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EROSION OF BANK DEPOSITS IN GRAND CANYON

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ABSTRACT

Sand bars below Glen Canyon Dam on Colorado River are multipurpose natural resources. They form the habitat for many species of riparian life, serve the recreational needs of the public and are important to native people. The erosion of sand bars downstream of Glen Canyon Dam has become a source of environmental concern to the public. Many sand bars in Grand Canyon are found in the vicinity of and/or are associated with recirculating zones (eddy systems). Fluctuating dam discharges change the eddy dynamics leading to cycles of erosion and accretion on sand bars. In this paper, the effects of dam operation and eddies on the stability of sand bars in Grand Canyon are examined.

INTRODUCTION

Glen Canyon dam in the northeast corner of Arizona is operated to satisfy premium peak electrical power demands in southwestern Unites States. Consequently, the discharge of water from the dam fluctuates on a daily basis creating a daily tide in the 410 kilometer stretch of the Colorado River downstream of the dam. Typical daily river stage fluctuation is between one and three meters with some narrow river sections reaching four meters.

Before the existence of the dam, floods (which occurred annually in late spring) scoured the banks of the Colorado River. However, the flood waters contained and transported a considerable amount of sediments that reworked and replenished the scoured areas as the flood receded. With most of the sediments now trapped behind the dam in Lake Powell, the supply of sediments downstream of the dam comes mainly from ephemeral tributaries such as the Paria and Little Colorado Rivers during infrequent floods. Vegetation and riparian habitats were sparse within the region of the riverbanks subjected to scouring from flood waters in the pre-dam period. Now, lush vegetation exists along the river corridor providing a fertile environment for biological life.

Throughout the stretch of the Colorado River downstream of the dam are debris fans at the confluences of tributaries. Debris fans disrupt flow in the main channel, thus providing locations favorable for deposition of fine-grained sediments. Debris fans contain sediments ranging in size from silts to boulders and are popular as campsites for boaters and hikers.

The fluctuating flows from Glen Canyon dam affect the geomorphology and relative stability of the sand bars downstream of the dam. Bank cuts (slope failures, mass wasting), rilling, tunneling and other signs of erosion are prevalent on most of the deposits. Massive bank cuts are frequently observed when large fluctuating discharges are followed by low fluctuating discharges or low constant discharges.

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Four major processes - ground water seepage, river current scour, surface wave scour and eddy systems - have been identified as the causes of erosion of sand bars along the Colorado River downstream of Glen Canyon dam. Of these, seepage of bank-water is unique in that it is a ubiquitous one-way, or erosion only, process and is directly connected to fluctuating river stages (Budhu and Gobin, 1994).

Most sand bars in Grand Canyon are in the vicinity of and/or are associated with eddy systems or recirculating zones. The dynamics of these eddy systems on sand bars have not been thoroughly examined. Most studies on the effects of eddies on sediment transport have been confined to channel bed dynamics. Eddy systems that affect the bed geometry are predominantly vertically oriented with their axis of rotation perpendicular to the flow direction. However, eddy systems that affect channel banks are predominantly horizontally oriented (Yalin, 1992). In this paper, a conceptual model of how eddy dynamics under fluctuating dam discharges affect channel bank deposits (sand bars) is presented and compared with data collected during an environmental impact study in the Colorado River.

ACCRETION/EROSION WITHIN RECIRCULATING ZONES

Many sand bars in Grand Canyon are in the vicinity of and/or are associated with recirculating zones (Kieffer, 1985). Each recirculating zone may consist of one or more eddies. Two modes of sand bar formation within recirculating zones in Grand Canyon were identified by Schmidt and Graf (1990). On the

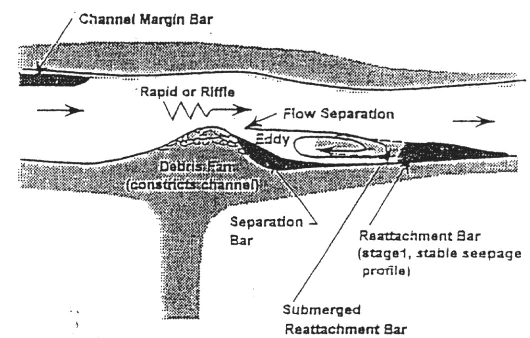

Figure 1 Two types of sand bar deposits and accretion/erosion at Stage 1

upstream end of the recirculating zone (Fig. 1), a separation bar, which consists of fine to very fine sediments, is formed. While, on the downstream side of the recirculating zone, a reattachment bar of coarser sediments than the separation bar is formed.

Consider a reattachment bar within a recirculating zone that aggraded, as described by Schmidt and Graf (1990), to its maximum slope (Fig. 2). In Grand Canyon, the average maximum depositional slope

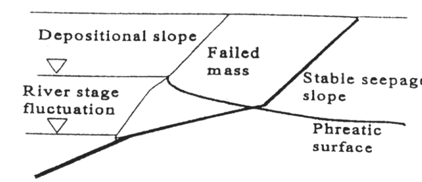

Figure 2 Depositional and stable seepage slope

is 28°, the average angle of friction of the sediment is 30° and the average unit weight is 16 kN/m^3 (Budhu and Gobin, 1994). The flow regime compatible with the size of this recirculating zone is arbitrarily designated as X and accretional/erosion process associated with it is denoted as stage I.

Budhu and Gobin (1994) showed that, under drawdown conditions, the depositional slope will fail (bank cuts, slope failures) from seepage forces. Data presented by Budhu and Gobin (1994) for sand bars in Grand Canyon showed that these seepage driven failures occurred at low river stage. The slope failures are usually progressive and it was shown (Budhu and Gobin, 1996) that a theoretical stable seepage slope (α_s) is achieved when

$$\alpha_s = \tan^{-1}\left(\frac{\gamma'}{\gamma_{sat}}\tan\phi\right) \qquad (1)$$

where γ' is the effective unit weight, γ_{sat} is the saturated unit weight and ϕ is the effective angle of friction of the soil. Since for most soils, $\gamma'/\gamma_{sat} \approx 1/2$ (γ_{sat} = 17 to 20 kN/m^3 for most soils) and thus $\alpha_s \approx 1/2\phi$.

At low river stage the depositional slope under flow X would fail from seepage forces. Because the flow velocity within the main channel is low, the failed mass of sand would remain in the vicinity of the recirculating zone, becoming subaqueous sediments. The subaqueous sediments then become potential sediment supplies for the recirculating zone and can be redeposited on the stable seepage slope. If the slope of the redeposited sediments exceeds the stable seepage slope, slope failures would recur. If flow regime X is maintained, a cyclic process of accretion and erosion would perpetuate.

Suppose the dam discharge (flow) is increased, and the flow regime changes from X to Y. Under flow regime, Y (stage II), the recirculating zone would extend in the direction of flow (Schmidt and Graf,

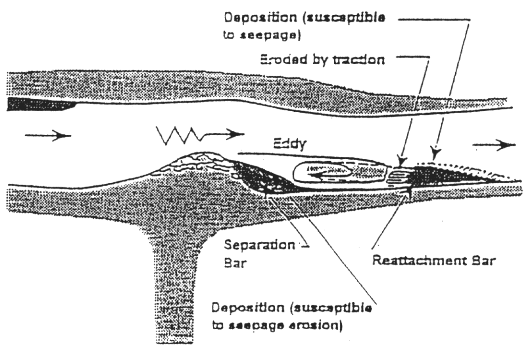

Figure 3 Stage II - Effects of increase in discharge on sand bar stability

1990) as shown in Fig. 3. The extreme upstream end of the extant reattachment bar would be subjected to tractive forces from the eddies and erode (Fig. 3). Part of the eroded volume of sediments would be trapped by the recirculating zone while the other part will be transported downstream by the main channel current. Some sediments trapped in the recirculating zone may be redeposited on the upstream separation bar and on the downstream end of the reattachment bar. Eroded sediments transported by the main channel current may be deposited on the downstream end of the reattachment bar or transported downstream. When the river stage is lowered and if the depositional slope is greater than α_s, then seepage induced slope failures would occur. The failed mass of sediment would then enter the recirculating zone and is available for redeposition to continue the cycle of accretion and erosion.

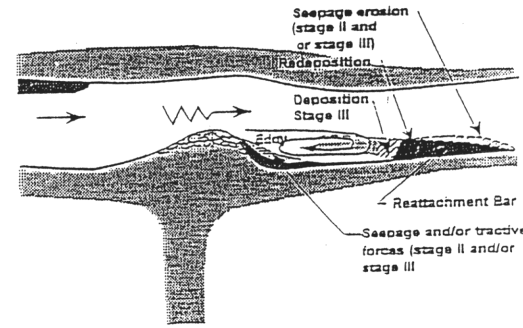

Figure 4 Effects of decrease in dam discharge on sand bar stability

If the flow regime (dam discharge) is changed to flow regime, Z (stage III), so that the maximum discharge is lower than flow regime, X, then the recirculating zone would shrink as illustrated in Fig. 4. Deposition may now occur on the upstream side of the extant reattachment bar eroded in stage II by tractive forces. Sediments deposited on the separation bar during stage II may be eroded by seepage erosion at the end of stage II or by tractive forces at the beginning of stage III (Fig. 4).

If the dam discharge then reverts to flow regime X (stage IV), the eddy system will again rework

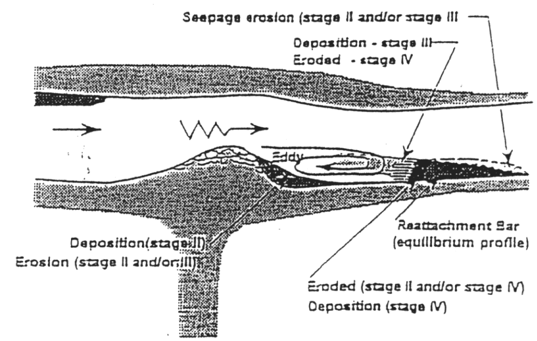

Figure 5 Stage IV - Changes in sand bar after one cycle of fluctuating discharge

the sediments (Fig. 5). Portions of the upstream end of the reattachment bar built up during stage III will now be eroded by tractive forces of the eddy system. The eroded sediments are likely to remain in the recirculating zone. If there is no loss of sediments from the system, then the original area of the sand bar in stage I will be regained in stage IV. However, under stage II, there is a net loss of sediments (sediments that are transported downstream) from the recirculating zone. The implication is that if the cycle, stage I to stage IV, continues and no new sediments are trapped in the recirculating zone, the sand bar will reduce in size.

Other factors also contribute to the dynamics of the recirculating zones, eg., sediments transported by floods or high dam discharges from the tributaries into the main channel may also enter the recirculating zone adding another dimension to the accretion/erosion process. The influx of sediments can cause the reattachment bars to be built wider and higher. However, the new geometry would be incompatible with the local dynamics of the recirculating zone and erosion by tractive and seepage forces will occur when the usual dam operation pattern resumes.

COMPARISON OF FIELD DATA WITH THE GENERAL ACCRETION/EROSION CONCEPTUAL MODEL.

Since 1989, the U.S. Bureau of Reclamation initiated a series of experimental flow regimes to determine if flow regimes different from normal dam operations would alleviate the negative environmental impacts on resources downstream of the Glen Canyon dam. Several sand bar sites were monitored to determine their morphological changes under different flow regimes. Many of these sand bars were also monitored during normal, unregulated flow regimes (Cluer, 1995). Topographical changes as measured by Cluer (1995) for one sand is shown in Fig 6 and the corresponding unregulated flow regime is shown in Fig 7. The separation bar eroded and some of those sediments were deposited on the reattachment bars. Cluer (1995) documented sand bar changes similar to those described by the conceptual model.

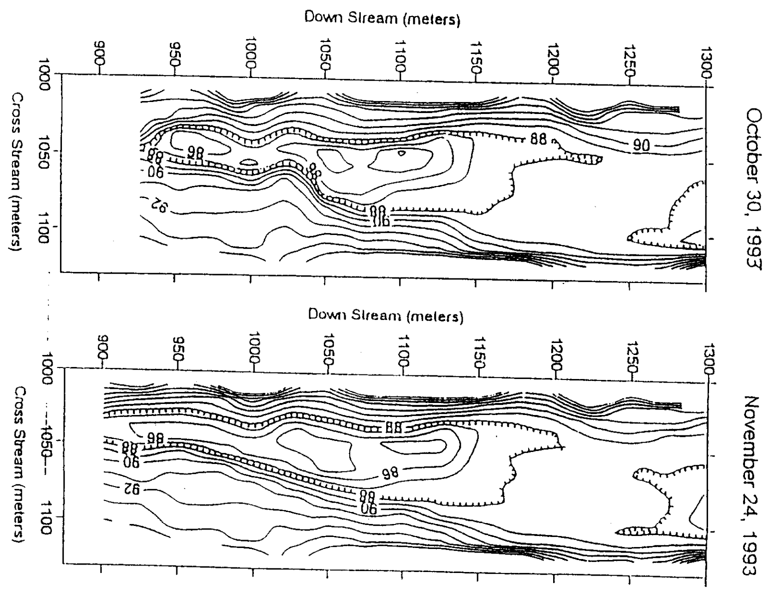

Figure 6 Erosion of a sand bar by an eddy system during 25 days of dam discharge fluctuation.

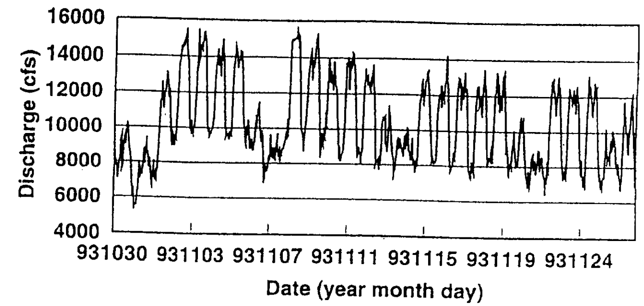

Figure 7. Dam discharge from October 30- November 24, 1993

CONCLUSION

The accretion/erosion of sand bars in Grand Canyon is a complex process involving dam operation parameters and natural phenomena. A cyclic process of accretion/erosion occurs on sand bars in the vicinity of recirculating zones or eddy systems. Fluctuating dam discharges change the sizes of these recirculating zones causing erosion of some parts of the sand bars and accretion on others. Sand bars that aggrade to slopes greater than the stable seepage slope will collapse to an equilibrium profile and the collapsed mass of sand supplies sediments to the eddies in the recirculating zones to perpetuate the accretion/erosion cycles. Fluctuating dam discharges can lead to net sediment loss and unless the river system is replenished with fresh sediments some sand bars will erode totally.

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