Dr Ashiq CIV-14

- Coarse bed rivers have a wider size distribution of bed material and bed load;
- Sediment transport in these river takes place only during the period of high flows and bed material like boulders move only with the extremely high discharges;
- These rivers are less susceptible to aggradation and degradation;
- This type of river is less responsive to modest changes in discharge and discharge duration compared with the fine bed rivers; and
- A bed formation of riffle/pool or step/pool type is very common in these rivers.

2.2 Initiation of Bed Load Transport

2.2.1 Initiation Process

Initiation of bed load movement is an important phenomenon in the field of sedimentation and especially for gravel bed rivers where bed load is a significant component of the total sediment load. It is the beginning of movement of bed particles that were stationary some time before. As soon as they have initiated their movement they continue to move for an unspecified time and distance. The precise discharge and time at which initial movement occurs in a river is a subjective determination. Some observers may consider initiation of bed load transport to occur at the time when the first few particles start moving, whereas others may say that it occurs when there are particles moving over a significant part of the bed surface.

Owing to the variation in particle sizes and their positioning in different directions, initiation of bed load movement for all particles does not occur at one time. Vibration of bed-material particles is an indication that movement is about to begin. This indicates the response of particles to the passing flow, which causes pressure differences and shear stresses that lead to lift and drag forces. If these forces increase over time, the in-place vibration may change to motion. Meanwhile, other particles may respond to increasing shear stresses and pressure differences over their surfaces by a more-abrupt initiation of motion, without vibration. As individual particles begin to move, they leave behind vacant spaces that change the local flow field at the bed surface. This alters lift and drag forces acting on other particles and may help to mobilise several particles simultaneously (Matin, 1993).

There are several conditions which influence the initiation of bed load movement like sudden releases of water from an upstream reservoir, snow melt, rain storm etc. All these events change the flow status that start the movement of bed material. Channel realignment in rivers may also be a condition that leads to the initiation of bed load movement if water currents are concentrated at some parts of the channel bed. The sediment that was at rest before this alignment may start to move, depending upon the flow intensity and degree of armouring layer (a surface layer of coarser material formed due to winnowing of fines). Removing The bed load movement in this case will be limited to space and time. As soon as channel achieves the restabilization this movement will stop (Klingeman and Matin, 1993).

2.2.2 Significance of Initiation Process

The following salient features described by different investigators highlight the significance of the process and reflect why it is so important to understand initiation phenomena, especially, in coarse bed-material rivers (Mohammadi, 1976; Simons and Senturk, 1977; Matin, 1993; Klingeman and Matin, 1993):

- 1 For determining maximum flows required to flush out the fine sized sediment and organic matter present on the river bed among the gravel particles. The presence of these fine size sediment particles reduce the permeability by filling the spaces between the gravels necessary for aquatic habitat.

A deeper channel cut into the sea or river bed, to enable larger ships to pass through [illegible]

- 2 For maintaining bed stability in navigational channels that otherwise may be affected by the waves generated by the ships or boats.
- 3 To explain the difference between river bed stability and mobility.
- 4 To provide premises for the analysis and design of stable river beds.
- 5 For creating certain types of bed form on river beds that may be useful for dual purposes of flood control and navigation.
- 6 For maintaining the stability of toxic substances hazardous for human and aquatic life when present in river beds.
- 7 To understand the bed load process which is necessary in the development of bed load transport functions.

2.2.3 Factors Affecting Initiation of Bed Load Movement

It is not a easy task to predict the initiation of bed load movement even for a certain reach. One reason that makes it difficult is the definition of initiation itself. There are some other factors: the most basic factor is the non-uniformity of the bed-material in shape, size and density and its heterogeneity in composition. An additional difficulty is the large and small particle interaction present in the river bed; like embeddedness and hiding and exposure. The details of the factors and the way they affect the initiation process are as under:

fixed in place

2.2.3.1 Hiding, Exposure and Particle Embeddedness

In gravel bed streams, larger particles are exposed to water currents whereas smaller particles are hidden behind the larger ones. Due to their exposure to the water currents larger particles can move with relatively smaller flows than required to move sediment particles of uniform sizes, whereas smaller particles get the advantage of sheltering and thus require stronger flows to initiate movement as compared to the uniform sediments of same size. It can be said that initiation of particle movement or its stability along with many other factors also depends upon its position within the overall distribution, relative to the reference (characteristic) diameter (Egiazaroff, 1965; Andrews, 1983; Proffitt and Sutherland, 1983; Parker, 1990; and Klingeman and Matin, 1993). A particle may be embedded by the surrounding particles and thus it would require larger flow to move as it was without embeddedness. Similarly a smaller sized embedded particle may require larger flow to move than a larger size unembedded particle. The strong influence of bed sediment particle interlocking and imbrication on the threshold condition of sediment movement has also been described by Powell and Ashworth (1995). Likewise, Komar and Li (1986) and Li and Komar (1986) have stated the strong influence of grain imbrication/fabric.

overlapping of edges

2.2.3.2 Particle Shape Variation

Bed-material mixtures may contain particles of different shapes such as flat, rounded, well rounded, angular, pencil-shaped, block-like, disk-like etc. All these varying shape particles do not move at the same time and with the same discharge. Particles with shapes relatively more obstructive to the flow are likely to initiate their movement earlier and thus affect the overall initiation of bed load movement (Matin, 1993). Komar and Li (1986) and Li and Komar (1986) while investigating the pivoting angle (which is important for grain entrainment) of the grain about its contact point with the underlying grain found that for a bed of uniform grain size the threshold condition for the bed material movement partly depends upon the shape of particles. The latter investigators (Li and Komar 1986) stated that if " other factors being equal, the measurements of pivoting angles demonstrate that the order of increasing difficulty of entrainment is spheres, ellipsoidal grains, angular grains, imbricated grains". The significance of grain shape on the bed material movement have also been investigated by other investigators like Kirchner et al. (1990), James (1992), Gomez (1994) etc.

2.2.3③ Spatial and Temporal Variations in Particle Sizes

Bed-material particle size composition sometimes varies very rapidly laterally, longitudinally and vertically. So far as the lateral and longitudinal variations are concerned vast variation in bed-material particle size composition is possible at a single location. A sample of bed-material may comprise particles from as small as sand to as large as cobbles and boulders. These lateral and longitudinal variabilities are important with respect to the bed-material movement. Klingeman and Matin (1993) while working on Oak Creek observed that the initiation of bed-material transport occurs locally first rather than generally throughout the channel width. This variability is related to the spatial difference in bed morphology, flow hydraulics across and along the channel and downstream fining (details regarding downstream fining can be seen in Hoey and Ferguson 1994. Paola and Seal 1995, Parker and Seal 1995, and Cui et al. 1996). Natural channels display such variations even when channel width and gradient appear to be the same. In the vertical dimension as in case of armouring, the top layer (armoured/paved) comprises coarser particles than the sub-armoured layer or material below the sub-armoured layer. However, this variation is not significant for the initiation of bed-material transport but important for the general bed-material transport, because the flow acts only on the surface layer.

The variation in particle size composition could be a temporal variation (i.e. bed material particle size variation with time) as a bed-material composition before, during and after peak flows may vary. Such variation in a braided gravel bed river (Sunwapta

River, Alberta) has recently been investigated by Ashworth et al. (1992). Similarly, between different seasons (i.e. snow melt, rainy and dry season) particle size composition could vary.

2.2.3(4) Density Variation

Varying sizes and shapes of the bed-material particles may have spatially varying densities depending upon the geology of the catchment area contributing sediment to the river. However, variation in densities of bed-material is not significant in gravel bed rivers. But for sophisticated studies, in which greater accuracy is required, variation in densities is better to be recorded from place to place in all three dimensions (Matin 1993).

2.2.3(5) Slope and Large Scale Roughness

It has been found that the value of the Shields' parameter, a standard means of calculating critical flow condition for initiation of bed load, rises up to 0.1 or more for streams with 1% and higher slopes and with depth to sediment size ratio below ten (Ashida and Bayazit 1973, Bathurst 1987b). This change in Shields parameter might be due to the large size clasts that affect the characteristic shape of the velocity profile. Bathurst et al. (1987) correlated the slope effects with critical discharge (empirically) required for the initiation of the bed load movement for non-uniform bed-material channels. They used data from rivers and flumes with bed-material sizes varying from gravel to boulders and slope from 0.1% to 10%.

fragment of rock broken off from larger rock.

2.2.3(6) Particle Size Distribution Modality

Initiation of bed-material movement depends upon the degree of modality (a parameter that defines the distribution of bed-material having one or more prominent modes with a significant drop in the percentages of sediment in size grade between them) i.e. whether it has unimodal, bimodal or multimodal distribution. In unimodal particle size distribution, where bed is composed of 100% gravels, all sizes of the bed-material begin to move at nearly the same bed shear (all values within ±10% of the mean) (Kuhnle 1993). Kuhnle (1993), on the basis of the studies conducted by White and Day (1982), Wiberg and Smith (1987), Wilcock and Southard (1988) and Wilcock (1993) concluded that for size distribution of unimodal type and approximately of log-normal type sediment, initiation of most sizes, in bed material, takes place at the same time. In another study Kuhnle (1992) identified that for a bimodal (sand and gravel) size distribution initiation of sand takes place at lower threshold than for the gravel fraction.

Wilcock (1992, 1993) and Wilcock and McArdell (1993) in a different setup studied the initiation of bed-material of a bimodal nature. Wilcock (1993) proposed a parameter to characterise the degree of modality of a sediment and then related it to the critical shear stress of the size fractions present. His modality parameter is:

$$B = \left(\frac{D_c}{D_f}\right)^{1/2} \sum P_m \tag{2.1}$$

where D_c and D_f are grain sizes of coarse and fine modes; P_m = proportion of sediment contained in two modes. This parameter is helpful to determine the bed material modality and thus to understand the the initiation process.

In contrast to the above mentioned studies, Church et al. (1991) in an investigation of bed-material with multimodal size distribution concluded that on average, the sand fraction showed the equal mobility. Ashworth and Ferguson (1989) in a study of three powerful non-uniform rivers concluded that "precise equal mobility of small and large particles was approached in the data set with the highest shear stresses and transport rates". Similar results were also obtained by Wathen et al. (1995) in an investigation of the Allt Dubhaig River (Scotland), with bimodal bed formation, as they stated that "analysis of fractional transport rates and maximum grain size in relation to peak shear stress suggests that gravel transport is slightly size selective but sand transport is close to equal mobility".

2.2.3.7 Particle Position

The position of particles in a stream bed plays an important role in their movement. In a riffle-pool bed formation, pebbles situated on the ridge of the riffle will initiate their movement earlier than those located in the pool where velocities are relatively less effective. For lower flows, particles situated on the toe of the riffle slope (i.e. just before the pool) will move before those located at the far end of pool. As the flow increases this situation may be reversed, as bottom velocities in the pools reduce to a lower value than that at the riffles slope (Keller 1971, Jackson and Beschta, 1982).

2.2.3.8 Mutual Interaction

Mutual interaction of particles plays an important role in the initiation of bed load movement (Reid and Frostick 1984). During a study at Turkey Brook by Reid and Frostick (1984) it has been observed that pebbles interlocked in cluster forms withstand flows even when bed shear is significantly greater than the threshold values predicted in laboratories on the basis of flume studies. On the basis of threshold conditions recorded at Turkey Brook it has been suggested that D_{90} should be used as effective particle size instead of D_{50} (Reid and Frostick, 1984). It has also been observed that tractive force required for the onset of the motion is two-thirds of that required for the cessation of the bed load transport.

بیز سیونا ، جم ہونا

In another study at Turkey Brook, Reid and Frostick (1986) observed that mean value of stream power at the cessation of the bed load transport is only 20% of that required to initiate bed load movement. They described it to be the main cause of poor correlation between the sediment transport observed and those computed using bed load equations, as bed load transport equations have been developed using the concept of single threshold condition associated with the incipient motion.

2.2.4 Theories for Initiation of Bed Load Movement (Critical Conditions)

The critical condition for the initiation of bed load movement has been described by different investigators. DuBoys (1879) stated it: "excess of some quantity above the critical level at which transport begins". Simons and Senturk (1977- p508) said: "when the flow over movable boundaries of a channel has hydraulic conditions exceeding the critical condition for motion of the bed-material, sediment transport will start". At another place while discussing sediment transport equations Simons said "most transport equations calculate the sediment transport as a function of the excess of some flow quantity, such as shear stress or discharge, above the critical level". Carson and Griffiths (1987) described this condition as "some critical or threshold level of discharge, velocity or related parameter must be attained before the gravel on a channel bed will start to move downstream". Klingeman and Matin (1993) stated: "transport initiation process requires larger flows that must exceed the threshold-motion values". However, this "critical condition" as described by different scientists is an assumption that there is no sediment transport at lower flows. In reality there can be, but of such a small amount that in practical terms it can be ignored.

On the premise of this critical state of bed load transport, various investigators developed functions for the initiation of bed load movement, using various theories/conditions which are described below.

2.2.4(1) Critical Discharge (q_c) Theory

Schoklitsch (1930, in Simons and Senturk, 1977) after proving DuBoys' (1879) model of sliding layers to be wrong described that his function is a poor criterion when applied to field computations, because the shear distribution in the channel cross-section is quite non-uniform. After being disappointed by the DuBoys' model, due to its poor performance, Schoklitsch (1934) considered that there would be some critical value of discharge at which bed load will initiate its movement. He then used Gilbert's (1914) data and developed a function. Later on, in 1950 he modified his 1934 critical discharge function. Finally, in 1962 he (Schoklitsch) again modified his previous version of the function using all the previous concepts and developed a new well known function (Schoklitsch 1962) for the quantitative analysis of critical discharge. This is

$$\boxed{q_c = 0.26\left(\frac{\rho_s}{\rho}-1\right)^{5/3}\frac{D_{40}^{3/2}}{S^{7/6}}} \tag{2.2}$$

where ρ_s and ρ are densities of solid and liquid; D_{40} = particle size at which 40 % of the material is finer; and S = slope)

(Bathurst et al. (1987) while working (with a flume channel) on the initiation of bed load movement determined the value of critical discharge at which initiation of bed load-material will start. In this study the slope of the flume ranged from 0.25 to 20% and uniform particle size ranged from 3 to 44 mm.

$$\boxed{q_c = 0.15\sqrt{g}D^{1.5}S^{-1.12}} \tag{2.3}$$

Bathurst et al. (1987) also developed a relationship for non-uniform beds using data from flumes and rivers with gravel or boulder beds with sediment sizes up to D_{16} = 130 mm and D_{50} = 260 mm and slope in the range 0.25 to 10 percent, and found empirically that, for the beds as a whole.

$$\boxed{q_c^* = \frac{q_c}{\sqrt{g}D_{16}^{1.5}} = \frac{0.21}{S^{1.12}}} \tag{2.4}$$

where D_{16} is the size fraction of the surface or armour layer for which 16% of the material is finer. The use of D_{16} rather than the more convenient D_{50} was found to be necessary to allow for the non-uniform size distribution of the bed material and agrees with observations (Carling, 1983) that initiation of transport in boulder-bed streams is associated with the finer fractions of the size distribution.

By using the same data as Bathurst et al. (1985), Milhous (1989) modified Schoklitsch's (1962) critical discharge function (Equation 2.2). His modified function is:

$$\boxed{q_c = 0.0345\sqrt{g}D_{50}^{3/2}S^{-1.12}} \tag{2.5}$$

Owing to the associated advantages with the above mentioned theory (water discharge based) it will be adopted in this study.

2.2.4.2 Critical Shear Stress (τ_c) Theory

While investigators felt that critical mean velocity (V_{mc}) changes with flow depth (d), for beds of given particle size, they diverted their attention toward the use of shear stress also known as tractive stress (i.e. pull of water on the channel boundary per unit area). Shields (1936) was the first researcher to determine the relationship between the critical shear stress (τ_c), for bed-material movement and particle size. His derived expression is

$$\tau_f = \frac{\tau_c}{(\gamma_s - \gamma)D} \tag{2.6}$$

where τ_f is dimensionless critical shear stress, Shields called it the entrainment function (commonly called as Shields' parameter) and is equal to 0.056 (for hydrodynamically rough surfaces, as gravel beds); $(\gamma_S - \gamma)$ is specific weight of submerged sediment ($=16.2*10^3$ N) and γ_S and γ are the specific weights of the sediment and water, respectively. If D is particle size in mm; and τ_C in Pascal (when specific gravity is 2.65) then Equation 2.6 changes to

$$\tau_c = 0.91D \tag{2.7}$$

Henderson (1966, p-91) by assuming steady and uniform flow conditions, determined the actual mean shear stress on the channel bed, which is $\tau = \gamma RS$ and for wide channels (B/d > 15) R = d; $\tau = \gamma dS$. By replacing τ_c in Equation 2.7 Henderson derived the following expression

$$\frac{D}{dS} = 11 \tag{2.8}$$

Shields (1936) determined τ_f values (Equation 2.6) by using uniform sand in flume channel, therefore, problems arise while applying it to natural gravel streams (Carson and Griffiths, 1987) and steep mountain boulder bed streams (Bathurst et al. 1987). Bathurst et al. (1987) mentioned that the value of Shields' parameter (τ_f) rises up to 0.1 or higher for steep mountain boulder bed streams. While Church (1978) recorded the value of τ_f varying from 0.002 (for overloose gravels) to as high as 0.12 (for tightly packed 'underloose' bed material).

2.2.4.3 Critical Stream Power (ω_c) Theory

Bagnold (1966) first presented the stream power theory. In this, work or energy expenditure of a stream and the quantity of sediment transported are related;

$$P = \gamma QS \tag{2.9}$$

where P is total stream power in a river reach, Q = water discharge and S= average slope of water surface. Dividing P by stream width (B) mean specific stream (term introduced by Carson and Griffiths, 1987) power may be obtained.

$$\omega = P/B = \gamma RSV_m = \tau V_m \tag{2.10}$$

In this equation, term V_mS is the unit stream power (i.e. power dissipated per unit weight of water) (Yang 1973). Carson (1986a) disagreed with the term of unit stream power, due to its definition and defined unit stream power as 'power dissipated per unit area of stream bed (also called specific stream power) divided by the acceleration due to gravity'. He tried to introduce another term 'stream power' (ω/g) and denoted it with symbol ω but later on withdrew his idea due to general reputation and acceptance of the term 'unit stream power' by the vast majority of investigators.

Yang (1984) applied his unit stream power idea to the gravel bed stream, by following the same technique as he did before (Yang 1973). Carson (1986b) in an appraisal commented that while using $V_m S$ as a predictor of gravel transport concentration, with tractive stress (τ) and specific stream power (τV_m). Yang (1973) appeared to have made a mistake in his formula, as he ignored the wall effect by taking $\tau = \rho g d S$ rather $\rho g R S$.

Bagnold (1980) developed a semi-theoretical equation for critical stream power. He assumed that $\rho_s = 1600$ kg/m^3 and $\tau_f = 0.04$. His critical stream power expression is

$$\omega_c \cong 290 D^{1.5} \log\left(\frac{d}{D}\right) \tag{2.11}$$

where D = particle size in mm and d = flow depth.

As stream power is simply a modified product of mean velocity and tractive stress, therefore, all the related problems with these theories will multiply.

2.2.4.4 Critical Velocity (V_{mc}) Theory

Initially, investigators focused toward the use of critical mean velocity for the initiation of bed load transport. Hjulstrom (1935) was the first to start work with velocity as a function of particle size and developed a well known curve by using velocity profiles for particles smaller than 100 mm. However, major attention in his study was toward sediment with size smaller than 20 mm. Later on, Lane (1955, p-1240), while presenting a design criteria for stable channels discussed the concept of critical velocity for the initiation of bed load transport. In another study, Russian investigators stated that critical mean velocity values given by Lane (1955) increase by 10 % - 45% for finer gravels (5 mm < D < 10 mm) and 10% - 25% for coarse material, if flows carry large concentrations (0.1% to 2.5%) of fine sediment.

Isbash (1936) developed an expression for critical velocity at finish of bed load transport. The values of critical mean velocities computed by this expression are less than Bagnold's (1980) values, for initiation of bed load transport. This difference between the two velocity values also proved that the threshold values at the initiation of bed load transport are greater than those at the cessation of bed load transport. Isbash's expression is

$$V_{mc} = 5.3\left[(G_s - 1)D\right]^{1/2} \tag{2.12}$$

where V_{mc} = critical mean velocity for cessation of bed load transport; G_S = specific gravity (=2.65); and D is particle size in mm.

Owing to the interlocking of gravels with each other and hiding of small particles behind the bigger ones the value of critical mean velocity required for initiation of bed load movement is substantially higher than that needed to continue bed load transport once it is initiated (Gilbert, 1914- in Carson and Griffiths 1987). Other investigators who worked on this approach are Kalinske (1942) and Colby (1964) but with sand bed channels. Colby's expression is

$$V_c = 0.4673 d^{0.1} D_{50}^{0.33} \tag{2.13}$$

where V_C = critical velocity; d = mean flow depth; D_{50} = particle size in mm.

This approach has been successfully applied to sand bed streams by Kalinske (1942) and Colby (1964) so it is difficult to understand why it has not been considered for gravel bed streams by these or other investigators.

2.2.5 Calculation Approaches for Initiation of Bed Load Movement

2.2.5.1 Initiation of Movement of Uni-Size (Uniform) Bed -Material

The problem of determining critical conditions for initiation of uni-size (uniform) sediment has long been considered. This problem is still of significant importance. Numerous researchers have been trying to approach this problem in different ways. To develop functions researchers relied upon different computation approaches including empirical (regression), semi-empirical (semi-theoretical) probabilistic, stochastic, dimensional analysis, and deterministic approachs. During these studies, mostly, a single representative particle size was used to represent the bed material. The computation (calculation) approaches (commonly) used in the development of initiation models are given in the following sections.

2.2.5.1.1 Empirical Approach

Schoklitsch (1934, in ASCE, 1975) advanced the work done on empirical approach done by his predecessors by developing a function for the initiation of bed-material movement. According to this, critical tractive stress is independent of the gradation of the material. Later on Lane (1955) developed a function for threshold value of the critical shear stress for coarse bed-material by using empirical approach. He used D_{75} (in contrast to D_{50} commonly used by the investigators) as the representative diameter (in mm) of the sediment, in which D_{75} is the size for which 75% of the bed