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History and Development of Design of Regime Channels: A State of the Art Review

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Abstract
Channels carrying sediment laden water and constructed in erodible alluvial materials must be designed to be silt stable or in regime such canals by definition neither scour nor silt. The design of channel involves the selection of channel alignment, shape, size and bottom slope. In general, a channel changes incessantly in its position, shape and slope, as a consequence of hydraulic forces acting on its bed and banks. The design of irrigation system was first introduced based on the theory regime put forward by Gerald Lacey during the period 1924–1934. Some canals that were designed using Lacey theory have not been satisfactory. A common problem found in the design of channels was siltation. In this paper the history and development of "theory of regime channels" has been discussed. Several theories were proposed since from last three century. Brief review on all regime theories based on literature available has been presented.

Keywords: *design of channel, sediment, Regime theory*

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INTRODUCTION

The basic concept starts with "for the given discharge and an additional amount of silt of known quantity, how much will be the width, depth and bed slope of the channel to convey both the water and silt from one point to another if the canal is to flow between banks and on a bed, all made of its own sediment" Regime represents a balanced state of river form rather than an instantaneously variable state. That means stable or "in regime" channels do not change over a period of one or several water years. It then expresses the natural tendency of channels carrying sediment within alluvial boundaries to seek a dynamic equilibrium [1, 2]. The regime theory defines a regime channel as a non-silting, non-scouring equilibrium channel carrying its normal suspended load. The theory implies a unique solution for a stable channel, at a given steady discharge, transporting a known concentration of solids in alluvium of given character.

A channel is said to be regime state when all the geometrical conditions are satisfied and are in balanced condition to convey the salty water. A channel is designed to convey salty water both bed and bank scour or fill, changing depth, gradient or slope and width until a balanced state is established at which the channel is described to be in regime. The regime geometry depends on discharge, quantity, nature of bed and other silt conditions. Many theories have been proposed to attain regime dimensions. Lack of exact knowledge, therefore, still leads in design to provision of dimensions too good in few directions and in maintenance to a waste of labor and money on enlarging channels to unstable dimensions.

REVIEW OF LITERATURE

Chezy (1775) provided the design tool to the irrigation engineers. At that time the only method was the formula developed by Chezy from consideration of the resistance of channels to flow.

$$V = C\sqrt{RS} \quad (1)$$

In which V is the velocity, R is the hydraulic mean depth, C is a coefficient incorporating the frictional resistance and S is the slope of the channel. Some of the early canal systems designed and constructed based on the above theory were the Western Jamna (1825), the Upper Bari Doab (1859), Sirhind (1872) and Lower Swat (1880) in the Indus Basin. Many researchers have evolved different formulae for determining the coefficient C in Chezy equation. These formulae extensively used but were found unsatisfactory for designing channels carrying heavy sediment loads.

Kennedy R.G. (1895), proposed his theory of silt transport after observations extending over number of years on 30 selected sites on the channels of the Upper Bari Doab (UBD) system which he considered to be in regime. He was the first to formulate the basic law that shallower canal sections are capable of transporting greater silt loads which is now almost universally recognized as an empirical, but well established, design basis. His basic assumptions were that the vertical components of eddies supported silt particles, the silt transporting power of a channel was dependent solely upon its velocity which controls the eddies, the silt transporting power was also dependent upon the depth which limits the effect of the eddies, and the silt transporting power of a channel was not influenced by its bed width. On the basis of these assumptions and using the observed data UBD channels, Kennedy developed his famous equation [3].

$$V_0 = 0.84\,D^{0.64} \tag{2}$$

In which V_0 is the 'critical velocity' which was defined as the non-silting non scouring velocity and D is the depth of the channel. Kennedy's equation correlates the velocity with depth, the width of the section being ignored. Notwithstanding this limitation, the equation implied a reduction in the permissible depth which caused the width of the section to be materially increased as compared to the design practice followed at that time.

Spring (1903), first suggested an approximate relationship between size of bed silt particles, in alluvial rivers and the probable maximum scour likely to occur in them [4]. Kennedy (1904), gave certain rough rules for the ratio of bed width to depth for designing silt stable canals [5]. The channels systems in the Punjab irrigation which were designed on the basis of Kennedy's formula were Lower Chenab (1900), Lower Jhelum (1901), Upper Chenab (1912), Lower Bari Doab (1913) and Upper Jhelum (1915) which are amongst the most important canal systems in Pakistan having total design capacity of about 52000 cusecs. Later on, a set of hydraulic diagrams for non-silting canals with discharges of 1 to 12000 cusecs, bed slopes 1 in 100 to 1 in 10000 and for values of Manning's N ranging from 0.018 to .03 were proposed. Garret's diagrams were based on Kennedy's equation.

Woods (1917) recognizes that, a number of designs could be worked out from Kennedy's diagram for the same value of V_0 developed Kennedy's rough rules to define bed width to depth ratios [6].

Lindley (1919) carried out an extensive survey of the Lower Chenab Canal system and made 786 observations on channels totaling 2700 miles in length. On the basis of this data he developed the following equations [5].

$$V = 0.95\,D^{0.57} \tag{3}$$

$$V = 0.59\,B^{0.355} \tag{4}$$

$$B = 3.80\,D^{1.61} \tag{5}$$

Where, B is the width of the channel.

Lindley's main hypothesis was that the sediment load carried in a channel controlled the bed width in the same way as it unquestionably defined the depth. These results were considered as an outstanding development in designing silt stable canals as they demonstrated the important effect of the geometry of the channel section on its sediment transport capacity [7].

Woods (1927) further analyzed Lindley's data and developed the following general formulae

$$D = B^{0.434} \tag{6}$$

$$V_0 = 1.34\log_{10} B \tag{7}$$

$$S = \frac{1}{2(\log_{10} Q)1000} \tag{8}$$

Where, S is the slope of the channel and Q is the discharge [8].

Attention is drawn to the fact that, according to Woods' formulae for any given discharge, there was only one slope under which the canal would remain silt stable. Thus all the three basic variables of a stable canal section were defined and the "degree of freedom" was eliminated. The Sutlej valley Canals (1926-32) with a total capacity of 48000 cusecs taking off from Ferozepur, Suleimanki, Islam and Panjnad Headworks and the Sukkur Canals (1932) having a total capacity of 47000 cusecs were designed on the basis of Kennedy's formulae taking into account the improvements suggested by Lindley and Woods. Lacey's preliminary results of investigations were available at that time but his equations were not sufficiently developed to be used as a basis for design.

Bottomley (1928) put forward the idea that non-silting, non-scouring irrigation channels would be secured if the slope of the channel is of the same order as that of the parent river regardless of the relation of width to depth and the shape of channel [9].

Lacey (1929) tried to rearranged the previous available data and proposed a new method of designing silt stable channels. He reduced the number of independent parameters to a minimum. His studies indicated that a geometric conception of depth was out of place when dealing with the forces generating a channel and moulding its boundary and wetted perimeter. He also proposed that the depth D in Kennedy's formula should be replaced by hydraulic mean depth R. He recalculated all available data on the basis of V and R and plotted on a logarithmic scale a series of parallel straight lines and obtained the formula [10].

$$V = K\sqrt{R} \qquad (9)$$

For many years the silt grade upon which Kennedy founded his formula was recognized as a standard. Lacey accepted the standard, designated it as a "silt factor", $f = 1$ and produced the formula.

$$V_0 = 1.1547\sqrt{f\,R} \qquad (10)$$

$$f_{VR} = 0.75\,\frac{V^2}{R} \qquad (11)$$

Where, f_{VR} is a friction factor and is a function of V and R.

In which, V_0 has the same significance as Kennedy's, and K is a constant depending on the size and quantity of silt. From Lindley's data, Lacey plotted V_0 against the product of the section area and the square of the silt factor pertaining to the particular channel and developed the equation.

$$A\,f^2 = 4V_0^5 \qquad (12)$$

Eliminating 'f' from equations (10) (11) and (12) Lacey produced the following relationship between the wetted perimeter and discharge.

$$P = 2.668\sqrt{Q} \qquad (13)$$

The above equations are the standard formulae upon which Lacey's "Regime theory" is based. They are referred to as Lacey's Regime equations. They can be cast into various other useful forms. For developing the flow formulae, Lacey accepted the basic Chezy's formula and assuming that in alluvial channels, the rugosity coefficient N as a function of the silt envelope and independent of all other factors. By using Chezy's and Manning's formulae, the following equation was developed.

$$V = \frac{1.3458}{N_a} R^{\frac{3}{4}} S^{\frac{1}{2}} \qquad (14)$$

In which N_a is a measure of the absolute rugosity of the silt envelope. From data of channels in regime, Lacey calculated the value of N_a from Eqn. (14) and derived the equation as

$$N_a = 0.0225\,f^{\frac{1}{4}} \qquad (15)$$

The above equations are referred to as Lacey's Flow formulae. They can also be cast into the following useful forms.

$$S_0 = \frac{1}{1844.3}\frac{f^{\frac{5}{3}}}{Q^{\frac{1}{6}}} \qquad (16)$$

$$V = 16.046\,R^{\frac{2}{3}} S^{\frac{1}{3}} \qquad (17)$$

$$f_{RS} = 192\,R^{\frac{1}{3}} S^{\frac{1}{2}} \qquad (18)$$

Regime dimension diagrams based on regime equations were plotted for a range of discharges of 4 to 100 cusecs and 100 to 20000 cusecs which gave the values of B and D, for known values of Q and f. Similarly regime slope diagrams were plotted based on flow equations which gave the slope S, for known value of Q and f. They are referred to as Lacey's Diagrams.

CBIP (1934) Central Board of Irrigation Policy accepted officially Lacey's method as a standard practice for designing silt stable channels [11]. Some of the major channel irrigation systems in Pakistan designed on the basis of Lacey's formulae were Haveli (1939), Thal (1946).BRBD Link(1951), B-S Link(1954), MR Link(1956), Kotri (1955), Taunsa(1958) and Guddu canals(1962). The total capacity of these channels is 152000 cusecs. Also many older channels were successfully remodeled in accordance with his method. The significance of Lacey's formulae $V = K\sqrt{R}$ may have been even deeper than realized at that time by Lacey, for interpreted dimensionally; his equation meant that for silt stable flows Froude Number was a constant. In fact squaring the formulae and dividing by the acceleration of the force of gravity "g" that obtained.

$$\frac{V_0}{R\,g} = \text{Constant} = F \qquad (19)$$

The Lacey's formula was capable of being interpreted in this manner was first suggested by Tehikoff (1937) [12]**.** The constancy of Froude Number may be characteristic of a much more general law than Lacey's silt formula.

Bose (1936) derived a formula after statistical analysis of the field data of a number of canals in the Punjab

$$S \times 10^3 = 2.09\left(\frac{m_r^{0.86}}{Q^{0.21}}\right) \qquad (20)$$

In which $\mathrm{m_r}$ is the weighted mean diameter of the bed material [10].

Inglis (1936), in his discussion on Bose's paper pointed out that the value of silt factor (f) in Lacey's regime and flow formulae was not the same. He suggested that the regime formula should be rewritten as follows

$$V = 16\,R^{\frac{2}{3}}\,S^{\frac{1}{3}}\left(\frac{f_{VR}}{f_{RS}}\right)^{\frac{1}{2}} \qquad (21)$$

In which $\left(\frac{f_{VR}}{f_{RS}}\right)^{\frac{1}{2}}$ was defined as a measure of divergence from regime. His analysis indicated that the weighted mean diameter of material exposed on bed varied as $Q^{\frac{1}{10}}$ for the Lower Jhelum and Lower Chenab Canals.

Bose and Malhotara (1939), carried out investigation of the inter relation of silt indices and discharge elements for some regime channels in the Punjab and derived the following formulae [14].

$$P = 2.68\left(Q\right)^{\frac{1}{2}} \qquad (22)$$

$$S = \frac{0.00209\,d^{0.86}}{Q^{0.21}} \qquad (23)$$

$$\frac{R}{P} = \frac{S^{\frac{1}{4}}}{6.25\,d} \qquad (24)$$

In which'd ' is the weighted mean diameter of the sediment in millimeters.

Both the silt factor ' f ' of Lacey and the weighted mean diameter'd' of Bose define the size of the sediment but not the sediment charge or the rate at which sediment is transported.

Inglis (1948) recognized this limitation and after analyzing the data of channels of Lower Chenab system produced a set of dimensional equations to take care of the sediment charge. He concluded that sediment charge had less effect on the area of a channel, relatively high effect on the slope and shape and considerable effect on the width of the channel [16]. The formulae developed by Inglis (1949) were too complicated for use in actual practice [16].

Blench (1951), using Lacey's equations as a starting point developed a "Generalized Regime Theory". He pointed out that Lacey used a single factor ' f ' thereby averaging out the relative importance of the bed and side effects. This assumption enabled Lacey to work in terms of the wetted perimeter and the hydraulic radius. As the greater part of the observed data used by Lacey referred to wide and shallow channels sections, the same of exponents would remain valid if the average bed width and the depth were substituted in place of P and R. On this basis, Blench developed the following formulae;

$$\frac{V^2}{D} = b \tag{25}$$

$$\frac{V^3}{B} = s \tag{26}$$

$$\frac{V}{g\,D\,S} = C\left(\frac{V\,B}{\nu}\right) \tag{27}$$

In which 'b' and 's' are constants which were defined as "bed factor" and "side factor" 'ν' is the kinematic viscosity of water, and 'C' is a constant. These equations were said to provide a complete solution to the design problem [17].

Lacey's empirical approach was severally criticized on the ground that it was not based on a theoretical solution of the problem of sediment transportation reducing the observed engineering phenomenon to rational Newtonian mechanics. This criticism was also due to the fact that the "Regime Theory" did not find universal application and was inconsistent with the observed data of canals in other countries. For instance, study on the data of the Imperial Valley canals indicated that instead of the silt factor "f" increasing with the size of the bed material as Lacey's theory shows, the silt factor was actually decreased.

Lane (1937) carried out a comprehensive study of stable channel shapes and concluded that Lacey's equations were deficient in that they accounted for only the silt grade and not the silt charge. He stressed that the quantity of solids in motion was an important factor in the shape of stable channels in alluvium. Lacey in his discussion on Lane's paper observed that the ratio $\frac{V^2}{R}$ for any grade of silt epitomized "turbulence" irrespective of the silt charge [18].

Lacey (1939) attempted to support the theoretical significance of his empirical equations and produced a new theory described as the "Shock Theory" which again was not the usual rational theory of " Shock" of analytical mechanics but a general idea yielding a reasonable explanation of his empirical formulae. In attempting to explain his empirical method as a "theory" based on rational mechanics. Lacey exposed himself to severe criticism from authors of the American, French and Germen research who pointed out many fallacies in his method [19].

Lacey (1946**)** continued to defend the physical significance of his equations and produced a new set of equations introducing another factor V_S , the terminal velocity of falling particles. His new equations were neither fully accepted in India and Pakistan nor by the American research group. The solutions presented by Lane white and Einstein, however influenced the development of formulae presented by Inglis, Bose and Blench and although they attempted to make Lacey's empirical formulae appear more rational, their equations involved so many constants which were not tested by measurements that their application in practice was found difficult. Lacey's original equations were simple, agreed well with the field data and continued to be accepted as a sound practical basis for designing silt stable channels. Although the design methods suggested by Lane, White and Einstein were founded on a rational theoretical basis, they failed to provide the engineer a practical criterion for designing silt stable channels under the conditions prevailing in India and Pakistan [20].

Chien (1957) investigated that sediment load was omitted as an explicit variable in regime equation. As to be expected, the silt factor f does include implicitly the sediment load and hence, there exists a functional relationship between the silt factor f and the sediment load [21].

Simons and Albertson (1963) extended the data base for stable channel from USA, India and Pakistan with much wide range of variables than those used by Lacey or Blench. They developed regime type relationship for designing channels carrying sediment less than 500 ppm (excluding wash load) by classifying the stable channels in following categories depending on nature of bed and bank material: i) channels with bed and bank of sandy material, ii) Channels with sandy bed and cohesive banks, iii) channels with both bed and bank of cohesive material, and iv) channels with both bed and bank of coarse non- cohesive Material. Equations for each category for perimeter P , area A, bed width B, hydraulic radius R and slope S are developed in the form of power law [22]. Indian canals generally fall under category (ii). Gill (1968) explained Lacey's equation using Darcy-Weisbach relation, Brown-Einstein equation for sediment transport, and continuity equation for flow [23]. He, however, differentiated between f as a function of V and R and f as a function of R and S. Based on the measurements of velocity, depth, width, slope and sediment load collected by the Alluvial Channels observation Program(ACOP) in Pakistan, the following equations were proposed

$$f_{VR} = 0.75\,\frac{V^2}{R} \qquad (28)$$

$$f_{RS} = 192\left(R S^2\right)^{\frac{1}{3}} \qquad (29)$$

$$f_{D50} = 1.76\left(D_{50}\right)^{\frac{1}{2}} \qquad (30)$$

Where R is hydraulic depth defined as A/W. A And W are area and width of the water surface. The other equation for slope is

$$S = \frac{f_m^{5/3}}{1830\,Q^{1/6}} \qquad (31)$$

Where $f_m = \sqrt{\left(f_{VR}\, f_{RS}\right)}$. Since regime Channels have different f_{RS} and f_{VR}, the use of f_m was not justified.

Chitale (1966) analyzed data of Punjab, U.P., Bengal, Sind Canal systems and gave a set of equations in SI units which were similar to Lacey's Equations [24]. The Lacey's design equations do not include bed load transport as a variable. However the Channels on which Lacey's equations are based carry total annual average sediment load less than 200 ppm by weight because of the measures usually taken to reduce sediment entry in channels. Hence Lacey channels will neither be satisfactory for clear water channels nor for channels carrying sediment load more than their carrying capacity.

Uppal and Sehgal (1966), from a study of some channels of upper Bari Doab canal system in Punjab arrived at coefficients, which were different from those found by Lacey and indicated a variation of 11% in $P:Q$ relation. Similarly in $B:Q$ relation an average value of coefficient of 0.411 was obtained which was 13% lesser than that given by Lacey [25].

Stevens and Nordin (1987) have taken data from the 1962-63 CHOP data tabulation (West Pakistan Water and Power Development Authority) for Pakistan canals flowing at or near the full supply discharge. As the data were limited, the three sizes, 0.1, 0.2 and 0.3 mm were grouped together. At the lower velocities, the transport rate of one size cannot be discriminated among the others. As an outcome, the following equation was obtained i.e., $q_s = 0.18V^3$, when the bed material load is in *tons/day/ft width* and V is in *ft/sec* [27]. In terms of concentration, C in *mg/L*, the transport equation can be represented as,

$$C = \frac{67V^2}{R} \qquad (32)$$

They developed new regime equations by combining with equation $V = 1.17\sqrt{f\,R}$ and Eqn. (33), the following equation was obtained.

$$f = \frac{C}{91.7} \qquad (33)$$

This equation is employed to eliminate Lacey's silt factor from all Lacey's equations. The resulting new equations were given as follows

$$P = 4.84\sqrt{Q} \qquad (34)$$

$$R = 2.11\left(\frac{Q}{C}\right)^{\frac{1}{3}} \qquad (35)$$

$$S = \frac{C^{\frac{5}{3}}}{6.05\times10^6 \times Q^{\frac{1}{6}}} \qquad (36)$$

$$V = 0.0983\,Q^{\frac{1}{6}}\,C^{\frac{1}{3}} \qquad (37)$$

$$A = 10.20 Q^{\frac{5}{6}} C^{\frac{1}{3}} \quad (38)$$

Stevens and Nordin (1987) explains that, if the values of concentration in the canal can be specified from field data and design considerations, the equations proposed by the authors provide better estimates of design depth and velocity than Lacey's or other later modifications. These equations are simpler and follow more closely the idea of basing design equations on Newton's laws and continuity considerations [26].

SOME COMMENTS ON REVIEW ARTICLES

There is some reservation about the general applicability of Lacey's equations to stable channels and rivers flowing through sandy material. Divergence from Lacey's equations has been observed by Inglis in India, Lane in U.S.A, Blench in Canada, Leopold and Maddock in case of rivers in U.S.A and in Egypt. Two probable reasons attributed for this divergence are effects of lithology and sediment load carried by stream or channel. Data collected by Leopold and Maddock (1953) as well as others indicate that flow depth is proportional to $Q^{0.4}$. Since computed depth using Lacey's equation is used in Lacey-Inglis method, some discrepancy is likely to occur [27].

The Lacey–Inglis method is meant for non – cohesive sandy material with mean sediment size of about 0.15–0.43 mm. In this size range, the geometric standard deviation of the bed material would vary between 1.4 and 1.8. The method is not valid outside this range. In the case of coarser material with larger standard deviation, as scour progresses, armoring occurs by selective removal of finer material from scour hole and hence smaller scour depth will occur. For very fine material, with cohesion, it is generally considered that there will be greater resistance to scour and hence reduced scour depth will result. However, recent studies on scour in cohesive material revealed that depending upon antecedent soil moisture and drainage conditions prevailing in cohesive soils, the scour in them can be less, equal or even more than that in cohensionless material under similar flow and pier conditions [28]. These effects are not considered in the Lacey- Inglis method. As pointed out by Chitale (1988, 1993), the Lacey-Inglis method is valid for sandy rivers of meandering type, and should be used only in such cases [29, 30]. Further, It is known that in the case of rivers, scour at the pier can be due to three reasons:

(i) Pier scour due to modification of the flow due to the presence of pier;
(ii) Scour due to contraction when channel width is reduced at the bridge site by road embankment and guide bunds; and
(iii) Scour due to non-uniform distribution of flow in the bridge waterway which, in turn, is due to presence of bend, non-uniform cross section, and other obstructions.

All these effects are inherent in scour depth calculated using the Lacey- Inglis method. Hence it is unreasonable to compare this scour depth with that calculated using the formulae based on laboratory studies where only the first category of scour is estimated. Further, the last two effects being particularly site specific, larger variations in scour depth are likely to occur which cannot be related to Q and f alone.

CONCLUSIONS

The nature chooses the width, depth and bed slope of the channel to convey both the water and sediment from one point to another point, if the water and sediment are to flow in a self formed alluvial channel. Review is still to be needed to attain regime conditions. Lacey's regime equations explicitly include all issues except the rate of sediment transport. Additional changes are necessary to formulate regime equations for higher velocities and concentrations that would have a much broader application in the analysis and design of alluvial channels and hydraulic design of structures.

APPENDIX

Some of the symbols which are used in this paper are as follows:
A= cross sectional area of flow, b=bed factor, C= coefficient or constant or Chezy's constant or sediment concentration, D= depth of channel, D_{50} = median size, by weight, of

sediment particle or m_r = mean diameter of bed material, f = Lacey's silt factor
g=acceleration of force of gravity, K=constant, N=rugosity coefficient, P= wetted perimeter, Q=water discharge, R= hydraulic mean radius, s=side factor, S=Channel bed slope, V= average velocity in cross section, V_0=critical velocity, V=kinematic viscosity
W= width of water surface .

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