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MODELIRANJE GIBANJA SKALNIH PODOROV – PREGLED
MODELLING OF ROCKFALL MOTION – A REVIEW

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Pomemben element rizičnega menedžmenta v gorskem svetu je analiza naravnih nevarnosti, ki jih povzročajo tudi skalni podori (skupni izraz za odlome in prosto padanje kamenja, skal in večjih skalnih blokov ter podobne oblike masnega gibanja pod vplivom težnosti). Skalni podori so zaradi svoje energije in hitrosti gibanja skalnih gmot še posebej nevarni dejavniki tveganja. Zato jim širom sveta namenjajo veliko pozornost in jih v raznih oblikah tudi modelirajo – napovedujejo njihovo pot in doseg. V prispevku so prikazane glavne značilnosti najpomembnejših enostavnih modelov obnašanja skalnih podorov, pripravljene na osnovi pregleda literature. Dispozicijski modeli so tisti, ki nam povedo, kje lahko pride do skalnih podorov. Procesni modeli simulirajo dinamiko podornega procesa. Glede na pristop k obravnavani procesa jih lahko delimo na empirične modele in analitične modele. Empirični procesni modeli na splošno temeljijo na povezavi med topografskimi faktorji in območjem odlaganja skalnega podora. Analitični procesni modeli pa so sestavljeni iz modela trajektorij in modela trenja. Analitični modeli opisujejo in simulirajo v dveh ali treh dimenzijah gibanje podorne mase in se ločijo glede na način, kako upoštevajo podorno maso (masna točka, oblika togega telesa) in kako simulirajo gibanje po pobočju (poskakovanje, kotaljenje, drsenje). Modeli na osnovi geografskega informacijskega sistema izkoristijo prednosti tega sistema in potekajo v treh korakih: določitev območij izvora podorov, določitev trajektorij posameznih skalnih blokov in določitev območij izteka (odlaganja) podorne mase. Glavni namen pregleda modeliranja gibanja skalnih podorov je, da bi strokovnjakom olajšali izbor ustreznega modela za lokalno in regionalno merilo.

Ključne besede: *skalni podori, skalni odlomi, modeliranje, geografski informacijski sistemi, naravna tveganja, rizični menedžment, prostor*

An analysis of natural hazards caused by rockfalls (common expression for falling stones and boulders; and other similar forms of gravitational mass movements) is an important element of risk management in mountainous regions. Due to their energy and velocity rockfalls represent an especially dangerous hazard factor. Because of that rockfalls are given much attention all over the world and they are modelled in different ways – simulating their paths and run-out distances. In this paper, a literature review of the main characteristics of the most important non-comprehensive rockfall models is presented. The dispositional models are those that tell us where a hazardous process may occur. The process-based models simulate rockfall process dynamics. They can be classified in relation to the process approach into empirical models and into analytical models. Empirical process-based models are generally based on the relationship between topographic factors and rockfall run-out zone. Analytical process-based models are composed of a trajectory model and a friction model. They describe and provide 2-D or 3-D simulation of the movement of the rockfall masses and can be differentiated regarding the way how the rockfall mass (lumped mass, rigid body shape) and the movement on the slope (bouncing, rolling, sliding) are described, respectively. The GIS-based models use the advantages of this system and work in three steps: the determination of rockfall source areas, the determination of trajectories of single boulders, and the determination of run-out distances and run-out zones. The main aim of the review on modelling of rockfall motion is to make it easier for the professionals to choose an adequate rockfall model at local and regional scales.

Key words: *rockfalls, rockslides, modelling, geographical information systems, natural hazards, risk management, environment*

1. UVOD

Skalni podori različnega dosega so predvsem v gorskem svetu pogosta in obenem zaradi svoje energije običajno zelo intenzivna oblika naravnih tveganj (Brilly *et al*., 1999). Tipičen primer skalnega podora v ozki alpski dolini je npr. podor Osojnik v dolini Trente (slika 1).

1. INTRODUCTION

Rockfalls with different run-out distances are of frequent occurrence especially in mountainous areas and due to their energy they normally represent a severe form of natural hazards (Brilly *et al*., 1999). As a typical example of a rockfall in a narrow alpine valley, on Fig. 1 the Osojnik rockfall in the Trenta valley, W Slovenia, is shown.

Slika 1. Skalni podor Osojnik v dolini Trente (foto: avtorji, 2004).
Figure 1. The Osojnik rockfall in the Trenta valley (photo: authors, 2004).

Izraz skalni podor se v tem prispevku uporablja skladno z definicijo Kienholz *et al*. (1998) za odlom in gibanje posameznih skal (kamenja in blokov; Steinschlag v nemščini) kakor tudi za skalno maso, ki lahko razpade v posamezne bloke (Felsturz v nemščini), ki delujejo eden na drugega le v manjši meri.

Tako kot druga masna gibanja, kot so kamninski zdrsi, kamninski in zemljinski plazovi ter pobočni drobirski tokovi, se skalni podori prikazujejo v kartah nevarnosti. Te karte so različnega merila, izdelane na različnih osnovah, med katere spada tudi modeliranje nastanka in gibanja skalnih podorov (Petje, 2005). Rezultati takega modeliranja se lahko koristno uporabijo pri analizah tveganja pred skalnimi podori, za kar v Sloveniji od leta 2002 (sprejet nov Zakon o vodah) obstaja zakonska podlaga in obveza (Đurović & Mikoš, 2004).

The term rockfall in this paper will be used according to the definition by Kienholz *et al*. (1998) for detachment and motion of single rocks (stones and boulders; Steinschlag in German) as well as of a rock mass that can disintegrate into single blocks (Felsturz in German) that interact with each other only to a minor extent.

Like other mass movements, such as rockslides, landslides and slope debris flows, rockfalls are shown on hazard maps. These maps are of different scales and made on different bases, which include modelling of rockfall initiation and dynamics (Petje, 2005). The results of such a modelling can be usefully applied in risk analyses of rockfalls for what in Slovenia since 2002 (new Water Act) legal basis and obligation exist (Đurović & Mikoš, 2004).

V prispevku so prikazani načini modeliranja gibanja skalnih podorov, razdeljeni v skupine modelov. Namen prikaza je pomagati izbrati model skalnega podora, ki se lahko uporabi za analizo tveganja pred skalnimi podori v lokalnem ali regionalnem merilu. Primer uporabe dvodimenzijskega modela v lokalnem merilu je prikazan drugje (Petje, 2005).

In this paper, ways of modelling rockfall motion are shown, divided into separate groups of models. The aim of the review is to help select a rockfall model that may be used for rockfall risk analysis at local or regional scale. A case study using a two-dimensional model at local scale is given elsewhere (Petje, 2005).

2. VRSTE MODELOV

Računalniško simuliranje naravnih procesov v geomorfologiji uporablja dva popolnoma različna pristopa: realistični pristop in funkcionalistični pristop (Howes & Anderson, 1998). Nasprotno pa se modele, ki se jih uporablja pri naravnih nesrečah, deli na dispozicijske in procesne modele (Hegg & Kienholz, 1995).

Dispozicijski modeli (imenujemo jih tudi statični modeli) služijo za raziskavo možnih izvorov nevarnosti – povedo nam, kje lahko pride do nevarnega procesa. V določenih primerih lahko določimo pretekle podorne procese skozi daljše časovno obdobje na osnovi geoloških dokazov (neme priče kot npr. posamezni skalni balvani, položaj in debelina odkladnin). Tako lahko določimo doseg podora z neko povratno dobo. Vendar pa se povsod tega ne da določiti, saj se lahko spremenijo razmere, pri katerih poteka preperevanje, ali pa se odkladnin skalnega podora ne more ločiti od ledeniških ali drugih odkladnin (Evans & Hungr, 1993).

Procesni modeli (znani tudi kot dinamični modeli) simulirajo dinamiko procesa. Glede na pristop k obravnavani procesa jih lahko delimo na empirične procesne modele (funkcionalistični pristop po Howes & Anderson, 1998) in na analitične procesne modele (realistični pristop po Howes & Anderson, 1998).

Empirični procesni modeli (imenujemo jih tudi statistični modeli) na splošno temeljijo na povezavi med topografskimi faktorji in območjem odlaganja skalnega podora.

Analitični procesni modeli so sestavljeni iz:

- modela trajektorij in
- modela trenja.

Tako analitični procesni modeli določijo

2. GROUPS OF MODELS

Computer simulation of natural processes in geomorphology uses two fundamentally different approaches: realist approach and functionalist approach (Howes & Anderson, 1998). On the contrary, the models associated with natural disasters can be divided into dispositional models and process-based models (Hegg & Kienholz, 1995).

Dispositional models (also called statical models) are used for the research of possible source areas of hazards – they tell us, where a hazardous process may occur. In some cases recent or paleo rockfall processes in longer geological periods can be determined on the basis of geologic proofs (silent witnesses as i.e. single boulders, position and thickness of deposits). Thus a rockfall run-out distance with a return period can be determined. This cannot be determined under all circumstances, due to changes in field conditions regarding weathering, or rockfall deposits that cannot be differentiated from glacial or other deposits (Evans & Hungr, 1993).

Process-based models (also known as dynamic models) simulate process dynamics. They can be classified in relation to the process approach into empirical process-based models (functionalist approach after Howes & Anderson, 1998), and into analytical process-based models (realist approach after Howes & Anderson, 1998).

Empirical process-based models (called also statistical models) are generally based on the relationship between topographic factors and rockfall run-out zone.

Analytical process-based models are composed of:

- a trajectory model and
- a friction model.

They determine possible pathways, along

možne poti, po katerih se proces odvija (trajektorije pri podorih), ter za njih predvidijo hitrosti, kinetično energijo in mesta odlaganja (doseg procesa). S to ločitvijo na dva dela dosežemo boljše strukturiranje procesnega modela skalnega podora za uspešno rešitev problema. Računalniški (simulacijski) program je tako sestavljen iz modulov, kar poenostavi verifikacijo modela. Modeli trajektorij ne morejo simulirati realnih poti za pobočne procese, če ne vsebujejo podrobnega digitalnega modela višin.

V nadaljevanju bodo prikazane značilnosti dveh glavnih vrst procesnih modelov (empirični modeli, analitični modeli) brez navajanja vseh modelnih podrobnosti.

3. EMPIRIČNI PROCESNI MODELI

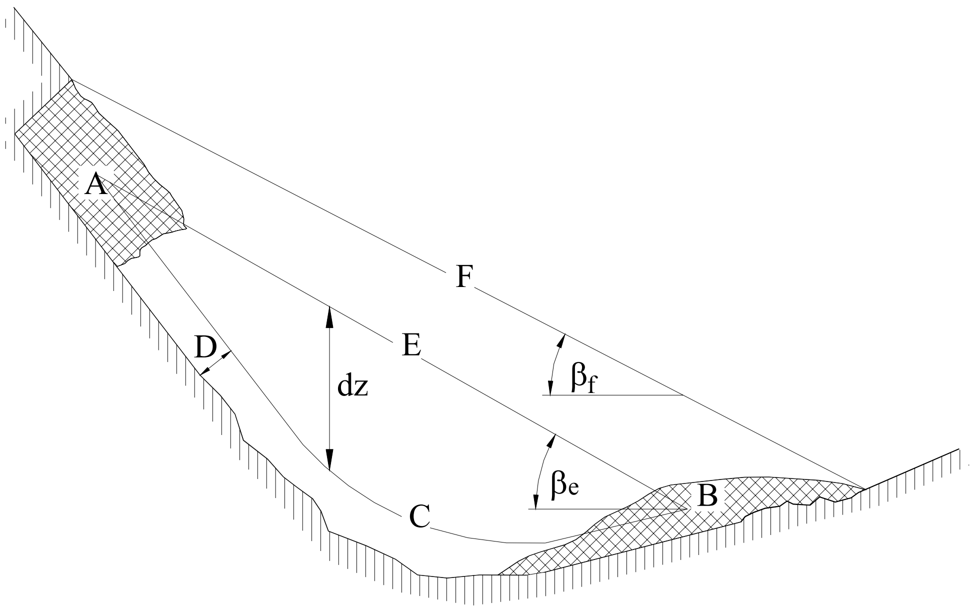
Scheidegger (1973) je ugotovil, da je dolžina dosega odvisna od kota med horizontalno črto in črto, ki povezuje začetno in končno težišče skalne mase, in je enak kotu trenja ϕ (0,57–0,83), ki kontrolira gibanje, ter je približno enak kotu gibanja (slika 2).

which the process takes place (trajectories with rockfalls) and determine velocities, kinetic energy, and areas of deposition (reach of a process). With this division into two parts a better process-based rockfall model structure for a successful solving of the problem is achieved. The computer (simulation) program thus consists of modules, what makes the model validation easier. The trajectory models cannot simulate true pathways for slope processes without incorporating a detailed digital elevation model (DEM).

Next in the paper, characteristics of the two main groups of the process-based models (empirical models, analytical models), will be shown without too many details.

3. EMPIRICAL PROCESS-BASED MODELS

Scheidegger (1973) stated that run-out distance is a function of angle between the horizontal line and the line that connects the starting point and the centre of the deposited mass and is equal to the angle of friction ϕ (0.57–0.83) that controls the movement, and approximately equals to the “travel angle” (Fig. 2).



Slika 2. Zasnova empiričnih modelov. Točki *A* in *B* sta težišči skalnega podora pred in po premiku mase; *C* označuje pot težišča skalne mase; *E* označuje energijsko črto; *F* označuje kot gibanja.
Figure 2. The concept of empirical models. Points A and B denote the centre of gravity of the rockfall before and after the mass movement, respectively; C is the pathway of the center of gravity of the rockfall mass; E denotes the energy line; F denotes the travel angle.

Onofri in Candian (1979) ter Toppe (1987) so predlagali princip "kota gibanja" (Heim, 1932) za določitev cone izteka. V slovenščini še nimamo uveljavljenega izraza za nemški izraz "Fahrböschung", zato predlagamo izraz "kot gibanja", ki je neposredni prevod angleškega izraza.

Horizontalna prepotovana razdalja x je tako izražena z višino padanja h:

Onofri and Candian (1979) and Toppe (1987) proposed to take this "travel angle" (Heim, 1932) for determining the run-out zone. In the Slovenian language there is no established term for the German term "Fahrböschung", so here a term "kot gibanja" is proposed, which is a direct translation from English.

The horizontal travel distance x is thus expressed by the vertical free fall height h:

$$x = \frac{h}{\tan\phi} \qquad (1)$$

Razni avtorji (npr. Hsü, 1975; Onofri & Candian, 1979; Domaas, 1985; glej pregled v Meiβl, 1998) navajajo, da je za večino podorov ta kot > 32°, vendar pa se za volumne podora nad 10^6 m^3 kot zelo hitro zmanjša. Kot, ki povezuje začetno in končno težišče mase, predstavlja translatorno komponento celotnega gibanja in se po tej dinamični značilnosti tudi razlikuje od kota gibanja. Vendar pa ravno tako ne vsebuje informacije o razširjanju materiala med gibanjem, ki je ključno za določitev prepotovane razdalje.

Scheideggerjev model (1973) upošteva trenje med drsečo maso in tlemi in ne upošteva deformacije mase med gibanjem. Konvencionalni model predpostavlja, da je horizontalna hitrost v_h enaka vertikalni hitrosti v_v, ki jo doseže padajoča masa tik pred trkom s tlemi, vendar pa se horizontalna hitrost zmanjša zaradi izgub pri trku. Tako lahko zapišemo:

Different authors (e.g. Hsü, 1975; Onofri & Candian, 1979; Domaas, 1985; see the overview in Meiβl, 1998) quote that for the majority of rockfalls this angle is > 32°, but for rockfalls with volumes > 10^6 m^3 this angle very quickly decreases. The angle that connects the starting point and the centre of gravity of the deposited mass represents the translational component of the whole movement and differs in this dynamical characteristic from the travel angle. However, it also does not incorporate information on spreading of material during motion, which is a key factor for determining the travel distance.

The Scheidegger model (1973) takes into account friction between the sliding mass and the ground and does not take into account mass deformations during travel. A conventional model assumes that the horizontal velocity v_h equals the vertical one v_v, which is achieved by the falling mass immediately before the impact with the ground. The horizontal velocity is reduced due to losses at impact. So one can state that:

$$x = \frac{r^2 h}{\tan\phi}, \qquad (2)$$

kjer je r koeficient odboja, njegova vrednost je pod 1:

where r is coefficient of restitution and its value is below 1:

$$v_h = r \cdot v_v \qquad (3)$$

Corominas (1996) je v raziskavi 204 plazov, od tega 47 skalnih podorov in skalnih plazov, ugotovil, da se z naraščanjem prostornine kot gibanja zmanjšuje in da to ne velja le za velike plazove. Zmanjšanje kota naj bi bila posledica učinka ovir in topografskih ovir. Pri večjih volumnih na odboje ne

Corominas (1996) examined 204 slides, out of them 47 rockfalls and rock avalanches, and found that with increasing volume the travel angle decreases and that this is not only valid for large falls and slides. The decreasing of the angle should be the consequence of obstacles and topographic constraints. With larger vplivajo ovire in vegetacija. Kot gibanja je odvisen od materiala, prostornine podorne mase in mehanizma gibanja in ne od potencialne energije oziroma višine padanja. Višina padanja ima vpliv na horizontalno prepotovano razdaljo, vendar ni nujno, da daljša horizontalna razdalja ustreza manjšemu kotu gibanja, lahko ustreza le večji relativni mobilnosti.

Davies in McSaveney (1999) sta z laboratorijskimi eksperimenti opazovala obnašanje skalnih podorov in plazov. Ugotovila sta, da je za skalne podore velikosti 1.000 do 10.000 m^3 geometrija odlaganja na pobočjih z naklonom 35° do 45° v močni povezavi s prostornino. Rezultati se ujemajo z meritvami na terenu. Za večje skalne plazove s prostorninami večjimi od 10^7 m^3 pa so značilni zelo veliki dosegi. Vzrok naj bi bil verjetno povezan s faktorji, kot sta drobljenje med gibanjem ter erodibilna podlaga.

Keylock in Domaas (1999) sta testirala tri empirične modele (imenujeta jih statistični modeli) in en preprost dinamični model glede njihove sposobnosti napovedovanja maksimalne dolžine dosega z uporabo preprostih topografskih parametrov. Ugotovila sta, da ima statistični model prednost, če želimo hitro in učinkovito določiti tveganje pred podori za večja območja.

Okura *et al.* (2000b) je z eksperimenti iskal zvezo med dosegom in prostornino. Iz eksperimentov in simulacij sledi, da obstaja jasna pozitivna povezava med dosegom in prostornino ter negativna povezava med razdaljo težišča mase in prostornino. Podori z naraščanjem prostornine težijo k utekočinjenju. Naklon pobočja in doseg sta v obratnem sorazmerju. Topografija je eden od zelo pomembnih faktorjev za določevanje dosega.

4. ANALITIČNI PROCESNI MODELI

Analitični modeli opisujejo ali simulirajo gibanje v dveh ali treh dimenzijah. Modeli v dveh dimenzijah se običajno uporabljajo v lokalnem merilu (posamezno pobočje), modeli v treh dimenzijah pa so primernejši za

volumes the obstacles and vegetation have no influence on rebounds. The travel angle depends on material, mass volume and mechanism of motion and not on potential energy or fall height. The height of falling has some influence on the horizontal travel distance but it is not necessarily true that larger travel distances correspond with smaller travel angles – it can correspond with higher relative mobility.

Davies and McSaveney (1999) performed laboratory experiments and observed behaviour of rockfalls and rock avalanches. They found out that for rockfalls of the size between 1,000 and 10,000 m^3 deposition geometry on slopes with a gradient between 35° and 45° is strongly related to the volume. The results agree with field measurements. For large rock avalanches with volumes larger than 10^7 m^3 extraordinarily long run-out distances are typical. The cause may well be connected to factors such as fragmentation during motion and the erodible base.

Keylock and Domaas (1999) tested three empirical models (called statistical models) and a simple dynamical model for their capability of forecasting the maximum run-out distance using simple topographic parameters. They found that the statistical model has an advantage, if rockfall risk in larger areas has to be determined quickly and effectively.

Okura *et al.* (2000b) searched a connection between the run-out and the volume. From experiments and simulations it follows that a clear positive correlation exists between the run-out distance and volume as well as a negative correlation between distance of gravitational center of mass and volume. Rockfalls with increasing volume tend to fluidization. The slope gradient and run-out distance are in inverse proportion to each other. Topography is one of important factors for determining the run-out distance.

4. ANALYTICAL PROCESS-BASED MODELS

Analytical models describe and simulate motion in two or three dimensions. Two-dimensional models are usually applied at local scale (individual slope), and three-dimensional models are more appropriate for obravnavo v regionalnem merilu (cela dolina, občina, posamezni kartni list). Pred obravnavo značilnosti analitičnih modelov v dveh oziroma treh dimenzijah bodo prikazani glavni modelni parametri ter občutljivost in zanesljivost teh modelov.

4.1 MODELNI PARAMETRI ANALITIČNIH MODELOV

Za izračun trajektorij padanja skal potrebujemo naslednje podatke:

- lokacijo potencialnih mest izpadanja skal, izvor (začetna točka, angl. orig. source area, detachment point);
- obliko in geometrijo skal;
- možno velikost skal, maso (interval od–do);
- mehanske lastnosti skal in pobočja;
- odbojni koeficient;
- značilne vzdolžne profile in topografijo pobočja;
- drobljenje skal ob padcu.

Eden izmed vhodnih parametrov v modelih je masa skal. Pri tem upoštevamo pravilo, da imajo večje skale manjšo verjetnost pojavljanja.

Vpliv geometrije brežine na rezultat izračuna določimo s spreminjanjem oblik terena med dvema točkama na brežini (določitev občutljivosti na obliko brežine). Za vpliv, ki ga ima lastnost hribine, delamo izračun z vpeljavo velike standardne deviacije odbojnega koeficienta R_n. Za mesto izvora padanja lahko v izračunu predvidimo številna mesta, ponavadi pa so najbolj kritična na vrhnjem delu brežine.

V naravi so oblika in velikost skale, mehanske lastnosti in natančna lokacija izvora težko določljive. Geometrija pobočja (gradient, dolžina, hrapavost materiala) se spreminja po pobočju in je ne moremo popolnoma zajeti. Večina programov uporablja profile, ki jih je določil uporabnik in zahtevajo podrobnejše informacije o materialu. Značilni vzporedni profili po padnici brežine so navadno dobljeni iz topografskih kart ali pa jih izdelamo s terestričnim terenskim snemanjem v podrobnem merilu. Litološke značilnosti in rabo tal se določi s terenskimi raziskavami, iz geoloških kart in kart rabe tal

an analysis at regional scale (whole valleys, communities, single cartographic sheets). Before dealing with characteristics of analytical models in two and three dimensions the main model parameters will be shown as well as models' sensitivity and realibility.

4.1 ANALYTICAL MODEL PARAMETERS

So as to compute the trajectories of falling rocks the following data are required:

- positions of detachment points or source areas;
- the shape and geometry of rocks;
- possible rock size and their mass (range from–to);
- mechanical properties of the rocks and the slope;
- coefficient of restitution;
- typical longitudinal profiles and slope topography;
- crushing of rocks at impacts.

One of the input parameters in the models is rock mass. In doing so the rule is obeyed, which defines that larger rocks have lower probability to detach.

The influence of slope geometry on the computational results can be determined by changing the slope shape between two points on the slope (sensitivity analysis on the slope form). The influence of rock characteristics can be determined by large standard deviation of coefficient of restitution R_n. For the source area of falling stones numerous points can be determined and the most critical ones are usually in the upper part of the slope.

The shape and size of rocks, mechanical properties and the precise location of sources are hard to determine in the field. The slope geometry (gradient, length, material roughness) changes along the slope and cannot be fully captured. The majority of computer programs use profiles, determined by users, and ask for detailed material properties. Characteristic longitudinal profiles along the slope gradient are usually obtained from topographic maps or produced by terrestrial field surveys in precise scale. The lithological properties and soil use are determined by field research, from geological maps and soil use maps or by the interpretation of aerial ali pa z interpretacijo aerofoto posnetkov. Večina programov dela zadovoljivo dobro samo na majhnih površinah, za katere so na voljo podrobnejše (tudi topografske) informacije. Rezultate napovedi zelo izboljšamo z natančno terensko analizo padanja kamnov na obravnavanem terenu.

Količina izgub energije ob trku ali kotaljenju je v veliki meri odvisna od oblike, velikosti, hitrosti in dinamike bloka (translatorna in kotna hitrost), geotehničnih lastnosti pobočja (granulometrična sestava, elastični modul, vsebnost vode …), geometrije, topografije in hrapavosti površine ter kota trka. Te parametre je težko točno določiti. Napovedovanje trajektorije je zato kompleksna operacija, ki vsebuje veliko negotovosti.

Razmerja med energijskimi izgubami in drugimi spremenljivkami niso točno določena. V večini primerov se vsi učinki zaradi plastičnih deformacij podlage in geometrične konfiguracije trka upoštevajo s »kontaktnimi funkcijami«, ki opisujejo kinematiko skale (hitrost) ali dinamiko (energijo) pred in po trku. Te funkcije so izražene kot koeficient odboja in koeficient trenja.

Koeficient odboja je tista spremenljivka, s katero umerjamo model padanja skal. V izračunu za poljuben odsek profila vnesemo dva odbojna koeficienta, normalni in tangencialni (preglednica 1). Normalni koeficient odboja R_n, ki se ponavadi spreminja med vrednostma $0{,}3 < R_n < 0{,}5$, se uporabi za primere, ko kamen udari na tla blizu kota 90°. Tangencialni koeficient odboja R_t, ki se ponavadi spreminja med vrednostma $0{,}8 < R_t < 0{,}95$, pa je primeren za padce skal, ki padejo na površino pod ostrim kotom.

Mehke cone zemljine in vegetacija zavzemajo spodnje dele obsega odbojnega koeficienta, odkrita hribina in asfalt pa zgornje. Toda že majhna sprememba koeficienta odboja prinese popolnoma druge rezultate. Na primer, če skala pade od trde hribine (R_n = 0,50) le 10 cm stran v mehko cono (R_n = 0,35), se lahko udarec popolnoma absorbira – v nasprotju z velikim odbojem v primeru udarca ob trdo hribino.

Medtem ko imajo inženirji dober občutek

photographs. The majority of computer programs only perform well in small areas, for which detailed (also topographic) information is available. The prediction results are greatly improved by precise field analysis of falling rocks in the area under consideration.

The energy consumption at impacts or rolling is to a large extent a function of shape, size, velocity, and block dynamics (translational and angle velocity), geotechnical slope properties (granulometric composition, module of elasticity, water content …), geometry, topography and surface roughness as well as impact angle. These parameters are hard to determine precisely. The trajectory prediction is therefore a complex task, incorporating large uncertainties.

The correlations between energy losses and other variables are not precisely determined. In most cases, all influences due to plastic deformations of the base and due to impact geometrical configurations are considered using "contact functions", which describe block kinematics (velocity) or dynamics (energy) before and after the impact. These functions are in the form of the coefficient of restitution and the friction coefficient.

The coefficient of restitution is the variable that helps validating a model of falling rocks. In the computation of a chosen profile section, two coefficients of restitution are given, the perpendicular and the tangential ones (Table 1). The perpendicular coefficient of restitution R_n, usually located between the limits $0.3 < R_n < 0.5$, is used for cases when a rock hits the ground near the angle of 90°. The tangential coefficient of restitution R_t, usually located between the limits $0.8 < R_t < 0.95$, is used for rocks that hit the ground at low angles.

Zones of soft soils and vegetation occupy the lower values of the coefficient of restitution, while bare rock and asphalt cover the upper values. However, only a minor change in the coefficient of restitution causes completely different results. For example, if a stone hits a soft zone (R_n = 0.35) that is only 10 cm away of hard rock (R_n = 0.50) a hit can be fully absorbed – instead of a large rebound in the case of a hit against hard rock.

While engineers in general have a good

za kot notranjega trenja, pa tega ne moremo reči za koeficient odboja. Kot smo že prej nakazali, je to mogoče rešiti tako, da z računalniškim programom opravimo povratno analizo, dokler ne dobimo pravih (izmerjenih) rezultatov padanja skal (tj. dejansko ugotovljena končna mesta padca skale).

feeling for the angle of repose, this is not true for the coefficient of restitution. This can be solved, as shown, by using a computer program and performing a back analysis until true (measured) results for falling rocks are obtained (i.e. stopping places of falling rocks that have been recognized in the field).

Preglednica 1. Tangencialni R_t in normalni koeficient odboja R_n ter koeficient trenja μ – prikazan za različne pokrovnosti tal (Dorren, 2003).
Table 1. Tangential coefficient of restitution R_t, perpendicular coefficient of restitution R_n, and friction coefficient μ – given for different soil cover (Dorren, 2003).

pokrovnost tal / soil cover	R_t	R_n	μ
klif, strme stene 60–90° / *cliff, steep rock faces* 60–90°	0.95	0.45	0.25
strma gola pobočja 40–60° / *steep bare slopes* 40–60°	0.90	0.40	0.45
gruščnata pobočja 30–40° / *talus slopes* 30–40°	0.88	0.32	0.60
gola pobočja 0–30° / *bare slopes* 0–30°	0.87	0.35	0.50
travnik / *meadows*	0.87	0.30	0.55
alpsko grmovje / *alpine bushes*	0.85	0.30	0.60
grmovje / *bushes*	0.83	0.30	0.65
gozd (200 dreves/ha) / *forest (200 trees/ha)*	do / *up to* 0.85 povprečno / mean 0.67	0.28	1.00
gozd (300 dreves/ha) / *forest (300 trees/ha)*	do / *up to* 0.85 mean 0.57	0.28	1.50
gozd (500 dreves/ha) / *forest (500 trees/ha)*	do / *up to* 0.85 mean 0.38	0.28	2.00
gozd (700 dreves/ha) / *forest (700 trees/ha)*	do / *up to* 0.85 mean 0.27	0.28	2.20

4.2 OBČUTLJIVOST IN ZANESLJIVOST ANALITIČNIH MODELOV

Na zmanjšanje zanesljivosti izračuna z analitičnimi modeli vplivajo:

- neznano mesto izvora padanja;
- spremenljive lastnosti hribine (vzdolž profila ni mogoče opredeliti vseh sprememb v lastnostih materiala, ker so odvisne od lokalnih sprememb v vzorcu razpokanosti, stopnji preperelosti …);
- spreminjanje oblike brežine;
- problem izbora kritičnih profilov za računsko analizo;

4.2 ANALYTICAL MODELS' SENSITIVITY AND RELIABILITY

The following causes for decreased reliability of results of analytical models are recognized:

- unknown source area;
- variability of rock properties (along the slope profile it is not possible to take into account all variations in material properties, which are caused by local changes in fracturing pattern, weathering stage …);
- variability in slope shape;
- the problem of selecting critical profiles for computational analysis;

- lokalne nepravilnosti, ki jih pri snemanju profila ni možno zajeti.

Osnovni inženirski pristop k izračunu je previdnost in konzervativnost pri izbiri vhodnih podatkov. Odločitev, koliko bomo konzervativni, pa je odvisna tudi od zunanjih faktorjev, kot je na primer gostota prometa. Pri cestah z malo prometa bomo privzeli 95 % mejo v diagramu porazdelitve možnih trajektorij, za avtoceste z gostim prometom pa bomo upoštevali vse možne trajektorije padajočih skal.

Za opredelitev nevarnosti padanja skal uporabljamo posebne izračune, ki temeljijo na statističnih metodah, med njimi se pogosto uporablja metoda Monte Carlo (Vose, 1996). Za vsak vplivni faktor po tej metodi določimo spodnjo in zgornjo mejo in statistično porazdelitev vrednosti med obema mejama. Računalniški program nato s slučajnim izbiranjem vrednosti spremenljivk med obema mejnima vrednostma več tisočkrat ponovi izračun in izračunava trajektorije gibanja skal. S spreminjanjem koeficienta odboja izračun umerimo glede na v naravi ugotovljene posamezne padce kamnov. Kot rezultat dobimo ovojnico trajektorij padanja skal. Ko izvajamo izračun, ponavadi vse vrednosti vplivnih faktorjev držimo enake, razen ene spremenljivke, kateri računalnik slučajno izbira vrednosti. Tako spremenljivko eno za drugo testiramo in ugotavljamo, kakšna je njena "pomembnost" v končnem izračunu. Kljub takemu pristopu pa se ne moremo izogniti vsem neznankam. Nujne so različne poenostavitve, ki se poznajo v manjši kakovosti končnega izračuna.

Realistično napovedovanje podorov je nadalje komplicirano s tridimenzijsko naravo dejanske geometrije pobočja. Dvodimenzijski programi ne upoštevajo tridimenzijskega učinka topografije na trajektorije (Agliardi & Crosta, 2003; Azzoni *et al*., 1995). Najpomembnejši 3D-učinek je lateralna disperzija trajektorij (Crosta & Agliardi, 2003). Lateralna disperzija je deviacija trajektorij od smeri z največjim gradientom in predstavlja ključni problem pri modeliranju, saj ima velik vpliv na način modeliranja dinamike, projektiranje ukrepov in določevanja nevarnosti. Crosta in Agliardi

- local irregularities which cannot be represented during field survey of profiles.

The basic engineering approach to computations is caution and conservation when selecting the input parameters. The decision, how conservative to be, is also related to outside factors such as traffic density. With roads of low traffic volumes, the 95 % boundary limit in the diagram of possible trajectories will be taken, and for highways with large traffic volumes all possible trajectories of falling rocks will be taken into consideration.

For assessing the hazard of falling rocks special computations are used, based on statistical methods, among those especially the Monte Carlo method (Vose, 1996). For each relevant factor using this method the lower and the upper limit and the statistical density function between these limits are determined. The computer program takes random values of variables between the given limits and repeatedly computes trajectories of falling rocks as often as several thousand times. By changing the coefficient of restitution the computation is validated by using stopping points of falling rocks as observed in the field. The result of this procedure is a trajectory envelope of falling rocks. When doing computations, usually all relevant factors are kept constant, apart from one variable, whose values are randomly selected by the computer. Doing so, all variables are tested one after another and the procedure gives their relative "relevance" for the final result. Despite such a procedure, all uncertainties cannot be avoided. Simplifications that result in the lower quality of final results are needed.

Realistic rockfall forecasting is furthermore complicated by a three-dimensional (3-D) nature of true slope geometry. Two-dimensional (2-D) programs do not take into account the three-dimensional effect of topography on trajectories (Agliardi & Crosta, 2003; Azzoni *et al*., 1995). The most important 3-D effect is the lateral dispersion of trajectories (Crosta & Agliardi, 2003). The lateral dispersion is the deviation of trajectories from the slope gradient and represents the key modelling problem, as it has a major influence on the way how dynamics is modelled, on designing of measures and hazard determination. Crosta and Agliardi (2003) researched the influence of weight,

(2003) sta raziskovala vpliv teže, hitrosti, naklona terena in mikrotopografije na disperzijo trajektorij. Največja slabost dvodimenzijskih programov je, da so neprimerni za določitev tveganja na širšem območju (regionalno merilo), kjer podrobnejše tematske informacije niso dosegljive.

Zaradi prisotnosti lateralne disperzije je težko a priori določiti trajektorijo v 2D-pristopu. 3D-učinek topografije je tako pomemben kot vpliv geometrije na dinamiko padajoče skale. Zato opis celotne topografije in stohastični pristop zagotavljata možnost modeliranja večjega števila trkov skale in tal, saj se upošteva prostorska spremenljivost parametrov in možnost manj pogostih in redkih trajektorij. Pomembno je poudariti tudi koncept »nepričakovanega dogodka« – najbolj nevarni dogodki se bodo manj verjetno zgodili. Zato je konservativni pristop, ki upošteva najbolj verjetno trajektorijo, lahko včasih nezadovoljiv. Vpliv 3D-topografije je večji pri večjih dolžinah trajektorij, saj se povečujejo napake zaradi variabilnosti parametrov zaradi naraščanja števila trkov in morfoloških vplivov.

V inženirski praksi se navadno skalne podore simulira v dveh dimenzijah vzdolž profilov, ki smo jih v naprej definirali. Čeprav je 2D-pristop najbolj razširjen zaradi uporabe komercialnih računalniških programov pa je interpretacija rezultatov in njena razširitev na sosednja področja lahko zelo subjektivna.

4.3 DVODIMENZIJSKI ANALITIČNI MODELI

Najprej bodo obravnavani dvodimenzijski modeli, ki se omejujejo na gibanje skale v vertikalni ravnini ter zato ne simulirajo stranskega gibanja skal. Nadalje je trajektorija skale v gibanju v teh modelih sestavljena iz ravnih odsekov z naklonom pobočja enakim merjenim srednjim gradientom na določenem odseku pobočja. In nazadnje je gibanje skal simulirano s fazami padanja in fazami stika s podlago. Faza padanja je simulirana z enačbo parabole, začetno hitrostjo v x- in y-smeri in težnostnim pospeškom. Točka trka s tlemi se računa s sečiščem parabole in ravnim odsekom pobočja.

velocity, slope gradient, and microtopography on trajectory dispersion. The most important weak point of 2-D models is that they are not appropriate for hazard assessment of larger areas (regional scale), where detailed thematic information are not reachable.

Due to existence of lateral dispersion it is hard to a priori determine a trajectory in a 2-D approach. The 3-D topography effect, thus, is important as a geometry effect on the falling rock dynamics. Therefore, only the complete topography description and stochastic approach ensure the possibility of modelling numerous impacts of stones on the ground, since the spatial variability of parameters is taken into account and thus also the possibility of less frequent or rare trajectories. It is important to stress the concept of the so-called "unexpected event": the most hazardous events will happen with lower probability. Thus, a conservative approach, which takes into account the most probable trajectory, can be unsatisfactory. The influence of a 3-D topography is higher with longer trajectory lengths, since the errors due to parameters variability increase due to increase in the number of impacts and due to morphological influences.

In engineering practice, rockfalls are normally simulated in two dimensions along the pre-defined longitudinal profiles. Even though a 2-D approach is most frequently used due to the use of commercially available computer programs, the interpretation of the results obtained and their extrapolation to neighbouring areas may be very subjective.

4.3 TWO-DIMENSIONAL ANALYTICAL MODELS

Firstly, two-dimensional models will be discussed that are limited to the rock motion in the vertical plane. As a consequence, lateral motion cannot be simulated. Furthermore, a rock trajectory in these models is composed of straight reaches with a slope gradient equal to the measured mean gradient in the single slope reach. And lastly, rock motion is simulated by phases of falling and phases of contact with the ground. The falling phase is simulated by the equation of the parabola, the initial velocity in the x and y directions and the gravitational acceleration. The point of impact with the ground is computed by the intersect between the parabola and the straight reach of the slope.

Kirkby in Statham (1975) sta razvila model za gibanje skal prek vršaja s predpostavko, da skale drsijo po površini vršaja. Rezultati so bili primerljivi z rezultati laboratorijskih eksperimentov. Model je najprej izračunal hitrost padajoče skale v ob vznožju stene višine h:

Kirkby and Statham (1975) developed a model for motion of rocks on a talus slope using an assumption that rocks slide across the slope surface. The results were comparable to the results from laboratory experiments. The model firstly computes the velocity of a falling rock v at the toe of the rock face with the height h:

$$v = \sqrt{2gh} \tag{4}$$

Na osnovi hitrosti padajoče skale v je bila izračunana komponenta hitrosti tangencialno na pobočje s predpostavko, da se ta hitrost med prvim udarcem s tlemi ni spremenila. Lokacija, kjer se skala ustavi, je bila določena z deležem med hitrostjo padanja in silo upora, ki je bila določena z dinamičnim kotom upora.

Dvodimenzijski modeli upoštevajo specifičen algoritem za računanje hitrosti kotaljenja in drsenja z uporabo Coulombovega zakona upora:

Using the velocity of a falling rock v, the velocity component tangential to the slope was computed under the assumption that this velocity did not change during the first impact with the ground. The position where a rock stops was determined by a ratio between the falling velocity and the resistance force, which was determined by the dynamic resistance angle.

The two-dimensional models take into account a specific algorithm for computing rolling and sliding velocity using the Coulomb friction law:

$$F_t = \mu_f \cdot m \cdot g \cdot \cos\beta \tag{5}$$

kjer je F_t sila upora (tangencialno na pobočje, kgm/s^2), μ_f je koeficient upora, m je masa skale (kg), g je pospešek sile teže in β je srednji gradient pobočja (º). Izračunana sila upora se lahko uporabi za račun hitrosti drsenja in kotaljenja skale. Koeficient upora je najpomembnejši faktor za določitev hitrosti.

Za določitev hitrosti pred in po odboju se uporabljata dva principa. Oba principa računata hitrost pred in po trku na osnovi izgube energije. Prvi princip definira izgubo energije s koeficientom učinka trka, ki je delež skupne kinetične energije skale pred in po trku. Drugi princip računa energijsko izgubo na osnovi tangencialnega koeficienta odboja, ki deluje vzporedno s pobočjem, in normalnega koeficienta odboja, ki deluje pravokotno na pobočje.

Dvodimenzijski modeli so primerni za lokalno merilo (pregled v preglednici 2).

where F_t is friction force (tangential to slope surface, kgm/s^2), μ_f is friction coefficient, m is rock mass (kg), g gravity, and β is average slope gradient (º). The friction force can be used to calculate the sliding and rolling velocity of rocks. The friction coefficient is the most important factor when determining velocity.

Two principles are used for determination of velocity prior and after a rebound. In both cases the velocities are calculated based on energy loss. The first principle defines the energy loss with the coefficient for the efficiency of collision, which is the ratio of total kinetic energy of the rock prior and after the impact. The other principle calculates energy loss based on the tangential coefficient of restitution, which acts parallel to the slope and normal coefficient of restitution acting perpendicular to the slope.

Two-dimensional models are adequate at local scale (overview in Table 2).

Preglednica 2. Nekateri dvodimenzijski analitični procesni modeli, uporabni za lokalno merilo, in njihove značilnosti.
Table 2. Some two-dimensional analytical process-based models, applicable at local scale, and their characteristics.

model *Model*	opis podorne mase *rock mass description*	opis gibanja *movement description*
Bozzolo & Pamini (1986)	togo telo / *rigid body*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*
Bozzolo *et al.* (1988)	togo telo / *rigid body*	trki & poskoki / *impacts & bounces*
Hungr & Evans (1988)	masna točka/*lumped mass*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*
Pfeiffer & Bowen (1989)	masna točka/*lumped mass*	trki & poskoki / *impacts & bounces*
Kobayashi *et al.* (1990)	masna točka/*lumped mass*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*
Zinggeler *et al.* (1991)	masna točka/*lumped mass*	trki & poskoki / *impacts & bounces*
Evans & Hungr (1993)	masna točka/*lumped mass*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*
Azzoni *et al.* (1995)	togo telo / *rigid body*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*
Chau *et al.* (1998)	togo telo / *rigid body*	poskakovanje, kotaljenje & drsenje *bouncing, rolling & sliding*

4.4 TRIDIMENZIJSKI ANALITIČNI MODELI

Tridimenzijske modele so med drugimi razvili Descoudres in Zimmermann (1987), Scioldo (1991), Gascuel *et al*. (1998), Guzzetti *et al*. (2002) in Aglairdi & Crosta (2003). Le redki tridimenzijski modeli upoštevajo interakcijo med padajočimi skalami. V zadnjem desetletju je modeliranje napredovalo pri določitvi koordinat, hitrosti, kotne hitrosti v 3D-prostoru. Tako modeli simulirajo spremembo kinetične energije delcev kot rezultat neelastičnih trkov med sabo in s pobočjem. Taki modeli temeljijo na metodi končnih elementov (Okura *et al*., 2000a) ali na analizi diskontinuitetnih deformacij DDA (Koo & Chern, 1998). RIG-DDA metoda (izboljšana DDA-metoda) vsebuje kinematiko vseh oblik gibanja in interakcijo med bloki. Možno je simulirati gibanje mase skal, ki vsebuje veliko skal vzdolž nepravilnega pobočja v sprejemljivem računskem času. Yang *et al*. (2004) predlagajo tridimenzijsko metodo DDA za simulacijo gibanja in napovedovanje trajektorije padanja. Model upošteva skalo kot sferično togo telo.

4.4 THREE-DIMENSIONAL ANALYTICAL MODELS

The three-dimensional models were designed among others by Descoudres and Zimmermann (1987), Scioldo (1991), Gascuel *et al*. (1998), Guzzetti *et al*. (2002), and Aglairdi & Crosta (2003). Only rarely three-dimensional models take into consideration the interactions between falling rocks. Within the recent ten years, modelling has advanced in terms of determination of coordinates, velocity and angular velocity in a 3-D space. Thus, models simulate the change of kinetic energy of particles as a result of non-elastic impacts among themselves and with the surface. Such models are based on the finite element method (Okura *et al*., 2000a) or on discontinuous deformation analysis (DDA) (Koo & Chern, 1998). The RIG-DDA method (improved DDA method) contains the kinematics of all kinds of movement and interaction between blocks. It is possible to simulate the movement of rock mass, which includes rocks along the uneven slope within an acceptable calculation time. Yang *et al*. (2004) propose a 3-D DDA method for simulation of movement and prediction of falltracks. The model considers the rock as a spherical rigid body.

5. MODELI NA OSNOVI GIS

Geografski informacijski sistemi so učinkovita orodja za analizo prostorskih pojavov in za upravljanje prostorsko opredeljenih podatkov. S tem predstavljajo dragocen pripomoček pri presoji tveganja. GIS-i so primerni tudi za upravljanje podatkov o katastrih in o škodnem potencialu.

Naravne nesreče so večdimenzijske in predstavljajo interdisciplinarni pojav, ki ima močno prostorsko komponento, kadarkoli se pojavi. Razumevanje pojava in reševanje zahteva dostop do prostorsko orientiranih podatkov različnih izvorov, meril, resolucije, časovnega razvoja in analiz v štirih dimenzijah.

Po ESRI (2002) lahko obseg dela razdelimo na:

- zajem podatkov;
- shranjevanje podatkov (v vektorski in rastrski obliki);
- poizvedovanje (identifikacija obstoječih podatkov);
- analizo podatkov (analiza oddaljenosti, prekrivanje, mrežne analize);
- prikaz podatkov (kartografija, priprava preglednic in poročil);
- izhod (karte, Internet, slike, dokumenti).

Presoja nevarnih naravnih procesov zahteva informacije o površju, pokrovnosti tal in geoloških razmerah. Če naj presoja poteka na osnovi GIS, morajo biti te informacije na voljo v elektronski obliki.

Prednost vektorskih podatkov je v enostavnejšem shranjevanju podatkov, krajšem računskem času, boljši natančnosti. Rastrska karta se sestoji iz matrike kvadratkov. Vsak piksel ima svojo vrednost. Med piksli ni logične povezave. Rastrski podatki imajo tudi svoje prednosti. Pri računanju dosega podora je bistven relief, ki ga imamo navadno v rastrskem formatu, tako da rezultate dobimo ravno tako v rastru. Površje prikazuje digitalni model višin (DMV), ki je navadno v rastrski obliki. Za Slovenijo je uporaben DMV, izdelan na osnovi radarskih podatkov (Oštir *et al.*, 2000). V splošnem se redko uporablja tudi trikotna nepravilna mreža (TIN).

Iz podatkov o višinah se lahko izvedejo

5. GIS-BASED MODELS

Geographic Information Systems are an efficient tool for analysis of spatial phenomena and management of spatial data. Hence, they represent a valuable tool in risk assessment. GIS are further applicable in managing the data on land register and damage potential.

Natural hazards are multi-dimensional and represent an interdisciplinary phenomenon with a strong spatial component during each occurrence. Our understanding of the phenomenon and addressing the problem requires access to spatially referenced data of different origins, scales, resolutions, time course and analyses in four dimensions.

According to ESRI (2002) the work can be divided into:

- data capture;
- data storage (vector and raster data);
- querying (identification of existing data);
- data analysis (analysis of distance, overlapping, network analysis);
- displaying data (mapping, working with tables and reports);
- output (maps, Internet, images, documents).

The assessment of hazardous natural processes requires data on surface, soil cover and geological conditions. If the appraisal is based on the geographic information system, these data should be available in electronic form.

The advantages of using vector data are easier data storage, shorter calculation time and better accuracy. The raster map is composed of grids. Every pixel has a value. There are no logical connections between pixels. Raster data also have their advantages. In calculating the run-out distance of a rockfall the key element is the relief, which is usually in the raster format, and the results are also in the raster format. The surface is represented by the Digital Elevation Model (DEM) which is usually in the raster format. For Slovenia, a DEM is useful that was prepared using radar data (Oštir *et al.*, 2000). Generally, Triangulated Irregular Networks (TIN) are seldom used.

drugi, za presojo nevarnosti pomembni parametri površja, npr. nagib površin, velikost prispevnega območja. Digitalni model višin je tudi osnova za določitev trajektorij nevarnih procesov. Ugodno je, če je dodana k digitalnemu modelu višin tudi hidrografska mreža v digitalni obliki. Podatki o pokrovnosti tal morajo povedati, ali so tla sestavljena iz skalovja (kamnin), ledu ali golega drobirja (zemljin) oziroma so porasla. Geološke informacije so nujne za označitev podlage v bližini površine, povedo nam podatke o strukturnih značilnostih, lastnostih kamnin in o vrsti zemljin.

Pomembno je, da so ti osnovni podatki na voljo po celi površini raziskovanega območja v homogeni obliki in v ustrezni prostorski ločljivosti. Minimalna ločljivost je odvisna od procesa, ki se bo simuliral, kakor tudi od ciljnega merila. V splošnem velja pravilo, da lahko pri ploskovnih procesih delamo z bolj grobo ločljivostjo kakor pri linearnih procesih.

Pri uporabi GIS je velika nevarnost v tem, da je analize čisto tehnično možno izvesti tudi z neprimernimi osnovnimi podatki, to pa večinoma iz rezultatov ni takoj razvidno. Da se izognemo takšni situaciji, je nujno pri analiziz uporabljati karte primerljivih meril.

GIS-modeli so tisti, ki tečejo pod GIS-okoljem, ali pa so rastrski modeli, katerih vhodni podatki so pridobljeni z GIS-analizami. GIS-modeli za podore se sestojijo iz treh postopkov:

- identifikacija območja izvora podora;
- določitev trajektorije;
- račun območja izteka.

Število GIS-modelov stalno narašča (Carrara *et al*., 1991; Carrara, 1995; Guzzetti *et al*., 2002; Chau *et al*., 2004a; 2004b; Mayer *et al*., 2004; Rowbotham & Dudycha, 1998; Temesgen *et al*., 2001; van Westen & Getahun, 2003) – kljub temu ne morejo popolnoma nadomestiti terenskega dela.

Prednosti, zaradi katerih se odločamo uporabljati GIS, so naslednje:

- Možnost obdelave geografskih podatkov: geografski podatki se sestojijo iz kombinacije geometrijskih podatkov (položaj objekta v prostoru) in vsebinskih podatkov (lastnosti objekta).

From the elevation data other surface parameters relevant for hazard assessment can be derived, such as surface slope, and size of the catchment area. The Digital Elevation Model is a basis for determination of trajectories of hazardous processes. It is beneficial if a digital hydrographic network is added to the DEM. The data on soil cover should reveal if the soil consists of rocks, ice or gravel, and whether the surface is vegetated. Geological data need to characterise the ground near the surface, and provide information on structure, rock features and soil type.

It is important that these basic data are available for the entire study area in a homogeneous form and in an adequate spatial resolution. The minimum resolution depends on the process to be simulated and the targeted scale. In general, in areal processes rougher resolution is used than in linear processes.

In using the geographic information systems the danger lies in the fact that analyses can (technically) be performed with inadequate basic data, which cannot be instantly deduced from the results. To avoid such a situation, maps in comparable scales should be used throughout the anaysis.

The GIS models are the models working under the GIS environment, or raster models whose input data are acquired with GIS analyses. GIS models for rockfalls are composed of three procedures:

- Identification of the areas of rockfall origin;
- Determination of the falltrack;
- Calculation of the run-out zone.

The number of GIS models is in constant increase (Carrara *et al*., 1991; Carrara, 1995; Guzzetti *et al*., 2002; Chau *et al*., 2004a; 2004b; Mayer *et al*., 2004; Rowbotham & Dudycha, 1998; Temesgen *et al*., 2001; van Westen & Getahun, 2003) – they cannot completely replace field work.

The advantages of using GIS are the following:

- Possibility of processing geographic data: Geographic data consist of a combination of geometrical data (position of a structure in space) and content-related data (attributes). Such

Takšni podatki potrebujejo posebno vrsto funkcij za obdelavo in analizo. GIS vsebuje obe vrsti funkcij, poleg tega je možna dodatna obdelava s programi CAD (Computer Aided Design).

- Možnost vključitve digitalnih modelov reliefa: pri procesih gibanja mase ima relief eno od najbolj pomembnih vlog, predvsem naklon in izbočenje pobočja.
- Nadaljnje prostorske analize: določitev tveganja in s tem poznavanje infrastrukture in objektov na določenem območju.

GIS je zelo primeren za izdelavo dispozicijskih modelov, drugače pa je pri procesnih modelih. Problemu se lahko izognemo tako, da vgradimo zunanji program, ki obdela podatke in jih nato vrne nazaj v GIS, kjer se jih lahko nadalje analizira.

6. ZAKLJUČKI

Poglavitni namen v prispevku podanega pregleda modeliranja gibanja skalnih podorov je strokovnjakom pomagati pri izboru ustreznega modela za lokalno in regionalno merilo. V prispevku so predstavljene glavne značilnosti izbranih modelov skalnih podorov, ki se trenutno uporabljajo v svetu. Gibanje skalnih podorov lahko raziskujemo in napovemo z uporabo empiričnih procesnih in analitičnih procesnih modelov ter z uporabo modelov, ki temeljijo na GISu.

Empirični procesni modeli temeljijo na povezavi med topografskimi faktorji in območjem izteka oziroma dolžino dosega, včasih jih imenujemo tudi statistični modeli.

Analitični procesni modeli v dveh ali treh dimenzijah opisujejo in simulirajo gibanje podorne mase in se ločijo glede na način, kako upoštevajo podorno maso (kot masno točko; razne oblike togih teles) in kako simulirajo gibanje po pobočju (poskakovanje, kotaljenje, drsenje).

Modeli na osnovi GIS izkoristijo prednosti tega orodja in potekajo v treh korakih: določitev območij izvora podorov, določitev trajektorij posameznih skalnih blokov in določitev območij izteka (odlaganja) podorne mase. Področje uporabe teh modelov je predvsem regionalno merilo.

data require a specific kind of functions for processing and analysis. GIS incorporates both kinds of functions and enables further processing with CAD (Computer Aided Design) tools.

- Possibility of inclusion of DTM: In processing that involves the movement of mass, the relief plays a significant role, especially regarding its slope angle and unevenness.
- Further spatial analyses: Risk assessment and thus the knowledge of infrastructure and structures in a certain area.

In contrast to process-based models, GIS is highly applicable in disposition models. The problem can be avoided by adding a software that processes the data which are then returned back to GIS, where they can be analysed further.

6. CONCLUSIONS

The main aim of the review on modelling of rockfall motion in this paper is to help professionals to choose a rockfall model adequate at local and regional scales. In the paper, the main characteristics of the selected rockfall models that are currently used worldwide are presented. Rockfall motion can be studied and forecasted by using empirical process-based and analytical process-based models or by using GIS-based models.

The empirical process-based models are based on the connection between topographic factors and the run-out distance (also called statistical models).

The analytical process-based models describe and simulate movements of the rockfall masses in two or three dimensions. They can be differentiated regarding the way how the rockfall mass (as a lumped mass; different rigid body shapes) and the movement on the slope (bouncing, rolling, sliding) is described, respectively.

The GIS-based models use the advantages of this tool and work in three steps: The determination of rockfall source areas, the determination of trajectories of single boulders, and the determination of run-out distances and run-out zones. The application of these models is especially at regional scale.

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