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EVALUATION OF SCOUR DEPTH IN SOILS AND ROCKS – STATE OF THE ART GUIDELINES

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By

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ABSTRACT

The importance of evaluating a suitable value of scour depth for the hydraulic structures placed in various ground conditions cannot be overemphasized. However, there are confusions and controversies in the profession regarding using representative methods for different design scenarios. This situation gains more importance, while dealing with different soils and rock formations, variable flow conditions and a variety of structures.

In practice, engineers have been using different approaches, which are likely to result into under-designing and over-designing of the substructures thus either jeopardizing safety of the work or making it unduly costly and at times, cumbersome to construct.

This paper carries out a judicious review of the prevalent practices with their pros and cons and provides the best guidelines in the light of the experience gained on various projects as well as the latest literature on this topic.

It is expected that the guidelines provided by this paper will be entirely useful for adopting a uniform and well-considered systematic practice for the evaluation of the scour depth for the hydraulic structures, ensuring their safety and cost-effectiveness.

Keywords: Scour Depth, Soils & Rocks, Evaluation Methods, Guidelines

1. INTRODUCTION

One of the key issues that the flowing water brings with it in natural environment as well as man-made infrastructure is the problem of scour. Scouring has its own risks, complications and probability of failure for the structures, subjected to scouring, if not catered for appropriately.

Evaluation of scour potential and its magnitude in various soil types has been in practice for long yet inconsistent practices are in vogue in the profession.

Scouring or erosion phenomenon taking place in soft rocks is also of practical importance but more challenging as little work has been reported on it in the literature. This is often overlooked and gut feelings govern the pick and choice. On the other hand, erosion / dislodging of blocks of hard rock is an even more complex phenomenon and is governed more by the geological factors rather than flow patterns.

2. SCOURING OF SOILS

Scour is a phenomenon that involves removal of bed material with flowing water which may or may not be carrying suspended sediment. It can occur on channel/river bed, banks and around hydraulic structures such as bridge piers and abutments. Scour is not just instigated by structures obstructing the flow path, but also in channels without any obstructions. It is a natural process that keeps occurring over time in a channel with flow of water over an erodible boundary.

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Different materials scour at different rates. Loose and granular soils can scour very quickly as compared to cohesive soils. Structures built in rivers or channels are prone to scour at/around the foundations. This can compromise the safety and stability of these structures. Therefore, it is considered essential to estimate scour at such locations so that preventive measures can be taken accordingly.

Scour locally affects the bed material removal at a particular structure or reach. Scour may be temporary and cyclic in nature where bed material is eroded during high flows and but refilled during the flood recession.

3. TYPES OF SCOUR

Scour is difficult to estimate accurately in the field and most design equations are based on theory supported by laboratory data.

The types of scour with respect to occurrence, location and reach are as follows:

1. General scour
2. Local scour
3. Contraction/Constriction scour

3.1. General Scour

General scour can be defined as the removal of sediment from river bed with flow affecting a certain reach length. In general scour, both river/stream bed and banks experience scour simultaneously, with or without the presence of any hydraulic structure such as a bridge crossing (Figure-1). General scour occurring at a certain reach length over longer duration can cause aggradation and degradation. The progressive degradation, or lowering of the stream bed as a result of natural or engineered process is also termed as General Scour (May et al., 2002).

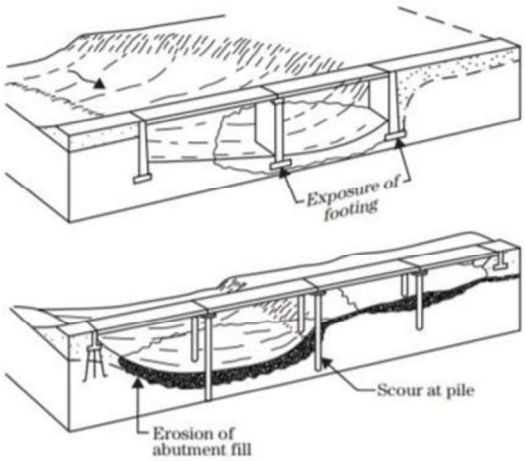


Figure-1: General scour at stream bed

3.2. Local Scour

Local scour involves erosion of the streambed caused by individual structural elements, such as bridge piers and abutments that create an obstruction to flow. It occurs only in the immediate vicinity of the flow obstruction (such as bridge piers and abutments). The change in flow characteristics is sudden and confined only to the vicinity of structural member creating the obstruction (Figure-2).

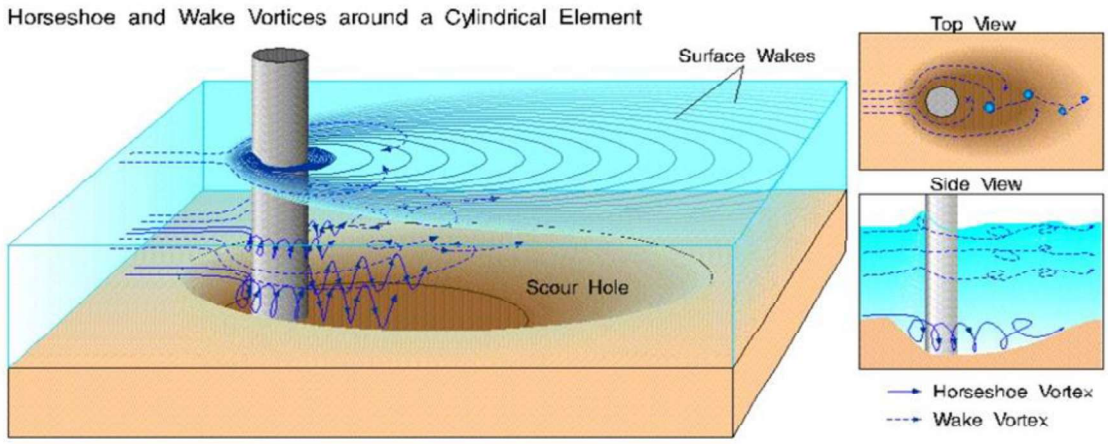


Figure-2: Local scour at bridge piers / abutments

3.3. Contraction Scour

This type of scour occurs when a stream or channel cross-section undergoes reduction in flow area due to natural or artificial contraction. Artificial contraction can be due to construction of a bridge, culvert, weir etc. that obstructs the flow path at this cross-section causing decease in flow area. Since flow area is inversely related to velocity, its reduction causes increase of flow velocity through the contracted section resulting in contraction scour. Other factors instigating contraction scour can be blocked bridge bays due to debris jam or illegal encroachments, making the channel narrower than its natural configuration. Contraction scour is also known as Constriction Scour.

According to Laursen and Tock (1956) (Federal Flood Commission, 2001), the increase in depth over a constriction can be calculated using the following equation:

$$(y_m + h_o)/h_o = 1/(1-m)^{\beta}$$

where,

y_m = scour depth in constriction (ft)
h_o = flow depth upstream of constriction (ft)
m = B_2/B_1
B_1 = upstream width of river (ft)
B_2 = constriction width of river (ft)
β = coefficient ranging 0.67 to 0.80

Other Miscellaneous Types of Scour

3.4. Bedform Scour

Bed form scour occurs due to formation of troughs between crests of bedforms, usually in sand bed streams. Examples include dunes and anti-dunes. No definite analytical relationship is available to estimate this type of scour.

3.5. Bend Scour

Bend scour occurs in the outer parts of stream or channel bends as a result of spiral flow. It depends on bend curvature, width-to-depth ratio, bank erodibility, bed material grading and strata. According to Thorne (1993), scour depth at a bend can be calculated using following equation (Federal Flood Commission, 2001):

$$y_m/h_o = 1.07 - \log(R/B-2) \text{ for } 2 < R / B < 22$$

where,

y_m = scour depth at river bend (ft)
h_o = flow depth in upstream straight reach of the river (ft)
R = radius of curvature at the centerline (ft)
B = water surface width in upstream straight reach of the river (ft)

3.6. Confluence Scour

When two streams or channels combine, the combination of high flows from both streams results in Confluence Scour. It occurs due to magnification of flows at the confluence, change in water level and angle of flow. According to Breusers and Raudkivi (1991), the scour downstream of a confluence can be calculated using following equation (Federal Flood Commission, 2001):

$$y_m/h_o = C_o + 0.037u$$

where,

y_m = scour depth at confluence (ft)
h_o = average flow depth of the two branches (ft)
C_o = coefficient depending on material properties in river bed (1.29 for fine sand to 2.24 for gravel)
u = angle between two upstream branches (degrees)

3.7. Swirl Scour

This type of scour occurs when fast moving water currents flow past a still water area and swirls are generated. Depending on the severity, swirls can cause abnormal deep scour due to centrifugal effect of flow movement. Since it is difficult to assess the flow velocities in swirl, no definite analytical relationships have been developed in this respect. In the absence of reliable calculations of the scour that a swirl can create, the definite locations where swirls are likely to be generated are identified and provided with additional protection.

Main Factors Affecting Scour

- Effective Waterway
- Bridge Piers and abutments
- Velocity
- Flow Approach
- Stream Bed Material
- Obstructions
- Stream Meander

4. Scour Estimation

The scour depth (R) below water surface can be calculated by various methods which are discussed in the next section. After scour depth estimation, the scour below stream bed can be calculated as follows (Figure 3):

$$R' = x*R$$

then,

$$E = HFL - R'$$

then,

$$d_S = RBL - E$$
$$\text{or } d_S = R' - d_m$$

where,

R' = Factored scour depth
x = Factor of safety
R = Scour depth below flow surface
E = Scour elevation
HFL = Highest Flood Level
RBL = River Bed Level
d_m = Mean flow depth (ft)
d_S = Scour depth below stream bed

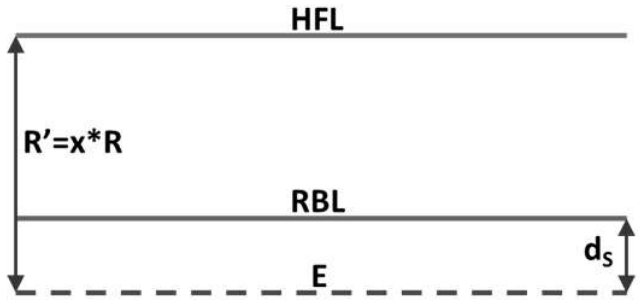


Figure-3: Scour below stream bed

Table-1: Value of FOS 'x'

Location	'x'
Straight reach of channel	1.25
Mild bend of channel	1.50
Moderate bend of channel	1.75
Severe bend of channel	2.00
Right angled bend of channel	2.50
Upstream floor of structure	1.75
Downstream floor of structure	2.25
Nose of guide bank	2.50
Transition from nose to straight of guide bank	1.75
Straight reach of guide bank	1.50
Pier nose	2.00
Nose of spur, depending upon the location and river approach	2.50 to 3.00

4.1. Lacey's Method (as expanded by USBR)

The scour depth below channel bed from Lacey's equation as expanded by USBR in 1984, can be calculated as follows (Federal Flood Commission, 2001):

$$d_m = 0.47*(Q/f)^{1/3} \quad \text{FPS units}$$

$$d_m = 0.143*(Q/f)^{1/3} \quad \text{SI units}$$

$$d_s = Z * d_m$$

where,

d_m = mean depth at design discharge (ft or m)
Q = design flood discharge (cusec or cumecs)
f = Lacey's silt factor
d_S = depth of scour below stream bed (ft or m)
Z = multiplying factor for predicting maximum scour depth (see table 3)

The Lacey's silt factor 'f' can be estimated from the following (Table 2).

Table-2: Value of median grain size 'D_m' and Lacey's silt factor 'f'

Soil Type	D_m (mm)	'f'
Large boulders and shingle	129.13	20.00
Boulders and shingle	72.64	15.00
Boulders and gravel	50.44	12.50
Medium boulders, shingle and sand	32.28	10.00
Coarse gravel	26.15	9.00
Gravel	7.28	4.75
Heavy sand	1.29	2.00
Coarse sand	0.73	1.50
Medium sand	0.51	1.25
Standard silt/Fine sand	0.32	1.00
Medium silt	0.16	0.70
Fine silt	0.08	0.50
Very fine silt	0.05	0.40

4.2. Blench Method

The scour depth below channel bed from Blench equation (1969) as recommended by USBR can be calculated as follows (Federal Flood Commission, 2001):

$$d_{fo} = (q_f^{2/3})/(F_{bo}^{1/3})$$

$$d_s = Z^* d_{fo}$$

where,

d_{fo} = depth for zero bed sediment transport (ft)
q_f = design flood intensity (cusecs/ft)
F_{bo} = Blench's "zero bed factor" (ft/s^2; see Figure 4)
d_S = depth of scour below stream bed (ft)
Z = multiplying factor for predicting maximum scour depth (see Table 3)

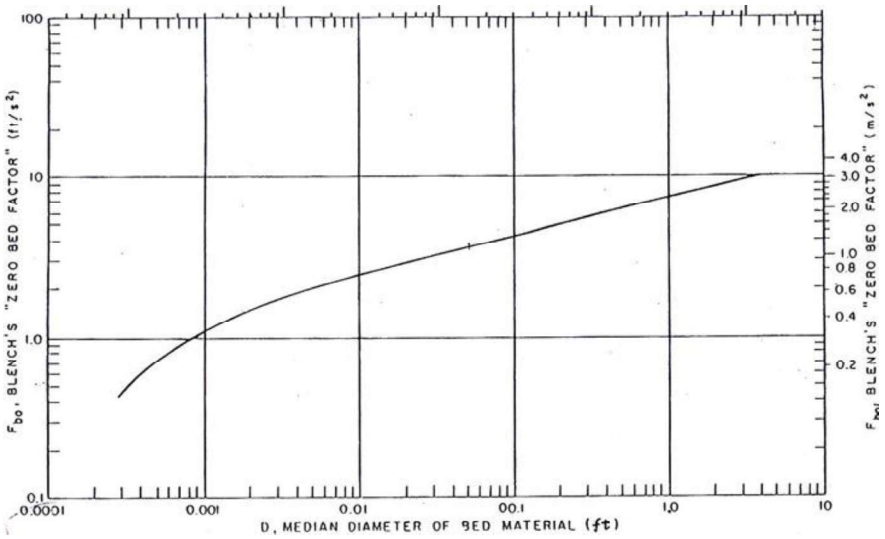


Figure-4: Blench Factor F_{b0}

Table-3: Multiplying Factor 'Z'

Condition	Value of Z		
	Neill	Lacey	Blench
Straight reach	0.50	0.25	0.60
Moderate bend	0.60	0.50	0.60
Severe bend	0.70	0.75	0.60
Right angle bend		1.00	1.25
Vertical rock bank or wall		1.25	
Nose of piers	1.00		0.50-1.00
Nose of guide banks	0.40-0.70	1.50-1.75	1.00-1.75
Small dam or control across river		1.50	0.75-1.25

4.3. Neill Method

The scour depth below channel bed from Neill equation (1973) as recommended by USBR can be calculated as follows (Federal Flood Commission, 2001):

$$d_f = d_i*(q_f/q_i)^m$$

$$d_s = Z*d_f$$

where,

d_f = scour depth below design flood water level (ft)
d_i = average depth at bankful discharge in incised reach (ft)
q_f = design discharge intensity (cusec/ft)
q_i = bankful discharge intensity in incised reach (cusec/ft)
m = exponent varying from 0.67 for sand to 0.85 for coarse gravel
d_S = depth of scour below stream bed (ft)
Z = multiplying factor for predicting max. scour depth (Table-4)

4.4. Jain Method

The scour depth below channel bed from Jain equation (1981) as recommended by USBR can be calculated as follows (Federal Flood Commission, 2001):

$$d_s = 1.84*b*(d/b)^{0.3}*(F_c)^{0.25}$$

where,

d_S = Depth of scour below stream bed (ft)
b = Pier width (ft)
d = Flow depth (ft)
F_c = Threshold Froude number = $V_c/(g*d)^{0.5}$
V_c = Competent mean velocity (ft/s)
g = Gravitational acceleration (ft/s^2)

4.5. Brown's Method

This method is specifically adopted for hilly areas with steep slopes of straight rivers and torrents. It is particularly suited for the northern mountainous areas of Pakistan. Using Brown's formula, the scour depth for different types of discharge floods can be calculated by the following formulae (Federal Flood Commission, 2001):

For rivers subject to sustained floods,

$$\mathbf{D = 1.32(Q/C_r)^{3/10}}$$

For rivers and torrents subject to sudden and short-lived floods,

$$\mathbf{D = 1.0(Q/C_r)^{3/10}}$$

For rivers subject to fluctuating flood discharge throughout the year,

$$\mathbf{D = 0.78(Q/C_r)^{3/10}}$$

For rivers and torrents in gorges with inerodible banks and a deep alluvium bed,

$$\mathbf{D = 1.32(Q/C_r)^{3/10} \text{ for gorge width} >= 2.4(Q/C_r)^{1/2}}$$
$$\mathbf{D = 2.25(Q/W_r.C_r)^{3/5} \text{ for gorge width} < 2.4(Q/C_r)^{1/2}}$$

where,

D = maximum scour depth from design flood level to down (ft)
Q = design flood discharge (cusecs)
C_r = Kennedy's velocity ratio
W_r = width of gorge (ft)

The formula for sustained flood is adopted where 50% or more catchment area lies in plain areas. The formula for short-lived spates is adopted when more than 50% catchment lies in hilly areas. The value of Kennedy's Velocity Ratio 'Cr' depends upon the existing bed material of the nullah/stream at the proposed site and the value is adopted from Table-4 as follows.

Table-4: Value of Kennedy's Velocity Ratio 'Cr'

Bed Material	C_r
Fine Sand	0.80
Medium Sand	1.00
Coarse Sand	1.25
Fine Gravel	1.50
Medium Gravel	1.75
Fine Gravel	2.00
Small Boulders and Gravel	2.50
Medium Boulders and Gravel	3.00
Large Boulders and Gravel	4.50

It is to be noted that the Lacey's Silt Factor 'f' and Kennedy's Velocity Ratio 'Cr' are decided on the basis of the grain size analysis of the bed material, within the expected scourable zone.

4.6. HEC-RAS ANALYSIS BASED METHOD

HEC-RAS software can be used to estimate bridge/culvert scour. For this, the bridge data is required from the hydraulic analysis in the software. The median particle size of bed material 'D_m' is also a required input. The computation utilizes live bed scour equation as well as clear water scour equation by Laursen. It should be noted that if the critical velocity of the bed material is greater than the mean velocity at the approach section ($V_c > V$), then clear water contraction scour is assumed. If the critical velocity of the bed material is less than the mean velocity at the approach section ($V_c < V$), then live bed contraction scour is assumed. It is possible to use any of the equations as desired.

For computing the clear-water contraction scour, HEC No. 18 publication recommends using Laursen's equation. The use of Pier and abutment scour equations is explained in HEC-RAS' instruction manual.

SCOUR IN ERODIBLE ROCK

This section presents two modes of scour and erosion in rock. The first mode referred to as quarrying and plucking, involves the removal of relatively intact rock blocks in fissured and jointed rock masses which are otherwise relatively hard and durable compared to soils. The second mode is a more gradual and progressive process caused by bed load abrasion of the rock surface over relatively long periods of time, such that the pier is exposed to many flood events over the life of the bridge.

QUARRYING AND PLUCKING

The Erodibility Index classification described in this manual is used to estimate the depth of pier scour when quarrying and plucking of intact rock blocks is the dominant mode of erosion. Rock discontinuities have the greatest influence on scour processes in this mode. A schematic diagram of this process is presented in Figure-5.

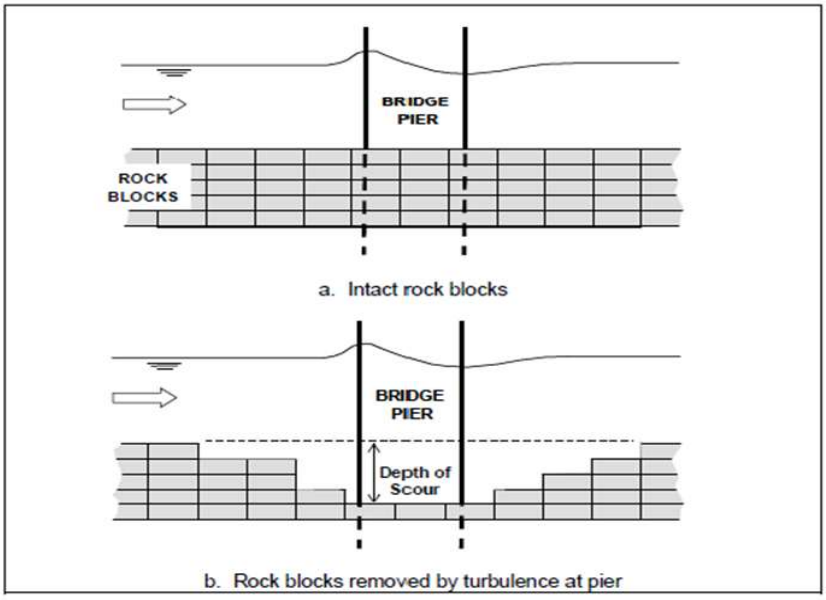


Figure-5: Conceptual Model of Quarrying and Plucking at a Bridge Pier

The Erodibility Index, K, is calculated as:

$$K = (M_s)\ (K_b)\ (K_d)\ (J_s)$$

where,

K = Erodibility Index
M_s= Intact Rock Mass Strength Parameters
K_b= Block Size Parameters
K_d= Shear Strength Parameters
J_s= Relative Orientation Parameter

Following tables are used for selecting the M_s, K_b, K_d and J_s values. The intact rock mass strength parameter M_s is related to the unconfined compressive strength as shown in Table 5.

Table-5: Values of the Rock Mass Strength Parameter (M_s)

Values of the Rock Mass Strength Parameter M_s			
Hardness	**Identification in Profile**	**Unconfined Compressive Strength (MPa)**	**Mass Strength Number (M_s)**
Very soft rock	Material crumbles under firm (moderate) blows with sharp end of geological pick and	Less than 1.7	0.87
	can be peeled off with a knife; is too hard to cut triaxial sample by hand.	1.7 – 3.3	1.86
Soft rock	Can just be scraped and peeled with a knife; indentations 1 mm to 3-mm show in the	3.3 – 6.6	3.95
	specimen with firm (moderate) blows of the pick point.	6.6 – 13.2	8.39
Hard rock	Cannot be scraped or peeled with a knife; hand-held specimen can be broken with hammer end of geological pick with a single firm (moderate) blow.	13.2 – 26.4	17.70
Very hard rock	Hand-held specimen breaks with hammer end of pick under more than one blow.	26.4–53.0 53.00-106.0	35.0 70.0
Extremely hard rock	Specimen requires many blows with geological pick to break through intact material.	Larger than 212.0	280.0

Joint spacing and the number of joint sets within a rock mass determines the value of K_b for rock. Joint spacing is estimated from borehole data by means of the rock quality designation (RQD) and the number of joint sets is represented by the joint set number (J_n). The values of the joint set numbers (J_n) are found in Table 6. As seen in the table, J_n is a function of the number of joint sets, ranging from rock with no or few joints (essentially intact rock), to rock formations consisting of one to more than four joint sets. The classification accounts for rock that displays random discontinuities in addition to regular joint sets. Random joint discontinuities are discontinuities that do not form regular patterns. For example, rock with two joint sets and random

discontinuities is classified as having two joint sets plus random. Having determined the values of RQD and J_n, K_b is calculated as:

$$K_b = RQD/J_n$$

With the values of RQD ranging between 5 and 100, and those of J_n ranging between 1 and 5, the value of K_b ranges between 1 and 100 for rock.

Table-6: Rock Joint Set Number (J_n)

Rock Joint Set Number J_n	
Number of Joint Sets	Joint Set Number (J_n)
Intact, no or few joints/fissures	1.00
One joint/fissure set	1.22
One joint/fissure set plus random	1.50
Two joint/fissure sets	1.83
Two joint/fissure sets plus random	2.24
Three joint/fissure sets	2.73
Three joint/fissure sets plus random	3.34
Four joint/fissure sets	4.09
Multiple joint/fissure sets	5.0

The discontinuity or shear strength number (K_d) is the parameter that represents the relative strength of discontinuities in rock. In rock, it is determined as the ratio between joint wall roughness (J_r) and joint wall alteration (J_a), where Jr represents the degree of roughness of opposing faces of a rock discontinuity, and Ja represents the degree of alteration of the materials that form the faces of the discontinuity. Alteration relates to amendments of the rock surfaces, for example weathering or the presence of cohesive material between the opposing faces of a joint. Values of Jr and Ja can be found in Table-7 and Table-8. The values of K_d calculated with the information in these tables change with the relative degree of resistance offered by the joints. Increases in resistance are characterized by increases in the value of K_d. The shear strength of a discontinuity is directly proportional to the degree of roughness of opposing joint faces and inversely proportional to the degree of alteration.

$$K_d = J_r/J_a$$

Table-7: Joint Roughness Number (J_r)

Joint Roughness Number J_r	
Condition of Joint	**Joint Roughness Number J_r**
Stepped joints/fissures	4.0
Rough or irregular, undulating	3.0
Smooth undulating	2.0
Slicken sided undulating	1.5
Rough or irregular, planar	1.5
Smooth planar	1.0
Slicken sided planar	0.5

Joint Roughness Number J_r	
Condition of Joint	**Joint Roughness Number J_r**
Joints/fissures either open or containing relatively soft gouge of sufficient thickness to prevent joint/fissure wall contact upon excavation	1.0
Shattered or micro-shattered clays	1.0

Table-8: Joint Alteration Number (J_a)

Joint Alteration Number J_a			
Description of Gouge	**Joint Alteration Number (J_a) for Joint Separation (mm)**		
	1.0 (1)	**1.0 –5.0(2)**	**5.0(3)**
Tightly healed, hard, non-softening impermeable filling	0.75	-	-
Unaltered joint walls, surface staining only	1.0	-	-
Slightly altered, non-softening, non-cohesive rock mineral or crushed rock filling	2.0	2.0	4.0
Non-softening, slightly clayey non-cohesive filling	3.0	6.0	10.0
Non-softening, strongly over-consolidated clay mineral filling, with or without crushed rock	3.0	6.0**	10.0
Softening or low friction clay mineral coatings and small quantities of swelling clays	4.0	8.0	13.0
Softening moderately over-consolidated clay mineral filling, with or without crushed rock	4.0	8.00**	13.0
Shattered or micro-shattered (swelling) clay gouge, with or without crushed rock	5.0	10.0**	18.0
Note: (1) Joint walls effectively in contact. (2) Joint walls come into contact after approximately 100-mm shear. (3) Joint walls do not come into contact at all upon shear. **Also applies when crushed rock occurs in clay gouge without rock wall contact.			

Relative orientation, in the case of rock, is a function of the relative shape of the rock and its dip and dip direction relative to the direction of flow. The relative orientation parameter J_s represents the relative ability of earth material to resist erosion due to the structure of the ground. This parameter is a function of the dip and dip direction of the least favorable discontinuity (most easily eroded) in the rock with respect to the direction of flow, and the shape of the material units.

If rock is dipped against the direction flow, it will be more difficult to scour the rock than when it is dipped in the direction of flow. When it is dipped in the direction of flow, it is easier for the flow to lift the rock, penetrate underneath and remove it. Rock that is dipped against the direction of flow will be more difficult to dislodge. The shape of the rock, represented by the length to width ratio r, impacts the erodibility of rock in the following manner. Elongated rock will be more difficult to remove than equi-sided blocks of rock. Therefore, large ratios of r represent rock that is more difficult to remove because it represents elongated rock shapes. Values of the relative orientation parameter J_s are provided in Table 9.

Table-9: Relative Orientation Parameter (J_s)

Relative Orientation Parameter Js.					
Dip Direction of Closer Spaced Joint Set (degrees)	**Dip Angle of Closer Spaced Joint Set (degrees)**	**Ratio of Joint Spacing, r**			
Dip Direction	Dip Angle	Ratio 1:1	Ratio 1:2	Ratio 1:4	Ratio 1:8
180/0	90	1.14	1.20	1.24	1.26
In direction of stream flow	89	0.78	0.71	0.65	0.61
In direction of stream flow	85	0.73	0.66	0.61	0.57
In direction of stream flow	80	0.67	0.60	0.55	0.52
In direction of stream flow	70	0.56	0.50	0.46	0.43
In direction of stream flow	60	0.50	0.46	0.42	0.40
In direction of stream flow	50	0.49	0.46	0.43	0.41
In direction of stream flow	40	0.53	0.49	0.46	0.45
In direction of stream flow	30	0.63	0.59	0.55	0.53
In direction of stream flow	20	0.84	0.77	0.71	0.67
In direction of stream flow	10	1.25	1.10	0.98	0.90
In direction of stream flow	5	1.39	1.23	1.09	1.01
In direction of stream flow	1	1.50	1.33	1.19	1.10
0/180	0	1.14	1.09	1.05	1.02
Against direction of stream flow	-1	0.78	0.85	0.90	0.94
Against direction of stream flow	-5	0.73	0.79	0.84	0.88
Against direction of stream flow	-10	0.67	0.72	0.78	0.81
Against direction of stream flow	-20	0.56	0.62	0.66	0.69
Against direction of stream flow	-30	0.50	0.55	0.58	0.60
Against direction of stream flow	-40	0.49	0.52	0.55	0.57
Against direction of stream flow	-50	0.53	0.56	0.59	0.61
Against direction of stream flow	-60	0.63	0.68	0.71	0.73
Against direction of stream flow	-70	0.84	0.91	0.97	1.01
Against direction of stream flow	-80	1.26	1.41	1.53	1.61
Against direction of stream flow	-85	1.39	1.55	1.69	1.77

Relative Orientation Parameter Js.					
Dip Direction of Closer Spaced Joint Set (degrees)	**Dip Angle of Closer Spaced Joint Set (degrees)**	**Ratio of Joint Spacing, r**			
Dip Direction	Dip Angle	Ratio 1:1	Ratio 1:2	Ratio 1:4	Ratio 1:8
Against direction of stream flow	-89	1.50	1.68	1.82	1.91
180/0	-90	1.14	1.20	1.24	1.26
Notes: 1. For intact material take Js = 1.0. 2. For values of r greater than 8 take Js as for r = 8. 3. If the flow direction FD is not in the direction of the true dip TD, the effective dip ED is determined by adding the ground slope to the apparent dip AD: ED = AD + GS					

The material characteristics to quantify the Erodibility Index parameters are generally obtained from borehole data, field observation and testing, and laboratory testing (to obtain the unconfined compressive strength). Depending on the importance of the project, it is also possible to obtain parameter values by making use of geologic descriptions of the material [see tables of Annandale (1995)]. Larger values of the Erodibility Index value K indicate greater resistance to erosion.

As a general rule, rock masses on which bridge piers are founded typically exhibit Erodibility Index K values ranging from 0.1 (very poor rock) up to 10,000 or greater (very good rock). For K values greater than 0.1, the critical stream power Pc in SI units (kilowatts per square meter) for initiating quarrying and plucking is related to K as given by Annandale (2006):

$$P_c = K^{0.75}$$

where,

P_c = Critical stream power necessary to initiate scour, KW/m^2
K = Erodibility Index

As developed by Annandale, the stream power of the approach flow upstream of a bridge pier (i.e., at a location not affected by the additional turbulence caused by the pier itself) is calculated by considering the turbulence production near the bed of the stream:

$$P_a = 7.853\ \rho\ (\tau / \rho)^{3/2}$$

where,

P_a = Stream power of approach flow, W/m^2
ρ = Mass density of water, 1000 kg/m^3
τ = Bed shear stress of approach flow, N/m^2 or Pa

Note that P_a in the above Equation is expressed in units of W/m_2, whereas the critical shear stress P_c given by equation is expressed in units of KW/m^2. To convert Pa to KW/m^2, the value resulting from equation must be divided by 1000.

In the vicinity of a bridge pier, the downward flow at the upstream face of the pier creates additional local turbulence in the form of the horseshoe vortex. As scour occurs, the stream power P at the bottom of the scour hole decreases as the scour hole becomes deeper. Scour will continue until the stream power at the bottom of the scour hole becomes less than the critical stream power Pc, at which point the scouring process can no longer be sustained. The relationship relating the relative depth of the scour hole to the stream power at the bottom of the hole for a variety of pier shapes (round, square, and rectangular) can be expressed as:

$$P/P_a=8.42e^{-0.712(y_s/b)}$$

where,

P = Stream power at the bottom of the scour hole, W/m^2
P_a= Stream power of the approach flow near the stream bed, W/m^2
y_s= Depth of sour hole, m
b = Pier width perpendicular to the flow direction, m

ABRASION

Abrasion is the gradual wearing-away of rock surfaces by the more or less continuous movement of water and bed load sediment over the bed of a channel (NCHRP 2011e). At bridge piers founded on rock, the local flow acceleration, horseshoe vortex and increased turbulence in the immediate vicinity of the pier result in more vigorous particle movement compared to the unobstructed channel. Therefore, abrasion scour at piers is much more pronounced than the general scouring of the streambed by this process.

ABRASION RESISTANCE OF ROCK:

The resistance of rock to abrasion from bedload movement is related to the physical properties of the rock mass. Dickenson and Baillie (1999) used a modification of the conventional slake durability test (ASTM D4644) to characterize the abrasion resistance of rock materials found in streambeds of Western Oregon. They eliminated oven drying from the ASTM slake durability procedure because complete drying was not representative of the streambeds they were studying, and used the modified test to determine an "abrasion number" based on the slope of the percent weight loss vs. time data from the test. They disregarded the first few readings of the test data because of rounding of sharp sample edges which is not representative of longer-term sample behavior.

Keaton et al. (NCHRP 2011e) further modified the test and developed a method to relate the sample weight loss data from the test to an equivalent scour depth vs. equivalent stream power relationship based on the dimensions of the slake durability test drum and its rate of rotation. Figure-6 presents data from this test using a bulk sample of siltstone from the Sacramento River near Redding, California.

The slope of the linear regression line through the test data is defined by Keaton et al. (NCHRP 2011e) as the "Geotechnical Scour Number" and is used to estimate abrasion scour at piers. In Figure-6, for example, the Geotechnical Scour Number for the siltstone sample is 0.00018; tests on other rock types compared with actual scour measured at four field sites with bridge piers founded in erodible rock resulted in Figure-7, which relates pier scour to the total amount of work done by the flow on the stream bed over the life of the bridge.

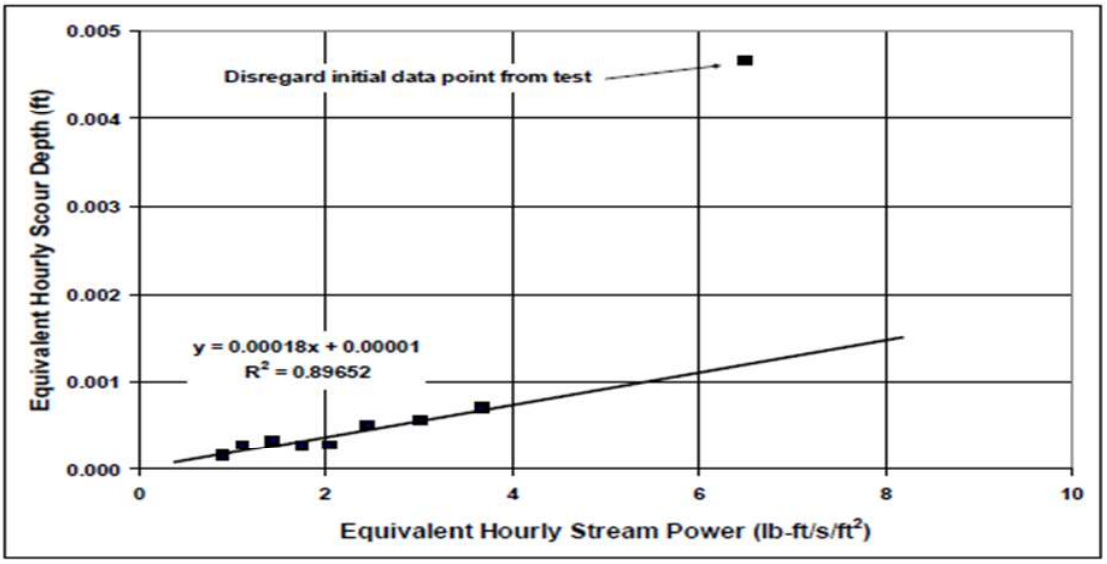


Figure-6: Example Data from Modified Slake Durability Test (NCHRP 2011e)

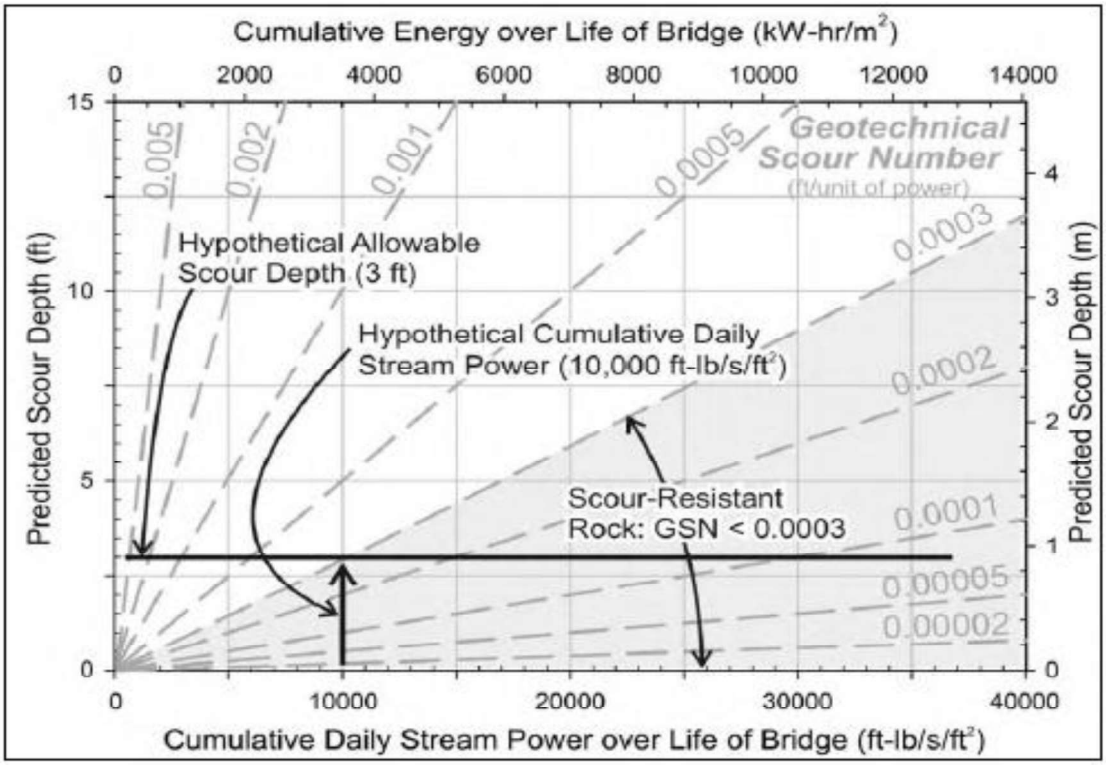


Figure-7: Pier Scour in Rock as function of Stream Power & Geotechnical Scour Number (NCHRP 2011e)

STREAM POWER AND DURATION:

Because the process of abrasion is gradual, in quantifying pier scour the effect of duration is more important than the hydraulic conditions that exist temporarily at the peak of a flood event. The product of power and time is work; therefore, integrating a time series of stream power over many years and many floods provides a meaningful measure of the total amount of work done by the flow on the streambed for the time period being considered. Such integration has been performed and described as "Cumulative Daily Stream Power" by Keaton et al. (NCHRP 2011e). The integral,

denoted Ω, is the area under the curve of stream power versus time for any particular duration, and is expressed in units of work per unit area (e.g., lb-ft/ft^2, KW-hr/m^2).

$$Y_s=(GSN)\ (\Omega)$$

where,

Y_s = Pier scour depth due to abrasion, ft (m)
GSN = Geotechnical scour number from modified slake durability test, ft per Unit of stream power (m per unit of stream power)
Ω = Cumulative stream power, lb-ft-day/s/ft^2 (KW-hr/m^2)

The concept of accumulating stream power to quantify work per unit area is illustrated by the use of a time series of average daily flows typically obtained from USGS gaging station records. Knowing the velocity V, depth of flow y, and energy slope S_f as functions of discharge, a time series of average daily stream power can be constructed as shown in Figure-8, which illustrates typical data from one water year.

In Figure-8 (a), it is assumed that there is a threshold discharge that initiates bedload motion, therefore a threshold discharge must be exceeded before abrasion processes can occur. The effective stream power causing abrasion is illustrated in Figure-8 (b). This figure illustrates the concept that over the course of a typical year, only a few flood events may contribute to the abrasive work that creates scour at a bridge pier.

In Figure-8, the total effective amount of work Ω done by the stream during the water year is found by integrating the daily stream power curve, as shown in Figure-9. This figure shows that the total amount of work done in this particular water year is 266 lb-ft-day/s/ft^2 in U.S. customary units. Converting to SI units and using the convention of KW-hr as the unit of work, this is 93 KW-hr/m^2 over the course of the water year. Over many years, the total amount of effective work done by the stream on its bed can be quantified as the sum of the daily work done by individual events.

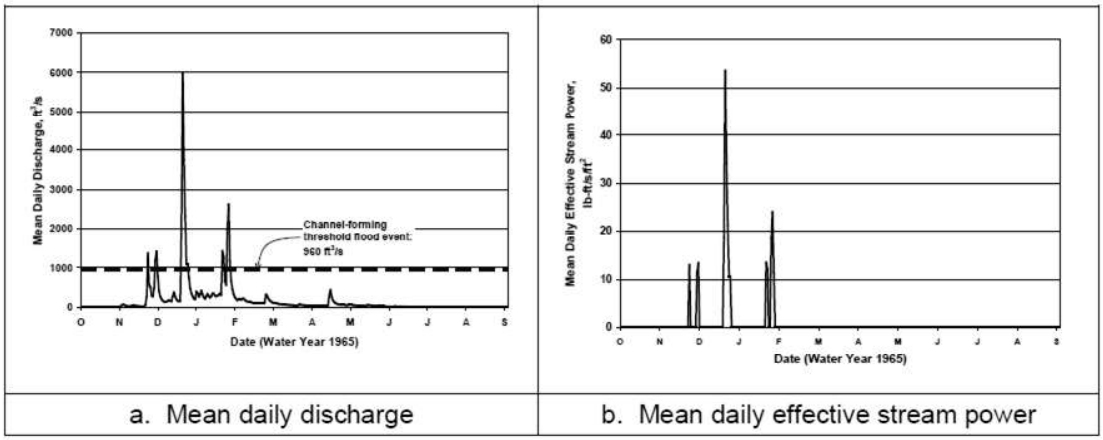


Figure-8: Transforming Mean Daily Flow Series to Mean Daily Effective Stream Power

Given a future cumulative hydraulic loading Ω_{fut}, the Geotechnical Scour Number can be used to estimate the future scour associated with that loading, for the particular rock formation. Estimates of future scour may then be made for a variety of purposes:

- Estimating scour over the remaining life of the structure
- Estimating scour at other existing structures with foundations in the same (or similar) rock formation
- Estimating scour at proposed structures on the same (or similar) rock formation

The difficulty with the above approach is quantifying the cumulative effective hydraulic load in the future. Considering that this method is concerned with long-term abrasion processes, a threshold concept will typically apply, and the practitioner must exercise judgment in determining an appropriate threshold considering local hydraulic conditions at the pier. Once a reasonable threshold is established, only the effects of larger, relatively infrequent events that exceed this threshold over the life of the structure need be considered.

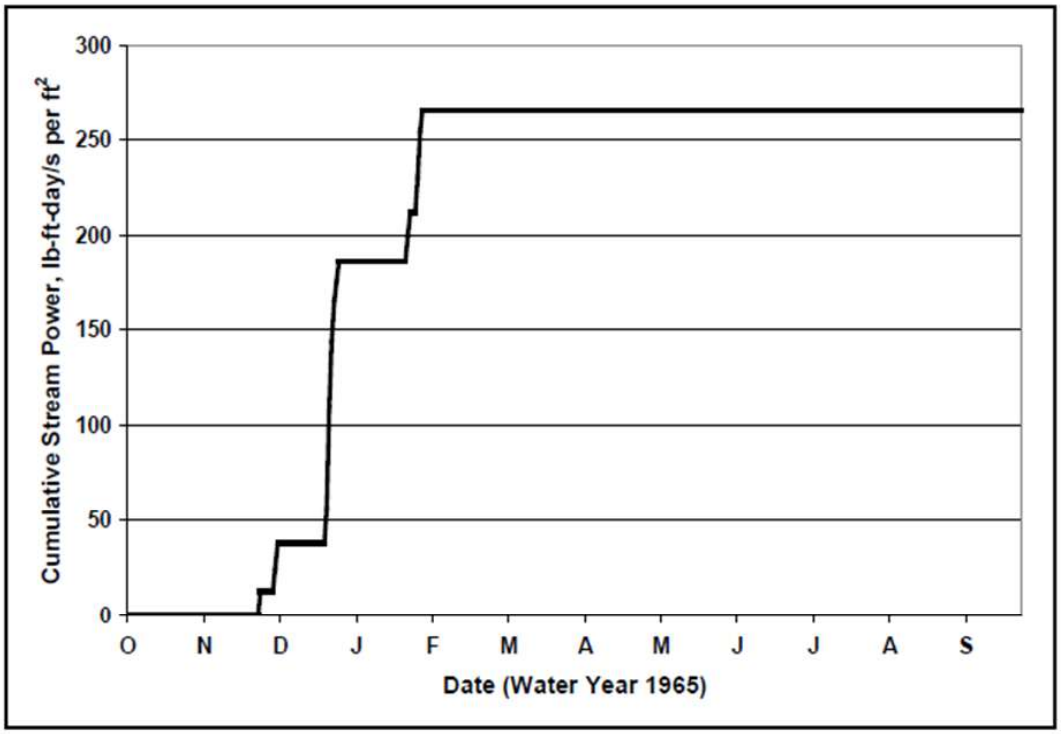


Figure-9: Cumulative stream power for the water year in Figure-8

Figures-9,10 and 11 depict the summarized studies conducted by Bollaert for the evaluation of evaluation of scour in rock at bridge site.

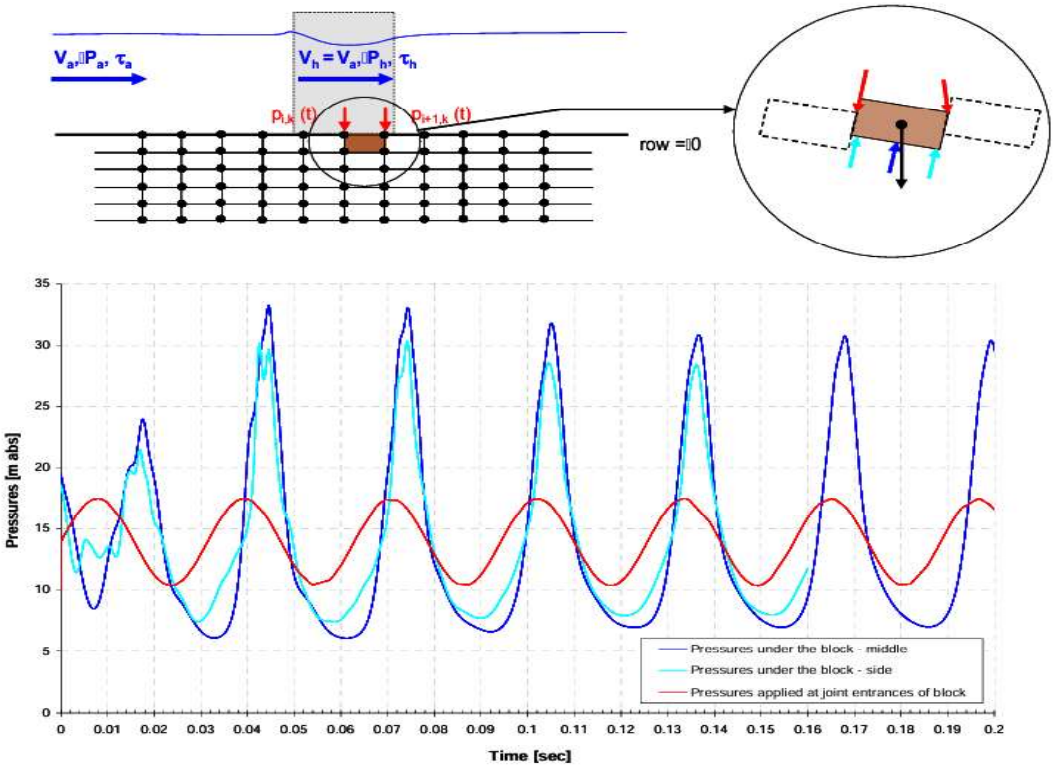


Figure-10: Pressure fluctuations over and under rock block

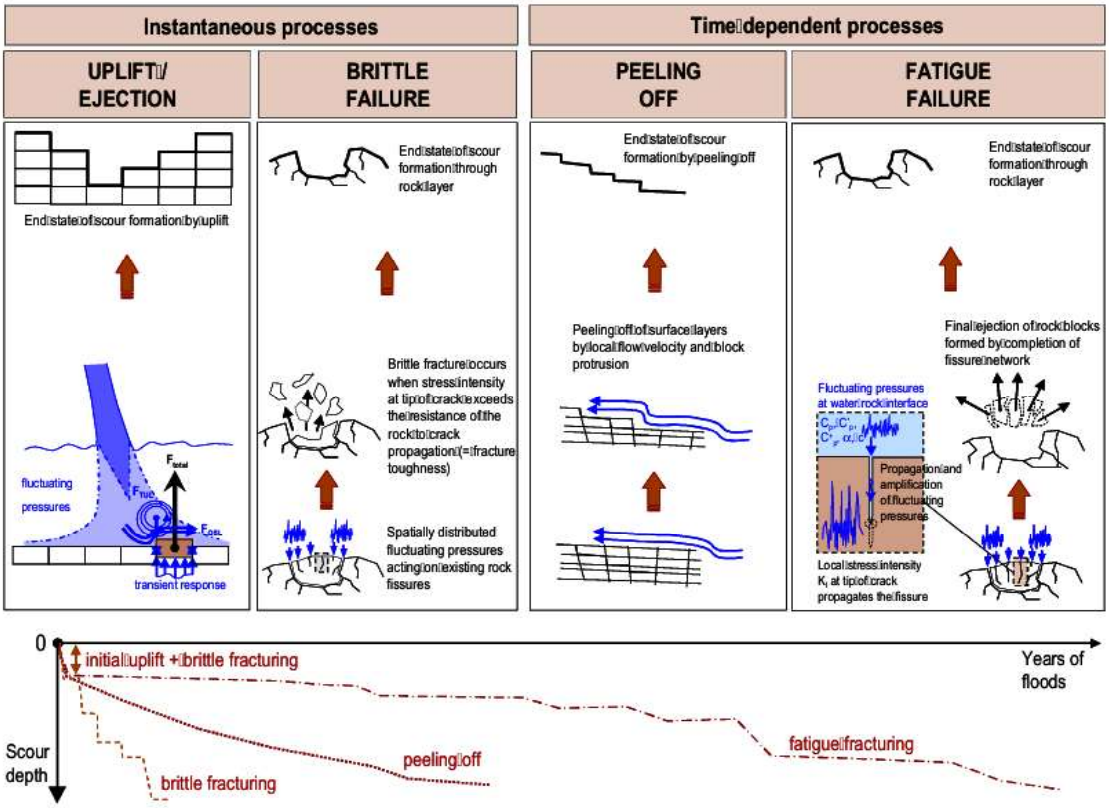


Figure-11: Rock Scouring Model Due To Bollaert

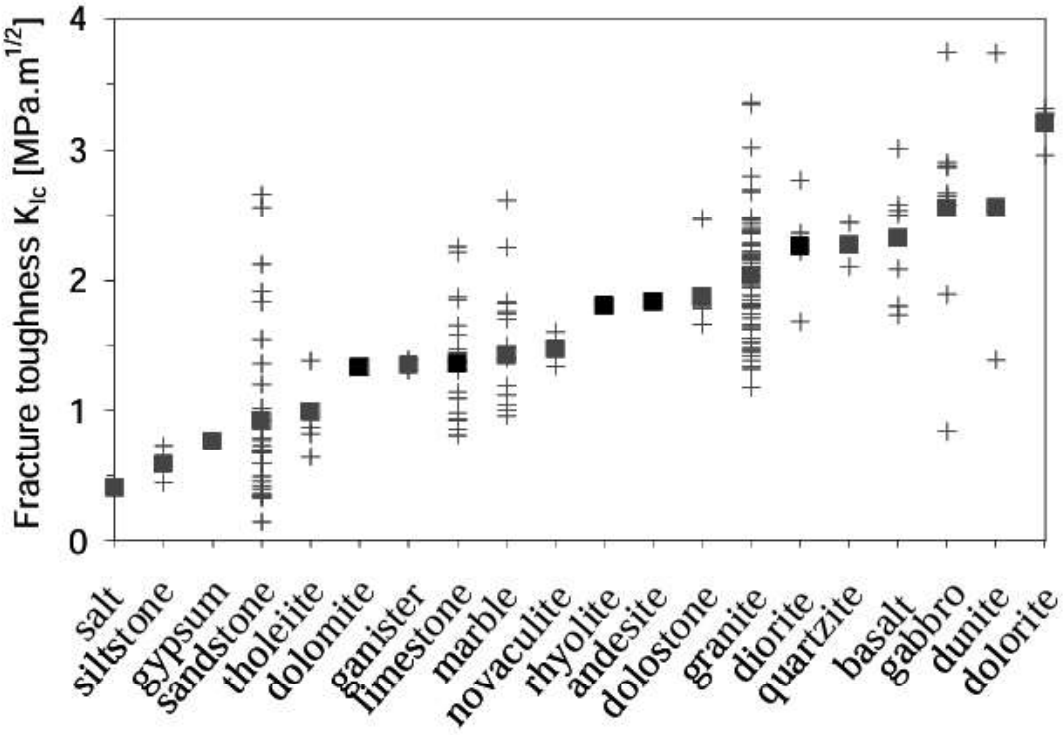


Figure-12: Rock Fracture Toughness

5. CONCLUSIONS

Out of the above methods, Lacey's method is considered state-of-the-art for plain areas and Brown's method is considered to be the best for hilly terrains. The HEC-RAS may be used in addition, as an option to further validate the evaluations.

The evaluation of scour in rock, whether plucking / quarrying or abrasion, is still in the process of evolution. The methods presented in this paper are mostly based on the research carried out by National Cooperative Highway Research Program (NCHRP) and the work by E.F.R. Bollaert.

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