PROGRAM GEO – Masco2d ver.3.0 per Windows

1. Theoretical bases

1.1 Introduction

The term 'rockfall' describes the phenomen of detatchment and following downslope motion of rock blocks, mainly isolated and with limitated volumes (up to a maxium of several cubic meters), from rock slopes usually very inclinated and tectonically disturbate.
The passage between this type of gravitative phenomenon and a rockslide is actually fuzzy: it is often estabilished by a geometrical criterion, classifing as rockslide events the ones which at least involves a rock mass of several hundreds of cube meters.
However, in the engineering practice, is more useful a mechanical-type criterion. Based on this criterion they are to be considered as rock landslides the ones which involve energy bigger than the ones usually absorbable by a rockfall protection systems (barriers and embankments). The energy limit can be placed close to 2000 kJoule.

The analysis of rockfall phenomena has the scope to individuate, by an acceptable approximation:

- the maximum distance run by the detached rock block;
- the more probable or unfavourable trajectories of the rock block to design the protection systems
- the maximum impact energy that can be absorbed by the protection system

For this purpose, the problem analysis has to be executed in two steps:

- a first one through a survey to identify the old rock detachments, their origin, their volumes and distribution;
- a second one through a numeric simulation of the more probable trajectories of the future rock detachments.

1.2 Analysis of the rockfall phenomena

1.2.1 Ground survey

An accurate ground survey is fundamental to allow to do forecasts about the cinematism of the rockfalls.
The ground survey has to lead to individuate:

- the detachment surfaces of the rock blocks; these generally correspond to a more fractured and inclined zones inside the slopes and are recognizable by the fresh surfaces of detatchement, characterized by a minor rate of weathering; in these outcrops it has to be performed a geomechanical survey to the purpose to characterize the rock mass by a geometrical point of view (number of joint sets, rock joint orientation, average spacing, etc.), useful it is the assessment of the maximum unitary block volume, computable, e.g., by the formula by Hudson and Priest (1979):

  $$(1)\ V_m = 8 / (s_1+s_2+s_3);$$

  (with s_1, s_2, s_3 = average spacing of the three main joint sets), which can give an indication of the maximum sizes of the rock blocks falling from the slope;

- the more probable trajectories traced by the falling rock blocks; these can be identified, with some degree of approximation, finding the grooves let by the bouncing and rolling blocks or the impact marks along the slope on trees, artefacts and rock outcrops; the fragmentation zones, due to the impact of the block on rigid surfaces, have to be marked; they can be identified by the presence of splinters released by the block during the impact.
- the distribution of the rock blocks at the toe of the slope; placements and volumes have to be measured; by these data can be assess the maximum and more frequent distances run by the blocks and their volumes.

1.3 Numerical simulation

1.3.1 Calibrating the model

Numerical simulation of rockfall phenomena has the purpose to allow the building of a model which permits to forecast the cinematical behaviour of the falling rock blocks. The calibration of the model has to be performed based on the data recorded by the ground survey and cannot be considered acceptable if it does not allow to reproduce the observed situation (block trajectories, block distribution, etc.).
In the modelization the motion is imposed bidimensional, that is along the X,Y plane, with the slope discretized in a set of straight segments. The rock block can be assumed punctiform, with reference to the motion of its baricentre only, or approximated to an triaxial ellipsoid.
The model needs determination of two set of parameters, the first one relative to the falling block, the second one to the slope.

1) Rock block parameters:

the input of the following variables is requested:

- volume of the block;
- size of the semiaxes **a**, **b** and **c** of the triaxial ellipsoid approximating the rock block;;
- unit weight of the rock block;
- initial velocity along X and Y (higher than zero if the block initially undergoes other forces apart the gravity, e.g. a seismic force).

2) Slope parameters:

For each tract of the slope is requested a set of parameters to compute the interaction between block and slope.

a)Restitution coefficient (K)

It is defined as the ratio between velocity after and before the impact of the rock block on the ground (V_1 / V_0 where V_1 is the after-impact velocity, V_0 the before-impact one); it is equal to zero in case of a completely anelastic impact (the whole kinetic energy of the impacting block is dissipated as heat and velocity after impact is null), it is equal to one in case of a

completely elastic impact (the whole kinetic energy of the impacting block is conserved and velocity after impact is equal to the before-impact one, that is V1=V0) and it ranges between 0 and 1 in case of partially elastic impact (part of kinetic energy is conserved and part is dispersed in form of heat, after-impact velocity of the block is given by V1= K x V0).
The value of K is mainly linked to the lithology and morphology of the slope. Broili (1979) suggests indicatively to assume values of K ranged between 0.75 and 0.80 in case of impact on a rock ground or on coarse debris and between 0.20 and 0.35 in case of impact on soil. Other authors (Mazzalai, Vuillermin, 1995) as an alternative propose the following values:

Ground type	**K**
Apex of debris conoid	0.05 – 0.10
Wood with a dense undergrowth, meadow	0.05 – 0.15
Debris with dense vegetation	0.10 – 0.15
Debris with sparse vegetation	0.20 – 0.30
Eluvial debris of thin thickness	0.30 – 0.40
Stiff artefacts and roads	0.40 – 0.60
Fractured rock	0.60 – 0.70
Intact rock	0.75 – 0.85

Wanting to distinguish the normal and tangential components of velocity of the falling rock block, they can be defined the parameters K_y and K_x (normal and tangential resitution coefficients) as follows:
$K_y = V_{1n} / V_{0n}$ [V_{1n} = normal velocity (orthogonal to the ground) of the block after impact; V_{0n} = normal velocity before impact];
$K_x = V_{1t} / V_{0t}$ [V_{1t} = tangential velocity (parallel to the ground) of the block after impact; V_{0t} = tangential velocity before impact].
Reference values of di E_y and E_x are suggested by Piteau e Clayton (1987) and by Hoek (1987).

Piteau e Clayton

Ground type	K_y	K_x
Intact rock	0.8 – 0.9	0.65-0.75
Debris mixed to big boulders	0.5 – 0.8	0.45-0.65
Debris mixed to small boulders	0.4 – 0.5	0.35-0.45
Slopes covered by vegetation	0.2 – 0.4	0.2 – 0.3

Hoek

Ground type	K_y	K_x
Intact and clean rock	0.53	0.99
Asphalted road	0.40	0.90
Rock covered by big boulders	0.35	0.85
Debris conoid	0.32	0.82
Debris conoid with vegetation	0.32	0.80
Soil	0.30	0.80

b) Block-slope friction angle (φ)

Along the slope tracts where the rock block moves bouncing or sliding, kinetic energy is dissipated by the friction between block and ground.. This friction is introduced in the computation through the parameter ground-block friction angle. In case of rolling block this angle gets values ranged between 20° and 35°, with the lower values inside the tracts with no roughness. In case of sliding block (e.g. block with slab shape) the friction is obviously higher.
Cocco (1991)suggests to consider, to assess the rolling friction angle, three components linked respectively to the lithology, to the vegetation cover and to the ground roughness with respect to the block sizes. Each component gives a contribution, the sum of which provides the total friction angle.
These the values of the partial contribution:

Lithology	**Partial contribution (°)**
Bare rock	19.5
Debris	21.0
Alluvion	26.5
Glacial till	26.5

Copertura vegetale	Partial contribution (°)
Bare soil or rock	0.0
Meadow	3.0
Bush	3.5
Orchard	6.0
Coppice	4.5
Wood	8.5

Asperità del terreno	Partial contribution (°)
None	0.0
Small	3.0
Medium	7.0
High	11.0

The seen above parameters, and particularly the ones relative to the interaction between block and slope, have to be inserted by trial and error, till to get detachment simulation with trajectories close to the observed or assessed on the ground.

1.3.2 Equations of motion

Neglecting the air friction, the forces conditioning the block motion along the slope are the gravity and the block-slope friction.
They are distinguished the tracts where motion is by free fall or bouncing from the ones where motion is by rolling or sliding. Computation is executed based on the equations suggested by Piteau and Clayton (1977) and by Bassato et al. (1985).

Free fall and bouncing

This kind of motion is dominant where the slope has an inclination higher than 45° (Ritchie, 1963).
The block initially moves with no contact with the ground. Final velocity of the falling block, that is the one owned immediately before the impact, in accordance with the Mechanics equations, is given by:

$$(2)\ V = \sqrt{2 \times g \times d};$$

with

g = $9.807\ m/s^2$, gravity acceleration;
d = Distance run by the block through air.

After the impact, the block is projected forward with a velocity given by:

$$(3)\ V = \sqrt{(V_i \times sen\beta)^2 \times K + (V_i \times cos\beta)^2 \times (K0 \times 0.3^{Log\ K})};$$

with
V_i = Impact velocity;
β = angle of incidence of the block trajectory with respect to the ground;
K = Restitution coefficient.

As to determination the projection angle of the block after the impact (angolo θ), experiences show that the assumption of a projection angle equal to the incident one, often used in numerical simulation, is generally not valid. By a practical point of view simulation can be carry out by two different ways: either it can be considered as a parameter with a random variability or linked to other variables , as the restitution coefficient K. Experiences carried out by several authors show that the angle θ can assume values ranged by the horizontal and the inclination of the ground whatever be the incidence angle (Paronuzzi, 1989). Such values can be practically considered distributed in a random way, e.g. with an uniform, normal or lognormal probability distribution, because influenced by the roughness or small obstacles on the ground. As an alternative, one often uses a correlation with the restitution coefficient K:

$$(4)\ tg\ \theta = K \times tg\ \beta;$$

where β is the angle of incidence of the block.
Given that the restitution coefficient K is only approximately known, this approach should be used along with a probabilistic analysis only (e.g. by the Montecarlo's method).

β. Rolling and sliding

This kind of motion is dominant where the slope has an inclination lower than 45° (Ritchie, 1963).
In case of rolling, the block moves by a rototranslation motion along the slope through a sequence of small bouncing, or, in case of pure translation, keeping the contact with the ground along a face, generally the more extended.
Final velocity at the end of the specific slope tract can be assessed through the expression:

$$(5)\ V = \sqrt{V_i^2 + (10/7) \times g \times s \times (tg\ \alpha - tg\varphi)}$$

in case of rolling, or woth the formula:

$$(6)\ V = \sqrt{V_i^2 + 2 \times g \times s \times (sen\ \alpha - tg\ \varphi \times cos\alpha)}$$

in case of sliding, with

V_i	=	initial velocity along the considered tract;
s	=	distance run by the block along the tract;
α	=	Inclination of the slope;
φ	=	block-slope friction angle.

The turning from a rolling motion to a sliding one, in case of ellipsoidal block, occurs when the following expression is verified:

$$(7)\ E < \Delta H \times g \times m;$$

where:

ΔH	=	difference between the higher semiaxes **a** and the lower one **c** (***a-c***);
g	=	gravity acceleration;
m	=	mass of the block;
E	=	$E = 0,5 \times m \times V^2 + 0,5 \times I \times \omega^2$, total energy owned by the block;
V	=	block velocity;
I	=	moment of inertia of the block, equal to (2/5)mR for a spherical block;
ω	=	angular velocity (rotational velocity of the block).

In case of spherical block $\Delta H = 0$, so motion will practically occur by rolling only.

1.3.3 Analysis by probabilistic method – Montecarlo method.

Indetermination implied in the assessment of the variables used in rockfall simulation, particularly with respect to K (restitution coefficient), φ (rolling and sliding friction angles) and V (rock block volume) suggests a probabilistic approach to the problem.
The method generally used is the Montecarlo one.
Montecarlo methods are based on the generation of random numbers, chosen inside specific range, which have statistical properties. Among the several possible application of these methods, there is that one called 'of sampling' which consists in deducting general propierties of a big set, examining a random subset of it only, considerated representative of the set itself. Obviously bigger the size of the random sample, more representative the deducted properties.
In case of application of the methods to a rockfall analysis, the procedure to be adopt could be the following:

- a distribution of the aleatory variables K, φ and V is generated, supposing that it is of gaussian kind;
- through a random number generator, a set of value ranging between 0 and 1 are created;
- one associates to each random numeric value of the set a value of E, φ e V,, based on the probability distribution curve of these variables (then by making sure that the frequency with which a specific parameter is used in the calculation be equal to its probability obtained by the gaussian curve of probability of the parameter itself); in this way the set of random numbers, previously generated, is turn in a set of E, φ e V, values;
- simulation is performed for each set of values E, φ and V.

The trajectories linked to each set K, φ, V allows to assess the effect of the dispersion of these variables over the fall paths.
To get stable dispersion of the trajectories normally it is necessary to execute several hundreds of simulation.

1.4 Sizing of protection systems

Once assessed, through the numerical simulation, distribution of the rock block trajectories, a first sizing of the protection systems can be performed. These systems have to be capable to intercept the falling rock blocks and to resist to the forces produced by the impacts.
They are to be performed two kind of verification.

1. Verification of overgoing by projection

Numerical simulation has to be repeated, varying position and height of the protection system. The way in which varies distribution of the block arrivals and the possibility, through trajectories examination, they overgoes the single protections is assessed.
It will be eventually adopted solution which allow to reach the maximum efficiency in block interception.

2. Verification of overgoing by breakthrough

The protection system has to be capable to resist to the impact and to dissipate kinetic energy of the falling block, given by:

$$(8)\ Ec = (1/2) \times m \times V^2 + (1/2) \times I \times w^2;$$

with

m = block weight;
g = gravity acceleration;
V = shifting velocity of the block barycentre.;
I = moment of inertia of the block;
w = Angular velocity of the block.

From the (8) can be noted that total kinetic energy is given by the sum of a component due to the shifting motion of the block barycentre ($0.5 \times m \times V^2$) and one linked to rotational motion around the barycentre itself ($0.5 \times I \times w^2$). The second component is usually neglected due to the difficult to assess the angular velocity.
They are here considered two kind of protection systems: the rigid and flexible rockfall barriers and the rockfall embankments. They are not

instead taken in consideration the protection systems that do not involve the assess of the falling block trajectories (e.g. rockfall protection mesh).

1.4.1 Rigid and elastic rockfall barriers

The rigid barriers are usually built by wood or steel, in some cases by reinforced concrete. The elastic barriers consist of steel meshes jointed to beams (postes) put in place in a set with a specific spacing. Impact energy is absorbed by deformation of the mesh or of the postes. They can be present dissipation devices (brakes).

1.4.2 Rockfall embankments

They are earth structures, usually of trapezoidal shape, sometime with a concrete or gabion wall in the upslope side, often completed with a trench (rocktrap) covered by material with low restitution coefficient (e.g.gravel).
In contrast to rockfall barriers, an embankment absorbs kinetic energy through work has to be performed by the the rock block to penetrate in the embankment itself. Therefore it has to be computed the penetration depth of the rock block and to verify that it be lower than the thickness of the embankment. If not the embankment has to be considered undersizing.
The penetration depth can be assessed by the formula by Kar (1978), in case of direct impact against the embankment material:

$$(16)Zf=[27183/\sqrt{(s)}] \times Nf \times (E/Ea)^{1.25} \times [P/(d^{2.31})] \times (V/1000)^{1.25}$$

with

s	=	compressive strength of the embankment material (kN/mq);
Nf	=	shape factor of the block (1 per corpi appuntiti, 0.72 per corpi piatti);
E	=	elasticity modulus of the rock block (kN/mq);
Ea	=	average elasticity modulus of steel(circa 206.850x 10^3) (kN/mq);
P	=	block weight (kg);
d	=	diameter of the impact footprint (m);
V	=	impact velocity (m/s).

The depth of penetration is given by:

$$(17)\ z(cm) = sqr(Zf) \times 2 \times d, \text{ se } z/d <= 2;$$

$$(18)\ z(cm) = (Zf+1) \times d, \text{ se } z / d > 2$$

By a practical point of view, considering the double possible solution [(17) e (18)], it has to be taken the maximum value and it has to be verificated that the relative z/d condition be satisfied. If not it has to be considered valid the second result.
In case of embankment with a wall in the upslope side, the (16) has to be rewritten as follows:

$$(19) Zf=[120328/\sqrt{(s)}] \times Nf \times (E/Ea)^{1.25} \times [P / (d^{2.8})] \times (V/1000)^{1.8}$$

In case the calculated depth be higher than the wall thickness, residual velocity has to be computed as follows:

$$(20)\ Vr = (V^{1.25} - Vm^{1.25});$$

with

V	=	impact velocity;
Vm	=	Minimum velocity to breakthrough the wall, computable imposing the value of the wall thickness in the (17) or (18) instead of z (as a function of the z/d resultant ratio), determining therefore Zf and solving the (19) with respect to V.

Penetration of the block, having a residual velocity Vr, in the embankment can be therefore computed by the (16).
Once known the penetration depth of the rock block, it can be performed an assess of the impulsive force due to the impact.
With the hypothesis of elastic-plastic behaviour of the soil composing the embankment and of a dynamic load variable in time, the maximum impulsive force generated by the block can be computed by the expression by Mc Carty and Carden (1962):

$$(21)\ Fmax(kgf) = K \times m \times V / T;$$

with

K	=	constant generally equal to 2.022;
m (kgf)	=	P/g, mass of the block;

P(kg) = weight of the block;
g = gravity acceleration(9.807 m/s^2);
V(m / s) = impact velocity;
T (s) = impact duration;

It is problematic the assessment of the parameter T, for which Kar (1979) and Knight (1980) propose the following formula:

$$(22)\ T(s) = 3.335 \times z / V;$$

with
z(m) = penetration depth of the block;
V(m / s) = impact velocity of the block.