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Resistance In Gravel Bed Channel In Highway

P.Mahendar Reddy & P.Gopi
1.M. Tech Student, Department of civil, Nalanda Institute of Engineering and Technology, Village Kantepudi, Mandal Sattenapalli, District Guntur, Andhra Pradesh, India
2. Assistant Professor, Department of civil, Nalanda Institute of Engineering and Technology, Village Kantepudi, Mandal Sattenapalli, District Guntur, Andhra Pradesh, India

ABSTRACT

A data set of 2890 field measurements was used to test the ability of several conventional flow resistance equations to predict mean flow velocity in gravel bed rivers when used with no calibration. The tests were performed using both flow depth and discharge as input since discharge may be a more reliable measure of flow conditions in shallow flows. Generally better predictions are obtained when using flow discharge as input. The results indicate that the Manning-Strickler and the Keulegan equations show considerable disagreement with observed flow velocities for flow depths smaller than 10 times the characteristic grain diameter. Most equations show some systematic deviation for small relative flow depth. The use of new definitions for dimensionless variables in terms of non-dimensional hydraulic geometry equations allows the development of a new flow resistance equation. The best overall performance is obtained by the Ferguson approach, which combines two power law flow resistance equations that are different for deep and shallow flows. To use this approach with flow discharge as input, a logarithmic matching equation in terms of the new dimensionless variables is proposed. For the domains of intermediate and large-scale roughness, the field data indicate a considerable increase in flow resistance as compared with the domain of small-scale roughness. The Ferguson approach is used to discuss the importance of flow resistance partitioning for bed load transport calculations at flow conditions with intermediate- and large-scale roughness in natural gravel, cobble, and boulder bed streams.

INTRODUCTION

Knowledge of the mean flow velocity in a channel reach is of primary importance for many aspects, including river engineering, risk analysis, environmental survey, numerical modeling validation, flow discharge, and bed load transport computation. In some circumstances, flow velocity can be measured directly (for instance with a current meter) or be calculated with the continuity equation ($U = Q/A$) when both the discharge Q and the wetted cross-sectional area A are known. But in many cases measurements are not possible, and a flow resistance equation must be used. When a rating curve is available, the flow resistance equation can be fitted for the site in question. Several flow resistance equations are of interest because they need no calibration when the river reach can be considered nearly uniform. This paper proposes to use a large field data set in order to test the adequacy of these equations for predicting the mean flow velocity in a uniform gravel bed river reach. It addresses the design of small open channels called roadside channels that are constructed as part of a highway drainage system. See Figure 1.

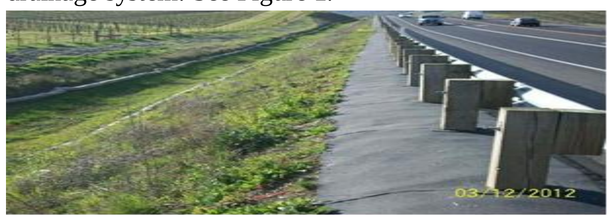

Figure 1 Small Roadside Channel

An open channel is a conveyance in which water flows with a free surface. Although closed conduits such as culverts and storm drains function as open channels when flowing partially full, the term is generally applied to natural and improved watercourses, gutters, ditches, and channels. While the hydraulic principles discussed in this chapter are valid for all drainage structures, the primary consideration is given to roadside channels.In addition to performing its hydraulic function, the roadside channel should be economical to construct and maintain. Some roadside channels serve as dual purpose channels which concurrently function as infiltration swales for storm water purposes. Roadside channel design should consider errant vehicles leaving the traveled way, be pleasing in appearance, convey collected water without damage to the transportation facility or adjacent property and minimize environmental impacts. These considerations are usually so interrelated that optimum conditions cannot be met for one without compromising one or more of the others. The objective is to achieve a reasonable balance, but the importance of traveler safety must not be underrated. Roadside channels play an important role in the highway drainage system as the initial conveyance for highway runoff. Roadside channels are often included as part of the typical roadway section. Therefore, the geometry of roadside channels depends on available right-of-way, flow capacity requirements, and the alignment and profile of the highway. Most roadside channels capture sheet flow from the highway pavement and cut slope and convey that runoff to larger channels or to culverts within the drainage system. See Figure2

Figure.2 Roadside Channel Outlet to Storm Drain at Drop Inlet

Hydraulic Consideration An evaluation of hydraulic considerations for the channel design alternatives should be made early in the project development process. The extent of the hydrologic and hydraulic analysis should be commensurate with the type of highway, complexity of the drainage facility, and associated costs, risks, and impacts. Most of the roadside channels and swales discussed in this chapter convey design flows less than 50 cubic feet per second and generally do not require detailed hydrologic and hydraulic analyses beyond developing the parameters required for the Rational Formula Manning's Equation, and the shear stress equations presented within this Chapter and Hydraulic Engineering Circular (HEC) No. 15, "Design of Roadway Channels with Flexible Linings". The hydraulic design of an open channel consists of developing a channel section to carry the design discharge under the controlling conditions, adding freeboard as needed and determining the type of channel protection required to prevent erosion. In addition to erosion protection, channel linings can be used to increase the hydraulic capacity of the channel by reducing the channel roughness.

Selection of "Design Flood": As with other drainage facilities, the first step in the hydraulic design of roadside channels is to establish the range of peak flows which the channel section must carry. The recommended design flood and water spread criteria for roadway drainage type installations are presented.

Safety Considerations: An important aspect of transportation facility drainage design is that of traffic safety. The shape of a roadside channel section should minimize vehicular impact and provide a traversable section for errant traffic leaving the traveled way. The ideal channel section, from a traversability standpoint, will have flattened side slopes and a curved transition to the channel bottom. When feasible, it is recommended that channels be constructed outside the clear recovery zone.

Maintenance Considerations: Design of open channels and roadside ditches should recognize that periodic maintenance inspection and repair is required. Provisions should be incorporated into the design for access to a channel by maintenance personnel and equipment. Consideration should be given to the size and type of maintenance equipment required when assessing the need for permanent or temporary access easements for entrance ramps and gates through the right of way fences

Figure.3Damaged Channel

Minor erosion damage within the right of way should be repaired immediately after it occurs and action taken to prevent the recurrence. Conditions which require extensive repair or frequently recurring maintenance may require a complete redesign rather

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Figure.4Concrete Lined Channel with Excessive Weed Growth

than repetitive or extensive reconstruction. The advice of the District Hydraulics Engineer should be sought when evaluating the need for major restoration

Economics: Economical drainage design is achieved by selecting the design alternative which best satisfies the established design criteria at the lowest cost.The economic evaluation of design alternatives should be commensurate with the complexity and importance of the facility. Analysis of the channel location, shape, size, and materials involved may reveal possibilities for reducing construction costs, flood damage potential, maintenance problems and environmental impacts.

Coordination with Other Agencies: There are many Federal, State and local agencies and private entities engaged in water related planning, construction and regulation activities whose interests can affect the design of some highway drainage channels. Such agencies may request the channel design satisfy additional and perhaps governing design criteria. Early coordination withthese agencies may help avoid delays in the project development process and post-project conflicts. Early coordination may also reveal opportunities for cooperative projects which may benefit both Caltrans and the water resources agency.

Environment: Many of the same principles involved in sound highway construction and maintenance of open channels parallel environmental considerations. Environmental problems can arise if riparian species inhabit the channel. Erosion, sedimentation, water quality, and aesthetics should be of prime concern to the highway design engineer. The Project Planning and Design Guide for discussion on control of water pollution.

Unlined Channels: Whenever feasible, roadside channels should be designed with natural bottoms. Use linings only when warranted. for typical permitted shear stress and velocity for bare soil and vegetation.

ROADSIDE DRAINAGE CHANNEL LOCATION

General

Assuming adequate functional design, the next most important design consideration is channel location. Locations that avoid poorly drained areas, unstable soil conditions, and frequently flooded areas can greatly reduce drainage related problems. Typically drainage and open channel considerations are not considered the primary decision factors in the roadway location; however they are factors which will often directly or indirectly affect many other considerations. Often minor alignment adjustments can avoid serious drainage problems.If a channel can be located far enough away from the highway, the concerns of traffic safety and aesthetics can be significantly mitigated. See Figure 5. The cost of additional right of way may be offset somewhat by the reduced cost of erosion control, traffic protection, and landscaping.

Figure 5 Small-Rock Lined Channel Outside of Clear Recovery Zone

Alignment and Grade: Ordinarily, the highway drainage channel must be located where it will best serve its intended purpose, using the grade and alignment obtainable at the site. Insofar as

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practicable, abrupt changes in alignment and grade should be avoided. A sharp change in alignment presents a point of attack for flowing water, and abrupt changes in grade can result in possible scour when the grade is steepened or deposition of transported material when the grade is flattened. Ideally, a drainage channel should have flow velocities that neither erode nor cause deposition in the channel. This optimum velocity is dependent on the size and slope of channel, the quantity of flowing water, the material used to line the channel, the nature of the bedding soil and the sediment being transported by the flow. For recommended permissible flow velocities in unlined channels.

Point of Discharge: The point of discharge into a natural watercourse requires special attention. Water entering a natural watercourse from a highway drainage channel should not cause eddies with attendant scour of the natural watercourse. In erodible embankment soils, if the flow line of the drainage channel is appreciably higher than that of the watercourse at the point of discharge, then the use of a spillway may be advisable to prevent erosion of the channel.

CHANNEL SECTIONS: Roadside and median channels are open-channel systems which collect and convey storm water from the pavement surface, roadside, and median areas. These channels may outlet to a storm drain piping system via a drop inlet (see Figure 861.2), to a detention or retention basin or other storage component, or to an outfall channel. Roadside and median channels are normally triangular or trapezoidal in cross section and are lined with grass or other protective lining.

CHANNEL STABILITY DESIGN CONCEPTS

General: The gradient of roadside channels typically parallels the grade of the highway. Even at relatively mild highway grades, highly erosive hydraulic conditions can exist in adjacent roadside channels. Consequently, designing a stable conveyance becomes a critical component in the design of roadside channels.The need for erosion prevention is not limited to the highway drainage channels; it extends throughout the right -of-way and is an essential feature of adequate drainage design. Erosion and maintenance are minimized largely by the use of flat side slopes rounded and blended with natural terrain, drainage channels designed with due regard to location, width, depth, slopes, alignment, and protective treatment, proper facilities for groundwater interception, dikes, berms, and other protective devices, and protective ground covers and planting.

Themaximum shear stress along the channel bottom may be estimated by the following equation:

$$\tau_d = \gamma d S$$

where:

τd= Shear stress in channel at maximum depth,lb/ft^2

γ = Specific weight of water

d = Maximum depth of flow in channel for the design discharge, ft

S = Slope of channel, ft/ft

CHANNEL LININGS

Flexible Verses Rigid: Lining materials may be classified as flexible or rigid. Flexible linings are able to conform to changes in channel shape and can sustain such changes while maintaining the overall integrity of the channel. In contrast, rigid linings cannot change shape and tend to fail when a portion of the channel lining is damaged. Channel shape may change due to frost-heave, slumping, piping, etc. Typical flexible lining materials include grass or small-rock slope protection, while typical rigid lining materials include hot mixed asphalt or Portland cement concrete. Flexible linings are generally less expensive, may have a more natural appearance, permit infiltration and exfiltration and are typically more environmentally acceptable. Vegetative channel lining is also recognized as a best management practice for storm water quality design in highway drainage systems. A vegetated channel helps to deposit highway runoff contaminants (particularly suspended sediments) before they leave the highway right of way and enter streams. See Figure 7

On steep slopes, most vegetated flexible linings are limited in the erosive forces they can sustain without damage to the channel and lining unless the vegetative lining is combined with another more erosion-resistant long-term lining below, such as a cellular soil confinement system. See Figure 7. The District Landscape Architect should be contacted to provide viable vegetation alternatives within the District,

Figure 7 Steep-Sloped Channel with Composite Vegetative Lining

however all design responsibilities belong to the Project Engineer

Flexible: Flexible linings can be long-term, transitional or temporary. Long-term flexible linings are used where the channel requires protection against erosion for the design service life of the channel. Per Index 861.12, more complete information on hydraulic principles and engineering techniques of flexible channel lining design may be found in HEC No. 15 and Chapter 5 of HEC No. 22.Flexible linings act to reduce the shear stress on the underlying soil surface. Therefore, the erodibility of the underlying soil is a key factor in the performance of flexible linings. Erodibility of non-cohesive soils (plasticity index less than 10) is mainly due to particle size, while cohesive soil erodibility is a function of cohesive strength and soil density. Vegetative and rolled erosion control product lining performance relates to how well they protect the underlying soil from shear stress, and so these lining types do not have permissible shear stresses independent of soil type. The soil plasticity index should be included in the Materials or Geotechnical Design Report.In general, when a lining is needed, the lowest cost lining that affords satisfactory protection should be used. This may include vegetation used alone or in combination with other types of linings. Thus, a channel might be grass-lined on the flatter slopes and lined with more resistant material on the steeper slopes. In cross section, the channel might be lined with a highly resistant material (e.g., cellular soil confinement system – see Index 865.3(1) *LongTerm*) within the depth required to carry floodsoccurring frequently and lined with grass above that depth for protection from the rare floods.

(1) Long Term. : Long-term lining materials includevegetation, rock slope protection, gabions (wire-enclosed rock), and turf reinforcement mats with enhanced UV stability. Standard Specification Section 72-4 includes specifications for constructing small-rock slope protection for gutters, ditches or channels and includes excavating and backfilling the footing trench, placing RSP fabric and placing smallrocks (cobble, gravel, crushed gravel, crushed rock, or any combination of these) on the slope. Where the channel design includes a requirement for runoff infiltration to address storm water needs, the designer may need to consider installation of a granular filter in lieu of RSP fabric if it is anticipated that the RSP fabric would become clogged with sediment. See following link to HEC No. 23, Volume 2, Design Guideline 16, Index 16.2.1, for information on designing a granular filter:

Figure 9 Long-Term Flexible Lining

General.:Manufacturers have developed avariety of rolled erosion control products (RECPs) for erosion protection of channels.RECPs consist of materials that are stitched or bound into a fabric. Vegetative and RECP lining performance relates to how well

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they protect the underlying soil from shear stresses so these linings do not have permissible shear stresses independent of soil types. Chapters 4 (vegetation) and 5 (RECPs) of HEC No. 15 describe the methods for analyzing these linings. Standard Specification Section 21-1 was developed primarily to address slope erosion products, however, the specifications for constructing turf reinforcing mats (TRM's), open weave textiles and erosion control blankets may also be applied to channels as temporary and transitional linings, and some TRM's may be used as permanent linings.

HYDRAULIC DESIGN OF ROADSIDE CHANNELS

General: Open channel hydraulic design is of particular importance to highway design because of the interrelationship of channels to most highway drainage facilities. The hydraulic principles of open channel flow are based on steady state uniform flow conditions, as defined in Index 866.2. Though these conditions are rarely achieved in the field, generally the variation in channel properties is sufficiently small that the use of uniform flow theory will yield sufficiently accurate results for most roadside channels.

Flow Classifications

Steady vs. Unsteady Flow.The flow in an openchannel can be classified as steady or unsteady. The flow is said to be steady if the depth of flow at a section, for a given discharge, is constant with respect to time. The flow is considered unsteady if the depth of flow varies with respect to time.

Uniform Flow.Steady flow can further beclassified as uniform or non-uniform. The flow is said to be uniform if the depth of flow and quantity of water are constant at every section of the channel under consideration. Uniform flow can be maintained only when the shape, size, roughness and slope of the channel are constant. Under uniform flow conditions, the depth and mean velocity of flow is said to be normal. Under these conditions the water surface and flow lines will be parallel to the stream bed and a hydrostatic pressure condition will exist, the pressure at a given section will vary linearly with depth.As previously mentioned, uniform flow conditions are rarely attained in the field, but the error in assuming uniform flow in a channel of fairly constant slope, roughness and cross section is relatively small when compared to the uncertainties of estimating the design discharge.

Gradually varied flow

Gradually varied flow is described as a steady state flow condition where the depth of water varies gradually over the length of the channel. Under this condition, the streamlines of flow are practically parallel and therefore, the assumption of hydrostatic pressure distribution is valid and uniform flow principles can be used to analyze the flow conditions.

Rapidly varied flow.

With the rapidly varied flow condition, there is a pronounced curvature of the flow streamlines and the assumption of hydrostatic pressure distribution is no longer valid, even for the continuous flow profile. A number of empirical procedures have been developed to address the various phenomena of rapidly varied flow. For additional discussion on the topic of rapidly varied flow, refer to "Open-Channel Hydraulics" by Chow.

Open Channel Flow Equations: The equations of open channel flow are based on uniform flow conditions. Some of these equations have been derived using basic conservation laws (e.g. conservation of energy) whereas others have been derived using an empirical approach.

GEOMETRIC ELEMENTS OF CHANNEL SECTIONS

SECTION	AREA, A	WETTED PERIMETER, P	HYDRAULIC RADIUS, R	TOP WIDTH, T	HYDRAULIC DEPTH, D	SECTION FACTOR, Z
Rectangle	by	$b+2y$	$\frac{by}{b+2y}$	b	y	$by^{1.5}$
Trapezoid	$(b+zy)y$	$b+2y\sqrt{1+z^2}$	$\frac{(b+zy)y}{b+2y\sqrt{1+z^2}}$	$b+2zy$	$\frac{(b+zy)y}{b+2zy}$	$\frac{[(b+zy)y]^{1.5}}{\sqrt{b+2zy}}$
Triangle	zy^2	$2y\sqrt{1+z^2}$	$\frac{zy}{2\sqrt{1+z^2}}$	$2zy$	$\frac{y}{2}$	$\frac{\sqrt{2}}{2}zy^{2.5}$
Circle	$\frac{1}{8}(\theta-\sin\theta)d_0^2$	$\frac{1}{2}\theta d_0$	$\frac{1}{4}\left(1-\frac{\sin\theta}{\theta}\right)d_0$	$(\sin\frac{1}{2}\theta)d_0$ or $2\sqrt{y(d_0-y)}$	$\frac{1}{8}\left(\frac{\theta-\sin\theta}{\sin\frac{1}{2}\theta}\right)d_0$	$\frac{\sqrt{2}}{32}\frac{(\theta-\sin\theta)^{1.5}}{(\sin\frac{1}{2}\theta)^{0.5}}d_0^{2.5}$
Parabola	$\frac{2}{3}Ty$	$T+\frac{8}{3}\frac{y^2}{T}$ *	$\frac{2T^2y}{3T^2+8y^2}$ *	$\frac{3}{2}\frac{A}{y}$	$\frac{2}{3}y$	$\frac{2}{9}\sqrt{6}\,Ty^{1.5}$
Round-cornered rectangle ($y>r$)	$(\frac{\pi}{2}-2)r^2+(b+2r)y$	$(\pi-2)r+b+2y$	$\frac{(\pi/2-2)r^2+(b+2r)y}{(\pi-2)r+b+2y}$	$b+2r$	$\frac{(\pi/2-2)r^2}{b+2r}+y$	$\frac{[(\pi/2-2)r^2+(b+2r)y]^{1.5}}{\sqrt{b+2r}}$
Round-bottom triangle	$\frac{T^2}{4z}-\frac{r^2}{z}(1-z\cot^{-1}z)$	$\frac{T}{z}\sqrt{1+z^2}-\frac{2r}{z}(1-z\cot^{-1}z)$	$\frac{A}{P}$	$2[z(y-r)+r\sqrt{1+z^2}]$	$\frac{A}{T}$	$A\sqrt{\frac{A}{T}}$

CHANNEL CHANGES

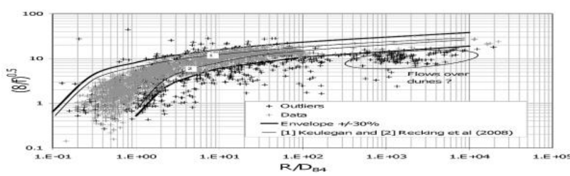
General: It is primarily addresses the design of small man-made open channels called roadside channels (gutters, ditches, swales etc.) that are constructed as part of a highway drainage system. However, both the terms 'open channel' or 'channel' may be applied to any natural or improved watercourse as well as roadside channels. A channel change is any realignment or change in the hydraulic characteristics of an existing channel. contact the District Hydraulic Engineer for support. The main reasons for channel changes to either natural or improved watercourses (flood control channels, irrigation channels etc.) within the right of way are toThe guidelines in Culvert Location generally recommend alignment of the thalweg of the stream with the centerline of the culvert, however, for economic reasons, small skews should be eliminated, moderate skews retained and large skews reduced. Road crossings requiring fish passage are strongly encouraged to retain the natural alignment of the stream, regardless of the skew. Alignment of the culvert centerline with the channel approach angle aids debris passage during storm flows and minimizes hydraulic turbulence which may impede fish passage. Sometimes a channel change may be to its vertical alignment. For example, inverted siphons or sag culverts may be used to carry irrigation channels crossing the right of way via vertical realignment entirely below the hydraulic grade line. However, maintenance concerns include sediment build-up and potential leakage problems with full-flow barrel(s).

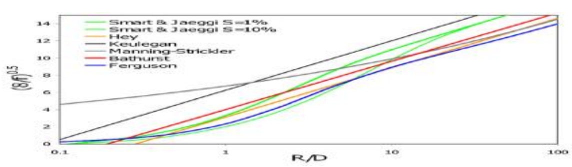
Design Considerations: Channel changes should be designed with extreme caution and coordinated with District Hydraulics. Careful study of the channel characteristics upstream and downstream as well as within the channel change area is required to achieve a safe and effective design.

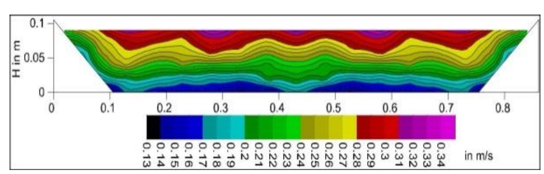
RESULTS AND DISCUSSIONS

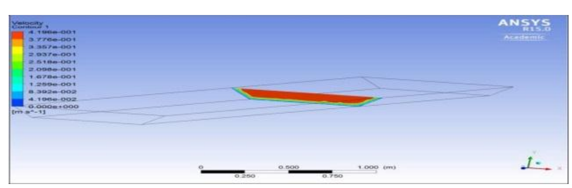
The Data Set and Equations

The initial data set used in this study is composed of 3942 measurements presented in Table 1 and Figure 1. The data represent field measurements of flow velocity in gravel bed streams, including channel slopes up to 24% and different channel bed morphologies. Parts of these data have already been used by *Recking et al.* [2008] and *Recking* [2010]. Other data are taken form *Church and Rood* [1983], and data from *Higginson and Johnston* [1988] are used as reported by *Wargadalam* [1993]. In these studies, flow velocity was obtained by several techniques, including the continuity from known flow discharge and cross sectional area ($U = Q/A$) and direct measurements with either a current meter or a tracer injection. If the grain size $D84$ was missing, it was estimated by $2.2D50$. This approximation is based on the median value for 141 pairs of available $D50$ and $D84$ values and concerns about 21% of the data used in the analysis. If the grain size $D90$ was missing, it was estimated by $1.25D84$, with the approximation being based on the median value for 30 pairs of available $D84$ and $D90$ values and concerning about 78% of the data used in the analysis. Some data may not be of good quality because of either measurement errors or data setmanipulation







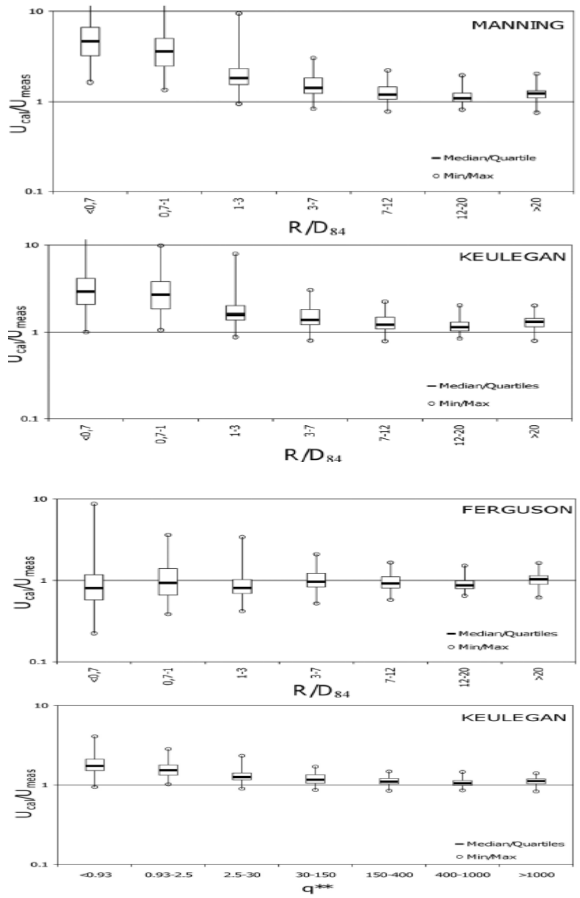


Application of Numerical Analysis

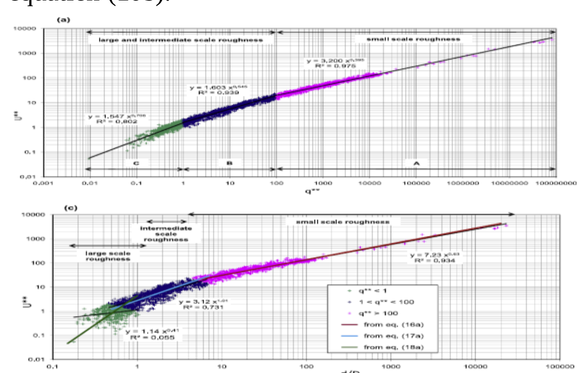
Velocity distribution obtained from ANSYS: Generally, experimental and theoretical analyses are the main tools for finding out the solution of open channel flow problems to meet the needs of field requirements. In recent times CFD techniques are being used extensively to solve the flow problems. In this study, a few simulations were carried out by using the commercial code namely ANSYS to simulate the present experimental investigation. Total five flow depth has to be considered for no load conditions. 13.5 mm gravels were used in beds of open channel flow to predict the velocity distribution along the channel bed. Here k-ε model is used for turbulence modelling. The k-ε equations are discretized in both space and time. In this study the algorithms adopted to solve the coupling between pressure and velocity field is PISO which is the pressure implicit splitting operators use in Fluent (Issa 1986). Fig. 5.2a.to Fig

Proposal of New Dimensionless Variables

Despite the good overall performance of the best performing flow resistance equations (Hey equation (7), Smart-Jäggi equation (9), and Ferguson equations (10a) and (10b); Figures 3 and 4 and Tables 2a, 2b, 3a, and 3b), there are some limitations: the log law equations can have problems at very small relative flow depths if applied in terms of *d*. For situations for which the discharge is known or given, the use of a traditional log law equation or of the VPE approach of Ferguson requires a partly complicated iterative solution procedure. This represents a practical disadvantage, for example, in catchment-based studies when a hydrograph is available from hydrologic considerations or for design problems in river engineering.



Explicit Form of VPE in Terms of New Dimensionless Variables: The analysis in section 3.3 showed the best overall performance for the Ferguson approach, i.e., equations (10a) and (10b). To obtain an explicit equation for given discharge *q*, the logarithmic matching technique as proposed by *Guo*[2002] was used to substitute the implicit equation (10b).



ANALYSIS OF RESULTS

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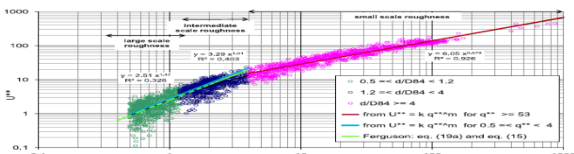
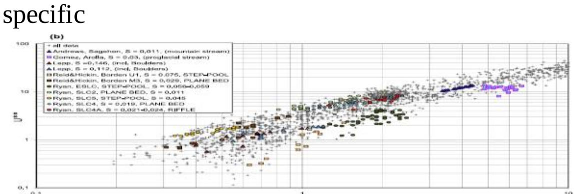
Potential Problems With Spurious Correlation Using the New Dimensionless Variables

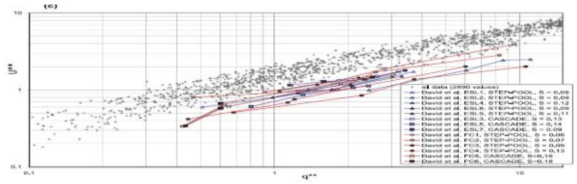
A major advantage of the *U***versus *q*** representation is that *q*-based equations for predicting flow velocity are more robust (less errors in the input variables) than *d*-based equations, especially when applied to rough steep channels [*Ferguson*, 2007; *Comiti et al.*, 2009; *Zimmermann*, 2010]. The analysis using *U***and *q*** also showed how the exponent *m* changes with decreasing values of (*d*/*D*84) or *q*** ; this cannot be easily shown with other methods. One may object that using the dimensionless numbers *U***and *q*** in regression analysis introduces some degree of spurious correlation since the same variables (*S*, *D*84) are contained both in the independent and dependent variables and *U* and *q* are also correlated through the continuity equation



Flow Resistance Variation at a Site

The data set of this study includes measurements taken at a given site or reach for varying flow discharges, and together with data from many different sites, the comparison of all measurements represents a combination of flow resistance variation both at a site and between sites. Figures 11a and 11b represent some of the data shown in Figure 5 with a separate identification of some sites or reaches for which measurements include varying discharge conditions. Despite some scatter of the at-a-site measurements, these data generally follow the same mean trend (i.e., having the same exponent *m* or *c* as defined by the bulk of the data), but indicating some variation of the coefficient *k* or *a*, which may be site specific





CONCLUSIONS

A data set consisting of 2890 field measurements covering a wide range of bed slopes, grain diameters, flow discharges, and river widths was used to test the suitability of several conventional flow resistance equations to predict the mean flow velocity. The Manning-Strickler, Keulegan, Smart-Jäggi, Hey, Bathurst, and Ferguson equations and a new equation were considered. The equations are based on either flume or field measurements or a combination of both. The equations were evaluated both with flow depth as input and with discharge as input, which typically requires iterative calculations. The tests demonstrated that some equations should be used with caution, especially in the intermediate- and the large-scale roughness domains with small relative flow depths. The Manning- Strickler equation appears to be unsuitable in this range of flow conditions. Generally, a much better prediction was obtained with all equations when the flow discharge *Q* or *q* was used as an input parameter instead of the relative depth *d/D*. However, for small relative depths most equations yield a systematic deviation between predicted and observed velocity. The best overall performance for flow resistance prediction was obtained with the VPE approach. Introducing new dimensionless variables *U***and *q*** in terms of non-dimensional hydraulic geometry equations resulted in a similarity collapse for the entire data range. Using a logarithmic matching method, the dimensionless variables allowed proposing an explicit equation of Ferguson's VPE approach.These dimensionless variables were further used to discuss how a power law flow resistance equation varies over three domains, approximately reflecting the three roughness scales proposed. The dimensionless variables were also useful for considering the limitations related to the development of a *q*-based approach at very low relative flow depths if the true average bed level for zero flow depth is not exactly known in the presence of large grains. The presented analysis suggests that between-site and at-a-site variations of flow resistance have strong similarities. On the basis of the Ferguson approach, a flow resistance partitioning method was presented to account for high flow resistance in the domains of intermediate- and large-scale roughness in natural gravel, cobble, and boulder bed streams, and this method was compared with similar approaches

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POLU MAHENDRAREDDY

B-tech: Samuelgeorge Institute of engineering&Technology,Markapur, Andhra Pradesh in 2015. M-tech: Highway Engineering from NIET in 2017.


P.GOPI Asst. Professor.B-tech from RVR& JC College of Engineering (2008-2012). M-tech: Transportation Engineering from NIT Kurukshetra.