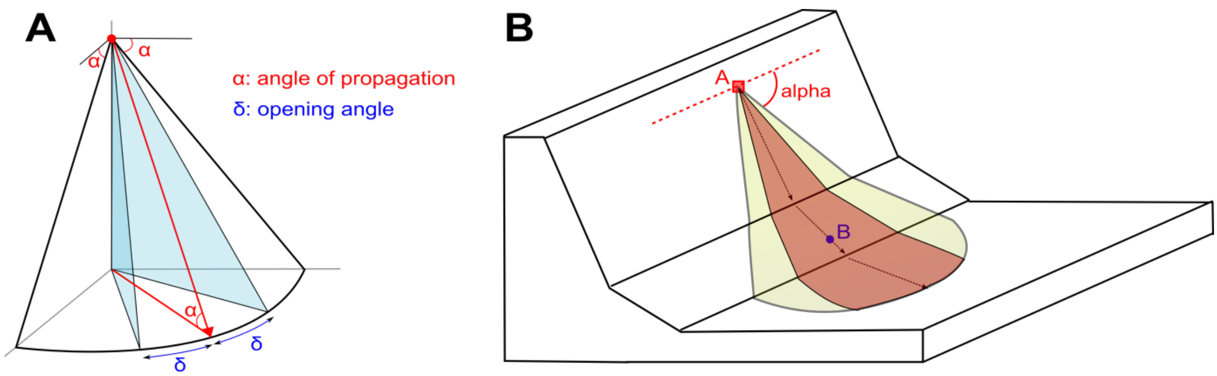


Figure 12 : A: Principle of the limiting opening angle used to reduce the possible dispersion of a rock fall from its main path. B: Application of the opening angle on a simplified topography (yellow: full cone propagation, red: propagation reduced laterally to the opening angle).

2.4.6 Final propagation zones

The final propagation zones are defined by the union of all the cone propagation areas. If a cell of the DEM is in at least one cone of propagation, then this cell is considered as "susceptible" and then included in a final propagation zone. A cell in a propagation zone can be included in only one cone or be at the intersection of several propagation cones. There is no distinction of the number of release cells that may reach a propagation cell in the final product. The final map is then a binary map: inside/outside an area susceptible to be reached by a rock fall (Figure 13).

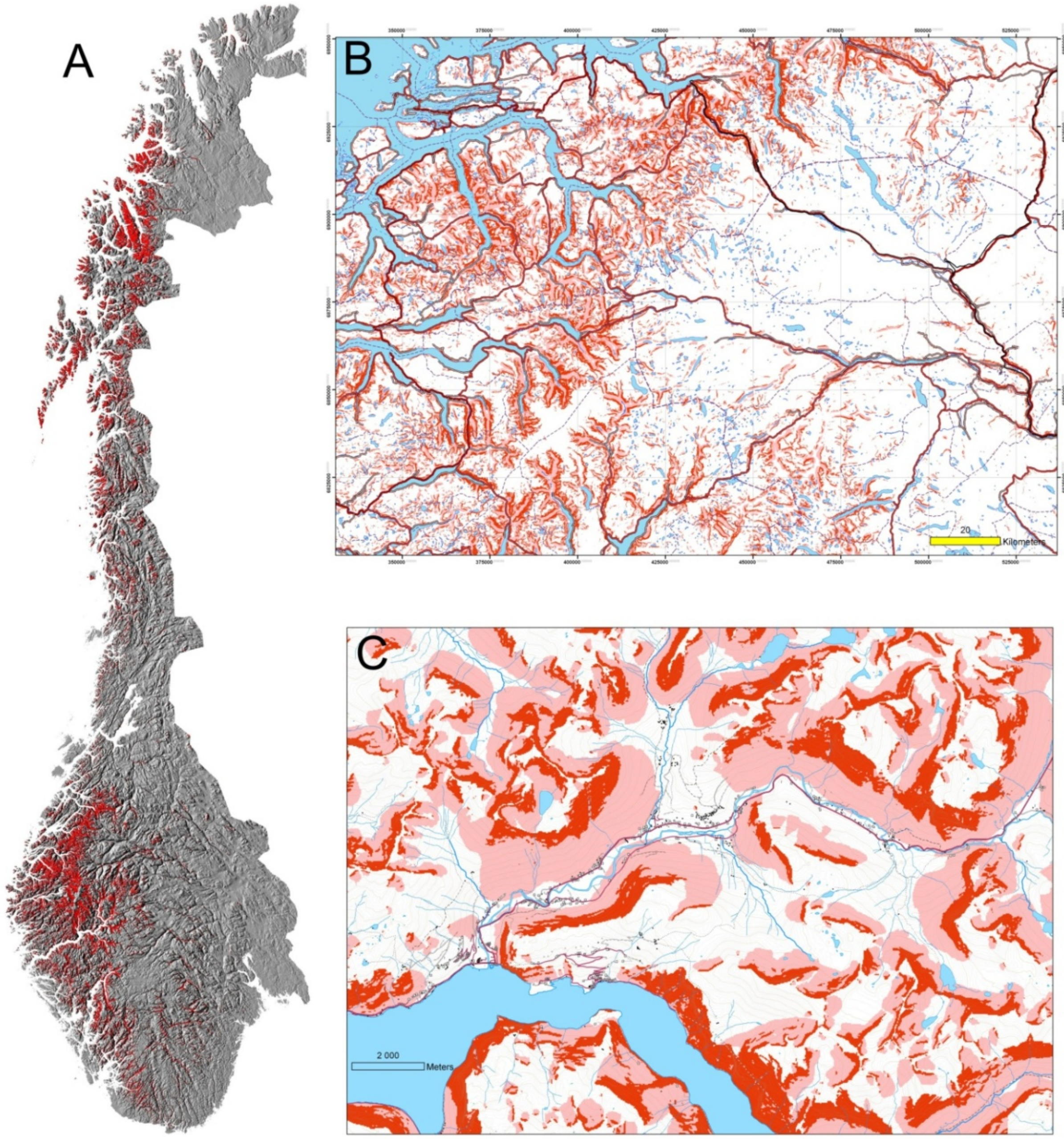


Figure 13 : A) Overview of the the final susceptibility map for rock falls overlain on a shaded relief. B) and C) Extracts of the rock fall susceptibility map. Red: release areas, pink: propagation zones.

3 Discussion

The technical description of the procedure used to draw these susceptibility maps is provided in the previous chapter. It is now important to discuss some issues related to the use of these maps. Modelling a complex phenomena such as rock fall implies strong simplifications, technical and strategic choices. All these factors will influence the final product and define its potential field of applications.

3.1 Information content

The maps produced in this project provide a qualitative assessment of the susceptibility for a location to be affected by a rock fall (in/out). They do not include any information about: the probability of occurrence of an event, its return period, its intensity or the consequences of an event on the elements at risk (population and infrastructures).

3.2 DEM resolution and error

The most important piece of input data is the 25 m gridded digital elevation model (DEM) provided by Statens Kartverk. Some limitations are inherent to the quality of this DEM: (1) some few errors were detected in the original DEM (unrealistic pits) and corrected, (2) the relatively low resolution of the DEM (one point each 25 m) is a more important limiting factor. As the DEM surface is a simplified representation of the real topography, some morphological features may be missing. In particular, steep slope calculation can be affected by strong underestimations (Figure 4). It has for main consequence that short steep cliffs can be missed during the detection of release areas.

3.3 Forest cover

It was decided in this project not to take into account the forest cover. The main reason for this choice are:

- No dataset of the forest cover and suitable for our purpose is available for the whole country. In addition such a dataset should be periodically updated to take into consideration land-use changes.
- Even if such a dataset was available, then the impact of forest cover on rock fall propagation should have been defined. This interaction is quite complex and many parameters are required to model it (trunk diameters, restitution coefficients,…) This is beyond the scope of this project, as it was decided to always consider the worst case scenario.

3.4 Parameters choice

Such small scale (= large area, few details) susceptibility assessment are made to be conservative: we prefer to overestimate than underestimate the hazardous zones. All the parameters used during the processing were selected along this conservative line. Then the final result aims to represent the worst case possible scenario. It means too that some propagation areas may be overestimated.

In particular, a frequent drawback of shadow angle models is the overestimation of the propagation when a high and steep cliff is over a flat bottom valley. Technical solutions exist to correct partly these drawbacks. They have not been tested or applied to the present product but should be considered for a next version.

It must be reminded that only rock falls are considered here, and not rock flows. Rock flows (or rock avalanches) may occur when a very large volume (millions of cubic meter) of rock collapses, but they are much less common than rock falls. In rock flow the interactions between the blocks are no more negligible and the propagation run-out is considerably longer. For comparison, the alpha angle of a rock flow can be 15° (in this project, the minimum threshold of alpha is 30°).

3.5 Operational use

A particular caution must be taken not to over-interpret these susceptibility maps. This maps aim to provide a first overview, a screening over the entire country, of the regions that may be exposed to rock falls. They can be used to identify risk hotspots at regional scale and to help prioritizing future more detailed hazard assessment. Even if in a digital format, they must not be used at scale more detailed than 1:50'000. They do not replace in any way fieldwork, detailed mapping and specific site investigations. In particular, these maps cannot be used for detailed planning such as house or road implementation

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