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기반암 하상의 침식과정 -수치 모형을 중심으로 한 고찰-

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Erosion processes in bedrock river -A review with special emphasize on numerical modelling-

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요약: 기반암 하상 하천은 산지 지역의 장기적 지형 발달에서 침식 기준면의 기능을 수행 하는 지형단위로서 하도와 제방에 기반암이 노출된 하천이다. 하상이나 제방에 퇴적 물질이 존재하는 경우가 많이 있으나, 그 두께는 퇴적물 1개에 해당하는 깊이인 경우가 많으며 이 역시 홍수시에 이동되는 것으로 보고되고 있다. 기반암 하상의 침식과정은 대부분의 침식속도가 느리고 침식과정이 대규모의 홍수 상황에서 발생하는 관계로 관찰, 계량화가 어렵다. 그 결과 침식과정에 대한 이해는 전반적으로 낮다고 볼 수 있으나 중요성에 대한 문제제기는 상당히 이루어지고 있다. 본 고에서는 기반암 하상의 구체적 침식과정에 대한 이론적 모형과 수리 모형들을 고찰 하고 기존의 모형들을 소개 하고자 한다.

주요어: 토양유실, 유실, 지리정보시스템(GIS), 범용토양유실공식(USLE), 하상변동

Abstract: A bedrock river is a channel in which bedrock is exposed along the channel bed or walls for at least approximately half of its length. In some case, a continuous alluvial veneer may be present, but this is completely mobilized during floods. From the point of long term landscape evolution during the Quaternary, the bedrock channel determines local base level and the lowering rate of bedrock channels controls the rate of erosion and transport processes and forms on the adjacent hillslopes. In this review, various erosional processes in bedrock river channels are classified and discussed. Especially, theoretical and numerical models on channel bed abrasion with bed load sediment particles are introduced and discussed.

Keywords: Bedrock channel, cavitation, plucking, abrasion, numerical model

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Introduction

A bedrock river is a channel in which bedrock is exposed along the channel bed or walls for at least approximatelyhalf of its length. In some case, acontinuous alluvial veneer may be present, but this is completely mobilized during floods (Wohl, 1999). The presence of a bedrock channel reflect a lack of sediment storage and high transport capacity, which are reflections of local variability of lithology, sediment supply, particle size and transport capacity of the flow. The high transport capacity is generally the result of steep channel gradient (Ashley *et al.*, 1988).

From the point of long term landscape evolution during the Quaternary, the bedrock channel determines local base level and the lowering rate of bedrock channels controls the rate of erosion and transport processes and forms on the adjacent hillslopes (Seidl *et al.*, 1994). So, it has been argued that bedrock rivers play a fundamental role in landscape history by setting the boundary conditions for landform evolution.

It is critical to understand individual erosional processes in bedrock rivers for proper representation for landscape modelling to understand the past and to predict the possible changes in the future with climatic change. Progress in the numerical modelling of the evolution of landscape with bedrock channels is also very limited, as understanding of the processes in bedrock channels is incomplete. Most numerical studies examine morphological changes in longitudinal profile forms. Basin scale studies use the very simple stream power erosion model, which is based on evidence from easily erodible channels. For the alluvial reaches or flume, decreased sediment input, for example, clearly lead to increased channel bed incision, but it is not clear whether this relationship can be applied to bedrock rivers in which the transport capacity is larger than the sediment input in most situations.

Erosion rates in bedrock rivers are very low and most erosion processes operate during high magnitude and low frequency floods. Because of this, field process studies on bedrock erosion processes are rare except in extreme circumstances (*eg.* Hartshorne *et al.*, 2002) and process investigations commonly use analogy from flume studies to provide insight into erosion process in bedrock rivers. However, in many cases flume study results are difficult to apply directly to bedrock rivers, because the appropriate laws to scale from flume to field are unknown. With limitation of proper investigation, most studies have been focused on the morphology of bedrock forms in and around channel. The erosional processes have been inferred in the way to find the origins of the forms(*e.g.* Bishop and Goldrick, 1992). Though there are some difficulties to connect forming processes and resulting features, the forms provide god indication of the possible processes.

In this review, various erosional processes in bedrock river channels are classified and discussed. Especially, theoretical and numerical models on channel bed abrasion with bed load sediment particles are introduced and discussed.

Classification of Erosion Processes

Various classification schemes can be developed for bedrock erosional forms erosion processes.

Wohl(1998) categorized bedrock features with the size of landforms (*e.g.* Figure 1). The classification system based on hierarchy of the fluvial system, like channel network −channel plan form−channel cross profile−minor forms. Though this classification system is very simple and easy to understand, the relationship between erosive forces and forms is not clear. It also should be noted that mechanical properties of erosion is not considered properly. Even the different nature of each erosional process is ignored.

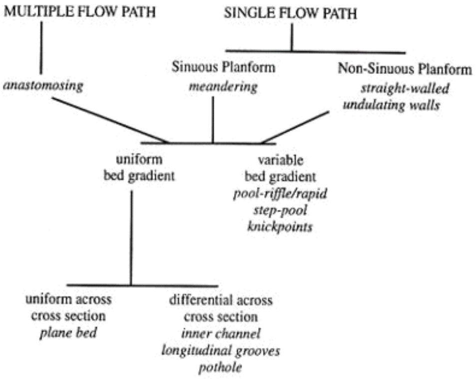

Fig. 1. Typology of meso-scale bedrock channel morphologies(Wohl, 1998, Fig.1)

Here processes are first grouped by whether or not erosional tools (particles in transport) mediate erosion (Table 1). As the roles of joints and other lithologic factors in erosion processes are beyond the prospects of this article, these will be discussed elsewhere.

The most importantfactor for initiating cavitation is the pressure against the channel bed, which is determined by flow depth and velocity. Plucking is difficult to classify precisely, as it includes related processes of loosening, dislodgment and transport. Dislodgment and transport processes depend mainly on flow hydraulics and on the size of the blocks. However, sediment particles accelerate plucking by causing hydro−wedging and crack propagation through collision. Even though the crack propagation process in the field is not clear, it requires stress to overcome the tensile strength of the rock to initiate and grow cracks (Ingraffea, 1987). The impact force of sediment collision against the channel bed, stress lodging in mechanical terms, could also contribute to crack growth (Whipple *et al.*, 2000).

Abrasion processes are tool−dependent, as without sediment particles no abrasion can happen. Erosion is maximized when hydraulic conditions and sediment transport

Table 1. Classification of erosional process by the primary agent of erosion.

Direct erosion by the flow	Erosion mediated by sediment particles
* Cavitation * Plucking: − Dislodgment and transportation − Loosening: vibration in place by fluctuating pressure * Corrosion	* Abrasion by suspended load * Abrasion by bed load * Plucking − Loosening: Hydro−wedging and crack propagation by sediment collision.

combine optimally. To understand abrasion rates, sediment transport processes need to be considered.

Bedload is the most important sediment transport process for abrasion as particles are continuously or regularly in contact with the bed during transport. Sediment starts to move when the bed shear stress exceeds a critical value. Particles slide or roll along the bed, when the excess shear stress is small. As shear stress increases, particles begin to hop and collide with the bed (saltation). The maximum height of particle hopping is limited by water depth and shear stress. It has been reported that the maximum height can reach 20 times the sediment diameter (Lee *et al.* 2002).

At higher transport stages, sediment particles begin to be suspended byturbulence. When a wide range of sizes of sediment particles is supplied to a reach, these two transport processes will occur together, and there will be interaction between bed load grains and suspended load grains, so affecting incision processes (Figure 2). These individual processes can be classified according to the hydraulic conditions in the channel (Table 2). The dominant processes changes from place to place, but also as stage changes.

Fig. 2. Erosional forms in a bedrock river (River Etive, Scotland).The bedrock river is experiencing various erosional processes. The erosional forms in bedrock show evidence of the operating erosion processes (abrasion (1), hydro-wedging (2), potholing (3) and plucking (4)). Abrasion produces smooth and polished surface, while plucking produces sharp bounded removal of rock mass. Hydro-wedging causes the crack growth by the sediment particles trapped between the rock blocks.

Table 2. A classification of hydraulic conditions and erosion processes

Hydraulic Condition	Low Stream Power <--------------> High Stream Power
Erosion Processes	Corrosion - Independent of hydraulic variables. Abrasion by bed load --------------------------- Abrasion by suspended load --------------- Vibrating, Wedging, Small scale Plucking ---- Cavitation Massive Plucking

At low shear stress, when shear stress is less than the critical shear stress for the start of sediment transport, only corrosion occurs. Its effectiveness depends on lithology, and is greatest in calcareous rocks.

When shear stress exceeds the critical shear stress, sediment particles start to move and start to erode the channel bed by collision (abrasion by bed load). At higher transport stages, small particles start to be suspended and larger particles begin to saltate. So, at this stage abrasion by bed load and suspended load occur simultaneously, and rock blocks are vibrated and cracks enlarged by pulsating water pressure.

In rare very high magnitude floods, cavitation may start to operate and rock blocks can be detached, while abrasion processes are working at a large scale. As all these mechanical processes are threshold-bounded, the number of processes acting to erode the channel bed increases with increasing flood magnitude. The efficiency of these individual processes will vary with lithology and the dominant erosion processes for a particular reach can only be decided by detailed study.

Corrosion

Corrosion is the process of chemical weathering of the channel bed in areas covered by calcite rocks. Other rock types are also eroded by corrosion, but the rates of erosion are negligible (Wohl, 1998). The corrosion process can be expressed for carbonates by the following reaction.

$$CaCO_3 + H^+ + HCO_3^- \Leftrightarrow Ca^{+2} + 2HCO_3^-$$

(Equation 1).

The carbonic acid (HCO_3^-) in the water is derived and supplied from the atmosphere and soil. The corrosion rate is independent of water velocity and all other hydraulic forces. It mainly depends on ion activity and the reaction constant. The value of ion activity reflects the mineralogy of the rock (Springer, 2002). This process can be very active within joints and can produce sculpted forms that cause vortex structures to develop and so contribute to overall erosion.

Plucking

Plucking is the process of detachment of rock blocks from the channel bed by the flow assisted by hydro-wedging and vibration. Plucking processes are dominant where the rocks are composed of jointed blocks, particularly in distinctively layered sedimentary rocks (Whipple *et al.,* 2000).

There is debate on the driving force that causes plucking. Snyder *et al.* (2003) argued that the critical variable to initiate plucking is closely related to shear stress. However, the physical process of the plucking is not as simple as could be assumed by relating it simply to a critical shear stress. The concept of the threshold for erosion is useful, but values for it have not been found either from the field study or from physical experiments. The plucking process has two subsequent processes: Loosening and Transporting (Table 3).

Table 3. Details of plucking of rock mass (After Annadale, 1995). The plucking of a massive rock mass occurs with two separate stages: Loosening and transporting. The loosening process separates the rock mass from others by crack propagation and vibration in place.

Loosening Processes	Transporting processes
1. Chemical and physical weathering along joints or fractures. 2. Hydraulic wedging of sediment particles into progressively opening cracks. 3. Vertical and lateral crack propagation induced by high stress as associated with impacts of large particles. 4. Crack propagation induced by pressure fluctuation.	Two major forces are involved in transport of rock mass. 1.Uplifting force by pressure fluctuation. 2. Shear stress forces on rock mass.

From studies of high speed water erosion in hydraulic structures (Annadale, 1995), the erosion rate by plucking is controlled mainly by loosening processes, especially hydraulic wedging and pressure fluctuations that serve as rate-limiting factors.

These two factors are interrelated and feedback to each other. Fracture lines or joints play a critical role in the hydro-plucking (hydro-wedging) process. Sediment particles enter cracks and particles are forced deeper into the joint by shattering of the rock mass and by fluctuating pressure. As the joint becomes wider, more sediment particles enter, so separating or loosening the rock. Without sediment wedges, pressure fluctuations cause cracks in the rock to propagate (Figure 3).

Fig. 3. Sediment particles in a crack in the River Etive. The sediment particles inside the crack are important tools for hydro-wedging (Tape shows flow direction). The yellow scale is 40 cm long. Sediment particles are stuck into the crack, so cannot be moved.

Variations in water pressure also cause plucking. High pressures in fast, turbulent flow propagate into joints or fracture lines and cause unbalanced lift forces on rock blocks (Montgomery, 1984). This effect is maximized in the case of high magnitude fluctuations of pressure on the channel bed. Ideal conditions for this process are large-scale boundary roughness and high flow velocity so that the areas downstream of hydraulic jumps are regarded as the most favourable zone for this kind of erosion.

The pressure fluctuation downstream of a hydraulic jump can be written as follows:

$$C_{p,\,fluctuation} = \frac{\Delta P}{\left(\frac{V_i^2}{2 \cdot g}\right)} \qquad \text{(Equation 2)}$$

were ΔP is the dimensionless pressure deviation from the mean pressure (m), and V_i is incident velocity (m sec^{-1}). Dimensionless pressure is a function of Froude number and the ratio between distance from the hydraulic jump and incident depth of flow. Fluctuations are maximized at the toe of jump and decrease downstream (Toso, 1986).

The fluctuation of pressure can cause the dislocation of large rock blocks in the channel bed (Figure 4). As flow expands at the end of the constricted channel, the flow condition changes from super-critical to sub-critical, causing pressure fluctuations in flood conditions.

Fig. 4. Dislocated rock mass in the River Etive, downstream of a rapid. The fluctuation of pressure can cause the dislocation of large rock blocks in the channel bed. The location of the figure is downstream of a rapid. As flow expands at the end of the constricted channel, the flow condition changes from super-critical to sub-critical, causing pressure fluctuations in flood conditions.The length of the pen in the photo is 12 cm. Blue lines are estimated initial joint positions and the red arrow shows the flow direction.

Pressure fluctuations also affect sediment particles on the channel bed as particles in scour holes are in constant motion, continuously bouncing and moving back and forth on the bottom (Urbonas, 1968).

Another approach to plucking is based on the force balance at entrainment of the block. This can be used to calculate critical flow velocity (Uc) requiredto transport detached bedrock blocks:

$$U_c^2 = \frac{2\cdot(\rho_s-\rho)\cdot g\cdot D_b}{\rho}\cdot\frac{\mu_f}{C_d+\left[C_l\cdot\mu_f\cdot(D_b/D_c)\right]}$$

(Equation 3)

$$\mu_f = \frac{\tau_{cr}}{(\rho_s-\rho)\cdot g\cdot D_a\cdot D_b\cdot D_c} \qquad \text{(Equation 4)}$$

$$C_d = \mu_f\cdot\frac{2g\cdot(K\cdot\gamma_s-A_b\cdot h\cdot\gamma)}{(\gamma\cdot A_d)\cdot U^2} \qquad \text{(Equation 5)}$$

where D_a, D_b and D_c are the long, medium and short axes of the block (m), respectively, C_d is the drag coefficient, C_l is the lift coefficient, K is the volume of the block (m^3), A_b and A_d are the basal and the flow normal submerged areas of the block (m^2), h is the water depth (m), g_s and g are the specific weight of the block and water, g is the acceleration due to gravity, U is the flow velocity (m sec^{-1}) and m_f is the friction coefficient, which approaches 0.82-0.89 in bedrock channels (Wende, 1999; Carling *et al.*, 2002).

Fig. 5 Separated rocks at a pool in the River Etive. Pressure fluctuations cause hydraulic jacking of the rock mass and causing progressive break up of the rock. The flume experiment by Robinson et al.(2001) showed that the critical transport discharge for the blocks downstream of the step is controlled by the hydraulic variables and block orientation. The erosion discharge increased as theblock dimension orthogonal to the bed surface increased. The rock blocks also to be ejected by net pressure differences over and under the blocks.

Field studies of bedrock rivers have found large bedrock blocks downstream of bedrock steps (Hack, 1956; Dury, 1970; Keller and Melhorn, 1978) (Figure 5). These rocks can only be transported during large floods. These blocks remain where they were detached until the flood magnitude is sufficient to transport them.

Cavitation

Cavitation is erosion caused by forces generated by the rupture of a liquid due to a decrease in pressure at roughly constant temperature. Some definitions of cavitation include the inception, growth, and collapse of a rupture. This process was found by engineers trying to find the cause of damage to steel structures that rotate at high speed (*e.g.* Cook, 1928). It has been regarded as a significant geologic process from the mid 1950s (Barnes, 1956), butdetailed studies have been sporadic, despite the fact that there are many reports of damage to spillways. Hjulstrom (1935) argued that potholes or other erosional features could be initiated and evolve by cavitation.

Cavitation occurs when a collapsing bubble produces a force against the bed, due to extremely high velocities (400m sec^{-1} -5000m sec^{-1}) (Dear and Field, 1988; Bourne and Field, 1992). If such a jet strikes a solid surface, high temperaturesand pressures can be realized in the area of jet impact (Spray, 1999). Even very fine suspended sediment particles increase the impact energy, as this energy increases as the square of velocity.

To achieve the conditions necessary for cavitation the local pressure of water must be lowered to the vapour pressure of the fluid. This condition can be written as follows:

$$C_p = \frac{P_v - P_r}{\left(\rho \cdot \frac{V^2}{2}\right)} \qquad \text{(Equation 6)}$$

where C_p is pressure coefficient, P_v is vapour pressure, P_r is reference pressure, and V is the velocity of the flow. Thepressure coefficient depends on Reynolds number, Froude number, concentration of fine suspended material in flow, and air entrainment into the flow. The critical value of the pressure coefficient is influenced by flow and environmental conditions.

The role of entrained air in the flow is critical for cavitation, the cavitation coefficient (C_p) increasing with air concentration. So, for cavitation erosion to occur, flow velocity should exceed 20 m sec^{-1}. Only extremely large-scale flood can have such high velocity.

Abrasion by sediment particles

Abrasion is the process by which sediment particles transported by the flow erode channel beds. Channel bed erosion by mobile sediment particles is an old idea. Gilbert (1877, 1914) emphasized that the role of sediment particles in channel bed erosion and doubted whether pure water in mechanical suspension has any appreciable erosive power, while also arguing that clear water without sediment particles could dissolve the bed by corrosion.

Other early writers commented on the tool effect of sediment particles (*eg.* Gregory, 1915; King, 1927 Blackwelder, 1942 Hjulstrom, 1935; Bryan, 1935 Kuenen, 1947), but this effect has been largely neglected in modern geomorphic studies. One reason for this neglect is that most geomorphic studies of river channels have focused on alluvial channels for nearly the whole of the 20th century (Young, 1985). As alluvial channels are composed of sediment particles, the role of sediment particles in bed erosion is hard to identify.

(1) Abrasion by suspended load

It is very difficult to quantify the role of suspended load in channel bed erosion, as suspension is the transport regime for relatively fine particles that have little contact with the channel bed (Bagnold, 1973 Leeder, 1999). However abrasion by suspended load has been regarded as a significant process for bedrock incision (Lugeon, 1914; Maxon and Campbell, 1935). Most floods in bedrock channels have extreme turbulence, causing frequent and high impacts of suspended load with the channel bed (Figure 6). As a result channel beds show rounded or polished surfaces, also called ‘fluting’ or ‘sand blasting’ (Maxon, 1940).

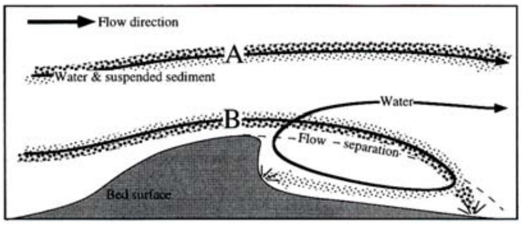

Fig. 6. Schematic of flow around a bed obstacle (Hancock et al., 1998, Fig. 6)

Anderson (1986) conceptualised the erosion by suspended load as:

$$\varepsilon_s = \frac{S_a \cdot (\frac{1}{2} \cdot \rho_s \cdot C_{vr} \cdot U^3)}{\rho_r}$$

(Equation 7)

where e_s is the erosion by suspended load, S_a is the susceptibility of the rock to erosion, C_{vr} is the volumetric concentration (kg) of specific sediment size(r), U is the flow velocity (m sec^{-1}) and r_r is the rock density (kg m^{-3}). The term in the brackets is the normal flux of kinetic energy to the rock surface per unit time (Anderson, 1986). The erosion rate at apoint increases with the volumetric concentration of suspended particles and flow velocity. The effectiveness of this process is hard to test, as susceptibility of the rock is undefined in quantitative terms. Forapplication in the field, C_{vr} is also difficult to define.

Experimental studies in flumes have raised questions on the effectiveness of abrasion by suspended load (Sklar and Dietrich, 2001). The erosion rate of the bed decreases exponentially with decreasing sediment size at the same flow conditions. Erosion by suspended load could be very effective at abrading rock surfaces that protrude high into the flow above the bedload dominated zone or the wall of the channel (Sklar and Dietrich, 2001; Whipple *et al.*, 2000). It is also argued that erosional features in bedrock channel are confined to a zone from 50% to 150% above the low water level.

However, some researchers argue that erosion by suspended load is critical for erosion in some areas that experience large-scale floods. The LiWu River in Taiwan experienced a 2240m^3 sec^{-1} flood in 2000 and it was found that massive blocks of quartzite and schist rock were removed from the channel bed (Hartshorn *et al.*, 2002). In that situation very large (up to 3m diameter) sediments can be transported, while most of particles in river are much smaller than that. In such flood conditions, most of the sediments on the channel bed could have been moved. Survey data show that some of the rock removed followed joints and there was no evidence of polished or fluted surface produced by that event (Hartshorn *et al.*, 2002). Therefore it is not clear that whether this massive erosion was caused by abrasion by suspended particles or other processes, like cavitation and plucking. Previous studies of high speed erosion in such large floods show that massive detachment from the bed can be caused by alternating pressure differences inside fissured rock, caused by a time lag between pressure fluctuations in the flow near the bed and inside the rock (Bowers and Tsai, 1969 Toso and Bowers, 1988 Fiorotto and Rinaldo, 1992; Bellin and Fiorotto, 1995). Additionally, upward pressure components could be strong enough to detach the rock fragment. The high roughness height of the irregular channel bed could result in very high differential pressure peaks (Reinius, 1986; Tesaker, 1992). The joint set acts as a path to transmit the pressure wave, delivering the wave very quickly, and it affects the stability of the rock mass divided by joints (Bollaert, 2002). When the pressure fluctuation effects are combined with the impacts of sediment particles or other material rapid erosion of the bed results (Bowers and Toso, 1988).

All of the physical processes causing bedrock erosion have threshold criteria for the initiation of erosion. As all of the erosional processes have different thresholds, erosion in bedrock channel may be thought of as a stochastic process.

(2) Abrasion by bedload

To understand erosion by bedload, both sediment movement characteristics and impact process should be understood. Foley (1980*a*) introduced a conceptual model for erosion by colliding bedload. Foley' s conceptual model is based on the sand blast model of Bitter (1963*a*). In Foley' s model, the volume of erosion by an impacting particle is determined by the sediment quantity, particle velocity, particle size, erosion threshold velocity and the hardness of the channel bed and sediment particles. Sklar and Dietrich (1998) extended Foley' s (1980*a*) model to produce a semi-quantitative model in which channel incision reflects the impact kinematics of individual particles, the number of impacting particles per unit time and channel width, and relative sediment flux to the reach. Sklar and Dietrich (2001) also found that erosion rates due to bedload are higher than those due to suspended load.

Foley (1980a) developed the first numerical model that includes the role of sediment particles in the erosion process. His model is a modified version of Bitter' s (1963*a*) model that described sand-blast wear on ceramics. Bitter' s model was based on the mechanics of individual impacting particles and emphasised that the volume of erosion by impacting particle is governed by the velocity,mass, erosion threshold velocity and hardness of the material. Bitter (1963*a*) proposed

$$W_D = \frac{\frac{1}{2}\cdot M\left[V-K\right]^2}{\varepsilon_B} \quad \text{(Equation 8)}$$

where W_D is the wear volume by deformation (m^3), M is the mass of the impacting particles (N sec^2 m^{-2}), V is the flow velocity (m sec^{-1}), K is threshold velocity for erosion (m sec^{-1}) and e_B is the amount of energy needed to remove one unit volume of material (J m^{-3}). The validity of Bitter' s model was supported by experiments (Bitter, 1963*b* Head and Harr, 1970; Gustavson, 2002).

In his modification, Foley introduced the role of the physical characteristics of saltation movement, saltation height and length, and sediment flux, as

$$\varepsilon_{Foley} = \frac{1}{2}\cdot\frac{Q_s}{\lambda}\cdot\frac{(v-K)^2}{e} + 2\cdot\frac{Q_s}{\lambda}\cdot\frac{C(v-K)^2}{\sqrt{V}}\cdot\left[U - \frac{C(v-K)^2}{\sqrt{V}}\cdot\zeta\right] \quad \text{(Equation 9)}$$

$$K = \frac{\pi^2}{2\sqrt{10}}\cdot\left(\frac{R_i}{R_s}\right)^{\frac{3}{2}}\cdot z^{\frac{5}{2}}\cdot\rho_s^{-\frac{1}{2}}\cdot\left[\frac{1-q_1^2}{E_1}+\frac{1-q_2^2}{E_2}\right]^2 \quad \text{(Equation 10)}$$

$$C = \frac{0.288}{z} \cdot \left(\frac{\rho_s}{z}\right)^{\frac{1}{2}} \qquad \text{(Equation 11)}$$

where R_i is the minimum radius of curvature of the sediment particle (m), R_s is the radius of a sphere of the same mass as the sediment particle (m), z is the bedrock elastic load limit, q_1 and q_2 are Poisson' s ratios for the sediment particles and the channel bed, and E_1 and E_2 are Young' s modulus for the sediment and the bed respectively.

The rate of erosion of the channel bed (e_{Foley}) is controlled mainly by effective sediment flux (Q_s/l), flow velocity (V), particle velocity (v), and the erosion threshold terms (K, z and e), which depend on the lithologic characteristics of the bed. In this formulation sediment particles erode the channel bed when their velocities exceed the threshold velocityfor erosion. This is a similar idea to the 'excessive stream erosion' approaches, in which erosion occurswhen shear stress exceeds a critical shear stress (Tucker and Whipple, 2002). Foley' s model was developed to explain the diversion and incision by post-glacial outwash at the River Dearborn in the U.S and has not been tested quantitatively. He estimated the erosion rate during glacial melting outwash using hydraulic and geologic data from the river (Foley, 1980*b*).

Foley found that, for a given discharge,the erosion rate for a lower slope is greater than for a steeper slope. He argued that this occurs because saltation length decreases more rapidly than sediment flux with a slight decrease in slope. He also noted that hydraulic parameters, collected from Dearborn River reaches, were not sufficient to use a more appropriate bedload transport model. Foley also found that his model overestimates the erosion rates (100-150 cm year^{-1} from his model prediction, 0.5 cm year^{-1} from other chronological studies) by overestimatingthe duration and discharge of flow that have enough hydraulic force to initiate erosion (Foley, 1980*b*). Foley also pointed out that bedrock erosion is a threshold-bounded stochastic process.

Sklar and Dietrich (1998) extended Foley' s (1980*a*) model to develop a general model for bedrock channel erosion. Their model (Equation 12) can be divided into three principal parts: ***A***: unit erosion by each colliding particle ***N***: number of sediment particles and ***R***: relative flux of sediments. The equation is,

$$\varepsilon = \left[\frac{\rho_s \cdot \pi \cdot \sin(\theta) \cdot (u_s^2 + v_s^2) - \varepsilon_t}{\varepsilon_v}\right] \cdot \left[\frac{Q_s}{\rho_s \cdot \pi \cdot D^3 \cdot W \cdot \lambda}\right] \cdot \left[1 - \frac{Q_s}{Q_t}\right] \qquad \text{(Equation 12)}$$

where q is the approach angle of sediment particles (degree), u_s is horizontal velocity of particle (m sec^{-1}), v_s is vertical velocity (m sec^{-1}), Q_s is sediment supply (kg sec^{-1}), Q_t is the transport capacity (kg sec^{-1}), D is sediment size (m), W is channel width (m), e_v is the energy needed to remove a 'unit volume' of bedrock from the channel bed (J m^{-3}), and e_t is the energy threshold which must be exceeded for erosion (J).

Sklar and Dietrich (1998)also added a term for relative sediment supply to the reach and also added more detailed physical characteristics of saltation by adapting Wiberg and Smith' s (1985) theoretical analysis of saltation. Most bedrock channels have sediment supply lower than transport capacity of the flow (*i.e.* $Q_s<Q_t$: Montgomery and Buffington, 1997; Wohl, 1999). In these cases, abrasion by sediment is dominant, so as sediment supply increases the erosion rate also increases. However, when sediment supply reaches a limit ($Q_s=Q_t$,), sediment particles start to be deposited on the bed and start to play a protective role. As the covered area extends, the erosion rate of the reach declines. Finally, when sediment supply exceeds transport capacity ($Q_s>Q_t$) the bedrock channel becomes an alluvial channel.

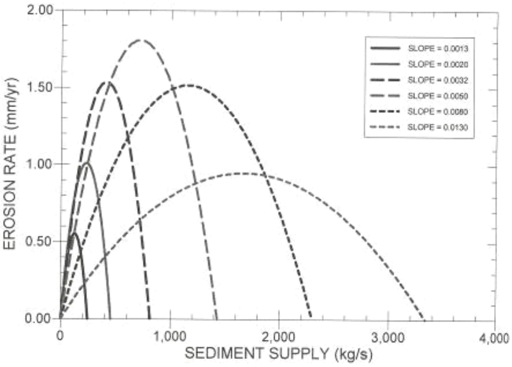

Fig. 7. Bedrock erosion rate as a function of sediment supply for various channel slopes as predicted by Sklar and Dietrich's model. Discharge=100m3 sec-1, channel width=26m and sediment size=40mm (Sklar and Dietrich, 1998, Fig. 11). Slope and sediment supply are the controlling factors.However, erosion rate decreases with slope with constant sediment flux. Even the maximum erosion rate of each slope shows a complicated pattern. Maximum erosion rate increases with slope at gentler slope, but further increases in slope reduces the maximum erosion rate

Sklar and Dietrich' s (1998) model suggested that sediment supply plays a dual role in channel erosion. At low sediment supply (Q_s/Q_t<0.5) erosion rates increased quickly with Q_s/Q_t to maximum rates. At Q_s/Q_t = 0.5, a further increase in Q_s leads to a decrease in erosion rates. Sklar and Dietrich (1998) described these effects of the role of increasing sediment flux as a transition from a 'tool effects dominates' stage to a 'coverage effects dominates' stage. The relationship between erosion rates and channel slope shows a non-linear pattern with changing slope (Figure 7).

It is noteworthy from these results that, for given sediment supply, gentler slopescould result in higher erosion rates than steeper slopes.

Kim (2004) proposed modified Sklar and Dietrich (1998)' s model which is abnormal non-linearities are removed and dimension incoherency were corrected (Equation 13). The basic structures of the improved and modified model of bedrock abrasion has three separate terms representing: (i) unit erosion by individual impact kinematics of the sediment particles (ii) number of sediment particles as a function of bedload transport rate and transport mode; and (iii) relative bedload supply rate. The modifications involved calibration of the impact force as a function of sediment particle size, changesin saltation characteristics, and the introduction of an effective sediment flux term (Q_{se}).

$$\frac{\Delta z}{\Delta t}=\left[\frac{\frac{1}{12}\cdot(\rho_s-\rho)\cdot D^3\cdot\pi\cdot\sin(\theta-S)\cdot(u_s^2+v_s^2)-\varepsilon_t}{\varepsilon_v}\right]\cdot\left[\frac{Q_s}{\frac{1}{6}\cdot\rho_s\cdot\pi\cdot D^3\cdot W\cdot\lambda}\right]\cdot\left[1-\frac{Q_s}{Q_t}\right]$$

(Equation 13)

The result of the numerical simulation(Kim,

2004) suggested that transport stage (t^*/t^*_{cr}) is the primary controlling factor over channel bed incision. The transport stage represents excess shear stress (Tucker and Whipple, 2002) and is more sensitive to slope than to discharge. It can be inferred that bedrock channel incision is strongly governed by slope.

The erosion pattern is also strongly affected by the sediment 'settings' in the numerical simulations. The simulations suggest that increasing sediment flux causes increasing erosion rate to a relative sediment flux (Q_s/Q_t) of ~0.5. Erosion rates subsequently decrease with increasing sediment flux. This result is consistent with the modelling results of Sklar and Dietrich (1998). In addition, introduction of effective sediment flux (Q_{se}), which scales the sediment flux with transport mode, predicts a lower erosion rate than does the nominal sediment flux (Q_s). The changing pattern of erosion with changing sediment flux was the same as in the case of nominal sediment flux.

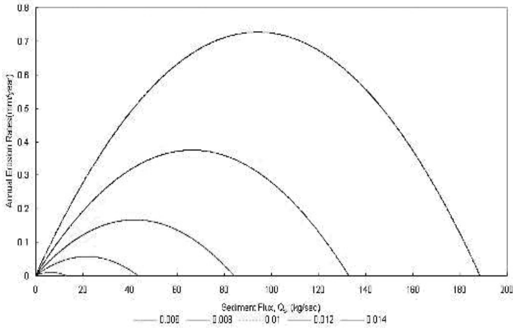

Fig. 8. Annual erosion rate with changing sediment flux. Discharge=15m3 sec-1, and channel width=12.4m. With constant discharge and same sediment flux, steeper slopes are predicted to have higher erosion rates than gentler slopes.

Numerical models suggest that the relationship between sediment flux and bedrock incision rate is parabolic (Foley, 1980a; Anderson, 1986; Sklar and Dietrich, 1998 Kim, 2004). With small relative sediment flux (sediment flux (Q_s)/ transport capacity (Q_t)<0.5), erosion rate increases with sediment flux. Erosion rate is a maximum at the 0.5 relative sediment flux and declines afterwards. The erosion curve is a symmetric parabola.

Figure 8 shows that erosion rate increases with sediment flux. For constant width, discharge and slope, incision rate of reach increases with increasing sediment flux to a maximum. However, this result is different from Sklar and Dietrich' s (1998) result for erosion rates with different channel gradient (Figure 7). They found that the maximum incision rate increaseswith increasing slope, but then declines with further increasing slope. They argued that the declining numbers of impact with increasing saltation length (l) causes declining erosion rate, as saltation length increases with higher transport stage (Sklar and Dietrich, 1998).

Conclusion

It is critical to understand individual erosional processes in bedrock rivers for proper representation for landscape modelling to understand the past and to predict the possible changes in the future with climatic change. Progress in the numerical modelling of the evolution of landscape with bedrock channels is also very limited, as understanding of the processes in bedrock channels is incomplete.

Table 4. Major erosion processes in bedrock channel.

Erosion process	Mechanism	Characteristics
Corrosion	Chemical attack	Independent of hydraulic condition. Limited lithology: Carbonate rocks
Abrasion	Physical impact of sediment particles	Occurs during low floods to high flood. Sediment particles are needed as tools for erosion.
Plucking	Physical impact of sediment particles and/or shear stress from the flow	Hydro-wedging by sediment particle. Crack growth by sediment collision and/or pressure fluctuation.
Cavitation	Physical attack by the vapour with high velocity and pressure	Rare in natural condition. May occur during very high magnitude flood.

Various erosion processes such as abrasion, corrosion, plucking and cavitation need to be investigated systematically to improve the understanding of bedrock channel erosion process (Table 4). Plucking and cavitation are very difficult to simulate with physical modelling, and they have an episodic nature due to the high threshold for these processes. Abrasion is the most common major process eroding the channel bed, and there is a strong need to clarify the abrasion process.

Most of numerical and theoretical works on bedrock erosion processes are reviews in the paper. However there are urgent needs for research on the controlling factors of bedrock incision, as successful and realistic modelling of bedrock channel erosion processes is vital for landform evolution studies. Especially physical modelling with proper scaling method is critical for the development of more realistic model (Bollaert 2002; Thompson and Wohl, 1998).

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