The Influence of Whit Borland and Maurice Albertson on my Research Related to Regime Theory Applied to Uniform Conveyance Channels

Daryl B. Simons[1], Ph.D., P.E.
Emeritus Professor, Civil Engineering Department, Colorado State University

1. Introduction

On August 15, 1947 a major decision affected determination of the geographical boundaries of historic India. Immediately after the decision reached by England and India subdivision (based upon religion) was made into three separate regions consisting of India, West Pakistan and East Pakistan. The subdivision did not equitably share water between the new India and West Pakistan. To avoid a war over water the World Bank subsequently funded a major project that included a way to equitably distribute the water resources of the area through a proposed system of seven Link Canals ranging in capacity from 7800 cfs to 33000 cfs. However at that time I had no concept of what this historical happening would have upon my development as a civil engineer dealing with water resources and sedimentation issues. The following is a brief history of how the government of the United States, Colorado Agricultural and Mechanical College (it became Colorado State University in 1957) and I contributed to the development of these canals.

2. Background

Dr. Maurice L. Albertson arrived on campus in August 1947 from the University of Iowa and launched a new era of progress, research and graduate study in the Colorado A and M Civil Engineering Department. Initially, he was able to pursue these efforts with the support of Dr. Nephi Christensen, Dean of Engineering, who had come to Colorado A and M in 1938 and was determined to get a water-resources research and graduate program initiated. Christensen had been at the California Institute of Technology where he had worked with Drs. Rouse, Einstein, Ippen, Vanoni and Daily on the USDA Soil Conservation research program. Consequently, he knew what he wanted to have created and he was looking for someone to come and do it at Colorado A and M. Albertson was selected to be that leader.

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[1] Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523-1372
Mjsimons@aol.com

In 1949, Dr. Dean F. Peterson became Head of Civil Engineering. He also provided strong support of the program, together with Presidents Dr. William E. Morgan (1951-1969) and Dr. Adrian R. Chamberlain (1969 to 1979) as well as subsequent presidents. Albertson provided initiative and a major impetus for a number of firsts at Colorado A and M. He was a prime mover in initiating the Ph.D. Program on campus. In 1958, he moved on from professor of Civil Engineering to Director of the Colorado State University Research Foundation (CSURF). This later became the position of Vice President for Research. Albertson also played an instrumental part in the formulation of the SEATO Graduate School of Engineering, the Peace Corps, and the Consortium of Nine Universities, which was organized to prepare proposals and seek funding of international activities in water resources, development, and irrigation. From CSURF, in 1962, he created and directed the CSU Office for International Programs. Albertson was assisted in his efforts by A. R. Chamberlain, Albertson's first Ph.D. student and the first Ph.D. candidate to achieve the degree at Colorado A and M.

In these positions of professor, and director of CSURF and International Programs, Albertson utilized his knowledge and persuasiveness, in terms of administrative staff, to bring prime movers into Civil Engineering, for example, Drs. Herbert Riehl, Vujcia Yevjevich and Warren Hall. During this period of time he developed an excellent rapport and obtained backing of research from several United States governmental agencies. These agencies included the U.S. Geological Survey (USGS), the National Science Foundation (NSF), the Corps of Engineers (COE), the U.S. Bureau of Reclamation (USBR), and the Soil Conservation Service (SCS). Other agencies that have been involved in supporting CSU research included the U.S. Agency for International Development (AID), the Nuclear Regulatory Commission, the United Nations, the State Department, and advanced research projects of the U.S. Army to name a few. To this day, Albertson is a progressive leader in expanding research at CSU.

Backtracking to the time that Albertson was a student under Rouse at the U of Iowa, the governmental agencies had organized an Interagency Sedimentation Committee, which prevails to this day. The committee was the first to develop sediment sampling equipment and techniques. Paul Benedict with the USGS, who supported Albertson for his Master's degree, was a key figure on this committee. Other members of the committee included Whitney M. Borland of the USBR and Don Bondurant of the COE. Benedict was very supportive of Albertson's new and struggling efforts at Colorado A and M. Albertson performed several experiments for him in the lab for practically no cost, which set the stage for future cooperation. Benedict was not entirely pleased with the relationship with Rouse at Iowa and he was instrumental in getting other USGS individuals and other governmental agencies interested in the new activities at Colorado A and M.

It wasn't until Dr. Luna Leopold was put in charge of the water resources components of the USGS that Benedict and other USGS people were able to get a really significant amount of money for work at Colorado A and M. It was the work that had been done early in the new water resources program, both in the laboratory and in the field, that made Colorado A and M the prime candidate over Iowa, Cal Tech, UC Berkeley and Georgia Tech to tap into this new money.

In these early years of development of the water resources program, there was appreciable interaction between Albertson and these various water resources oriented governmental agencies, especially those concerned with sedimentation programs. Albertson and Borland became quite close with Borland calling Albertson any time he had a planned field trip and issuing an invitation to Albertson to participate. These trips became sessions of great interaction and learning of established concepts of the discipline and also the needs of further investigation through research.

Benedict had numerous ideas about sediment transport and Albertson had more. One of the activities at Colorado A and M was the development of the turbulence flume, which had the objective of measuring total sediment load. The turbulence flume was installed on the Middle Loop River at Dunning Nebraska and trials were conducted for the USGS and the Interagency Sedimentation Committee. The flume achieved its goal and Benedict, Albertson and M.Q. Matejka (1955) presented information concerning the flume to ASCE. Everyone involved with this research, including Borland, was very pleased with the model study and how it compared with the field installation. These measurements were utilized to refine the modified Einstein procedure for computing total bed load in alluvial rivers, Colby and Hubbell (1961).

If it had not been for Albertson, I would not have had the foresight to attend Colorado A and M Civil Engineering programs and I would never have met Whit Borland. As a direct consequence of the major thrust of Albertson's involvement in bringing prime leadership and research to the Colorado A and M campus, I first met Borland in 1952, who was at the time Head of the Sedimentation Section at the USBR. Albertson, in those years as professor of Civil Engineering, taught two courses in hydraulic structures to graduate students. On one of his three-day trips into Nebraska to observe canals, diversion structures, rivers, and dams, Borland accompanied the students on the field trip and by that means I became acquainted with him and his ideas, his interests, and his work with the USBR. Borland was an interesting and knowledgeable individual who became my lifelong friend and a lifelong friend of CSU Civil Engineering. In my opinion, from these early and later interactions between Borland and Albertson, it is Albertson that deserves major credit for Borland's outstanding gift to the CSU Civil Engineering Department.

After the completion of my Ph.D. program, I worked with Borland for many years on cases of canal design and sediment transport that required litigation. My last major professional activity with Borland was supporting the James Bay Hydropower Project in Canada. Through contacts made on this project it was possible to recruit Pierre Julien as a professor of CSU Civil Engineering.

3. Discussion

At the period of time of the India partition, the USBR was designing the All American Canal, which was to have a capacity of 10,000 cfs. The principal engineers at the USBR involved in this project were E.W. Lane, formerly of the University of Iowa, and Whit Borland. Lane established contact with India and Pakistan engineers who were aware of regime concepts as well as two canals that were successfully operating in India that had been designed with flows on the order of 10,000 cfs to gain insight from their experience. These engineers proposed that the All American Canal should be designed according to regime principals and proposed three equations according to regime theory that dictated the dimensions of canals. Lane, however, did not agree because of the excessive width of right of way for the All American Canal, which the regime theory would dictate. The All American Canal did try to widen, but only a few feet. The gravel present in the bank material armored the All American Canal and it was stable at reduced width dictated by regime theory. Basically stated, regime theory recognizes that canals have three degrees of freedom including width, depth and slope and the diversion from the river to the canal should have sediment excluders or ejectors so small that the canal will transport the bed sediment introduced to the canal without aggradation. This interaction laid the groundwork for my future involvement with canals, and in particular with India and development of the Link Canals.

In 1946, Tom Blench of England was the Chief Engineer in charge of the design of water distribution including canals and dams in India for a one-year assignment. Blench had a positive effect upon my life's work in engineering as well as having a bearing upon the design of the Link Canals. Blench was relieved of his duties at the time the old India was subdivided into India, West and East Pakistan. He was then offered a position with the USBR, which he accepted. The following year the USBR ran into financial difficulties and Blench's position was terminated and thereafter he took a position at the University of Alberta at Edmonton Canada. Lane also resigned his position of Chief Hydraulic Engineer with the USBR to save several positions of junior engineers and he accepted a position that Albertson arranged with the CSU College of Engineering. Lane was one of Albertson's professors at the University of Iowa.

At this period of time I was a professor teaching at the University of Wyoming and working part time for J.D. Banner and Associates. Another development that had a bearing on my future was that Colorado A and M was contemplating developing a Ph.D. degree in Civil Engineering

Through Albertson's efforts, supported by Lane and Borland, it was decided to offer a summer short course titled "Design of Mobile Boundary Channels" using Blench's knowledge of regime theory (Blench, 1966).

Albertson and Peterson, Head of Civil Engineering, approached me to attend this short course. Through my association with this short course and the knowledge gained from working with Albertson, Peterson, Borland and Blench, my decision to pursue the Ph.D. degree at Colorado State University became a major aspiration of mine and in 1950 I began my quest.

Albertson was quite enthusiastic regarding regime theory. As we discussed my dissertation and the direction in which I should concentrate my research, he suggested I should use Lane, Borland, and Peterson as my initial committee to supervise my study of regime theory. As a group, we took a three-day trip into Wyoming to look at alluvial canals and formulate the direction of my research. As a consequence, the committee did accept the concept that a study of regime theory of American canals in the west would be an acceptable dissertation topic. It was estimated that it would take me two summers of data collection and I would require an assistant. Don Bender was then working on a Master's Degree at Colorado A & M and I selected him as my assistant. He completed his Master's Degree utilizing field data that we jointly collected from the canal study for my dissertation. Borland and Albertson suggested I should approach the Omaha Division COE through Don Bondurant, Head of Cannel Work and Sedimentation, for financial support. I developed a detailed work outline and gained approval from the cooperating governmental agencies prior to my meeting with Bondurant. The procedure was as follows.

1. Colorado A & M Civil Engineering would provide me the use of a vehicle, surveying equipment and a boat.
2. The USGS through Benedict would analyze the sediment samples that I collected.
3. The USBR through Borland would publish the results, if meaningful.
4. Albertson would formerly appoint my Ph.D. committee, which ultimately consisted of Peterson, Albertson, Dr. Virgil Bottom (Head of the Physics Department), and Dr. Max Stein (Mathematics Department) as well as consultation with Dr. Hans Einstein with the University of California at Berkley.

With this agenda completed, I approached Bondurant and he affirmed that the COE had money, but he needed an order from General Potter, then Head of the Omaha Division, to allocate and spend the funds for this research. This was a temporary dilemma for me. Then I recalled that H.T. Person, Dean of Engineering at the University of Wyoming, served on a committee with the Missouri River Commission that was headed by General Potter. I told Dean Person of my dilemma and he agreed to approach General Potter. Thereafter I was called by Bondurant to inform me that General Potter had given the okay to use funds for support of my research as well as for the assistant that I had requested for two summers.

In 1955, E.W. Lane published a paper that was oriented toward interpreting geomorphic processes in canals and rivers. The basic equation is

$$QS \propto Q_s D_{50} \tag{1}$$

where Q is the bankfull flow of rivers and the design flow of canals,

S is the slope of energy gradient,

Q_s is bed material transport, and

D_{50} is a measure of bed material.

Borland (1971) enthusiastically adopted this relation and he developed a graph that illustrates the meaning and interpretation of Eq. 1. This graph is presented as Fig. 1. The equation and graph is widely utilized today by engineers and geomorphologists to interpret the response of canals and rivers.

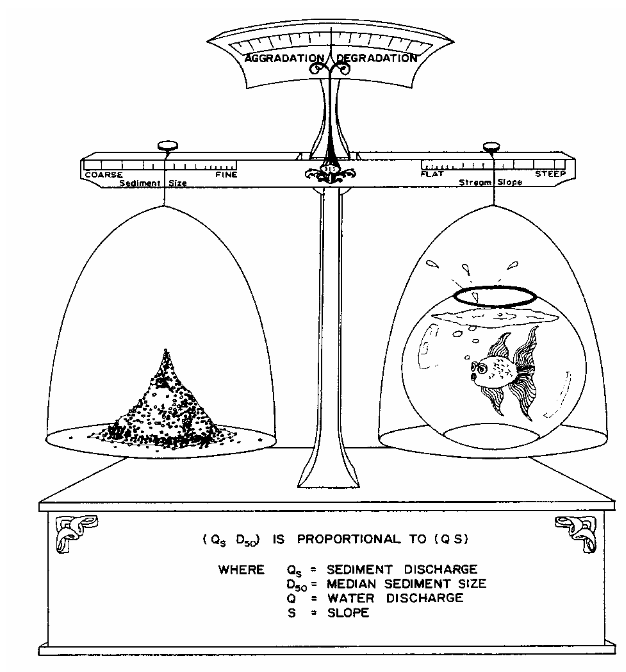

Figure 1. Schematic of the Lane Relationship Prepared by Whit Borland.

I spent the summers of 1951 and 1952 collecting data from 24 canals located in Colorado, Wyoming, and Nebraska. After the first summer of data collection, it was determined that the samples of suspended sediment were inadequate in volume. I spent the next summer revisiting the former canals and investigating new canals and I doubled the size of sediment samples to meet the requirements of the USGS. During my field investigations and development of the results I had excellent assistance and interaction from my committee members and from Whit Borland. In 1957, the committee accepted my Ph.D. dissertation and it was subsequently published by the

USBR as promised by Borland, as they found the results to be significant. Subsequently Simons and Albertson, 1961, submitted a paper to the ASCE and it was published in the 1961 ASCE Transactions and later we received the ASCE Croes Award for this paper.

In 1959 and 1960, the design of the Link Canals was a prime objective of the World Bank. I was selected to serve as a committee member investigating the design of the Link Canals. The Trimu Sidni Canal, which was the smallest of the Link Canals (Q = 7,800 cfs), was the first one designed and the first to be built. There was a relatively wide range of width, depth and slope submitted by the committee members. Independent of the committee, World Bank decided to average the designs without consulting the committee resulting in a canal that was narrower and steeper than regime equations dictated. The canal widened according to regime theory and was unstable. Thereafter the designs proposed by committee members Simons, Lacey and Blench were averaged and were adopted following regime concepts as identified by Simons and Albertson.

In 1956-57, Albertson, working with the USGS, consummated a contract that brought the USGS to Colorado A and M to conduct research on alluvial channels. Borland and Lane were involved in the agreement due to their interest and knowledge. Albertson recommended me to the USGS to head the project. Leopold (1953), Chief of the Water Resources Branch of the USGS, interviewed me and ultimately approved my leadership of the project. I started work part time in 1957 and E.V. Richardson, then a member of the USGS, was transferred to CSU full time in 1957. Together we launched the research utilizing the 150-foot long, 8-foot wide flume, which was rehabbed in 1956-57. The first series of runs we conducted in the big flume utilized a sand bed with a D50 equal to 0.46 mm. We completed 46 runs ranging from beginning of motion to flows including antidunes. We identified lower regime and upper regime depicted in Fig. 2. Unfortunately in the big flume with shallow depth less than or equal to 1 foot the subcritical, critical and supercritical flows common to hydraulics occurred at about the Froude Number equals 1 for the division between lower regime and upper regime. We did not stress that preliminary knowledge identified that the lower regime flows shifted to upper regime flows at a Froude Number of 1, which was wrong to assume.

Thereafter Richardson and I worked with sand from the Elkhorn River in Nebraska that had a D50 equal to 0.28 mm and subsequently with a sand out of a geological deposit that had a D50 equal to 0.18 mm. In total five sizes of bed material were utilized in these experiments as reported in Guy, et al. (1966). These runs with these sands proved the Froude number was not related to lower regime and upper regime.

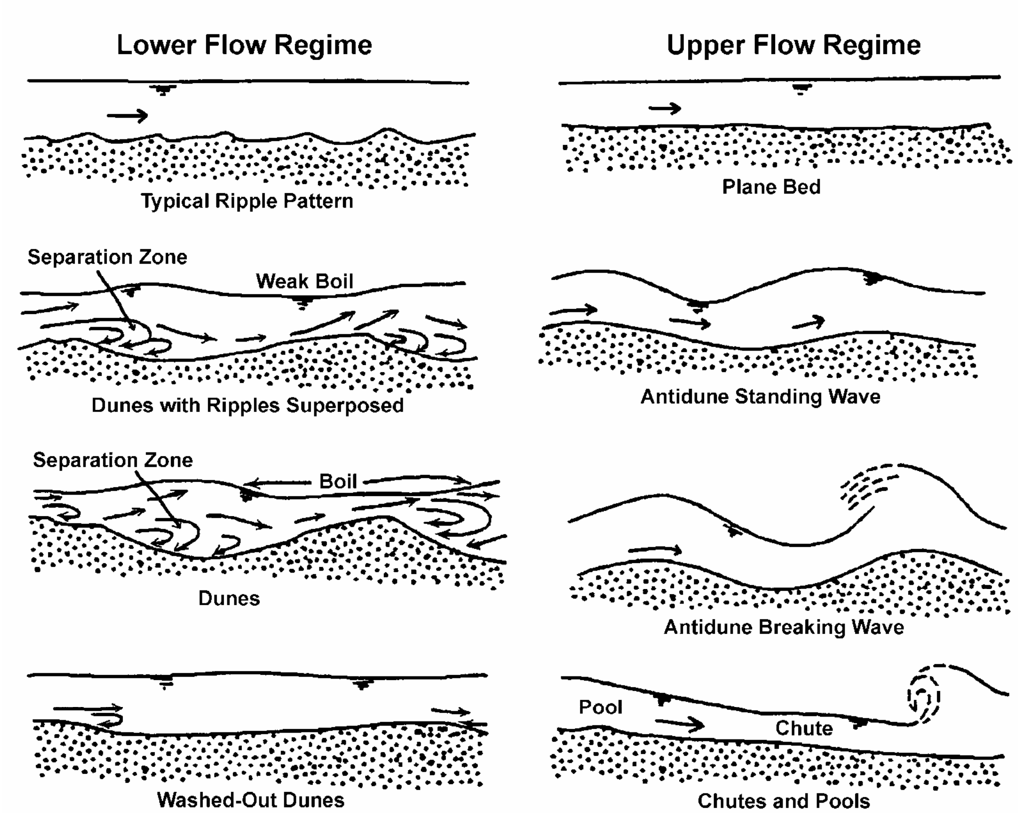

Figure 2. Forms of bed roughness in sand channels (Simons and Richardson, 1961).

In time the Link Canals were constructed and operated. Richardson and I worked with Dr. Khalid Mahmood. Both Richardson and Mahmood had finished their Ph.D. degrees in CSU Civil Engineering and we prepared a proposal to the NSF. The proposal was that we would study the Link Canals in Pakistan to see if they were adequately designed. It was funded and Mahmood conducted the field studies of the Link Canals. The data collected from these canals were utilized by me to clearly illustrate that lower flow regime and upper flow regime were not divided by a specific Froude Number. Figures 3 and 4 were formulated based upon flume data and Link Canal data. These figures illustrate that the upper flow regime and lower flow regime may be divided in a significant shift in resistance to flow and by a variable Froude Number, depth and size of bed material. The shifts in resistance to flow are on the order of n = 0.045 at lower flow regime and n = 0.012 at upper flow regime. The shift in n-values results in a looped rating curve with two possible depths for a specific discharge. The USGS studied existing records of sand-bed alluvial rivers and found that they all shifted to upper regime flow at flood stage.

In the simplest form for alluvial canals and rivers the basic equations are

$$W \text{ or } P = aQ^b \tag{2}$$

$$D \text{ or } R = cQ^d \tag{3}$$

$$A = PR = eQ^f \tag{4}$$

where W is the top width,

P is the wetted perimeter,

R is the hydraulic radius and also equals area divided by wetted perimeter,

d is the design depth,

A is the design cross section of the flow, and

Q is the design flow.

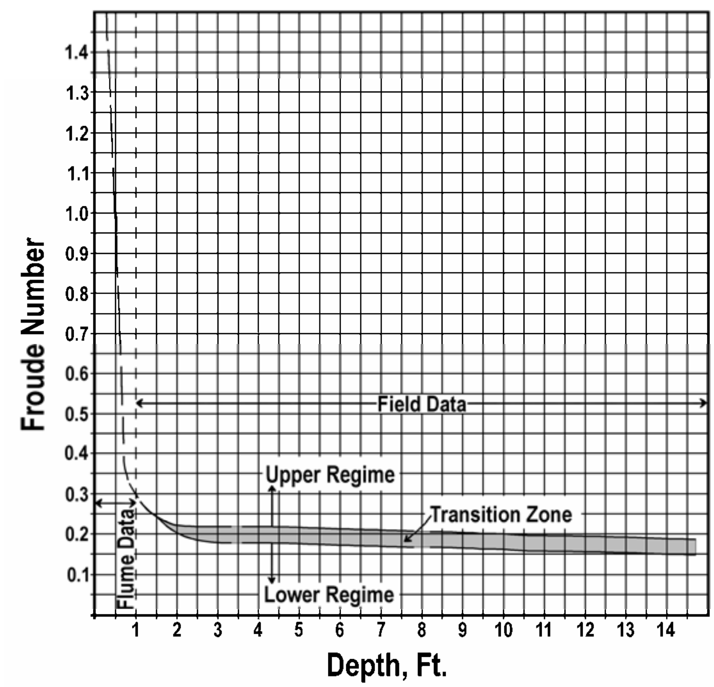

Figure 3. Relation between regime of flow and depth of flow for bed material with a median size equal to or less than 0.35 mm, based upon laboratory and field data, prepared by Simons.

The equations are numerous for the determination of slope. The most usual equation for slope in the United States is some form of Manning or Chezy Equation. The resistance coefficient in these equations is based upon form of bed roughness that will give stable banks.

Equation 1 proposed by Lane was modified by Simons and Richardson based upon the USGS studies. The modified equation is

$$QS \propto Q_s \frac{D_{50}}{C_f} \tag{5}$$

where C_f is the concentration by weight of wash load. The Lane Equation was the first stream power equation for sediment transport, for example

$$Q_s \propto \frac{QSC_f}{D_{50}} \tag{6}$$

which can be algebraically shown to be

$$Q_s \propto (\tau_0 V)\frac{WC_f}{D_{50}} \tag{7}$$

where V is the average velocity and τ_0 equals γRS which is the shear stress on the bed of the channel. This equation preceded the stream power equations proposed by Bagnold (1956) and Yang (1976, 1984).

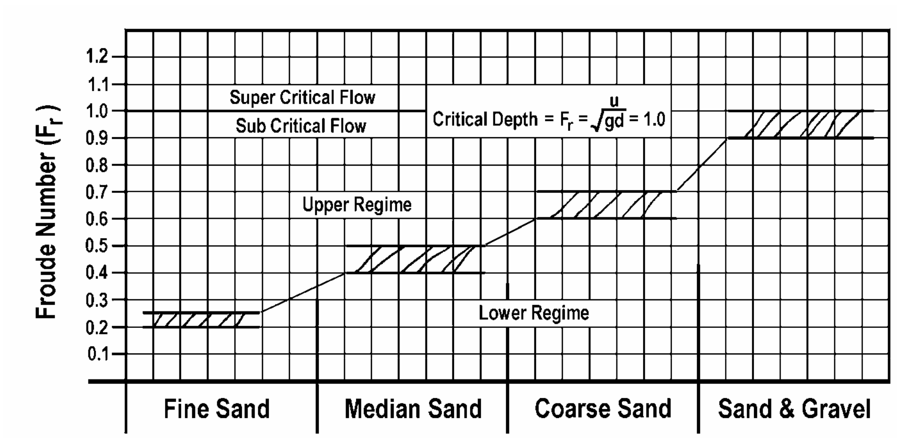

Figure 4. The crossover from lower to upper regime based on sand size and Froude Number, Simons.

4. Conclusions

- Regime equations, as developed, are applicable to both canals and rivers. The most precise relations are those developed for a particular canal or for a particular river.
- The division in terms of Froude Number is variable in terms of depth and size of sediment. The Link Canals shifted from lower regime to upper regime at a Froude Number as low as 0.16.
- Canals diverting through headworks from rivers may often require sediment excluders or sediment ejectors or both.
- The reason the All American Canal designed to a narrower width than dictated by the regime equations was successful was because of gravel in

the natural bank material. The canal widened a few feet sufficient to armor the banks of the All American Canal.

- The stream power equations presently developed for transport in open channels are a good methodology for determining the amount of bed sediment that canals will transport.

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