

# The Hydro-Potential (HP) Value: a Rock Classification Technique for Estimating Seepage into Excavations

## El Valor del Potencial Hidráulico: una Técnica de Clasificación de Rocas para Estimar la Infiltración en Excavaciones

William C. B. Gates

Kleinfelder, Inc, 2405 140<sup>th</sup> Ave. NE Bellevue, WA, USA

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### Abstract

*The hydro-potential (HP) value is a proposed rockmass classification semi-quantitative technique employed to evaluate development of groundwater in bedrock terrain. This technique may also be adapted to estimate groundwater seepage into excavations in bedrock. The method describes six fracture characteristics of the rock mass and assigns a numerical value from reference tables based on their fracture properties. The fracture characteristics are as follows: rock quality designation (RQD), joint number ( $J_n$ ), joint roughness ( $J_r$ ), joint hydraulic conductivity ( $J_k$ ), joint aperture factor ( $J_{af}$ ), and joint water factor ( $J_w$ ). The investigation was conducted in various lithologic terrains throughout the western United States. HP-values were compared to the yields of 21 local bedrock wells and four locations (11 sites) that demonstrated groundwater seepage problems. Contrasting the HP-values to bedrock well yields and seepage discharge displayed a significant inverse exponential relationship with strong correlation coefficients (R) exceeding  $-0.92$ , or about 86% of the HP-values correlate directly with discharge.*

### Resumen

*El valor del potencial hidráulico (HP) es una técnica semicuantitativa provada para la clasificación de masas rocosas, empleada para evaluar la presencia de aguas subterráneas en terrenos rocosos. Esta técnica se puede también adaptar para estimar la filtración del agua subterránea en excavaciones en roca. El método describe seis características de las fracturas de la masa de roca y asigna un valor numérico, encontrado en tablas de referencia, basado en las propiedades de la fractura. Las características necesarias son las siguientes: RQD, número de diaclasa ( $J_n$ ), aspereza de la diaclasa ( $J_r$ ), conductividad hidráulica de la diaclasa ( $J_k$ ), factor de apertura de la diaclasa ( $J_{af}$ ), y factor de agua de la diaclasa ( $J_w$ ). La investigación fue conducida en diversos terrenos litológicos en el oeste de los Estados Unidos. Los valores HP fueron comparados a la producción de 21 pozos locales y de cuatro localizaciones (11 sitios) que muestran problemas de filtración de aguas subterráneas. La comparación de los valores HP con las producciones de pozos y la descarga de la filtración, muestra una relación exponencial inversa apreciable con altos coeficientes de correlación (R) que exceden 0.92, ó, en otras palabras, cerca del 86% de los valores HP correlacionan directamente con la descarga.*

## 1 INTRODUCTION

Groundwater seepage into excavations for tunnels, mines and other construction sites presents challenging problems for mining and civil engineering projects. Having an empirical tool at the engineer's disposal to predict seepage would aid in planning for construction and design problems.

In 1997 the author proposed the hydro-potential (HP) value as a new rock mass classification, semi-quantitative technique employed to evaluate the potential for developing groundwater in bedrock (Gates, 1997). The HP-value is the

potential for a rock mass to hydraulically transmit groundwater. The method is a simple and quick technique used to evaluate rock outcrops surrounding and within the construction site.

Groundwater flow through fractured bedrock is controlled by several interrelated physical characteristics of the rock mass, including the lithology and rock quality, number, density, roughness, hydraulic conductivity, shape, aperture, and the connectivity of fractures. Louis (1969) demonstrated that flow through rock fractures follows similar fundamental laws to that of pipe flow.

The HP-value technique is a modification of the engineering rock mass quality designation (Q)

originally developed for evaluation of rock competency in tunnel design (Barton et al, 1974) and seismic rock fall susceptibility (Harp and Noble, 1993). The method describes six fracture characteristics of the rock mass and assigns a numerical value from reference tables based on their fracture properties (Tables 1 through 6). The equation for the Hydro-Potential value is as follows:

$$HP_{value} = \left( \frac{RQD}{J_n} \right) \left( \frac{J_r}{(J_k)(J_{af})} \right) (J_w) \quad (1)$$

Where:

- RQD = rock quality designation
- $J_n$  = joint set number
- $J_r$  = joint roughness number
- $J_{af}$  = joint aperture factor
- $J_k$  = joint conductivity factor
- $J_w$  = joint water factor

The numerical value of HP ranges from  $1.33 \times 10^{-3}$  (for exceptionally poor quality rock) up to 800 (for exceptionally good quality, competent rock). The author found that by comparing the HP-values to yields and specific capacities of bedrock wells the regression curve displayed a significant inverse exponential relationship with strong correlation coefficients, R, exceeding  $-0.91$  (Gates, 1997). As displayed in Figure 1, over 83 percent of the wells studied indicated higher yields and specific capacities correspond to lower HP-values for outcrops of similar lithology in the vicinity of the local bedrock wells.

Groundwater wells previously investigated are similar to bedrock drains with high rates of seepage discharge. In this research, the author investigated two tunnels and three road cuts in fractured rock that exhibited seepage problems and compared their discharge rates to the attendant HP-values.

For purposes of estimating the HP-value, the term “joint” is loosely, or non-genetically, used to refer to all discontinuities that can serve as conduits for groundwater, such as foliation, joints, faults, and other cracks.

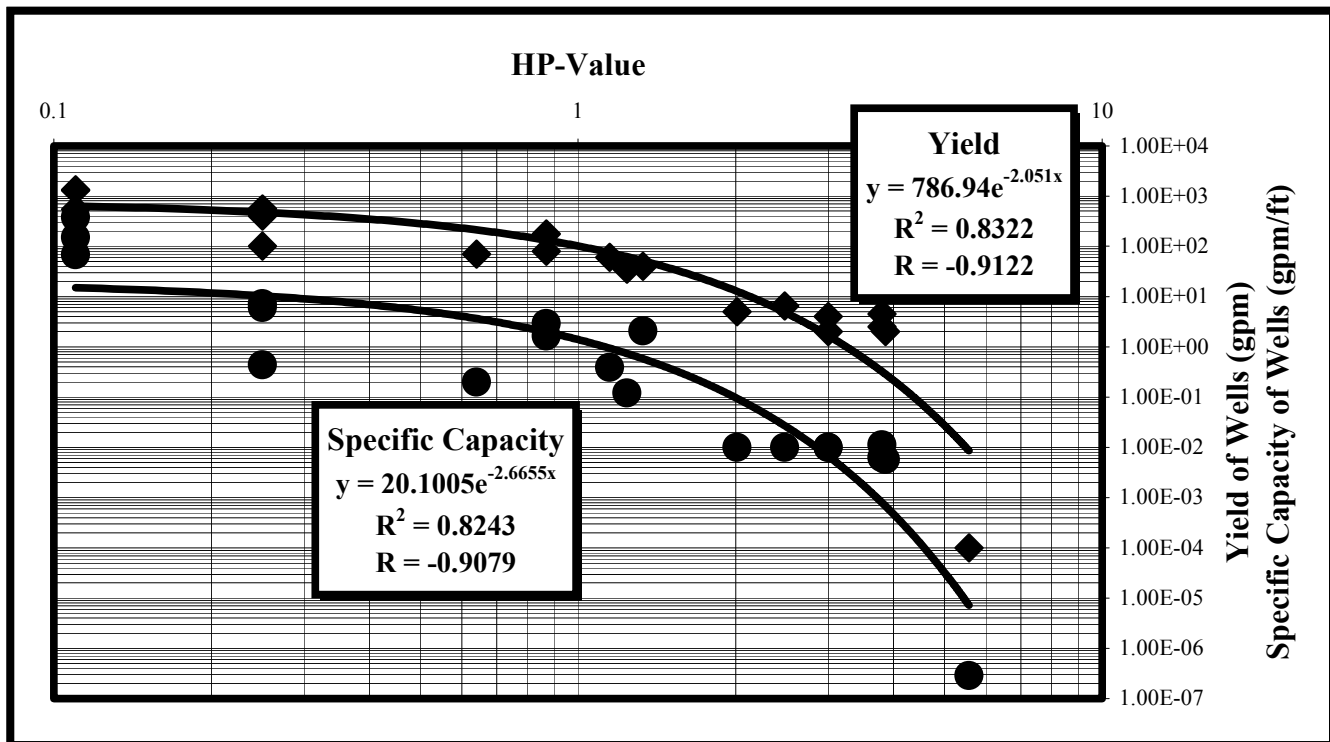


Figure 1. Comparison of HP-values to yields and specific capacities of local bedrock wells (modified from Gates, 1997). Note: 1 gallon per minute = 0.0631 liters/second.

## 2 COMPONENTS OF THE HP-VALUE

Applying the HP-value technique is relatively straightforward and simple using Tables 1 through 6, which describe each fracture characteristic.

### 2.1 Rock Quality Designation (RQD)

Table 1 lists the description and rating parameters for Rock Quality Designation (RQD) and rock quality classification (RQC) suggested by Deer (1963), Barton et al (1974) and Afrouz (1992).

Table 1: Rock quality designation (RQD) and classification (RQC) (after Deer, 1963; Barton, et al, 1974; Afrouz, 1992).

Number	RQC	RQD *
1	Very Poor	0-25
2	Poor	25-50
3	Fair	50-75
4	Good	75-90
5	Excellent	90-100

\* Where the reported or measured RQD value is  $\leq 10$  (including 0) a nominal value of 10 is used to evaluate the HP-value. RQD intervals of 5 (i.e. 100, 95, 90) are sufficiently accurate.

Typically, RQD is estimated based on percent of drill core recovered that exceeds 10cm (4-inches) long compared to the overall core run. Depending on the project, drill core may be unavailable in the field. If this is the case, one must estimate the average RQD based on rock outcrops surrounding the test well site. Planstrom (1975) suggested the following relationship for RQD in the outcrop when core was not available:

$$RQD\% = (115) - (3.3J_v) \quad (2)$$

Where:  $J_v$  = total number of joints or fractures per cubic meter of rock mass.

For  $J_v < 4.5$ , RQD = 100 (Planstrom, 1975).

### 2.2 Joint Set Number, $J_n$

The joint set number,  $J_n$ , represents the number of joint sets in the rock. This parameter is a characteristic of the orientation and density of fractures in the rock mass. Barton et al (1974) developed Table 2 that rates the rock mass on the basis of joint set number.

Fracture trace analyses coupled with stereonet and rose diagrams developed from measurement of attitudes of joints observed in the rock are excellent tools used to estimate the number of joint sets. Joints within the set display roughly the same orientation.

Table 2: Description and ratings for joint set number,  $J_n$  (after Barton et al, 1974).

Number	Description	Rating
1.	Massive, no or few joints	0.5-1.0
2.	One joint set	2
3.	One joint set plus random	3
4.	Two joint sets	4
5.	Two joint sets plus random	6
6.	Three joint sets	9
7.	Three joint sets plus random	12
8.	Four joint sets, random, heavily jointed, "sugar cube"	15
9.	Crushed rock	20

### 2.3 Joint Roughness Number, $J_r$

The joint roughness number,  $J_r$ , represents the smoothness or absolute roughness of the joint plane or potential flow conduit. Joint roughness controls the variation and effective aperture size of the fracture. Therefore, it controls the channeling of flow between the fracture walls. Louis (1969) demonstrated that fluid flow is dependent on fracture roughness. Joint roughness may be measured using a contour gauge and compared to a set of standard profiles developed by Barton and Choubey (1977). However, it is usually sufficient to estimate the roughness by inspection of the joint planes. Table 3 lists rating for the rock mass based on joint roughness number.

Table 3: Description and ratings for joint roughness number,  $J_r$  (after Barton et al, 1974).

No.	Description	Rating
1.	Discontinuous joints	4.0
2.	Rough or irregular, undulating	3.0
3.	Smooth, undulating	2.0
4.	Slickensided, undulating	2.0
5.	Rough or irregular, planar	1.5
6.	Slickensided planar	1.5
7.	Smooth, planar, polished	1.0

### 2.4 Joint Aperture Factor, $J_{af}$

Aperture size and shape are extremely important in evaluation of flow characteristics of a fracture. As indicated above, absolute roughness also controls the effective shape of the fracture aperture. According to Barton and Hsieh (1989), the volumetric flow rate through smooth-walled fractures is a function of the aperture size cubed. Similarly, Cook (1989) noted the volumetric flow rate for rough fractures in laboratory specimens varies as a function of the aperture size to a power ranging between 3 and 6. This is the effective or hydraulic aperture.

The average mechanical aperture size (Barton and Hsieh, 1989) of the fractures can be measured in the field using either a feeler gauge or a tape measure. The aperture size of the fractures exposed at the surface outcrop will provide an estimate of maximum width of fracture apertures in the sub-surface bedrock. Tectonic stress reduction from regional unloading by erosion of overlying rock, surficial materials, or exposure to surface weathering will affect the size of the aperture. However, Barton and Hsieh (1989) suggested this will not change the aperture distribution. Table 4 lists descriptions and ratings for the joint aperture factor,  $J_{af}$  described by Hencher (1987) and Harp and Noble (1993). The author modified the table to account for fracture apertures in the range of 0.1-mm to 20-mm. Tunnels with high Q-values and tighter fractures typically fall within this range. The author has found that reporting the 90<sup>th</sup> percentile of the average width of the aperture is sufficient.

Table 4: Description and ratings for joint aperture factor,  $J_{af}$  (modified from Hencher, 1987; Harp and Noble, 1993; Gates, 1997).

No.	Description	Rating
1.	All joints tight, < 0.1 mm	1.0
2.	Joints 90% 0.1 ≤ 1.0 mm	1.2
3.	Joints 90% 1.0 ≤ 5.0 mm	1.4
4.	Joints 90% 5.0 ≤ 10.0 mm	1.8
5.	Joints 90% 10.0 ≤ 20.0 mm	2.5
6.	Joints 90% 20.0 ≤ 50.0 mm	5.0
7.	Joints 90% 50.0 ≤ 100.0 mm	7.5
8.	Joints 90% 100.0 ≤ 200.0 mm	10.0
9.	Joints 90% > 200 mm	15.0

## 2.5 Joint Hydraulic Conductivity Factor, $J_k$

The hydraulic conductivity of a fracture is a function of the presence or lack of infilling material in the joint. Driscoll (1986) defines hydraulic conductivity as the rate of flow of water in meters per day (gallons per day) through a cross section of one square meter (one square foot) under an unit hydraulic gradient at the prevailing temperature expressed as m/day ( $gpd/ft^2$ ). Fractures healed with some type of mineral will exhibit a very low hydraulic conductivity. On the other hand, open, clean fractures will exhibit excellent flow because of high hydraulic conductivity. Table 5 summarizes the descriptions and ratings for the hydraulic conductivity number,  $J_k$ . Tight or healed joints receive a rating value of one indicating low hydraulic conductivity and no flow in the joint. A hydraulic conductivity rating

of five suggests open, clean joints with a potential for excellent flow. Average hydraulic conductivity ranges developed by Freeze and Cherry (1979) for clay, silt, silty sand, sand, gravel, fractured igneous and metamorphic rock, permeable basalt and karst limestone are the basis for Table 5. The author amplified their work by adding descriptions and ratings for the fractures. The values represent qualitative ranges of hydraulic conductivity, viewed in the field by inspection of the fractures.

Table 5: Descriptions and ratings for average hydraulic joint conductivity number,  $J_k$  (modified from Freeze and Cherry, 1979).

No.	Description	Rating	Hydraulic Conductivity m/day
1.	All joints tight or healed with calcite/ quartz, no flow.	1.0	<10 <sup>-5</sup>
2.	90% joints clay-filled, poor flow.	2.0	10 <sup>-5</sup> - 10 <sup>-2</sup>
3.	90% joints silty-sand filled, moderate flow.	3.0	10 <sup>-2</sup> - 10 <sup>-1</sup>
4.	90% joints clean sand to gravel filled, moderate to good flow.	3.5	10 <sup>-1</sup> - 10 <sup>3</sup>
5.	90% joint walls clean mostly open, good flow.	4.0	10 <sup>3</sup> - 10 <sup>5</sup>
6.	90% joints open, clean, excellent flow.	5.0	>10 <sup>5</sup>

Note: 1 meter/day = 24.5 gallons/day/ft<sup>2</sup>

## 2.6 Joint Water Factor, $J_w$

The HP-value is a function of the fracture characteristics. Annual precipitation rates, regional or local groundwater flow settings, and/or the impact of reservoirs and large bodies of water in the vicinity of interest do not directly control the HP-value. Nonetheless, the presence of groundwater discharging from joints along the rock outcrop enhances the probability of groundwater occupying the fractures in the sub-surface bedrock. Therefore, the presence of water in the fracture is a characteristic of the fracture.

The joint water factor is a measure of outflow of water from joints and is inversely proportional to water pressure within the joints (Barton et al,

1974). Table 6 lists the descriptions and ratings for the joint water factor,  $J_w$ , suggested by Barton et al (1974), and Hencher (1987) and modified by the author to include items 2 through 5 (description, drops/min and rating).

Ordinarily, surface rock outcrops surrounding the target basin are dry. Accordingly, a rating value of one is most common for these joints. However, in some cases there may be seeps or perennial springs exiting the joints of the rock outcrop. Joints for this rock would receive a rating less than one depending on the flow discharge.

Table 6: Description and rating for joint water factor,  $J_w$  (modified from Barton et al, 1974; Hencher, 1970).

No.	Description	Drops/min *	l/sec*	Rating
1.	Dry	<1	$< 1 \times 10^{-6}$	1.0
2.	Damp	$1 \leq 10$	$1 \times 10^{-6} \leq 1 \times 10^{-5}$	0.94
3.	Drops	$10 \leq 100$	$1 \times 10^{-5} \leq 1 \times 10^{-4}$	0.86
4.	Dripping	$> 100$	$1 \times 10^{-4} \leq 1 \times 10^{-3}$	0.76
5.	Seeping		$1 \times 10^{-3} \leq 1 \times 10^{-2}$	0.66
6.	Slight flow		$1 \times 10^{-2} \leq 1 \times 10^{-1}$	0.50
7.	Moderate flow		$1 \times 10^{-1} \leq 1$	0.33
8.	High flow		$> 1$	0.20

Note: 1 drop (minim)  $\approx 1 \times 10^{-6}$  liter  $\approx 2 \times 10^{-5}$  gallon, 1 liter/second = 15.85 gallons/minute.

For this research the author evaluated the fractures under both dry and wet conditions to compare seepage rates. Groundwater discharge was measured from horizontal drains in bedrock or low points of rock where moisture would flow together to form drops and dripping seeps. Discharge was measured by counting and timing drops per minute or by capturing water in a graduated container. Drops can be measured accurately up to about 100 drops per minute, after which one must employ some type of graduated container to catch the water.

### 3 APPLICATION OF THE HP-VALUE

During the mid to late 1990's, the author investigated over 20 well locations distributed throughout Northern California, Idaho, Utah, and Washington (Gates, 1997). Pumping yields and

specific capacities of the wells were compared to the HP-values of the local bedrock units. Figure 1 displays the results of the original investigation.

In this investigation, the author investigated 11 seepage sites at four locations within rock tunnels or along rock road cuts in Washington State. Table 7 identifies the site and tabulates the observed HP-values and seepage discharge from the rock fractures.

Table 7: Seepage observation and data collection sites in Washington State.

Location	Site	Lithology/ Rock Type	HP- Value	Seepage l/sec
Washington SR 12				
Rimrock Tunnel	MP165.21R	Diorite	4.03	$5.6 \times 10^{-3}$
	MP165.21L	Diorite	5.70	$5.6 \times 10^{-4}$
	MP165.27L	Diorite	4.99	$5.6 \times 10^{-3}$
	MP165.31C	Diorite	4.90	$1.3 \times 10^{-6}$
Washington SR 12	MP143.05R	Basalt & Volcaniclastic	3.64	$3.5 \times 10^{-2}$
Washington SR 97				
Ruby Creek Rock Slide	MP176.55R	Metamorphic Greenstone	2.96	$1.6 \times 10^{-3}$
	MP176.55R	Metamorphic Greenstone	3.09	$5.7 \times 10^{-3}$
	MP176.55R	Metamorphic Greenstone	4.59	$3.8 \times 10^{-3}$
Washington SR 20				
Tunnel #1	MP122.53R	Skagit Gneiss	6.04	$5.0 \times 10^{-5}$
	MP122.54L	Skagit Gneiss	7.47	$1.3 \times 10^{-6}$
	MP122.54R	Skagit Gneiss	6.35	$5.0 \times 10^{-5}$

Note: SR = State Route, MP = Milepost, L = Left Side, R = Right Side, C = Center line

State Route (SR) 12 traverses White Pass in the Southern Cascades of Washington State. Rimrock tunnel, located on SR12 at Mile Post (MP) 165, is the only unlined tunnel in the State. The rockmass is composed of very strong diorite. Corrected Q-values average about three suggesting the rock is competent but fractured. Fracture apertures are typically  $< 1$ -mm wide and HP-values average 4.9. In November 2001, the author observed groundwater dripping from the fractures in the

crown and sidewalls at an average rate of about  $2.9 \times 10^{-3}$  l/s (0.046 gpm). The water freezes creating ice accumulation hazards in the winter for vehicular travel.

West of Rimrock tunnel at MP 143 is a road cut in vesicular basalt. In October 2002, the author observed wet, dripping, moss-covered rock. Fracture apertures averaged about 4-mm. The average HP-value was about 3.6. Average seepage discharge from the fractures was about 0.53 gpm.

Ruby Creek rockslide, on SR 97, MP 176 north of Blewett Pass in the Central Cascades of Washington State, was recently repaired to control rockfall and future sliding. The rock is composed of very weathered greenstone metamorphic rock. Fracture apertures average about 1.5-mm in width with attendant HP-values of about 3.5. Horizontal drains were installed to control seepage and relieve pore pressures on the fracture planes. In September 2002 the author observed about  $6.9 \times 10^{-3}$  l/s (0.11 gpm) discharging from the horizontal drains.

Tunnel No. 1 spans SR 20 at MP 122 located in Washington's North Cascades. The tunnel is partially lined and has been reported to weep during the wet season with subsequent ice build up in the winter. The rock mass is composed of Skagit gneiss. Fracture apertures average about 2-mm in width with average HP-values of about 6.6. The author observed wet dripping fractures near the east portal; dripping at the rate of about  $1.3 \times 10^{-5}$  l/s (0.0002 gpm (about 10 drops per minute)).

Figure 2 compares the resultant HP-values to observed seepage at these sites. The results are similar to that which the author observed when comparing HP-values to both yield and specific capacities of bedrock wells. The curve displays a strong inverse relationship between HP-values and seepage. The correlation coefficient, R, exceeds -0.76, which is good for geologic correlations. Similarly the coefficient of determination,  $R^2$  suggest that 60% of the HP-values correlate with observed seepage values.

Figure 3 displays the relationship between HP-values to discharge from bedrock wells coupled with seepage discharge from fractured rock. Similarly, comparison of HP-values of the rock masses to both pumping yields of wells and seepage demonstrate an inverse and even stronger correlation. In this case, the correlation coefficient, R, exceeds -0.92, which is exceptional for geologic correlations. Similarly the coefficient of determination,  $R^2$  suggest that 86% of the HP-values correlate with both well discharge from

bedrock and observed seepage discharge from fractured rock. Moreover, equation (3) for the curve provides a tool to estimate seepage discharge based on observed HP-values for the local rock mass.

$$y = 919.71e^{-2.3144x} \quad (3)$$

Where:

y = Discharge (gpm) and

x = HP-value

Note: 1 gallon per minute = 0.0631 liters/second

Figures 1, 2 and 3 illustrate an inverse decaying exponential curve. Wells located in fractured bedrock with very low HP-values ( $< 1$ ) typically exhibit higher yields. On the other hand, wells located in competent rock with high HP-values exhibit low yields. This is expected and makes sense geologically. There is a higher probability of locating producing wells in very fractured rock as opposed to competent rock. Similarly, rock masses exhibiting lower HP-values may display seepage problems assuming groundwater is present in the fractures. On the other hand a competent rock mass that exhibits higher HP-values should have little seepage problems. The author has observed that rock masses which exhibit HP-values  $< 3$  are subject to potential seepage problems assuming groundwater is present in the fractures. Conversely, rock masses that exhibit HP-values  $> 3$  exhibit little seepage problems.

## 4 CONCLUSIONS

The hydro-potential (HP) value is a valuable rock-mass classification, semi-quantitative technique employed to evaluate both the potential of developing groundwater from bedrock and evaluating seepage potential from rock masses.

The HP-value is the capacity for a rock mass to hydraulically transmit groundwater. The method is a simple and quick technique used to evaluate rock outcrops surrounding a construction site. It is especially promising as a tool to predict seepage problems in tunnels and mine excavations.

Contrasting the HP-values to yields of 20 wells constructed in fractured bedrock coupled with seepage discharge from outcroppings of fractured rock displayed a strong inverse exponential correlation of -0.92. In addition, the coefficient of determination suggests that 86 percent of the HP-values correlate directly with well discharge and seepage. Similarly there is a strong inverse correlation between HP-values and observed

seepage discharge from the fractured rock masses. An HP-value of 3 appears to be the critical break where seepage problems may begin. That is rock masses that exhibit HP-values > 3 should exhibit little seepage problems because the rock is competent and the fractures are very tight. In contrast, rock masses that exhibit HP-values < 3 may exhibit seepage problems if groundwater is present.

The benefit of the HP-value is twofold. Not only does the technique increase the probability of locating suitable test well sites in bedrock; the HP-value is viable tool used to predict seepage problems in rock excavations such as tunnels and mines.

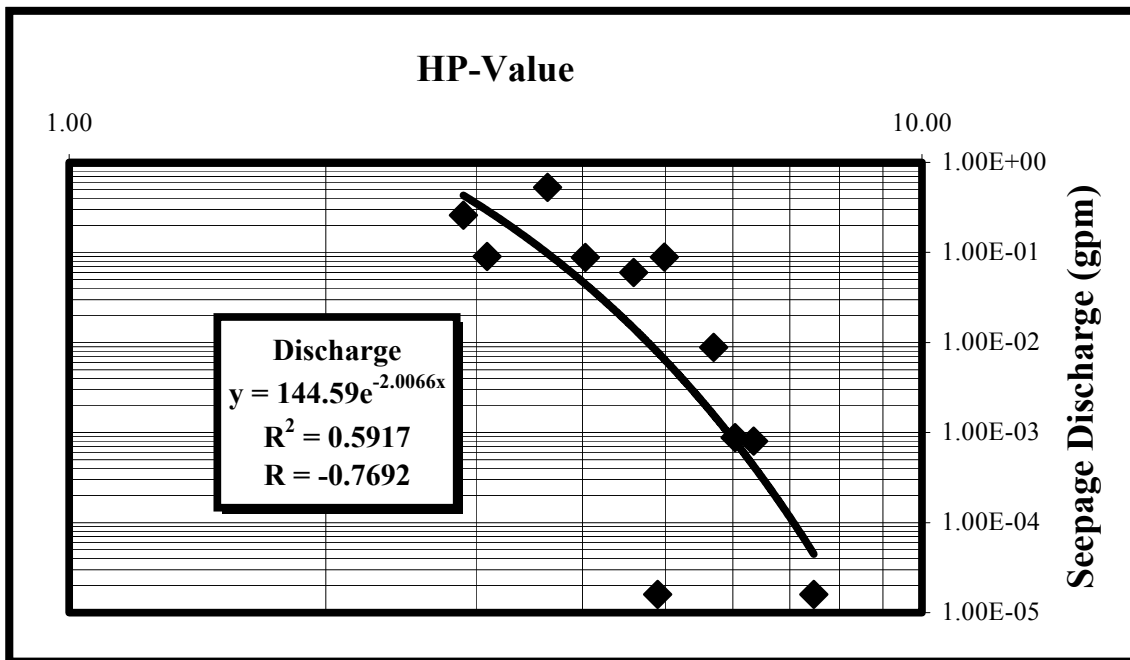


Figure 2 Comparison of HP-values to seepage discharge from fractured rock in tunnels and outcropping rock faces in Washington State. Note: 1 gallon per minute = 0.0631 liters/second

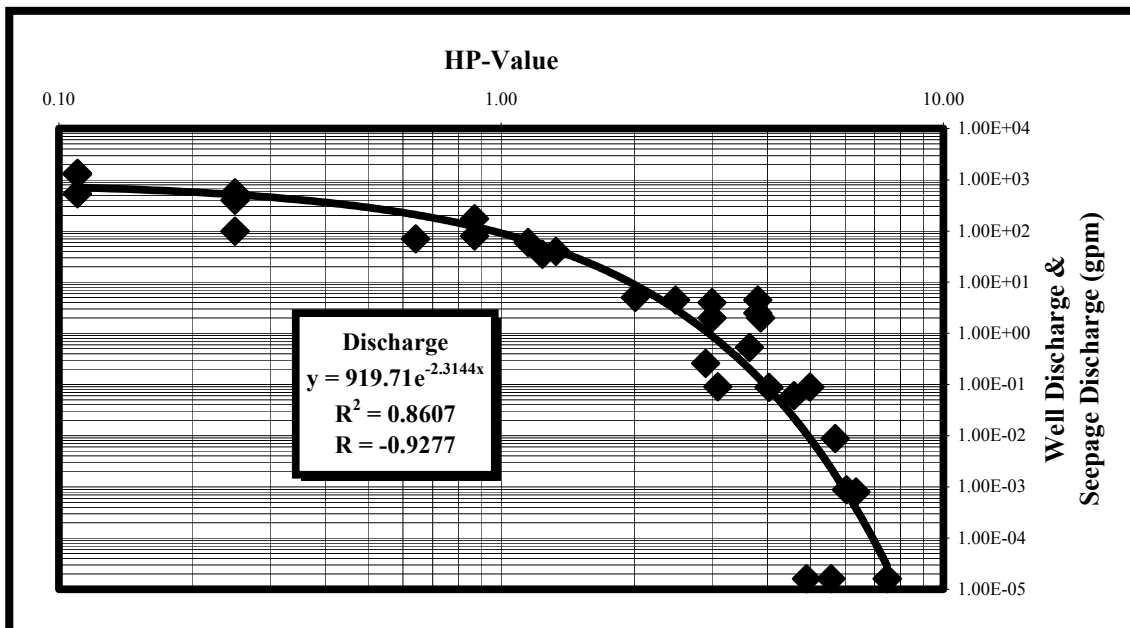


Figure 3. Relationship of HP-values to discharge from wells located in fractured bedrock and seepage from fractured rocks. Note: 1 gallon per minute = 0.0631 liters/second

## REFERENCES

- Afrouz, A. A. (1992). *“Practical Handbook of Rock Mass Classification Systems and Modes of Ground Failure”* CRC Press, Inc, Boca Raton, FL. 195.
- Barton, C. C.; and Hsieh, P., A. (1989). *“Physical and Hydrologic-Flow Properties of Fractures”* Field Guidebook T385, 28th International Geological Congress, American Geophysical Union, Washington D.C.. 36.
- Barton, N.; Lien, R.; and Lunde, J. (1974). *Engineering Classification of Rock Masses for the Design of Tunnel Support”* Norwegian Geotechnical Institute. 48.
- Barton, N.; and Choubey, V (1977). *“The Shear Strength of Rock Joints in Theory and Practice”* Rock Mechanics, 10. 1-54.
- Cook, N. G. W. (1989). *Natural Joints in Rock: Mechanical, Hydraulic and Seismic Behavior and Properties under Normal Stress”* Jaeger Memorial Lecture, 29th Symposium on Rock Mechanics, 1988. 75.
- Deere, D. U. (1963). *“Technical description of rock cores for engineering purposes”* Felsmechanik und Ingenieurgeologie, 1(1). 16-22.
- Driscoll, F. G. (1986). *“Groundwater and Wells”*. 1088.
- Freeze, A. R.; and Cherry, J. A. (1979) *“Groundwater”*: 604.
- Gates, W. C. B. (1994). *“The Hydro-Potential (HP) Value: A Rock Classification Technique for Evaluation of the Groundwater Potential in Bedrock”* Environmental & Engineering Geoscience, 3(2). 251-267.
- Harp, E. L.; and Noble, M. A. (1993). *“An Engineering Rock Classification to Evaluate Seismic Rock-fall Susceptibility and its Application to the Wasatch Front”* Bulletin of the Association of Engineering Geologists, 30 (3). 293-319.
- Hencher, S. R. (1987). *“The Implications of Joints and Structures for Slope Stability”* Slope Stability - Geotechnical Engineering and Geomorphology, John Wiley & Sons, New York, NY. 146 - 155.
- Louis, C. (1969). *“A Study of Groundwater Flow in Jointed Rock and Its Influence on the Stability of Rock Masses”* Imperial College Rock Mechanics Research Report 10, Imperial College. 90.
- Planstrom, A. (1975). *“Karakterisering av Oppsprekningsgrad og Fjellmassers Kvalild”* Internal Report, Ing. A. B. Berdal A/S, Oslo, Norway. 1-26.