EXCEL-BASED TOOL FOR THE RISK ANALYSIS OF ROCK-FALL PROTECTION GALLERIES

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Overview

- Methodology
  - Detachment process
  - Falling process
  - Failure gallery
  - Consequences
- Software demonstration

Introduction

- The knowledge of the risk enables the strategic planning of risk reduction measures and the budget planning.

- The currently used methodologies in the field of natural hazards have principle drawbacks :

  - Strong simplification→ restricted informative value

  - Probabilistic modeling knowledge required→ High effort

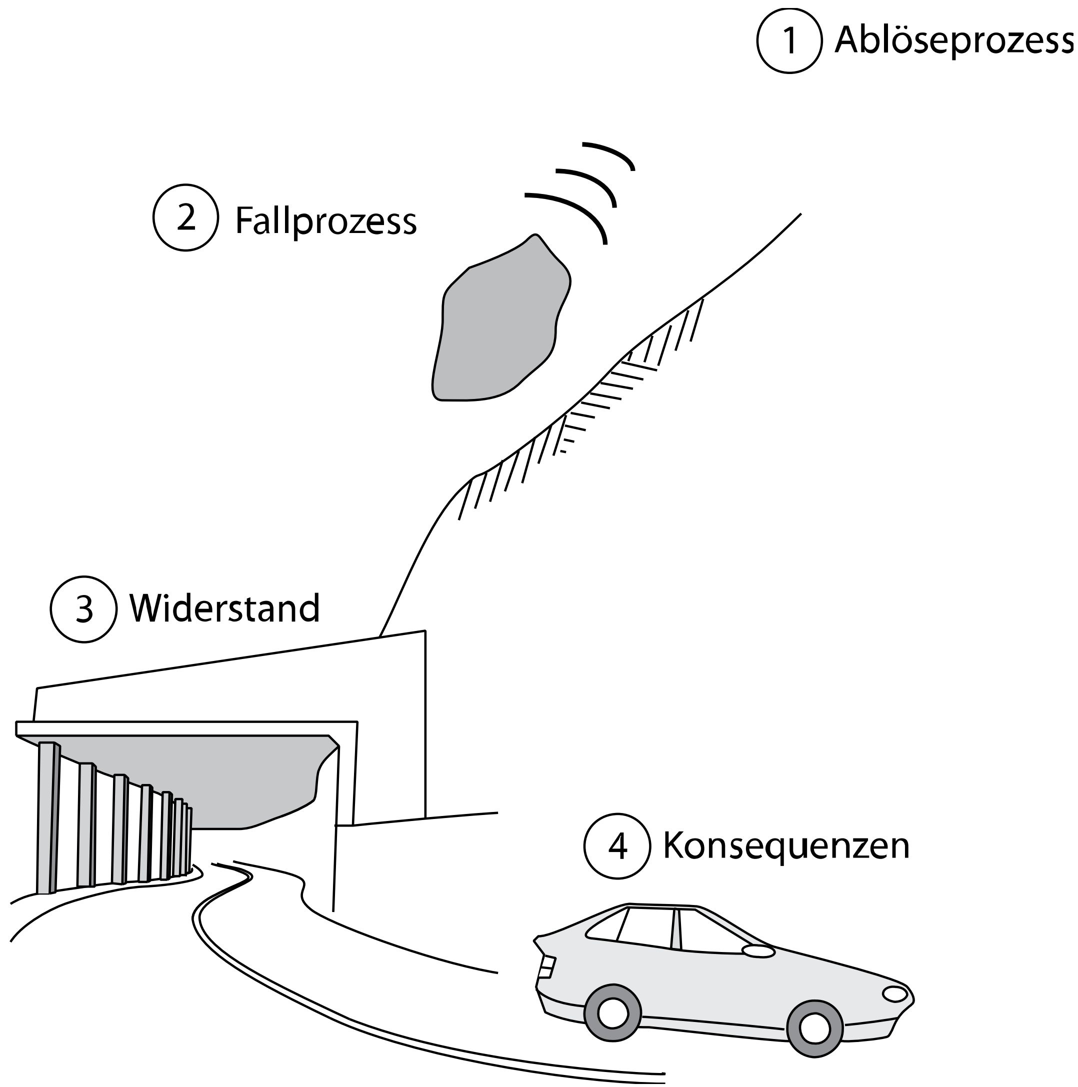
Introduction

- Generic models can close this gap

- Such models enables:

  - The efficient assessment of risks – and automatic generation of hazard maps

  - Use in the strategic planning (land use, investment in risk reduction measures)


1 Ablöseprozess
2 Fallprozess
3 Widerstand
4 Konsequenzen

Start | System definition

System definition

Gallery	
Name of the gallery	Galerie Tellsplatte
Name of the road	N4
Geological region	Helvetic Nappes
Year of construction [*aaaa*]	1998
Thickness of the slab [*cm*]	80
Cushion layer [*cm*]	100
Length [*m*]	144.8
Length of a section [*m*]	6
Number of lanes per direction [#]	2
Directions [#]	1

Project	
Name of the author	
Project ID	
Project Name	
Client	
Date	
Version	

Affirm system definition

Traffic characteristics	μ	σ	Distribution
AADT per direction [*Vehicles per day*]	2000	150	Log-Normal
HGV [*% of AADT*]	6		
Congestions hours [a^{-1}]	100	30	Log-Normal
Signalized speed [*km/h*]	80		

Modeling of the detachment process

System Exposures

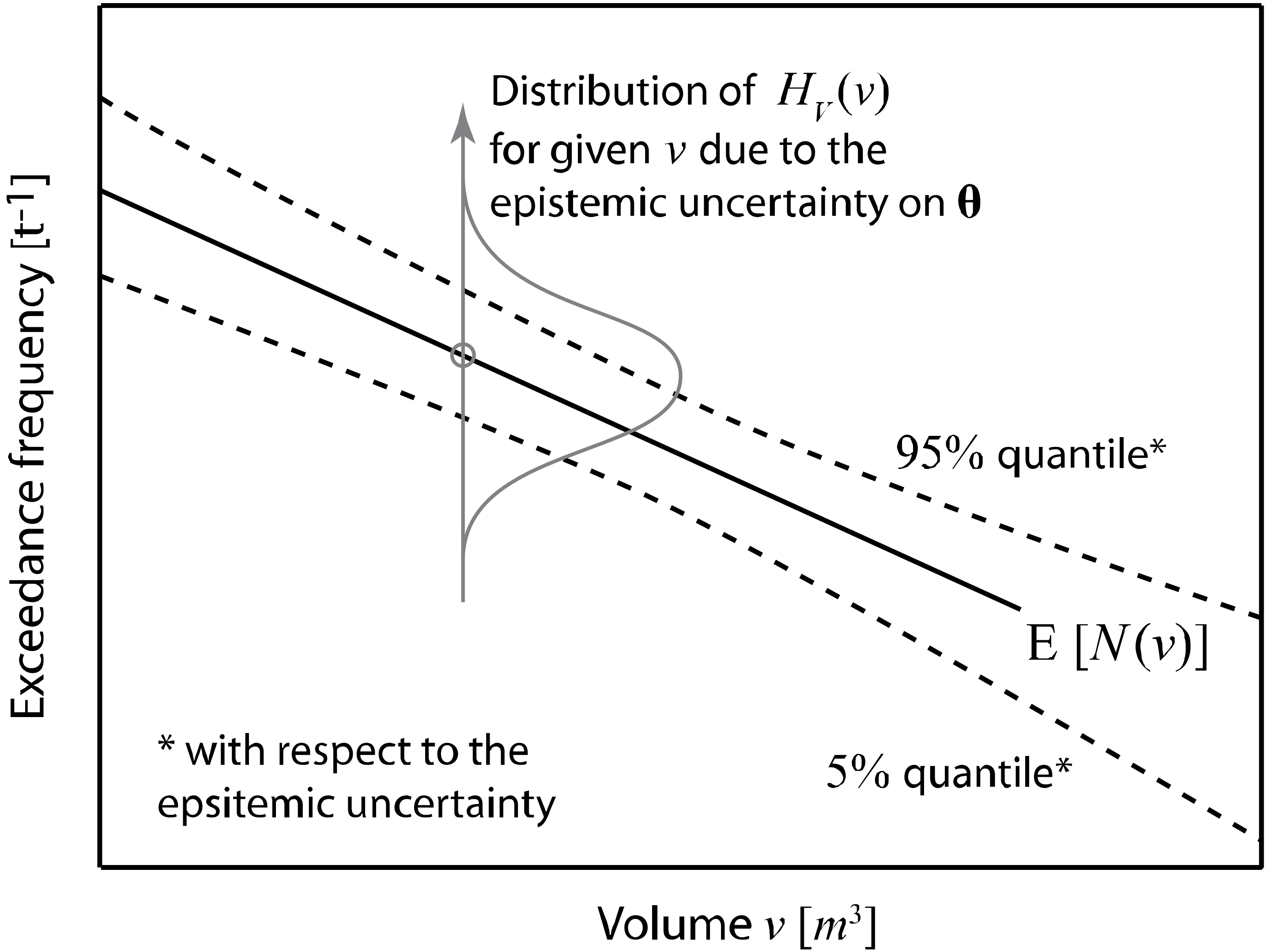
- The relevant parameter is the volume of a detached rock volume V or rock mass.
- Rockfall is an uncertain process – impossible to predict the time and extend of the next event.
- The relevant rock-fall parameter can be described as a random variable V.
- Typically described by its annual exceedance frequency $H_V(v) = E[\,N(v)\,]$.

Uncertainties in the modeling

It is reasonable to distinguish:

- Aleatoric uncertainties

- Epistemic uncertainties


Distribution of $H_V(v)$
for given v due to the
epistemic uncertainty on $\boldsymbol{\theta}$
95% quantile*
E $[N(v)]$
5% quantile*
* with respect to the
epsitemic uncertainty
Exceedance frequency [t^{-1}]
Volume v $[m^3]$

Uncertainties in rock-fall exposure

- The exceedance frequency can be described by , e.g.:

$$H_V(v|\theta) = a\, v^{-b}$$

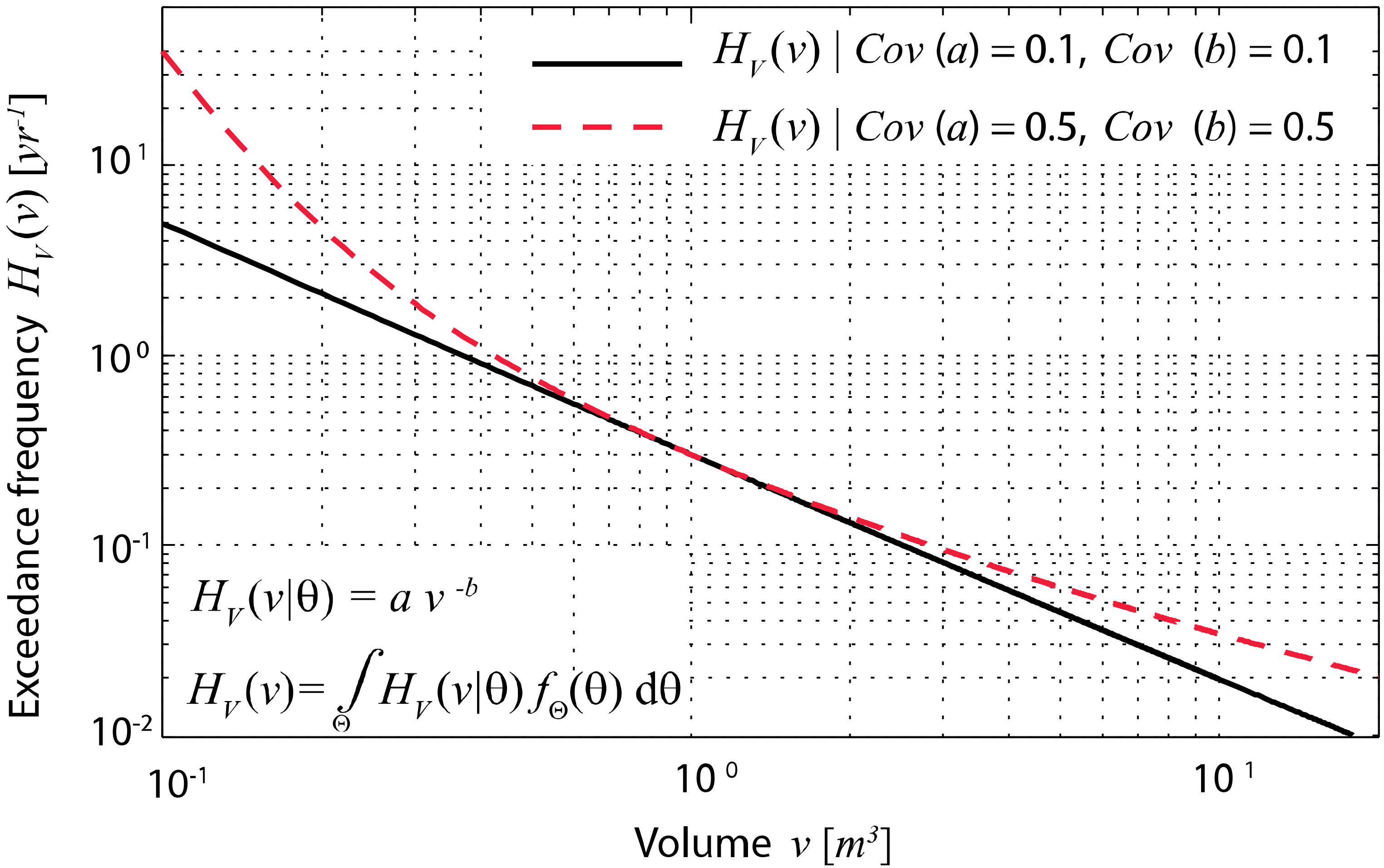
- Include the epistemic uncertainties by modeling the parameters (A,B) as a random vector $\theta = [a,b]^T$

$$f_\Theta(\theta) \qquad \Theta \sim LN(\mu_a, \mu_b, \sigma_a, \sigma_b, \rho_{a,b})$$

- The unconditional exceedance frequency can be calculated:

$$H_V(v) = \int_\Theta H_V(v|\theta)\, f_\Theta(\theta)\, d\theta$$

Uncertainties in rock-fall exposure



Modeling of the rockfall exposure

- For protection structures the annual maximum rockfall event is of interest.

- Derivation of the distribution $f_V(v)$ of the annual maximum rockfall event from the exceedance frequency $H_V(v)$:

exceedance frequency

$$f_V(v) = \frac{d}{dv}(\exp(- \underbrace{H_V(v)}))$$

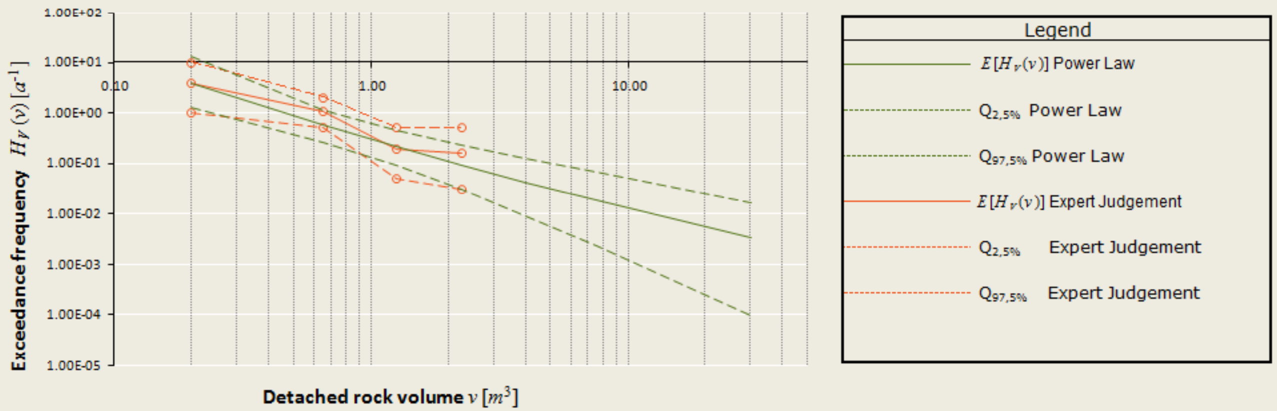
Start | System definition | Exposure model | Generic trajectory analysis

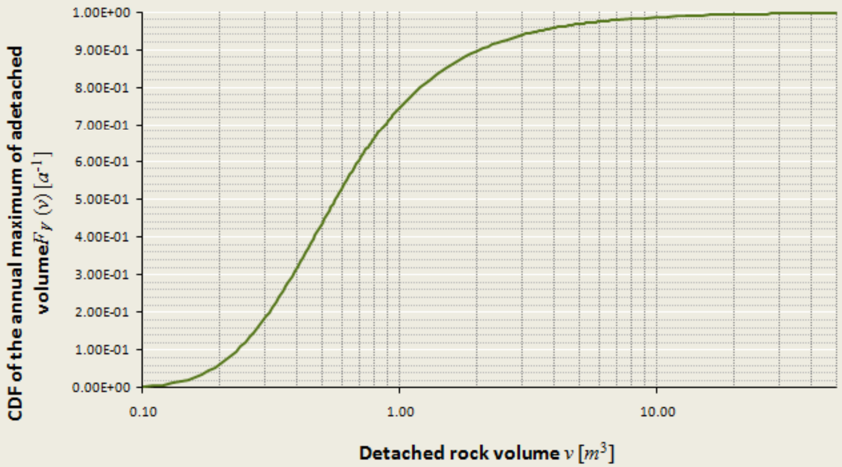
Detachment Model

	Volume V $[m^3]$			Exceedance frequency $H_V(v)$ $[a^{-1}]$ expert judgement				Exceedance frequency $H_V(v)$ $[a^{-1}]$ power-law-modell			
	Range		representative	Quantile		Moments					
	min V	max V	volume $[m^3]$	2.5%	97.5%	$E[H_V(v)]$	$\sigma_{HV(v)}$	$Q_{2,5\%}$	$Q_{97.5\%}$	$E[H_V(v)]$	$\sigma_{HV(v)}$
☑	0.1	0.3	0.2	1	10	3.758E+00	2.412E+00	1.258E+00	1.273E+01	3.875E+00	3.186E+00
☑	0.3	1	0.65	0.5	2	1.065E+00	3.886E-01	2.559E-01	1.106E+00	5.624E-01	2.208E-01
☑	1	1.5	1.25	0.05	0.5	1.879E-01	1.206E-01	8.887E-02	4.370E-01	2.106E-01	9.014E-02
☑	1.5	3	2.25	0.03	0.5	1.585E-01	1.301E-01	2.954E-02	2.282E-01	9.122E-02	5.105E-02
☐	3	5	4	N/A	N/A	N/A	N/A	8.653E-03	1.219E-01	4.147E-02	2.981E-02
☐	5	10	7.5	N/A	N/A	N/A	N/A	2.274E-03	6.632E-02	1.821E-02	1.684E-02
☐	10	50	30	N/A	N/A	N/A	N/A	9.685E-05	1.658E-02	3.303E-03	4.645E-03

Modelcharacteristik	
Likelihood=	5.885E-01
μ_a=	2.961E-01
μ_b=	1.539E+00
σ_a=	8.407E-02
σ_b=	3.490E-01
ρ_{ab}=	-4.600E-01

estimate model parameter





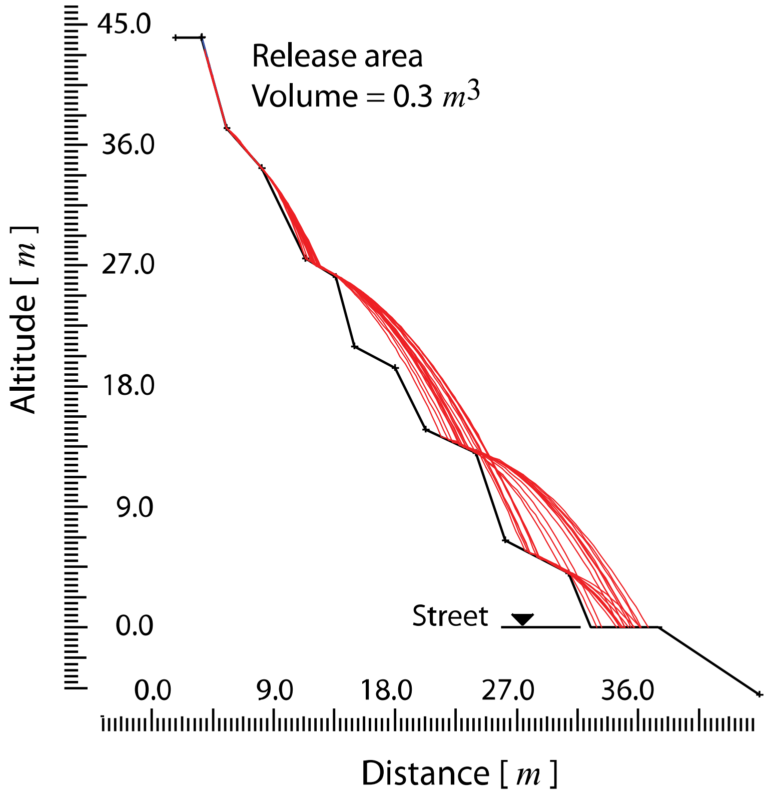
The falling process

Uncertainties in rockfall trajectories

- Once a rock is released its trajectory is mainly determined by the topography, its mode of motion and its material characteristics.

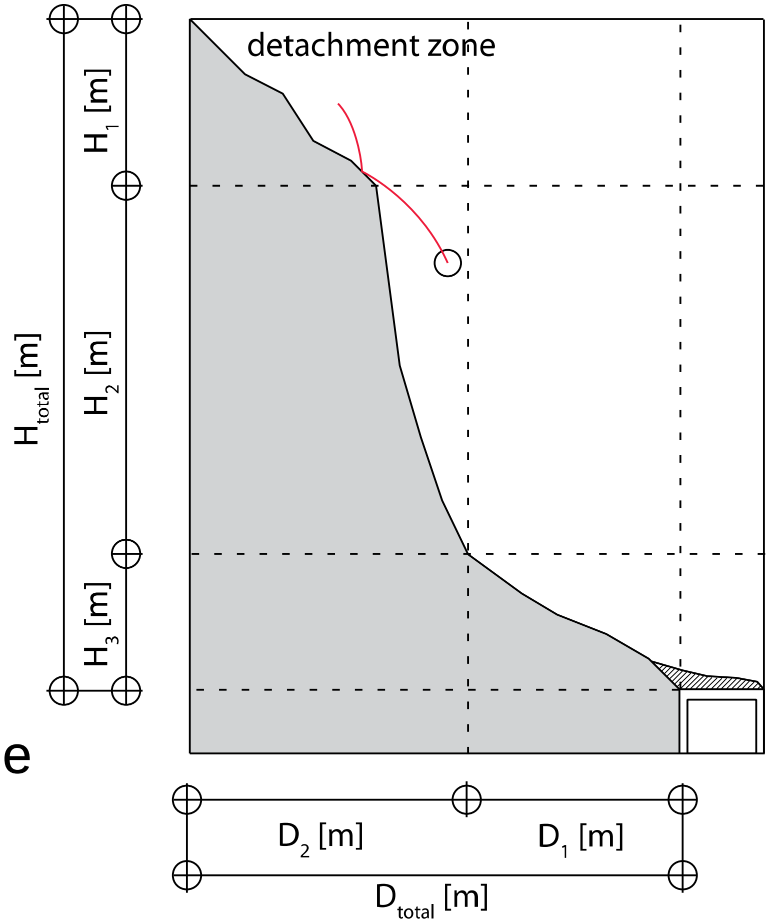
- Result of the trajectory simulation: energy/velocity at the impact location.

- Software:



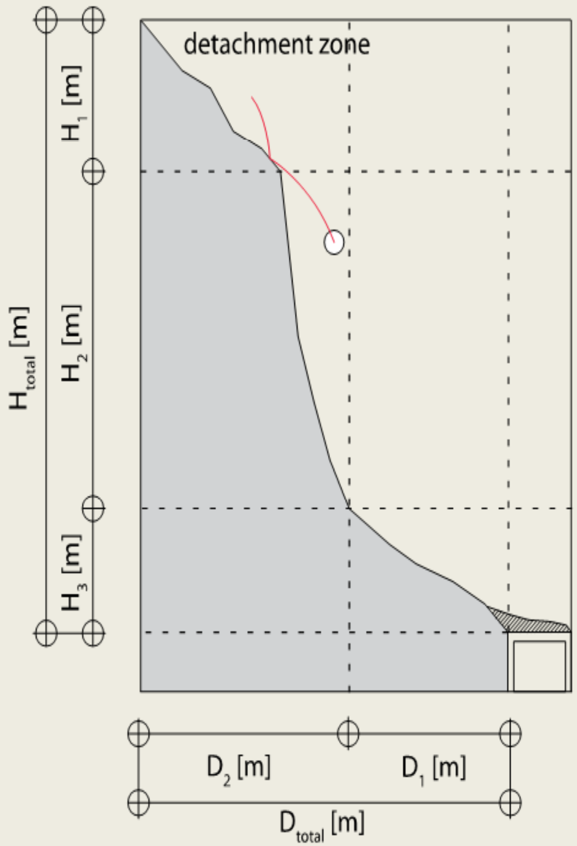
Generic characterization of the Slope

- Generic description of the topography
- Description of the geologic zones
  - Massif Central
  - Helvetic Nappes
  - Penninic Nappes
- 18.612 different combinations have been pre-calculated (each with 10.000 Simulation)



Generic trajectory model

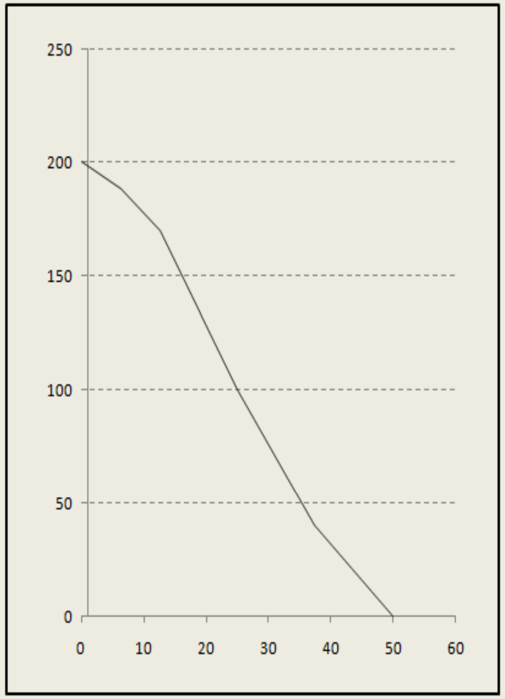
Start | System definition | Exposure model | Generic trajectory analysis | External trajectory analysis



Height model [m]	
H_{total} [m]=	200
H_1[m]=	30
H_2[m]=	70
H_3[m]=	100
D_{total} [m]=	50
D_1[m]=	25
D_2[m]=	25

create generic histogramm of impact velocity

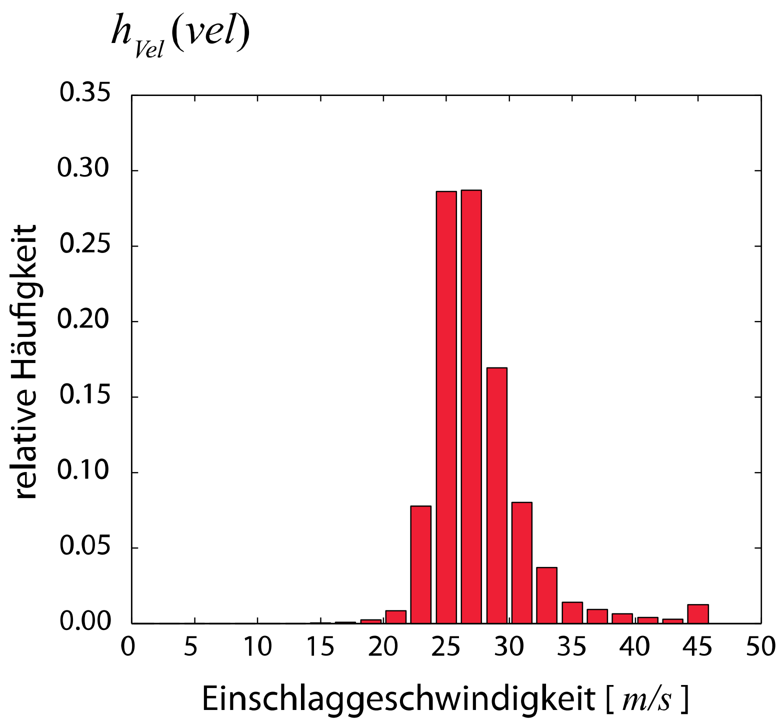
Visualation of the height model



Control Nr. : HA123A1B5.rsk

Generic characterization of the slope

- Results of the trajectory simulation are stored in a database (probability, velocity)



Trajectory model

Affirm density distribution

Impact Velocity

Interval [m/s] min	Interval [m/s] max	Frequency	Frequency
0	1	0.000E+00	0.0001001
1	2	1.001E-04	
2	3	9.005E-04	0.0058029
3	4	4.902E-03	
4	5	2.041E-02	0.0817409
5	6	6.133E-02	
6	7	1.159E-01	2.572E-01
7	8	1.414E-01	
8	9	1.268E-01	0.2327164
9	10	1.060E-01	
10	11	7.394E-02	0.1290645
11	12	5.513E-02	
12	13	5.043E-02	0.091946
13	14	4.152E-02	
14	15	3.822E-02	0.0736368
15	16	3.542E-02	
16	17	3.272E-02	0.0623312
17	18	2.961E-02	
18	19	2.611E-02	0.0438219
19	20	1.771E-02	
20	21	9.305E-03	0.0150075
21	22	5.703E-03	
22	23	2.801E-03	0.0047024
23	24	1.901E-03	
24	25	8.004E-04	0.0013007
25	26	5.003E-04	
26	27	4.002E-04	0.0006003
27	28	2.001E-04	
28	29	0.000E+00	0.000E+00
29	30	0.000E+00	
30	31	0.000E+00	0
31	32	0.000E+00	
32	33	0.000E+00	0
33	34	0.000E+00	
34	35	0.000E+00	0
35	36	0.000E+00	
36	37	0.000E+00	0
37	38	0.000E+00	
38	39	0.000E+00	0
39	40	0.000E+00	
40	41	0.000E+00	0
41	42	0.000E+00	
42	43	0.000E+00	0
43	44	0.000E+00	
44	45	0.000E+00	0
45	50	0.000E+00	

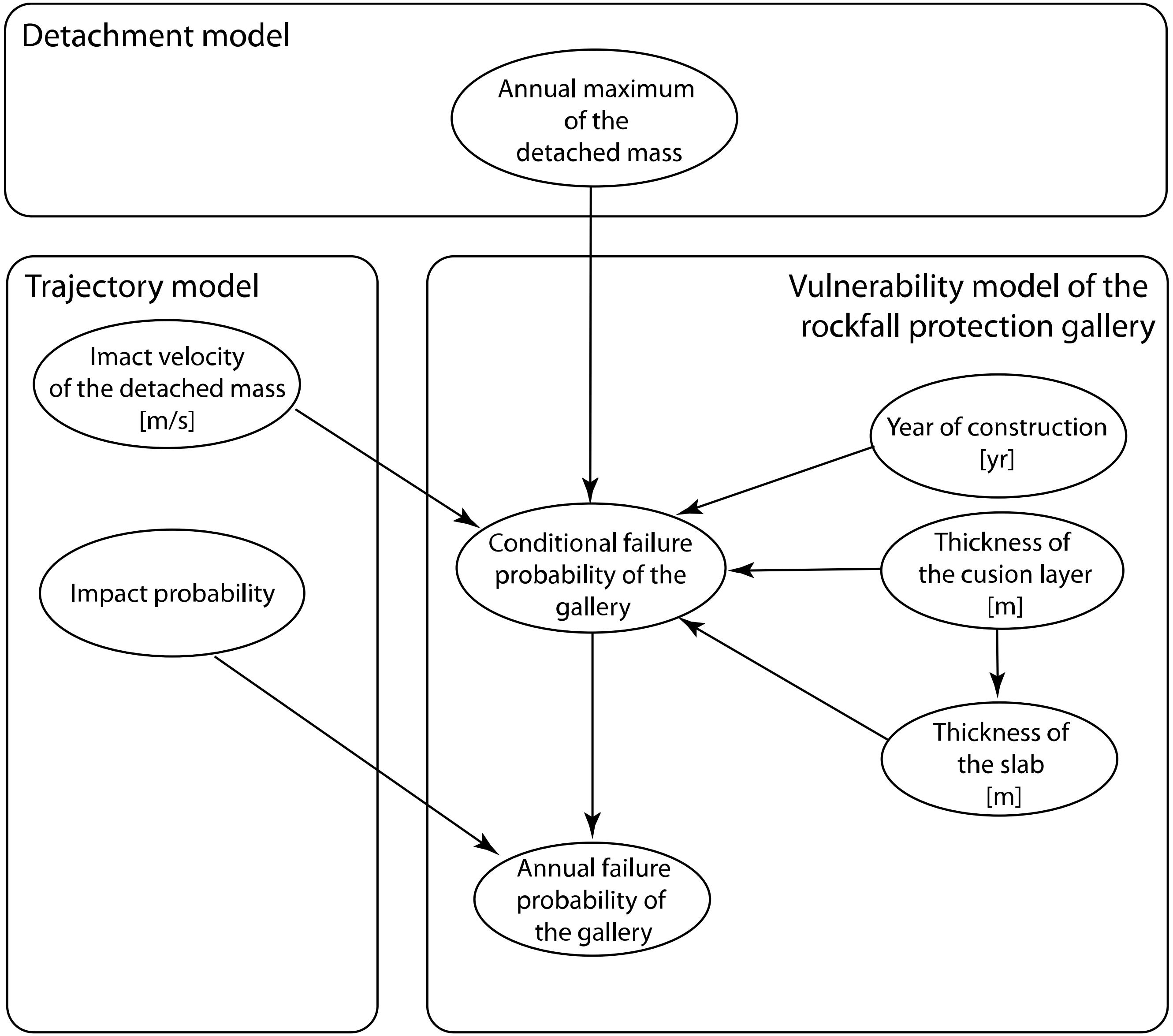
Conditional Impact Probability= 0.999 [-]

$\mu_{\text{impact velocity}}$ = 10.406451 [m/s]

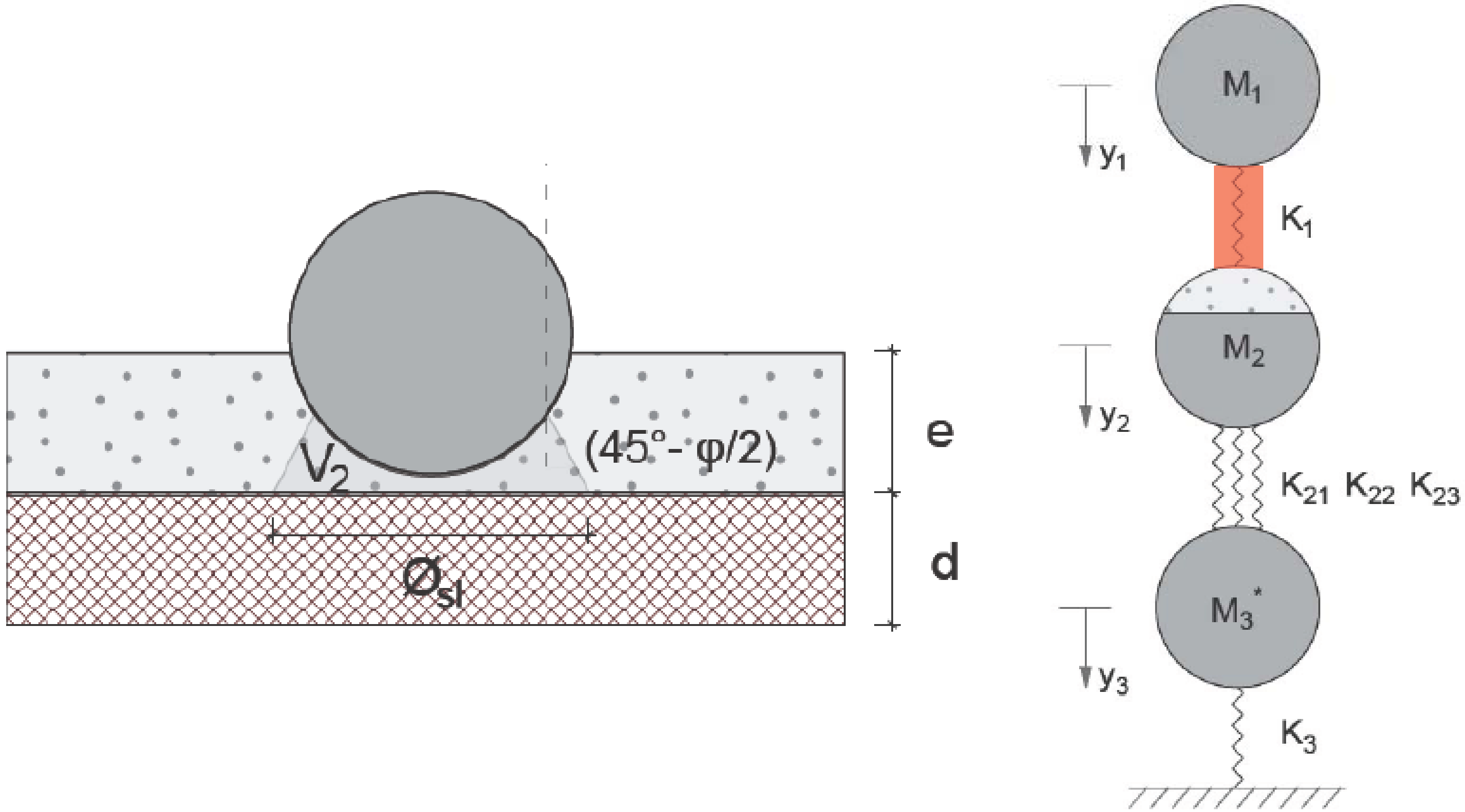
$\sigma_{\text{impact velocity}}$ = 4.1159716 [m/s]

$CoV_{\text{impact velocity}}$ = 0.3955212 [-]

Calculation of the probability of failure of the gallery

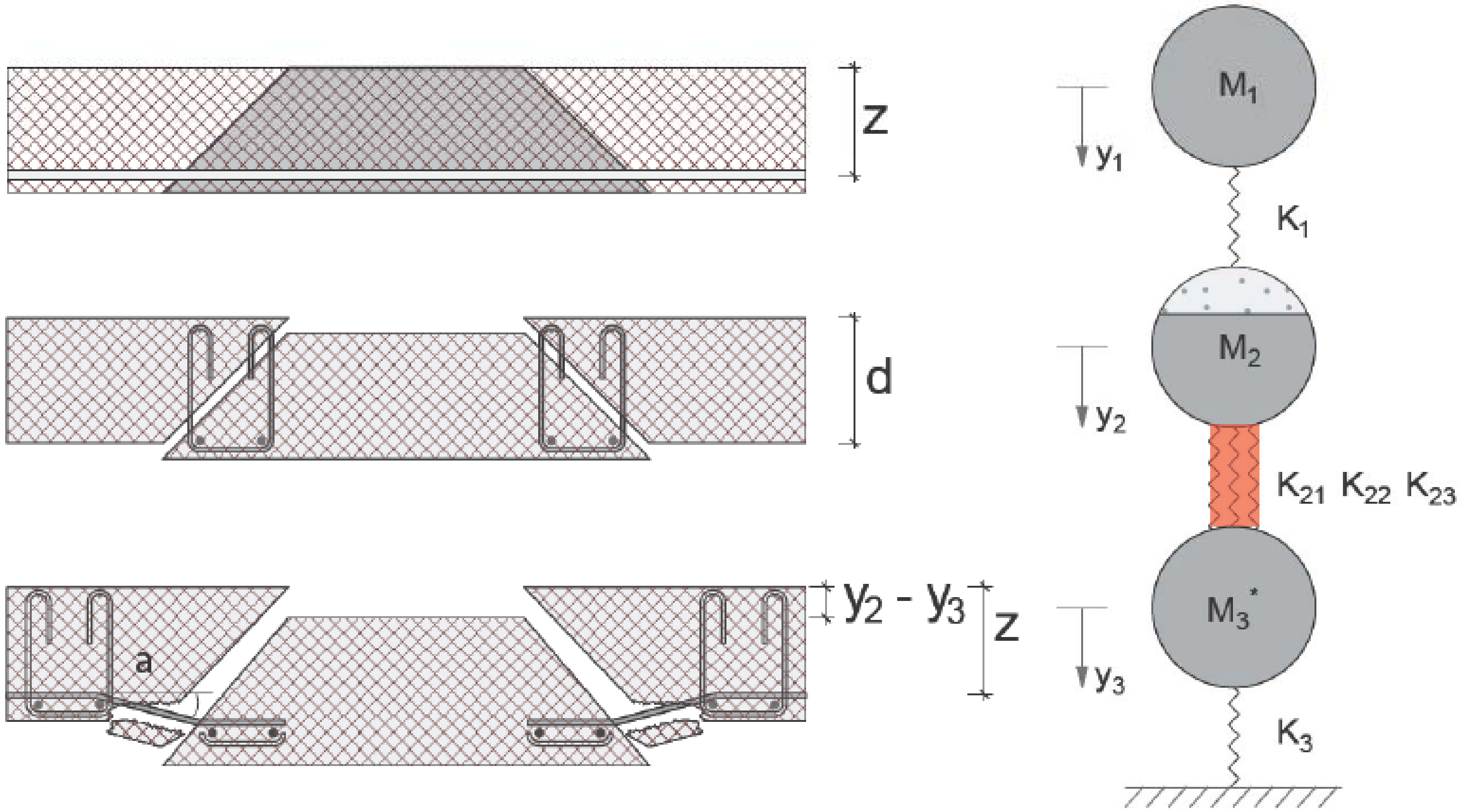

Detachment model
Annual maximum of the detached mass
Trajectory model
Imact velocity of the detached mass [m/s]
Impact probability
Vulnerability model of the rockfall protection gallery
Year of construction [yr]
Conditional failure probability of the gallery
Thickness of the cusion layer [m]
Thickness of the slab [m]
Annual failure probability of the gallery

Cusion layer



From: Schellenberg, K., (2008), ON THE DESIGN OF ROCKFALL PROTECTION GALLERIES, Dissertation, ETH Zürich.

Shear force



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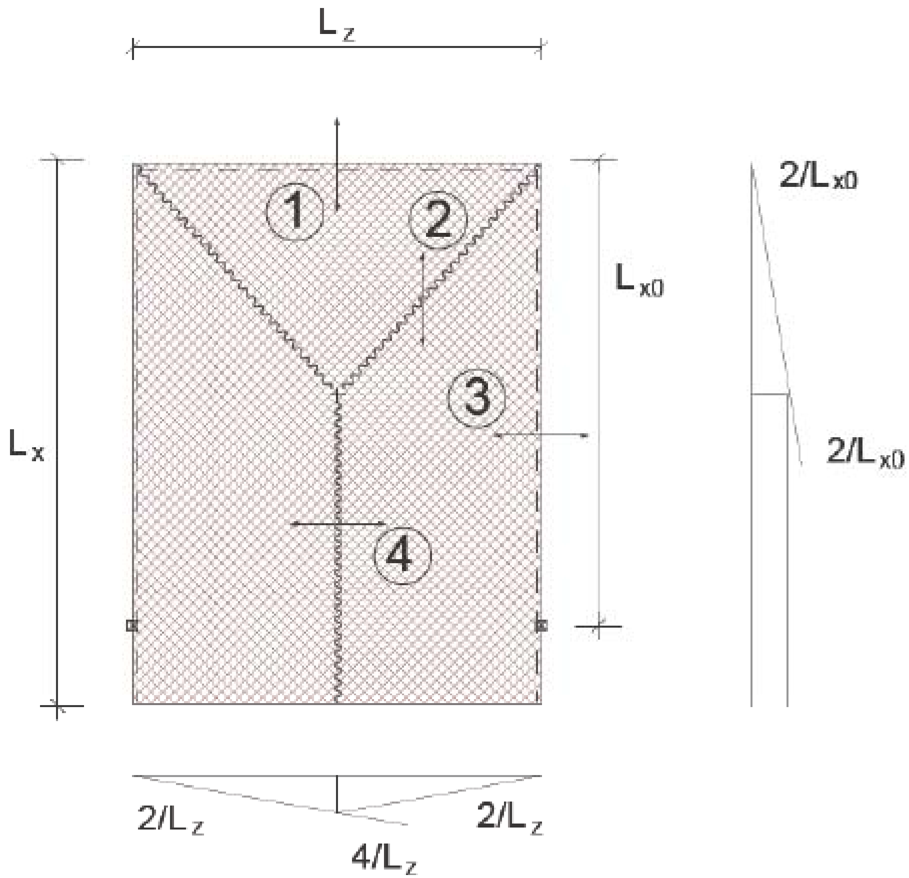
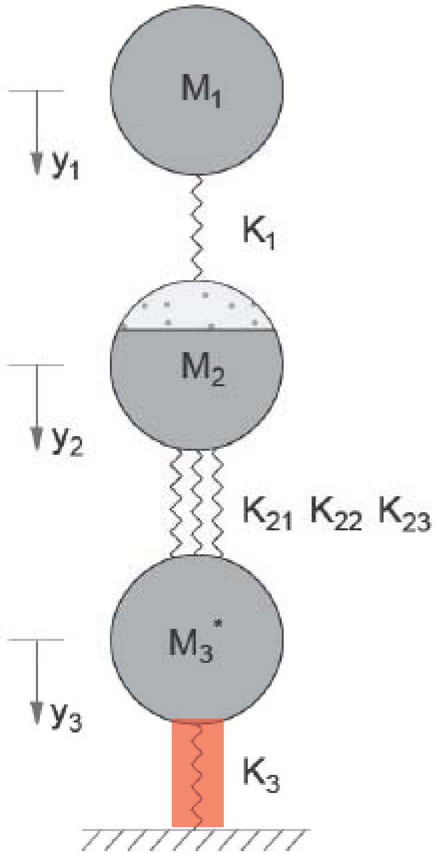
Bending of the global system





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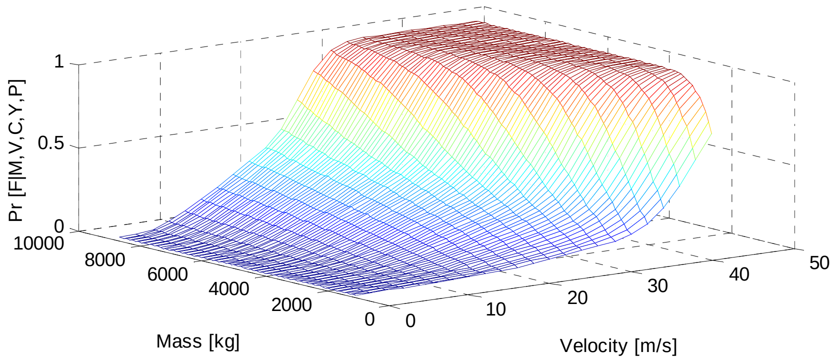
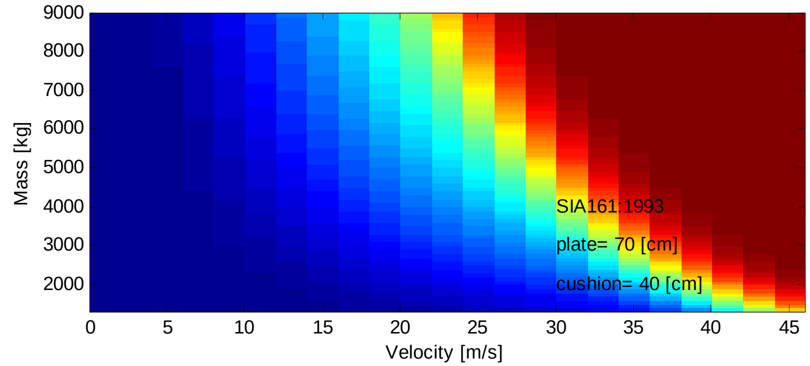
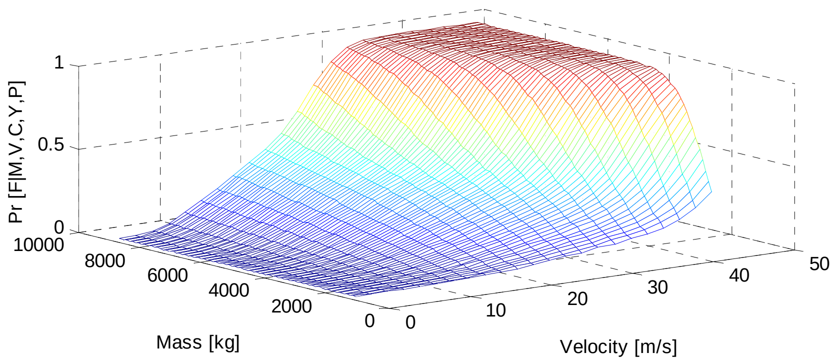
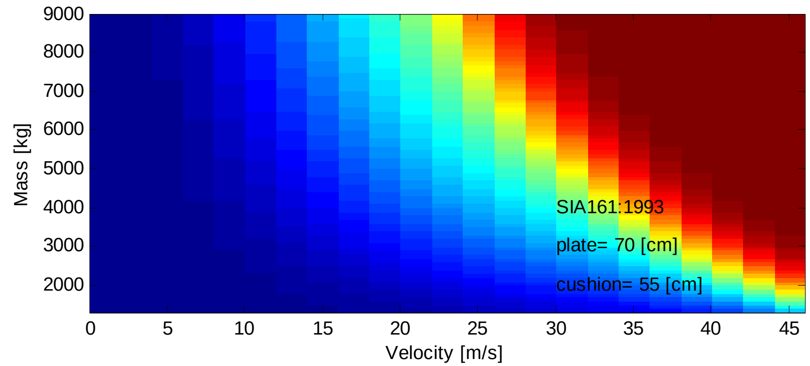
Development of vulnerability curves

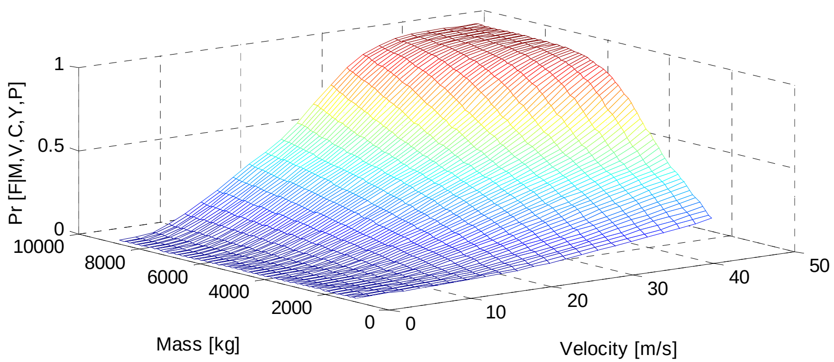
- Such deterministic (mechanical) models of assets can be used to develop vulnerability curves.
- Here, the model from Schellenberg (2008) is used
- Vulnerability curves represent the conditional failure (or damage) probability of an asset (conditional on the velocity and the mass of the stone).

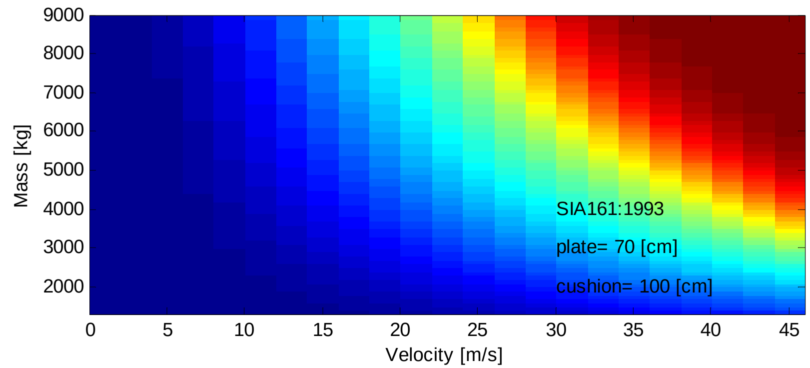

Pr [F|M,V,C,Y,P]
Mass [kg]
Velocity [m/s]


Mass [kg]
Velocity [m/s]
SIA161:1993
plate= 70 [cm]
cushion= 40 [cm]


Pr [F|M,V,C,Y,P]
Mass [kg]
Velocity [m/s]


Mass [kg]
Velocity [m/s]
SIA161:1993
plate= 70 [cm]
cushion= 55 [cm]


Pr [F|M,V,C,Y,P]
Mass [kg]
Velocity [m/s]

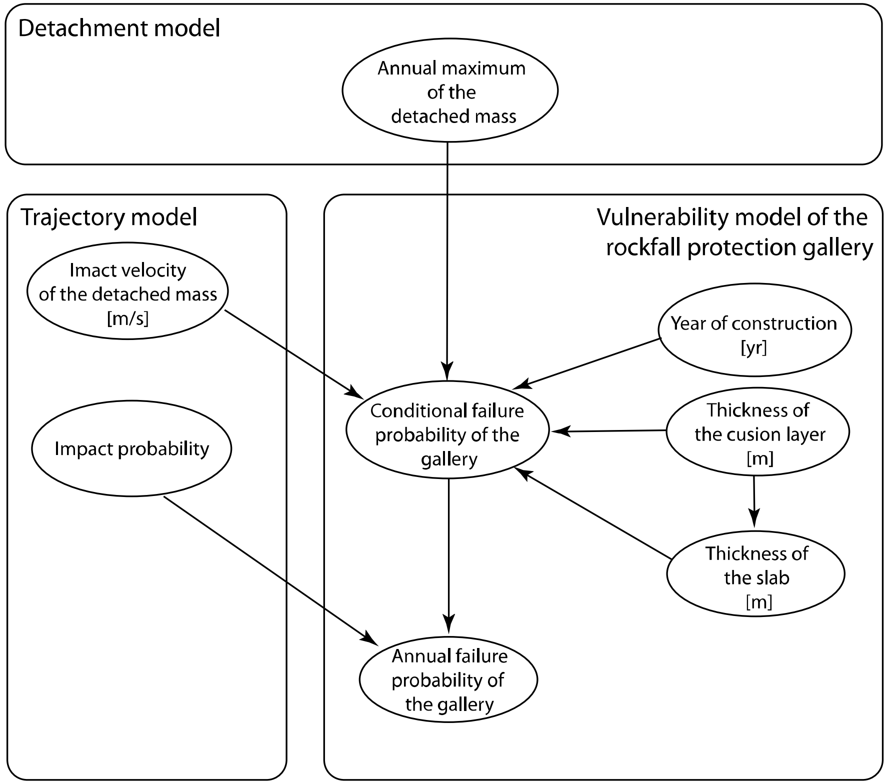

Mass [kg]
Velocity [m/s]
SIA161:1993
plate= 70 [cm]
cushion= 100 [cm]

Calculation of the failure probability

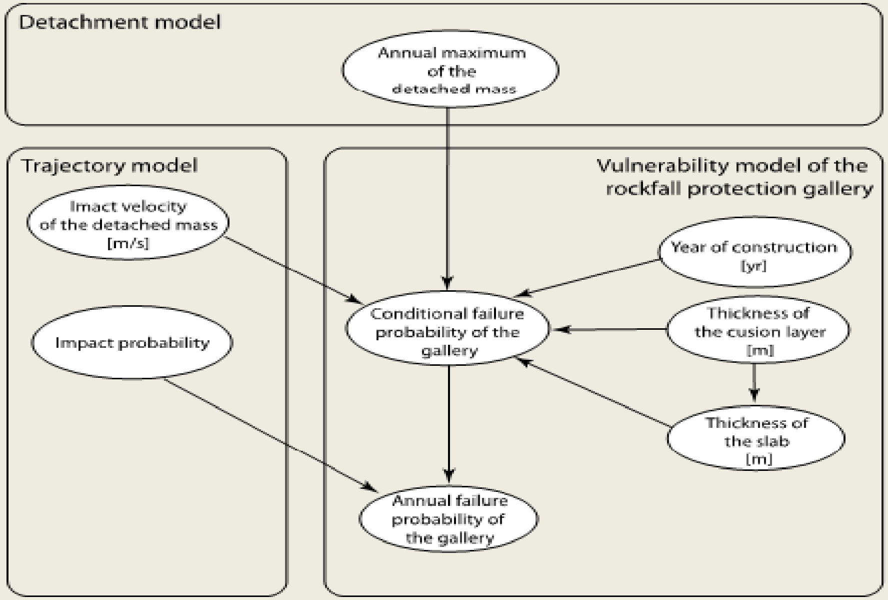
- The Bayesian network is used to calculate the unconditional probability of failure:

  - Mean value

  - Distribution

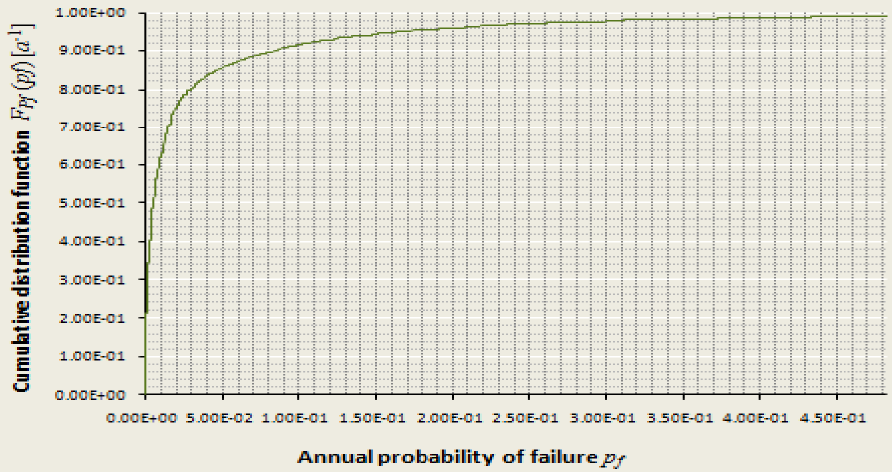


Bayesian Network



Bayesian Network created using GeNIe ©

Geological region	Helvetic Nappes	
Year of construction	1998	$[a]$
Cushion layer	100	$[cm]$
Thickness of the slab	80	$[cm]$
$P(impact \mid detachment) =$	0.999	
$E[P(F \mid impact)] =$	3.222E-02	$[a^{-1}]$
$E[P(F)] =$	3.221E-02	$[a^{-1}]$
$E[P(S)] =$	9.678E-01	$[a^{-1}]$
Reliability index β =	1.849	$[a^{-1}]$
$Var[P(F \mid impact)] =$	7.654E-03	$[a^{-1}]^2$
$CoV[P(F \mid impact)] =$	2.715	[-]



Consequence Model

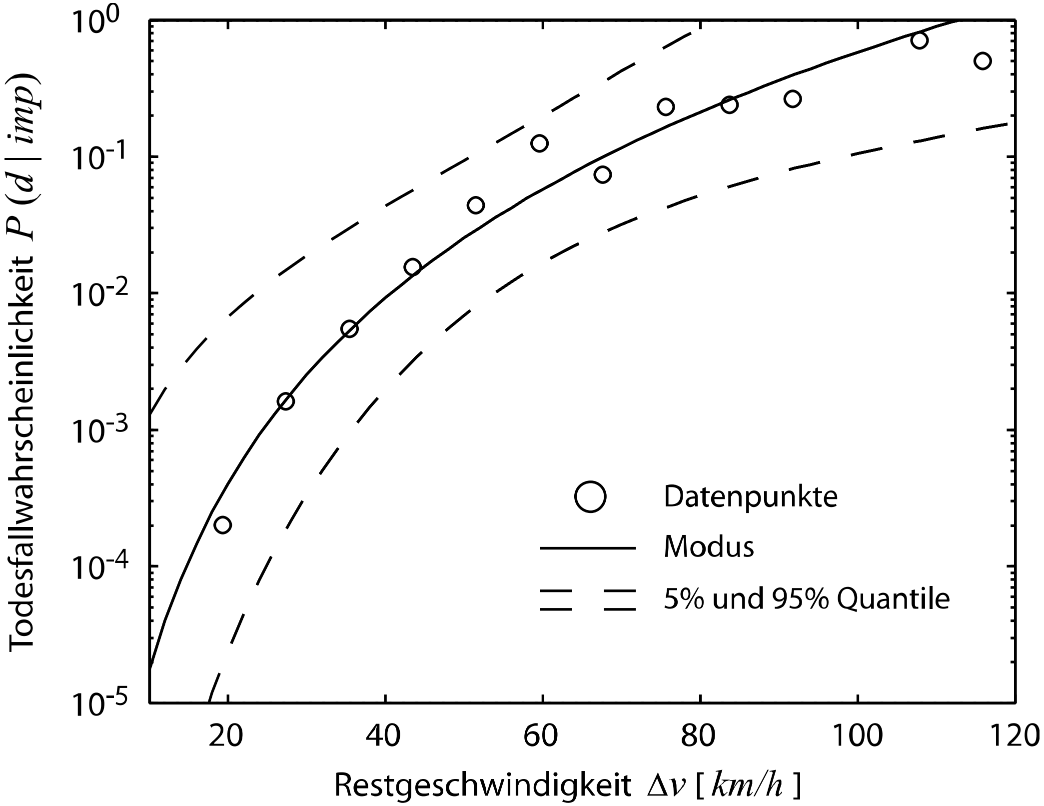
Start | System definition | Exposure model | Generic trajectory analys | External trajectory analys

Damage Gallery	μ	σ	Distribution
Property damage gallery [CHF/m]	25000	8000	Normal
Property damage road [CHF/m]	10000	500	Normal
Administration costs [CHF]	5000	100	Normal
Clean-up costs [CHF/m]	10000	200	Normal
Compensation Costs			
Cost per fatality [CHF]	3.00E+06	1.00E+06	Normal
Cost per HGV [CHF]	250000	20000	Normal
Cost per car [CHF]	17000	8000	Normal
Societal Costs			
Days of closed road	10	2	Log-Normal
Detour Length [km]	20	2	Log-Normal
Detor velocity [km/h]	100	15	Log-Normal
User costs [CHF/(h vehicle)]	35	15	Log-Normal

Vehicle impact

- The probability of an vehicle impact in free-flowing traffic:
  - Direct hit
    Probability of dying $\Pr[D] = 1.0$
  - Indirect hit
    Probability of dying $\Pr[D] = f(\text{velocity})$

Probability of dying



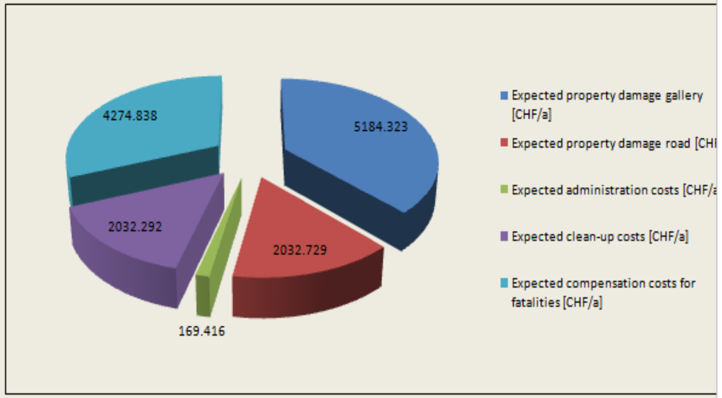
Adapted from: Evans, L. (1994). "Driver injury and fatality risk in two-car crashes versus mass ratio inferred using Newtonian mechanics." Accident Analysis & Prevention 26(5): 609-616.

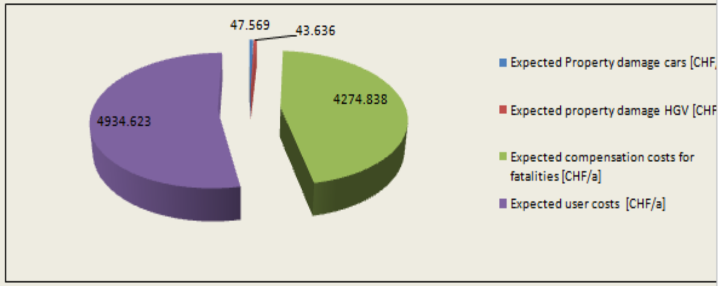
Calculation of the risk

Start | System definition | Exposure model | Generic trajectory analysis | Vulnerability model / BPN | Consequence Model | Risk analysis | Risk results

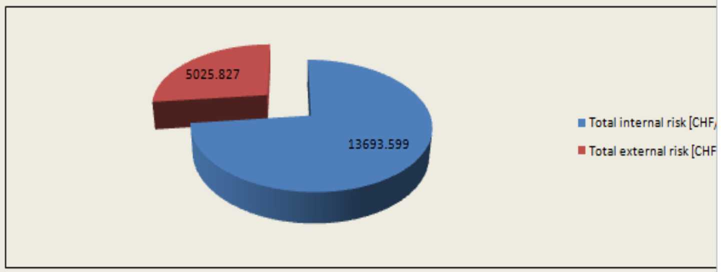
External trajectory analysis

Risk	μ	σ	CoV	Type of risk	
Expected property damage gallery [*CHF/a*]	5184.323	16058.584	3.098	*direct*	*internal*
Expected property damage road [*CHF/a*]	2032.729	5843.615	2.875	*direct*	*internal*
Expected administration costs [*CHF/a*]	169.416	486.364	2.871	*direct*	*internal*
Expected clean-up costs [*CHF/a*]	2032.292	5833.622	2.870	*direct*	*internal*
Expected Property damage cars [*CHF/a*]	47.569	157.058	3.302	*indirect*	*external*
Expected property damage HGV [*CHF/a*]	43.636	127.366	2.919	*indirect*	*external*
Expected number fatalities [a^{-1}]	1.440E-03	4.241E-03	2.946	*indirect*	*external*
Expected compensation costs for fatalities [*CHF/a*]	4274.838	13187.668	3.085	*indirect*	*internal*
Expected days of road closure [*days/a*]	0.339	0.996	2.941	*indirect*	*external*
Expected user costs [*CHF/a*]	4934.623	16886.901	3.422	*indirect*	*external*





Aggregated Risk	μ	σ	CoV
Direct internal risk [*CHF/a*]	9418.761	18063.600	0.521
Indirect internal risk [*CHF/a*]	4274.838	13187.668	3.085
Indirect external risk [*CHF/a*]	5025.827	16888.112	3.360
Total internal risk [*CHF/a*]	13693.599	22365.335	1.633
Total external risk [*CHF/a*]	5025.827	16888.112	3.360




Risk Results
Start
System definition
Exposure model
Generic trajectory analysis
External trajectory analysis
Vulnerability model / BPN
Consequence Model
Risk analysis
CDF of the direct internal risk [a⁻¹]
Direct internal risk [CHF]
CDF of the total internal risk [a⁻¹]
Total internal risk [CHF]
CDF of the total risk [a⁻¹]
Total external risk [CHF]
CDF of the number of fatalities [a⁻¹]
Fatalities [No.]
CDF of the days of road closures [a⁻¹]
Road closure [days]

6. Outlook

- Possible extensions and further developments:
  - Free roads
  - Areas
  - Implementing methodology in GIS
  - Perform large scale risk assessments

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ASTRA Project 2008/003