INSTABILITY OF SANDBARS IN GRAND CANYON

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ABSTRACT: The Glen Canyon Dam, located in the northeastern corner of Arizona, is operated to satisfy peak power demands of neighboring states. The discharge regime of the dam is such that the river stage in the Colorado River downstream of the dam varies diurnally as much as 4 m in some sections. It is alleged that these fluctuations of the river stage are responsible for the destruction of sandbars and, as a result, the loss of the extant biomass and the reduction of recreational facilities. In this paper, an analysis is developed to determine the equilibrium slope below which slope failures (mass wasting, bank failures) due to seepage of bank-stored water would be unlikely. The sediments enclosed by the equilibrium seepage slope (range 11°–14° for the sediments downstream of the Glen Canyon Dam) and the maximum slope angle (range from 26° to 32°) is subjected to ongoing aggradation and erosion. Field data from ground surveys support the analysis described in this paper.

INTRODUCTION

The Glen Canyon Dam, located in the northeastern corner of Arizona (Fig. 1), is an arch-gravity wall 183 m high with a base thickness of 107 m. It was opened officially in 1963 to provide flood control, water storage, and hydroelectric power for Arizona, Nevada, and California (Stevens, private communication, 1983). The dam is operated to satisfy peak power, which usually occurs at the middle of the day. Consequently, the discharge from the dam fluctuates on a daily basis. The river stage in the 402-km stretch of the Colorado River between the dam and Lake Mead rises and falls following the patterns of the dam releases. Typical fluctuation on a diurnal basis is between 1 and 3 m, with changes in some narrow river sections reaching 4 m.

Before the construction of the Glen Canyon Dam, the Colorado River was laden with sediments; sediment load fluctuated throughout its course. Now, sediments are trapped upstream of the dam in Lake Powell. The water downstream of the dam is clear—almost devoid of sediments—with significant power for erosion, and substantial capacity for sediment transport. Sediment concentration near Lees Ferry was in excess of 10,000 parts per million (ppm) prior to the construction of the dam. Now, the sediment concentration there is about 200 ppm (Schmidt and Graf 1990).

Throughout the downstream stretch of the Colorado river are debris fans at the confluences of ephemeral tributaries and the main channel. Schmidt and Graf (1990) identified four types of deposits (separation deposits, reattachment deposits, upper pool deposits and channel margin deposits) at these confluences as shown in Fig. 2. Sandbars are scattered along the banks of the main channel between tributaries. During floods or high dam releases, deposits at the confluences and fresh sediments from the ephemeral trib-

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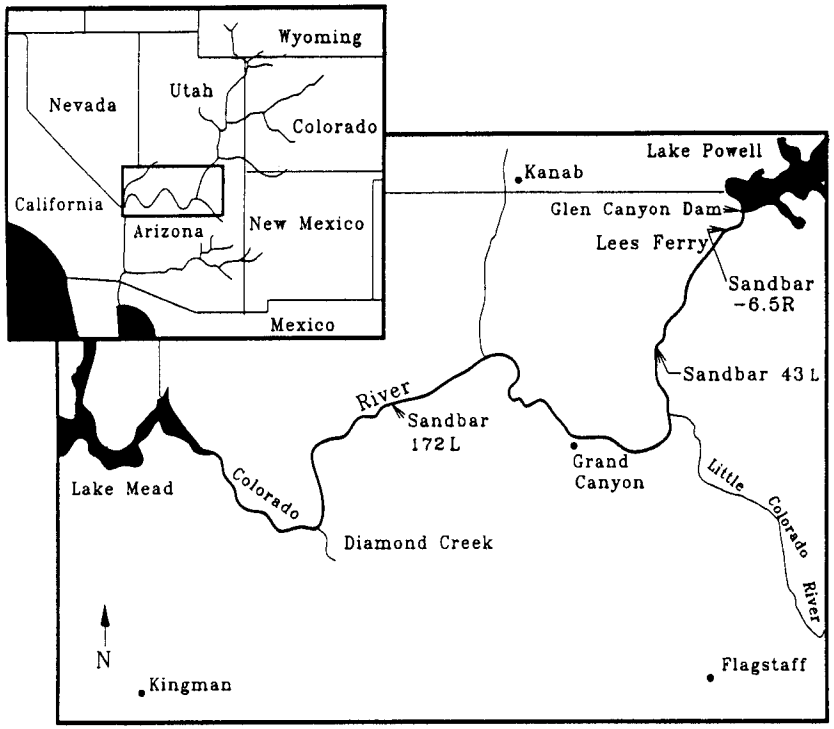

FIG. 1. Map of Study Area

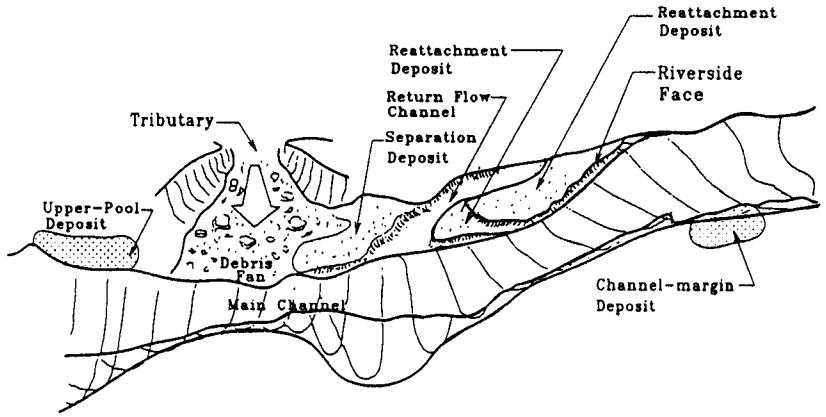

FIG. 2. Types of Fluvial Deposits Downstream of Glen Canyon Dam [after Schmidt and Graf (1990)]

utaries are transported and then deposited at locations conducive to aggradation. At these locations, where the velocity is much lower than the average velocity, new sandbars are formed and existing sandbars are either replenished, if prior erosion occurred, or increased in size.

There are continuous changes in the geomorphology and the stability of

the downstream deposits. Prior to the construction of the Glen Canyon Dam, receding floodwaters deposited large amounts of sediments to replenish scoured bars and/or build new ones. In the postdam era, only the suspended sediment load below the dam is available for bar replenishment. Laursen et al. (1976) predicted the depletion of sand deposits because transport capacity now exceeds the supply of sediments from the tributaries below the dam. Bank slumps (slope failures, mass wasting), rilling, tunneling, and other signs of erosion are now prevalent on the 219 sandbars between Glen Canyon Dam and Diamond Creek (Fig. 1). Bank slumps normally are observed when large fluctuating flows are followed by low fluctuating flows or low constant discharge. These observations tend to support the suggestion made by Dolan et al. (1974) that extensive erosion of sandbars would occur as a result of dam operation.

The sandbars support a rich and diverse riparian habitat, most of which developed during the postdam period. Before the construction of the Glen Canyon Dam, almost no vegetation existed below the old high-water level, because of scour from annual floodwater (Stevens 1983). Now, the lush vegetation along the river provides a fertile environment for biological life. Many of these sandbars are also used for public recreation.

River runners and the public are alarmed by the conspicuous bank cuts and other erosion features on the sandbars. Cyclic degradation and aggradation of these sandbars appear to the public to be related to the dam discharge regimes. In 1989, the U.S. Bureau of Reclamation initiated a series of alternative flow regimes to the normal dam operation to see whether any of these different flow regimes would reduce the impact on the downstream resources. Sixteen experimental test flows with different flow ranges and ramping rates were designed and implemented in the Bureau of Reclamation Glen Canyon Environmental Studies Phase II (USDI 1988). The results presented in this paper are from a two-year study period beginning September 1990.

Three processes—seepage induced erosion, tractive scour, and wave attack—have been identified in the erosion of sandbars downstream of the Glen Canyon Dam. Of these processes seepage is the most ubiquitous. The intention of this contribution is to describe the effects of transient groundwater seepage on river bank stability, and to analyze slope instability of sandbars downstream of the Glen Canyon Dam.

SEEPAGE EROSION AND OBSERVATIONS IN GRAND CANYON

Many terms are used in the literature to describe erosion caused by seepage of ground water. These terms include artesian sapping, spring sapping, seepage driven erosion, rilling, tunnel scour, seepage-induced transport, and seepage weathering. The term seepage erosion is used here to describe the aforementioned seepage-related phenomena. The mechanics of each of these phenomena may be slightly different. The emphasis in this paper is on slope failures (bank slumps, mass wasting), so the term seepage erosion refers, in most cases, to these failure events.

Howard and McLane (1988) summarized many earlier observations of seepage-related erosion phenomena and theories concerning the geomorphical changes in riverbanks, and presented laboratory evidence of erosion due to seepage stresses. They developed a fluvial transport model for seepage erosion based on the availability of an unlimited supply of water to perpetuate seepage erosion. Springer et al. (1985) and Ullrich et al. (1986) studied the effects of seepage on the stability of layered alluvial stream

banks. They concluded that sand seams promote bank failures in layered alluvial soils. Hagerty (1991a,b) documented several cases in which seepage was primarily responsible for riverbank erosion, and he insisted on the need for hydraulic engineers to recognize the importance of "piping/sapping erosion."

Seepage erosion was observed in most of the sand bars downstream of the Glen Canyon Dam. When the river rises, water infiltrates into and is stored in the river bank. As the river falls the volume of stored water must drain from the bank. If the rate of fall of the river is greater than the rate at which stored water can exit the bank, then the phreatic surface will be at a higher elevation than the river stage. A seepage face then develops between the river level and the exit point of the bank stored water. If the seepage velocity of the exiting ground water is sufficiently high, the soil mass can become like a viscous fluid and be carried away in suspension by the outflow of water (Fig. 3). The removal of sediments from the sandbars tends to steepen the slopes with concomitant bank or slope failures. Rivulets and gullies (rilling process) are formed below the exit point along the sandbars as the bank-stored water with its sediments rushes downslope toward the river. These rivulets and gullies are scoured deeper as the water picks up sediments along its path to the river (Fig. 4). Within the river bank deposits and above the exit points, the internal erosion of sediments can form tunnels. The walls of these tunnels eventually collapse as the tunnel becomes deeper and/or adjoining tunnels encroach on one another.

When the river stage is lowered, an elevated pore water pressure distribution remains within the river bank. The residual pore water pressures and removal of stabilizing external water pressure on the face of the bank can lead to slope failures under undrained conditions similar to slope failures in reservoir embankments under rapid drawdown. A typical example of this type of failure in a sandbar below the Glen Canyon Dam is shown in Fig. 5. The mass of material involved in bank slumps under undrained conditions is often very large, several hundred kilograms. A substantial area of the sandbar can be lost in a few seconds. On occasions, incipient slope failures under undrained conditions may occur during rapid recession of the river stage. That is, the failure plane is initiated but slumping is not discernible. The soil mass is now much weaker than it was prior to the formation of the failure plane. On the next rising river stage, the coupled effect of hydrostatic forces from water that enters the failure plane and tractive scour forces can result in failure of the weakened soil mass, which disintegrates and is taken

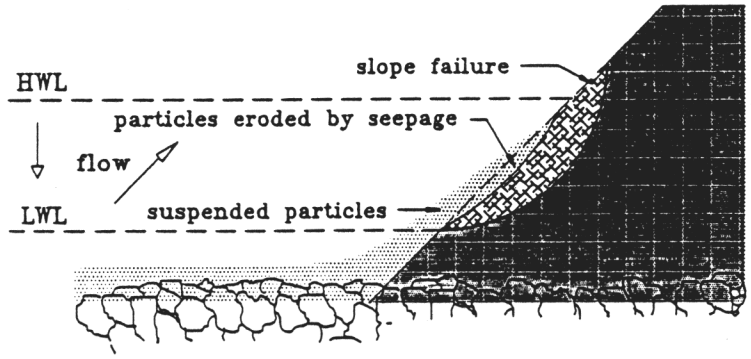

FIG. 3. Mechanism of Seepage-Driven Erosion

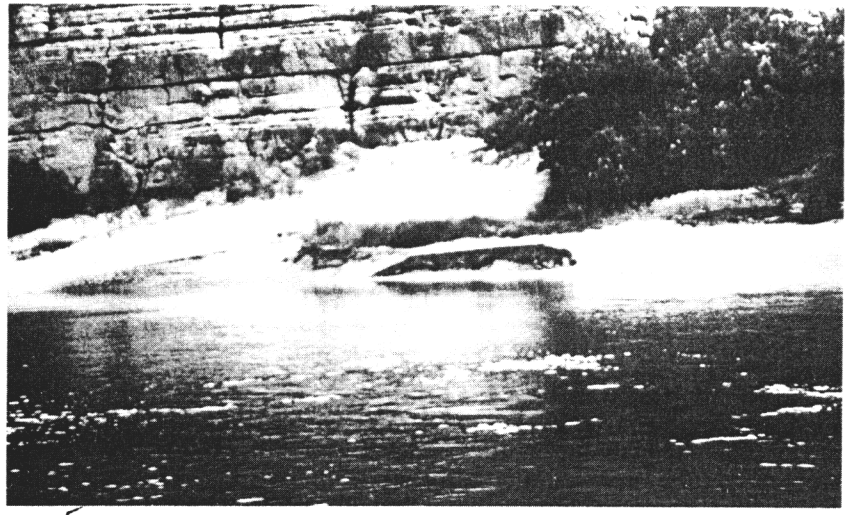

FIG. 4. Rivulets along Sandbar Downstream of Glen Canyon Dam (Left End of Sandbar Shows Slope Failures Caused by Oversteepening of Slope by Seepage)

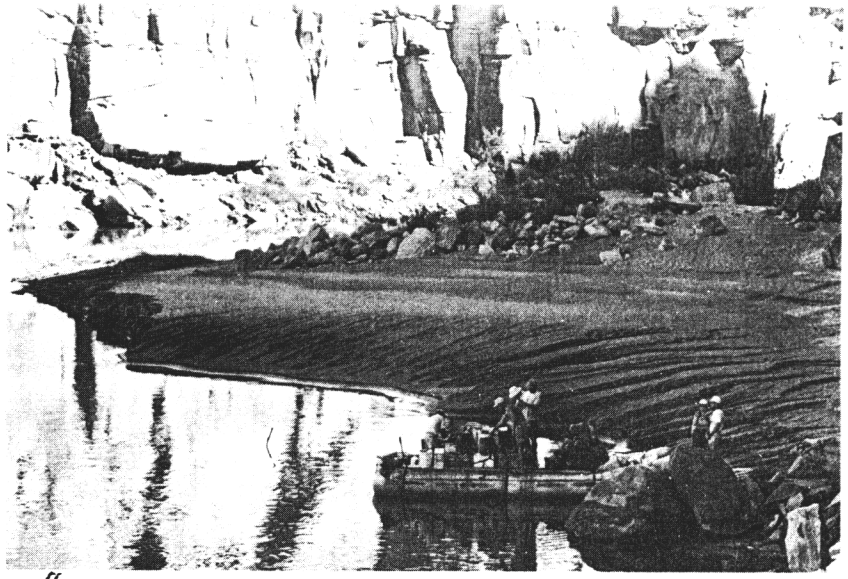

FIG. 5. Slope Failure on Sandbar Caused by Rapid Down-Ramping Dam-Discharge Rate

away by the flow. It is quite easy to confuse this seepage-induced failure to a tractive force-induced failure. The condition that is critical in provoking such failures is a rapid lowering of the river stage caused by a high dam-down-ramping rate, followed by a constant low discharge over a day or more. The latter allows for a prolonged period of seepage out of the sandbar and results in the formation of a more pronounced failure plane.

STABLE SAND BAR SLOPE UNDER SEEPAGE

It is well known to geotechnical engineers that seepage forces reduce the stability of slopes. The factor of safety can be reduced to as much as half of its initial (nonseepage) value. The maximum slope of a saturated or dry sand bar is the angle of friction (ϕ) of the sand. If seepage were to occur to an initially stable saturated or dry infinite slope of homogeneous sand, then the slope angle for stability (α_s), under seepage parallel to the slope, is reduced from ϕ to

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

where γ' = effective unit weight; and γ_{sat} = saturated unit weight of the soil. In the derivation of (1), found in many geotechnical textbooks [for example, Lambe and Whitman (1969)], it is assumed that the sandbar was initially inundated, the ground-water level was at the top of the sandbar and seepage took place parallel to the slope in a homogeneous sand mass. This analysis cannot be directly applied to the sandbars downstream of the Glen Canyon Dam because: (1) The sand bars are aggradated during floods or high dam discharges that are of short duration, so the ground-water level in many of the sandbars rarely equilibrate with the high-water level; and (2) the assumption of seepage parallel to the slope is only reasonable for the lower portion of the seepage face. The usual Glen Canyon Dam discharge regime has a low-discharge weekend component in which the dam discharge is constant (usually about 142 m^3/s) over a few days. This weekend discharge provides sufficient time for the bank-stored ground water to drain, allowing the phreatic surface to equilibrate with the low river stage (Fig. 6).

A modification to the analysis that yields (1) is now proposed. This analysis provides a simple basis to determine the limiting slopes, below which slope instability (bank slumps, mass wasting, slope failures) due to seepage would be unlikely. Consider a sandbar that was built up to its maximum slope due to a flood or a high dam discharge in which there was enough sediments in the river system for deposition on the extant sandbar (Fig. 7).

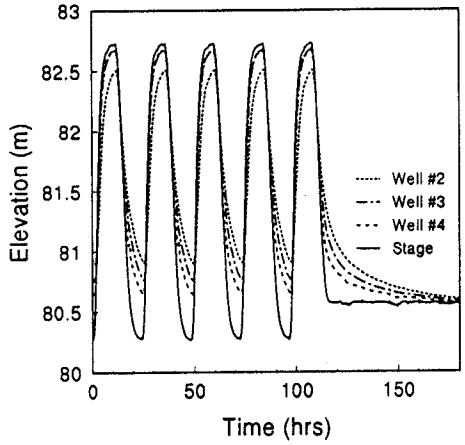

FIG. 6. Typical Well Data for Sandbar −6.5R (See Fig. 8 for Well Location)

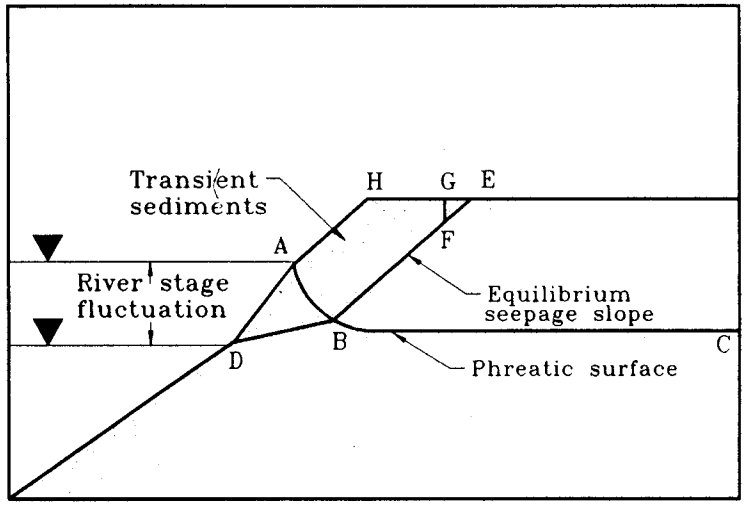

FIG. 7. Proposed Equilibrium Seepage Slope

The ensuing discharge from the dam will cause water to infiltrate into the sandbar, and at peak discharge the phreatic surface in the sandbar could be represented by the curve ABC. If the peak discharge is held for some period of time, the phreatic surface will move upward, with point A remaining fixed. The amount of bank-stored ground water will then increase. In general, the peak discharge is held for about 2–4 hr. The stable or equilibrium slope for stability under seepage is developed as follows.

1. The slope angle for a stable slope under seepage, (1), is approximately valid for the lower portion of the seepage face. That is, a line (plane) of slope α_s drawn from the lowest water level intersecting the phreatic surface at B represents the seepage equilibrium slope of the lower portion of the active sandbar face (Fig. 7).
2. The equilibrium slope for the portion of the sandbar above the phreatic surface will be its angle of friction (ϕ) described by line (plane) BE.
3. If the soil has some cohesion, then a vertical face (tension crack), GF, of depth

$$h_c = \frac{2c}{\gamma\sqrt{K_a}} \qquad (2)$$

where c = cohesion; γ = unit weight of the soil; and K_a = lateral earth pressure coefficient, will intersect the slope at BE at F. The presence of vegetation, in particular tree roots, would increase the depth of the vertical face. Capillary effects also cause the formation of vertical faces on the sand bars. However, such faces will be unstable when inundated.

The slopes DBFG and DBE represent the maximum stable slope of a sandbar under seepage for a soil with and without cohesion, respectively. These surfaces define the upper limit for slope stability under seepage and can be further degraded by rilling, tractive scour, wave impacts, and other erosion processes. The soil enclosed within BDFGHAD or DBFEHAD

constitutes transient sediments that would be in a state of flux. Sediments would accumulate and then disperse in a cyclic pattern following natural environmental conditions (for example floods) and/or operations of the dam. It was observed that built-up sandbars remained stable during slowly receding floods or high dam discharges but collapsed when regular patterns of dam discharges recommence to cause rapid fluctuations. The amount of potentially erodible sediments would increase as: (1) The range of fluctuation increases; (2) the minimum stage is lowered; and (3) the period at which peak discharge is held constant increases.

The foregoing is a very simple procedure to develop a limiting seepage surface for an otherwise complex problem. However, this procedure provides a first approximation to determine the extent of slope instability due to seepage erosion and to aid environmentalists in determining the range in which biomass would be in a state of flux.

EVALUATION OF THEORETICAL STABLE SLOPE WITH FIELD DATA

Three sites [sandbars −6.5R, 43L, and 172L (Fig. 1)] were instrumented by United States Geological Survey (Tucson Office) with pore water pressure, temperature, and tilt sensors. Ground and bathymetric surveys were conducted periodically at these three sites as well as at 26 other sandbars by a team of scientists from Northern Arizona University. Each sandbar was divided into between seven and 10 transects for detailed ground surveys. Time-lapsed photography was used by scientists from the Glen Canyon Environmental Studies office in Flagstaff, Ariz., to capture failure events on some sandbars. In this paper, the survey data from the sandbars and examinations of time-lapsed photographs from sandbar 172L are compared with the stable seepage surfaces described earlier.

A summary of the average soil property values for sandbars −6.5R, 43L, and 172L is shown in Table 1. The effective angle of friction at each instrumented site varies about 2° from the average values shown in Table 1. The cohesion values shown are the average values for the top 0.3 m of each instrumented sandbar. The average coefficient of permeability, determined from field permeability falling-head tests, is 1.3×10^{-4} m/s.

The soil parameters shown in Table 1 were obtained from tests performed according to the relevant ASTM procedures, where applicable. The angle of friction and cohesion were determined from direct shear tests performed according to the ASTM D3080-90 on disturbed samples obtained from boreholes at different depths. In the direct shear test, the sample was

TABLE 1. Average Soil Properties for Three Instrumented Sandbars

Sandbar (1)	Effective angle of friction (2)	Cohesion (kN/m²) (3)	Maximum void ratio (4)	Minimum void ratio (5)	In-situ void ratio (6)	D_{50}[a] (mm) (7)	C_u[b] (8)	Bulk unit weight (kN/m³) (9)
−6.5R	28	1.0	1.02	0.57	0.76	0.15	2.19	17.1[c]
43L	30	0.8	1.01	0.53	0.72	0.24	2.23	17.5[c]
172L	32	2.0	0.95	0.52	0.85	0.20	2.37	16.0[d]

[a]Mean grain diameter.
[b]Coefficient of uniformity.
[c]Unit weight of the stable sediments.
[d]Unit weight of the reattachment sediments.

placed in the mold and water was allowed to percolate through the sample. The intent was that the percolation of water through the sample would result in the densification of the sample to a state comparable with its in-situ state. Grain-size distribution was obtained from sieve analysis performed according to ASTM D 421 on material obtained at various depths within the sandbars. Laboratory tests were performed according to the ASTM D4253-83 and ASTM D 4254-83 standards to determine the maximum and minimum void ratios, respectively, for samples obtained at various depths. The bulk density and in-situ void ratio were determined from "undisturbed samples." These samples were obtained by gently pushing beveled edged sampling tubes into the bottom of excavations made in the sandbars. The soil around the sampling tube was then excavated and the bottom of the samples were cut level to the cutting edge of the sampling tube. The sample tubes were wrapped with fabric and coated with wax to prevent loss of moisture. The mass and volume of these samples were determined in the laboratory and the bulk density and in-situ void ratio calculated.

The maximum depositional slope attained during aggradation by most of the sandbars downstream of the Glen Canyon Dam was 26°, which was less than the angle of friction of soil samples tested in the laboratory. Two possible reasons for this are: (1) Small differences in densities between the laboratory samples and the field; and (2) the sandbars are formed under flowing water, which produces a destabilizing effect due to tractive forces from flowing water, resulting in a decrease in the maximum depositional slope.

Sandbar −6.5R is located 10.5 km upstream of Lees Ferry (Fig. 1) on the right bank of the Colorado River. The soil consists of a fine sand layer partially divided by a half-bowl-shaped layer of clayey silt approximately 14 cm thick (Fig. 8). This sand bar has a gentle slope of about 1:6. Rill erosion is evident on the sandbar face but no slope failure was recorded during the two-year study period. The stable slope AB (Fig. 9) determined from the survey data is 10° compared with a predicted value of 11.6° using (1) and the appropriate soil properties, $\gamma = 16$ kN/m³ and $\phi = 28°$.

Sandbar 43L is located 69.4 km downstream of Lees Ferry on the left bank of the Colorado River. The sand at this site consists essentially of a

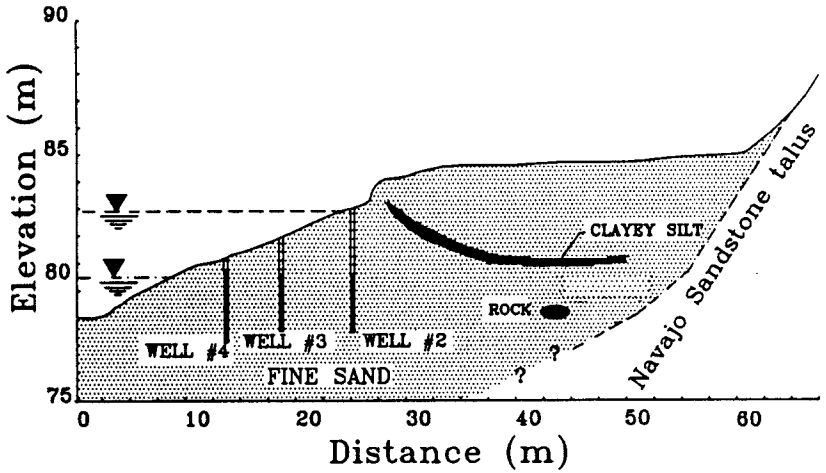

FIG. 8. Geological Section of Sandbar −6.5R

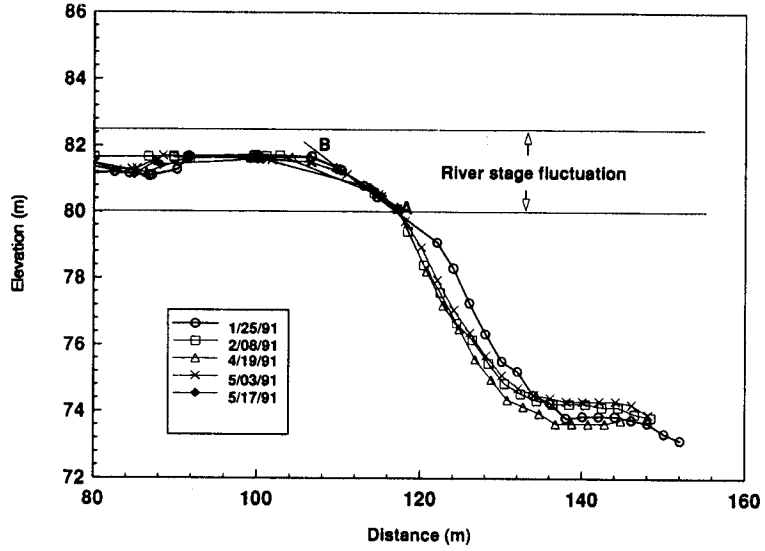

FIG. 9. Comparison of Predicted Equilibrium Seepage Slope with Ground Survey Data for Sandbar 6.5R

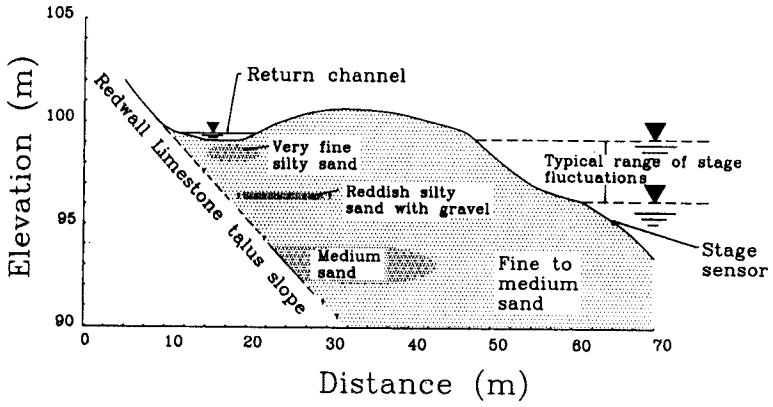

FIG. 10. Geological Section of Sandbar 43L

fine-medium sand with pockets of fine sand and gravel. At the back of this sandbar is a redwall limestone talus slope with a narrow but deep return channel (Fig. 10). Rill erosion dominated the sandbar face. A finite-element seepage analysis using the coupled stress theory of Biot (1941) was carried out to predict the phreatic surface under transient river stage for this sandbar with a slope of 26°. The procedures for dealing with unsaturated-saturated flow regions were similar to those suggested by Desai and Li (1983). The analysis was conducted for the largest dam discharge that occurred (in June 1991) during the study period (Fig. 11). At peak river stage, the predicted phreatic surface is shown by curve ABC (Fig. 12). The predicted equilibrium sandbar face is shown by the plane DBE with the slopes DB and BE of 12.6° and 30°, respectively. Maintaining the peak river stage at a constant level for 2–4 hr, did not change the position of B significantly. The predicted

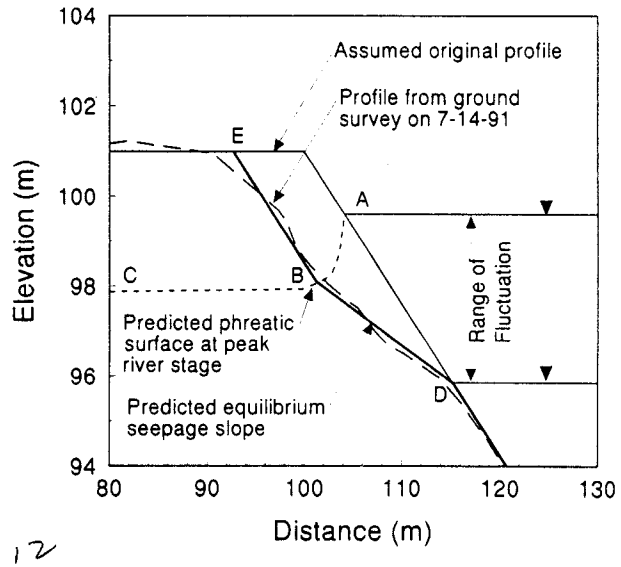

FIG. 11. Hydrograph Just Below Glen Canyon Dam for June 1991

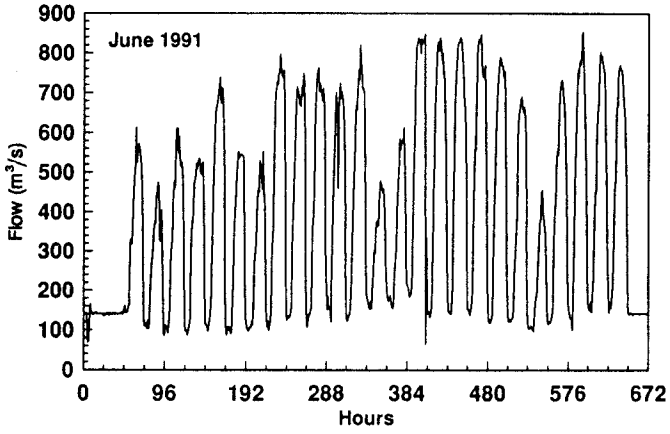

FIG. 12. Comparison of Predicted Equilibrium Seepage Slope with Ground Survey Data for Sandbar 43L

vertical face as a result of the small cohesion of the top 0.3 m of the sandbar is only 0.17 m $[2c/(\gamma\sqrt{K_a}) = 2 \times 0.8/(16\sqrt{0.33})]$ and is neglected. The predicted stable sand bar face is in good agreement with the survey data. No slope failure event was recorded on sandbar 43L during the two year study period; the sandbar aggradated during this period.

Sandbar 172L, located 277 km downstream of Lees Ferry, was the most dynamic sandbar of the three instrumented sites. The stratigraphy of this sandbar consists mainly of a fine to medium sand with an active aggradational/erosional zone (Fig. 13). Sandbar 172L was monitored by both ground surveys and time-lapsed photography. Rilling, slumping, slope failures, and aggradation occurred in several cycles during the study period. From May 19 to May 30, 1991, a constant discharge of 425 m^3/s was released from the

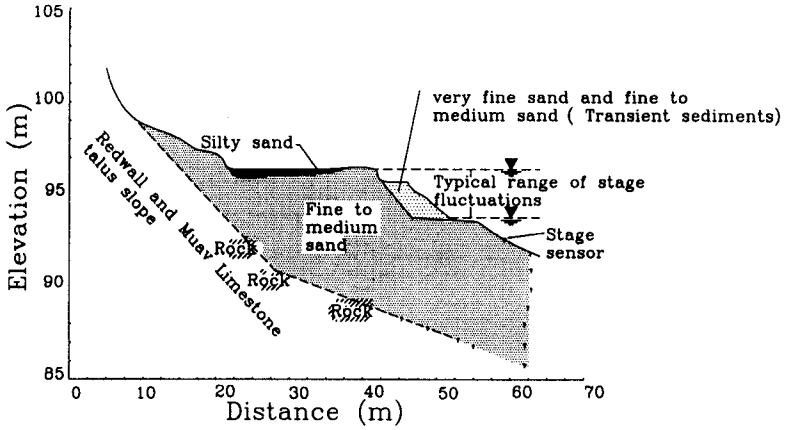

FIG. 13. Geological Section of Sandbar 172L

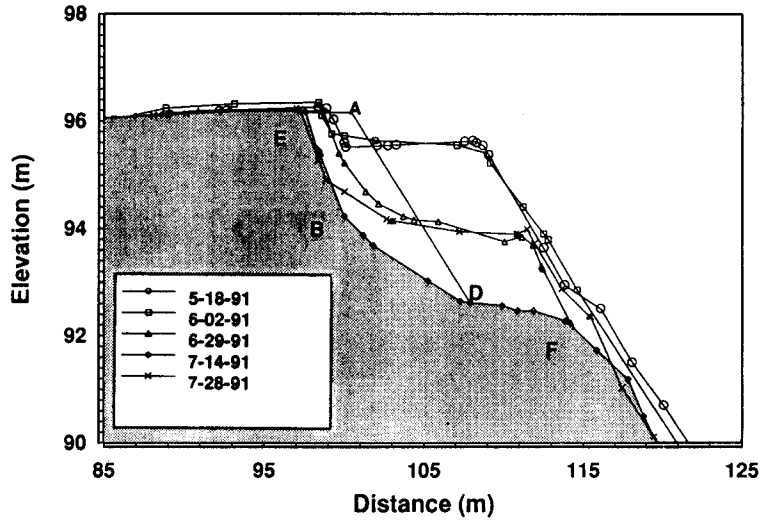

FIG. 14. Ground Survey Profiles from May to July 1991 for Sandbar 172L

Glen Canyon Dam. On May 18, 1991, a ground survey showed that this sandbar aggradated to a maximum slope, AD, of 26° (Fig. 14). On June 4, 1991, a 27-day test flow period designed to simulate wide fluctuating flows that are normally released during summer periods was initiated. The minimum discharge was 68 m^3/s and the maximum was 836 m^3/s, with a mean value of 380 m^3/s. Time-lapsed photography revealed that a massive slope failure occurred at low river stage on June 18. The failure extended up to the profile EBDF. The sandbar then aggradated from June 19 and collapsed again by July 14. The profiles measured by ground surveys on June 29 and July 28 (Fig. 14) represent the sandbar in an aggradational mode. When the sandbar aggradated up to approximately its maximum depositional slope (26°), further slope failures followed. But none of the slope failures proceeded beyond the profile EBDF. During the months of May, June and

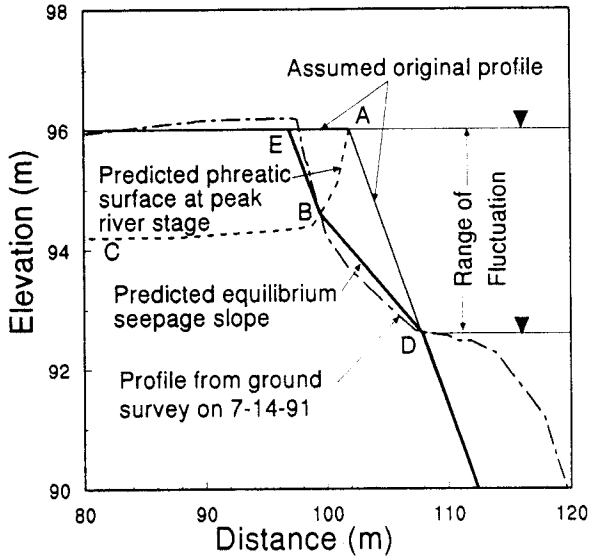

FIG. 15. Comparison of Predicted Equilibrium Seepage Slope with Ground Survey Data for Sandbar 172L

July, 1991, several cycles of slope failures and aggradation were observed on sandbar 172L.

Prior to a flood in 1983, caused by an unusual springtime release from the dam, the width of sandbar 172L was narrower than the current maximum width as shown in Fig. 14. The lowest river stage at that time was at about elevation 92.6 m (Stevens, 1992). It was assumed that sandbar 172L had achieved a maximum slope AD of 26° (Figs. 14 and 15) prior to the 1983 floods, and subsequently collapsed to the stable slope DBE. Using (1), the predicted inclination of BD is 11.6° and the inclination of DC is $\phi = 26°$. The predicted equilibrium seepage plane, DBE, appears to be in good agreement with the field data (Fig. 15). Any further enlargement of this sandbar with slopes greater than the stable seepage slope will eventually collapse back to the slope face DBE. The equilibrium seepage face, BDE, becomes the preferred failure plane since this plane is a natural discontinuity between the older and freshly deposited or reattachment sediments.

CONCLUSIONS

Seepage erosion significantly contributes to the destruction of sandbars downstream of the Glen Canyon Dam. The simple analysis proposed in this paper could be used to predict, as a first approximation, the equilibrium seepage sandbar face that could be attained under fluctuating river stages. The results of the analysis show that the equilibrium seepage slope below the phreatic surface in a sandbar will be approximately one-half the soil's angle of friction (range 11° to 14° for the sediments downstream of the Glen Canyon Dam), while above the phreatic surface the maximum slope angle will be the soil's angle of friction (range from 26° to 32°). Field data generally were in agreement with the predictions from the analysis.

The larger the range of fluctuation, the greater the active zone of seepage

erosion. Sediments, enclosed by this (dynamic) equilibrium seepage slope and the maximum slope angle, will undergo cyclic aggradation and erosion depending on the dam discharge regimes, the local hydraulic conditions, and the availability of sediments. The cyclic pattern of erosion (slope failures) and aggradation that is evident on many of the sandbars downstream of the Glen Canyon Dam involves transient sediments deposited during favorable hydraulic and hydrologic conditions.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_u = coefficient of uniformity;
c = cohesion;
D = mean grain diameter;
e = void ratio;
G = specific gravity of soil;
h_c = depth of tension crack;
i = hydraulic gradient;
i_{cr} = critical hydraulic gradient;
K_a = coefficient of lateral active earth pressure;
α_s = slope angle for stability under seepage;
γ = bulk unit weight;
γ' = effective unit weight; and
ϕ = angle of friction.