BED FORMS IN THE LOW FLOW CONVEYANCE CHANNEL

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Abstract: Plane bed and symmetric dunes were found to occur in the Low Flow Conveyance Channel near Socorro, New Mexico. The ability to determine bed types in fluvial channels is important for estimating flow resistance and sediment and hydraulic modeling. The flow resistance and sediment transport can ultimately affect flood stage. There are long primary dunes in the Low Flow Conveyance Channel. Superposed on the large primary dunes are secondary dunes. The data set used for this study consists of primary and secondary dunes collected at 5 discharges. Bed form population data shows a large number of primary dunes in the 500 to 1000 ft. long range, with stoss and lee side angles of about 1 degree. Secondary dunes range in length from 50 to 200 ft. The dune height ranged from 0.8 ft. to about 2.5 ft. The dune height and length are reported and compared with other data sets. The dune symmetry ratio (stoss side length divided by the lee side length) was also reported and it was found that the primary dune symmetry ratios are less than 3 while secondary dunes fall between 0.8 and 1.4. The symmetry ratio of asymmetrical dunes is generally greater than 5. The measured bed forms are compared with existing methods to predict bed form based upon sediment size and flow characteristic. Using the measured Low Flow Conveyance Channel dune data, $k_s^{'}$ is calculated and compared with the available literature. Conclusions are drawn about the general applicability of bed form phase predictive methods and methods to estimate $k_s^{'}$, to the Low Flow Conveyance Channel.

INTRODUCTION

Bed features develop naturally in alluvial sand channels whenever the velocity of flow and shear stress exceed threshold values. These bed forms affect resistance to flow, sediment transport, turbulence, flood stage estimates, and velocity and depth for habitat characterization. Various authors have generally shown that dunes have an asymmetrical shape, with a long stoss side slope, sharp crest, short steep lee side slope, and lee side flow separation (Chien and Wan, 1999; Nelson and Smith, 1989, and Bennett and Best, 1995). Laboratory and field evidence also shows that dunes can be symmetrical with stoss and lee side slopes having approximately equal length, without flow separation (Sanderson and Lockett, 1983: Kostaschuk and Villard, 1996; and Smith and McLean, 1997). Smith and McLean (1977) suggest that symmetrical dunes occur in situations where suspended sediment transport dominates so that suspended sediment settles on the lee side slope causing a more symmetrical shape. Sanderson and Lockett (1983) also observed humpback dunes that have symmetrical shape with a nearly flat dune crest. Several methods and diagrams have been developed, designed to predict the conditions under which plane beds, dunes, ripples and anti-dunes would occur. These bed phase diagrams are based mostly on flume data and may not be applicable to field conditions (Kostashuk and Villard, 1996). Secondary dunes can also be superposed on larger underlying primary dunes (Ashley, 1990; Harbor, 1998; Carling et al, 2000). The ratio of dune height/length can be related to the equivalent roughness of Nikuradse ($k_s^{'}$) (Van Rijn, 1982). The objective of this paper is to summarize the LFCC bed form data, compare these data with published bed form phase

diagrams, compare the measured $k_s^{'}$ with the method of Van Rijn (1982) and draw conclusions about the applicability of published methods to the LFCC..

Field Data: Measurements of hydraulics, bed forms and sediment transport have been made on the Low Flow Conveyance Channel (LFCC) near Socorro New Mexico (Figure 1). Field tests were conducted during May or June of 1997, 1998, 1999, and 2001 in a straight reach of the LFC near Socorro, New Mexico, USA. Figure 1 shows a plan view of the channel and the experimental cross section. The experimental program included measurements of bed material particle-size distribution, bed form, water surface slope as well as standard measurements of flow rate, and cross sections. The bed form and some of the channel hydraulics portion of the experimental testing procedure are reported herein. Target discharges ranged from 300 cfs to 1,500 cfs. Cross-sectional shape of the channel is trapezoidal with riprap side slopes and a mobile sand bottom. The side slopes are about 2.2 horizontal to 1 vertical, and the riprap size is D_{50}=152 mm (6 in) and D_{84}=250 mm (9.8 in).

The LFCC discharges were controlled at the inlet works located at San Acacia Diversion Dam (Figure 1). Table 1 contains the cross-sectional averaged hydraulic parameters for the various data sets. The Manning's roughness coefficients (n values) were determined by matching the measured water surface elevations with those estimated in a HEC-RAS (USACOE, 2001) model. The hydraulic parameters reported in Table 1 were computed by HEC-RAS once the calibration was complete. The mean suspended sediment transport for the plane bed 1999-600 cfs case was 636 mg/l, while the mean concentration dune bed 2001-585 cfs data set was

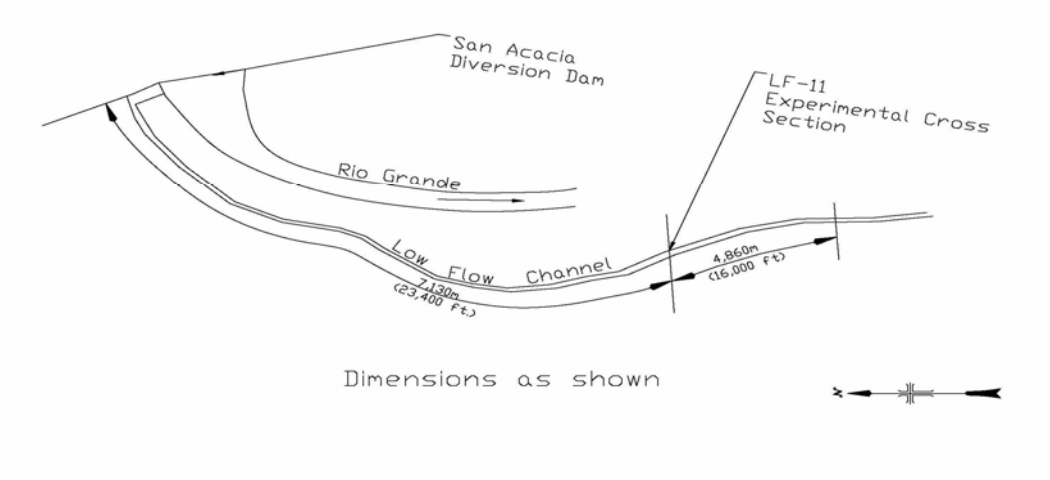


Figure 1 Plan view of the test reach.

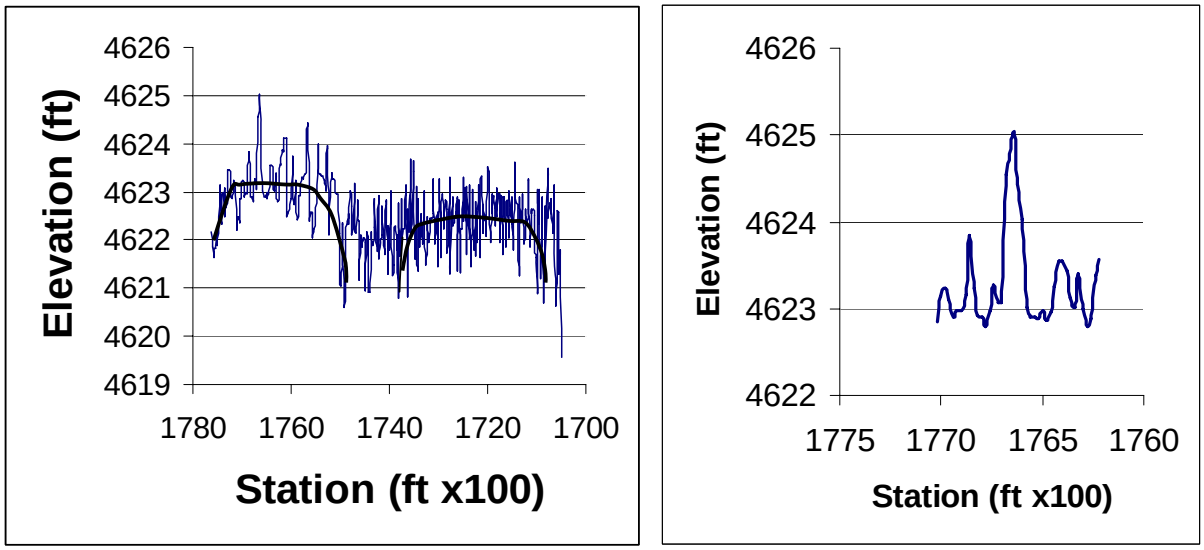
599 mg/l, or about 6% less. The bed elevation in all of the dune bed data sets remained about the same with the water surface elevation increasing with discharge.

Table 1 Hydraulic data for cross section LF-11. The measured flow is for the period during which the ADV and cross section measurements were made.

Year	Target Flow Cfs	Measured Flow cfs	Hydraulic Radius ft	Hydraulic Depth ft	Main Channel Avg. Depth ft	Energy Slope	Froude Number	Calculated Manning's N	Bed Forms
1997	1200	1191	4.86	5.3	7.63	0.000647	0.38	0.026	Dune
1998	1500	1552	5.70	6.15	9.55	0.000616	0.32	0.026	Dune
1999	600	625	3.95	4.03	5.04	0.000382	0.33	0.020	Plane
2001	600	585	4.04	4.77	7.34	0.000413	0.28	0.035	Dune
2001	300	1390	3.66	3.81	5.48	0.000260	0.23	0.024	Dune

DATA ANALYSIS

Dune Data: The LFCC dunes were symmetrical with stoss and lee sides of nearly equal steepness (Figure 2). Humpback dunes with flat tops with equal steepness stoss and lee sides also occurred. The primary symmetrical and humpback dunes had average lengths from 630 to 890 ft. (Table 2). Primary dunes are on average 7 to 10 times longer than secondary dunes (Table 2). The length of the flat top on humpback dunes for primary dunes ranges from 110 to 360 ft. and for secondary dunes the range is 10-100 ft. Primary dune lengths were "very large" (dune length > 330 ft.) while dune heights ranged from the "small" (0.25 < dune height < 1.3 ft.) to "medium" (1.3 < dune height < 2.5 ft.) based on the classification of Ashley (1990). Secondary dunes lengths were "large" and the height was "small" or "medium" based on the classification. The stoss and lee side slope angles were less than 1 degree, while symmetrical dunes reported on the Rhine river had lee side slopes of about 10 degrees with some as low as 1-2 degrees (Carling, et al., 2000). Fraser river dunes had stoss and lee side angles ranging from 2.4 to 18.9 degrees (Kostachuk and Villard, 1996). Dune symmetry ratio is defined as the stoss side length (L_s) divided by the lee side length (L_l). The majority of secondary dunes had a symmetry ratio ranging from 0.8 to 1.4(Figure 3), falling in the same range of symmetry ratios of symmetrical dunes found on the Fraser River (Kostachuk and Villard, 1996). By comparison, asymmetrical dunes on the Fraser River had symmetry ratios ranging from 5.67 to 8.17 (Kostachuk and Villard, 1996).

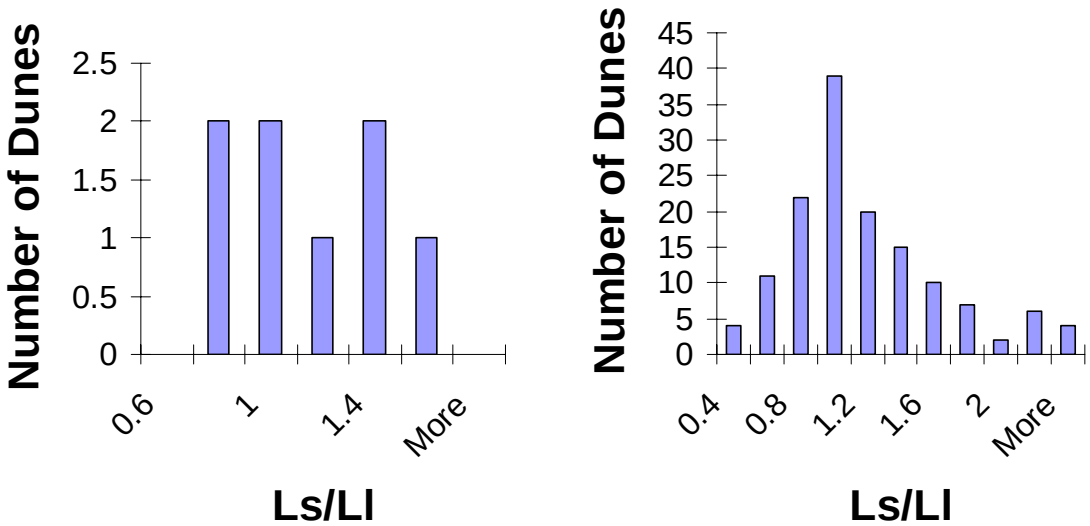


(a) (b)

Figure 2 Dune Profiles (a) Primary Dunes (the line denotes the approximate crest of the primary dunes) and (b) Secondary Dunes.

Table 2 Dune properties for 300, 600, 1,200, and 1,500 cfs discharges.

Date/Discharge	Average Dune Height/Length Ratio	Average Dune Height (ft.)	Average Dune Length (ft.)	Average Stoss Side Angle ($\sin^{-1}(H/L_s)$)	Average Lee Side Angle ($\sin^{-1}(H/L_l)$)
1997 1200 cfs					
Primary Dunes	0.00149	0.82	630	0.169	0.145
Secondary Dunes	0.00459	1.05	230	0.402	0.398
1998 1500 cfs					
Primary Dunes	0.0018	1.625	890	0.172	0.323
Secondary Dunes	0.0247	1.628	94	0.555	0.533
2001 600 cfs					
Primary Dunes	0.00583	2.78	730	0.515	0.413
Secondary Dunes	0.006978	0.767	111	0.458	0.454
2001 300 cfs					
Primary Dunes	0.00464	2.5	666	0.529	0.508
Secondary Dunes	0.01796	0.831	58	0.579	0.597



(a) (b)

Figure 3 Dune Symmetry Ratio (a) primary dunes, and (b) secondary dunes.

Five bed form phase diagrams were selected to examine the stability fields of the LFCC dunes: stream power diagram of Simons and Richardson (1963, 1966), shear stress diagram of Chabert and Chauvin (1963), Froude number diagram of Simons and Senturk (1992), mean velocity diagram of Ashley (1990), and the modified sediment mobility parameter diagram of Van den Berg and Van Gelder (1993). These five phase diagrams each have fundamentally different physical parameters to estimate bed form phases. Dunes were measured in all data sets except the 1999 data set, while the published stability fields showed anti-dunes, upper regime plane bed, transition between lower and upper regime, or transition between dunes and anti-dunes, Only the dunes measured in the 2001 300 cfs data set matched the prediction by Simons and Richardson (1963, 1966). In the Chabert and Chauvin's (1963) shear stress diagram and the velocity based method of Ashley (1990), the measured LFCC velocity exceeded the reported range of the methods. These data support the conclusion of Kostachuk and Villard (1996) that "flume based bed form phase diagrams are not applicable to dunes in deep natural flows." Laboratory models do not scale the same for sediment size, flow hydraulics and turbulence (Kostachuk and Villard, 1996), and results from such models may not be applicable to field conditions. Regardless of the interpretation of these results, it is apparent that published bed form phase diagrams cannot be readily applied to the LFCC data set.

<u>Equivalent Roughness of Nikuradse</u> ($k_s^{'}$)

Using the log law given as

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa}\ln\left(\frac{y}{y_0}\right) \qquad (1)$$

Table 3 Comparison of Measured LFCC Bed forms with Bed Forms Predicted by various Bed Form Phase Diagrams.

Data Set	Measured	Simons And Richardson (1963,1966)	Chabert And Chauvin (1963)	Simons And Senturk (1992)	Ashley (1990)	Van den Berg and Van Gelder (1993) Flume	Van den Berg and Van Gelder (1993) River
1997 (1200 cfs)	Dune	Anti-dune and Plane Bed	Shear Stress Exceeded the diagram	Transition[1]	Velocity Exceeded The Diagram	Upper Regime Plane Bed	Upper Regime Plane Bed
1998 (1500 cfs)	Dune	Transition between dunes and anti-dunes	Shear Stress Exceeded the diagram	Transition	Velocity Exceeded The Diagram	Dunes to Upper Regime Plane Bed	Upper Regime Plane Bed
1999 (600 cfs)	Plane	Dunes	Shear Stress Exceeded the diagram	Transition	Velocity Exceeded The Diagram	Upper Regime Plane Bed	Upper Regime Plane Bed
2001 (600 cfs)	Dune	Anti-dunes and Plane Bed	Shear Stress Exceeded the diagram	Transition	Velocity Exceeded The Diagram	Upper Regime Plane Bed	Upper Regime Plane Bed
2001 (300 cfs)	Dune	Dunes	Shear Stress Exceeded the diagram	Dunes	Velocity Exceeded The Diagram	Upper Regime Plane Bed	Upper Regime Plane Bed

[1]Transition between Lower Regime and Upper Regime

where $\bar{u}$ is the time average velocity at depth y, u_* is the shear velocity, κ is the Von-Karman parameter, and y_o is the zero velocity roughness height. The slope of the logarithmic portion of the stream wise velocity profiles was used to obtain the values of shear velocity u_* and the zero velocity roughness height y_o. By regressing u on to $ln\ y$ the zero velocity roughness heights (y_0) (Bergeron, and Abrahams 1992) is found from

$$u = m \ln y + c \tag{2}$$

$$y_o = e^{(-c/m)} \tag{3}$$

where *m* is the regression line slope, and *c* is the intercept. The grain roughness height is found using (Julien, 1995)

$$k_s^{'} = 30.2 y_o \tag{4}$$

where $k_s^{'}$ is the equivalent grain roughness height. For dune beds, Van Rijn (1982) developed an empirical equation for estimating $k_s^{'}$ using dune length and height

$$k_s^{'} = 1.1H(1 - e^{-25H/L}) \tag{5}$$

applicable in the range $0.01 \le H/L \le 0.2$. The majority of the LFCC data has *H*/L values less than this range except the secondary dunes in 1998 at 1500 cfs and in 2001 at 300 cfs, and somewhat compares with the method of Van Rijn (1982) (Table 4).

Table 4. Comparison of Predicted and measured.

	$k_s^{'}$ Van Rijn (1982) Eq. 5 (mm)	$k_s^{'}$ from the measured velocity profile (mm)
1998 1500 cfs Secondary Dunes	250	230
2001 300 cfs Secondary Dunes	100	140

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that dunes on the LFCC are symmetrical shaped with long, low height geometry that sometimes have flat or humpback crests. LFCC bed forms are not well represented by existing bed form phase diagrams and the equivalent grain roughness height for dunes is somewhat represented by the method of Van Rijn (1982). It is recommended that the bed form phase diagrams and the method for predicting the equivalent grain roughness height be adjusted to apply to the LFCC to estimate hydraulic and sediment transport conditions.

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