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EFFECTS OF SOIL MOISTURE DYNAMICS ON SLOPE FAILURE AT HYRUM RESERVIOR, UTAH

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ABSTRACT

Field observations of shoreline conditions at Hyrum Reservoir, Utah, were conducted during the summers of 1991 to 1993. A process of bluff retreat is described for a multiple-layered bluff environment of sand and clay layers. Failure is initiated by wetting and drying of clay sediments, which produces horizontal cracks within bluff material. These cracks appear to penetrate to a depth of approximately 100–150 mm before initiating vertical cracking in the sediments. The vertical cracks are propagated by continued drying of the surface sediment, ultimately leading to failure of the bluff material. The physical dimensions of sediment blocks succumbing to this mechanism range from a few hundred millimetres up to 3 m on a side, with a depth of approximately 100–150 mm. The mechanism described here appears to operate optimally when the supply of subsurface moisture is abundant and nearly continuous throughout the spring and early summer. Reservoir draw-down, large capillary fringe effects in the bluff and periodic wetting from upslope undrained hollows are the dominant moisture controls at this site. Moisture delivery to the face is strongly influenced by anisotropy of saturated hydraulic conductivity in the alternating clay and sand layers and related differences in sediment texture.

KEY WORDS slope failure; capillary fringe; slope hydrology

INTRODUCTION

Slope failure and landsliding have received considerable attention in the geomorphology and engineering literature (e.g. Abrahams, 1986; Chandler, 1986; Huang 1983). Stability analyses of shallow transitional slides have been applied to a variety of environments (Sel y, 1982; Sidle *et al.*, 1985). In stream and coastal environments, bank failure often occurs in near-vertical material, where wedge-type failures predominate. Susceptibility to movement in bank and bluff environments depends upon the balance of forces (motive and resistive) associated with the most critical mechanism of failure.

Thorne (1978; see also Thorne and Tovey, 1981) notes that of the potential factors causing failure, size, geometry and structure of the bank/bluff are key, along with the engineering properties of the material, the hydraulics of flow in the channel or waves at the bluff face and climate conditions. Table I presents a summary of selected failure mechanisms and the environments in which they commonly occur. For near-vertical slope surfaces, such as those found in a variety of bluff environments and along river banks, the mechanisms of failure are typically related to material properties (e.g. Grissinger, 1966; Thorne and Tovey, 1981), pore water pressures (e.g. Hagerty *et al.*, 1981; Chandler, 1986), and tractive erosion of bluff or bank material (e.g. Carson and Kirkby, 1972; Hooke, 1979). Hillslope failure mechanisms listed in Table I also focus on material properties and slope moisture conditions (e.g. Bird and Armstrong, 1970; Iverson, 1986; Chandler, 1986). However, upslope contributing area and slope (Dietrich *et al.*, 1986; Montgomery and Dietrich, 1992; Dietrich *et al.*, 1992) are also recognized as major controls on slope stability and channel

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Table I. Summary of selected slope and bank failure mechanisms

Operative mechanism	Example (source)
Tractive erosion by rivers and waves	River banks and coasts (Carson and Kirkby, 1972; Brunsden and Kesel, 1973; Hooke, 1979)
Cantilever failures	Composite stream banks (Thorne and Lewin, 1979; Thorne and Tovey, 1981)
Pore pressure	Clay slopes (Chandler, 1986); river banks (Hagerty *et al.*, 1981)
Reservoir filling or draw-down	Grand Coulee Dam (Schuster, 1979); Columbia River (Jones *et al.*, 1961)
Upslope contributing area or slope	Stream headcuts (Dietrich *et al.*, 1986; Montgomery and Dietrich, 1992; Dietrich *et al.*, 1992)
Slope hydrology	Landslides (Sidle *et al.*, 1985; Iverson, 1986)
Piping	Ohio River (Ullrich *et al.*, 1986)
Bed degradation (over-steepening)	River banks West Tennessee (Simon, 1989); laboratory channels (Alonso and Combs, 1990)
Pop-out failure	Steep banks (Carson and Kirkby, 1972; Simon, 1989)
Wedge failure	Loess deposits—Iowa and Tennessee (Lohnes and Handy, 1968); river banks (Osman and Thorne, 1988)
Groundwater sapping	Scarborough Bluffs (Bird and Armstrong, 1970); Ohio River (Ullrich *et al.*, 1986)
Material properties	Clay mineralogy (Grissinger, 1966; Goss, 1973; Bovis, 1986)
Slope maintenance	Cleanout from base of slope (Carson and Kirkby, 1972; Brunsden and Kesel, 1973)

head initiation.

Several investigators (e.g. Lohnes and Handy, 1968; McGreal, 1979) have conducted Culmann wedge failure analysis (Culmann, 1866) by showing that:

$$H_c = \frac{4c}{\gamma}\,\frac{\sin\beta\cos\phi}{[1-\cos(\beta-\phi)]} \tag{1}$$

where H_c is the critical height for slope failure, β is the potential failure plane, ϕ is the angle of friction, c is material shear strength, and γ is unit weight of the soil at natural moisture content. Lohnes and Handy (1968) note that it is common for a tension crack to develop behind the slope face, extending downward from the top of the slope. Culmann wedge analysis suggests that if the crack extends down to a potential failure plane, H_c is reduced by the crack depth (z) (Figure 1). The standard procedure for calculation of Equation 1 is to solve for H_c and then to determine the critical height of the slope with a crack ($H_c - z$).

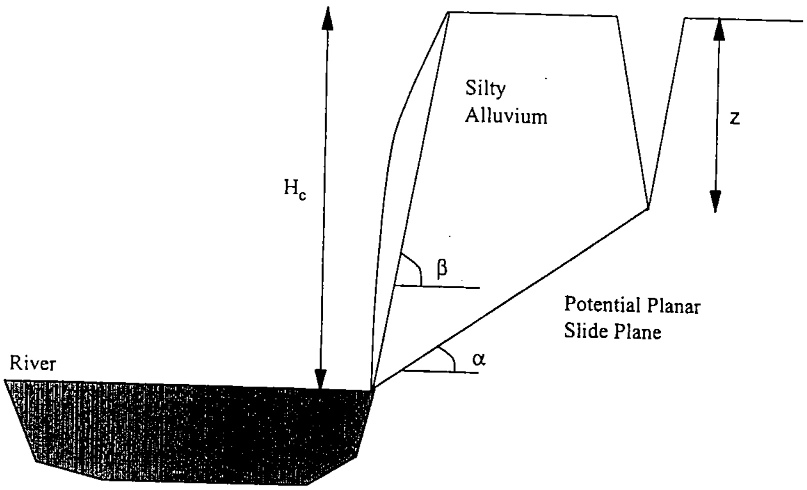

Figure 1. Culmann wedge analysis (after Lohnes and Handy, 1968)

In many natural bluff environments and along reservoir shorelines, other site-specific factors may play an important role in wedge-type failure initiation, including microclimate, upslope hydrology, sediment layering, reservoir draw-down and extreme bank height. Studies of slope failure in these environments have typically been conducted on massively bedded material (e.g. Turnbull *et al.*, 1966; Bird and Armstrong, 1970; Schuster, 1979). Rulon and Freeze (1985) found, however, that multiple seepage faces present on hillslopes consisting of layered material are very important structurally. They also noted that stability of these slopes is strongly dependent on the position and hydraulic properties of impeding layers. Extreme bank height may affect the utility of Equation 1. Shallow development of tension cracks in banks of extreme height will exert little or no influence on slope stabiity since $H_c \gg z$.

Studies have also shown that reservoir draw-down (Schuster, 1979) may effect wedge-type and other failures by changing or creating internal stress in shoreline materials. This stress act toward the free face of the bank or bluff, while at the same time creating unbalanced pore pressures with that water behind the bluff face.

Although reservoir draw-down lowers the local water-table, the capillary fringe of some materials may significantly extend the influence of saturated zone conditions. Gillham (1984) and Zaltsberg (1986) show, for example, that the height of the capillary fringe in fine sand, sandy loam and sandy clay is in the range 0·35–1·2 m, 1·2–3·5 m and 6·5–12·0 m, respectively. The capillary rise formula can be written:

$$h = \frac{2\sigma}{\rho g r} \tag{2}$$

where h is the height of rise, σ is the surface tension of water, ρ is the density of water, g is the acceleration due to gravity, and r is the radius of curvature of the meniscus. The height or rise for different materials is most strongly influenced by r. O'Brien (1982) notes that in many field settings, a declining water-table (or reservoir surface) would produce the impression of drainage from the groundwater zone, whereas, in fact, little mass transfer may have occurred. For bluff failure concerns, this can be an important but little recognized factor.

This paper describes a bluff failure system in which the conditions noted above (layered material, large annual draw-down, extreme bluff height and strong capillarity) exist. The objectives of this research are to:

1. characterize the intact bluff and slumped bluff environment, including bluff and nearshore topography, sediment layering, texture and chemical composition, moisture conditions and draw-down history, and
2. develop a conceptual model of bluff failure based on traditional wedge-type analysis, by combining the effects of measured sediment layering properties and slope/water-table conditions.

STUDY AREA AND METHODS

The study area for this research is the Hyrum Reservoir located along the Little Bear River, Cache County, Utah. The reservoir has a drainage area of approximately 570 km^2 and a shoreline of approximately 8·9 km. It was opened as an irrigation and recreation facility in 1935. Since that time, Hyrum Reservoir has experienced extensive shoreline erosion resulting in diminished reservoir capacity and increased turbidity of lake water. The reservoir area is located within the region once inundated by Lake Bonneville, circa 20 000 years BP (Williams, 1962; Sack, 1989). The surficial geology of the location was characterized by Williams (1962) as consisting of fine sand and silt deposits overlain by deltaic sand and gravel of the Provo formation. Evans *et al.* (1991) have re-mapped the area and attribute the fine sands and silts (along with clay sediments) to lake deposits of the Bonneville stage. In the study area, sand layers range from 5 to 35 mm in thickness and silt/clay layers are approximately 50–150 mm in thickness (see Figure 3). Total vertical relief of these deposits ranges from 3 to 8 m in the study area.

Repeated topographic surveys were conducted along a study section of the south shore of Hyrum Reservoir during August and September of 1991 and 1992 (Figure 2). An additional field investigation of shoreline processes and morphology was conducted during the spring and early summer of 1993. The objective of this final visit was to identify the nature and extent of geomorphic processes acting at high water levels.

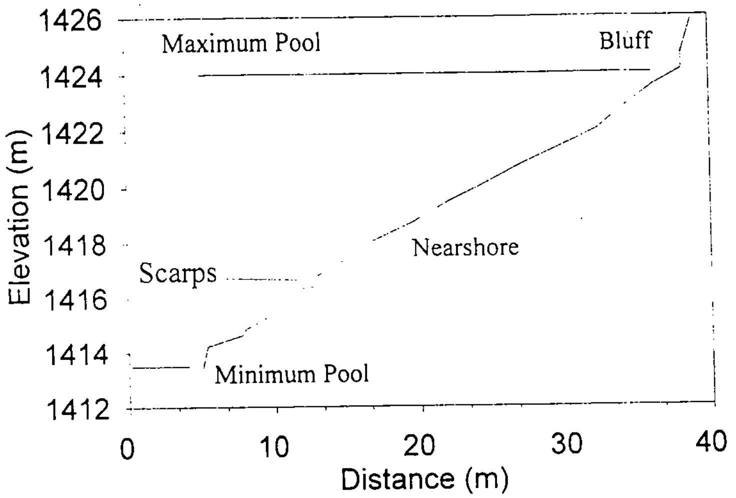

Figure 2. Profile of bluff and nearshore environment

The bluff and foreshore were characterized using a geodetic total station and reflecting prism. Within the study section, several large blocks (0·5–1 m^3) of bluff sediment had become detached or, in some cases, failed entirely. The block material was noticeably drier than surrounding bluff materials *in situ* (see Figure 3). In order to characterize these differences, a 3 m × 6 m bluff face containing a number of these features was selected for detailed measurements. In the field, attempts were made to measure soil matrix potential using a 'quick draw' vacuum gauge tensiometer. Most measurements were out of tensiometer range. Accordingly, sediment samples were extracted from both intact and incipient failure locations for laboratory analysis of sedimentological and hydrological properties.

Sediments were analysed for texture, gravimetric moisture content, saturated hydraulic conductivity and clay mineralogy. For textural analysis of the sediments, four samples were extracted, two from clay-rich layers and two from layers consisting primarily of sand. Sediment was analysed using the hydrometer method (Gee and Bauder, 1986) and characterized by portions of sand, silt and clay according to USDA standards. Nine sediment samples were analysed for gravimetric moisture content, θ, using standard oven drying techniques (Gardner, 1986). Four of these samples came from intact bluff material, two were from blocks exhibiting characteristics of incipient failure, two additional samples were taken from directly behind a detaching block, and a final sample was taken adjacent to a detaching block. Saturated hydraulic conductivity, K_s, was determined from laboratory constant-head ring permeameter tests. A constant head was maintained above a 2300 mm^2 soil surface for a 4 h time period. Separate tests were run to determine horizontal and vertical components of K_s for clay-rich sediments. Sand samples were repacked prior to determining K_s and therefore only a single test was completed. Finally, four sediment samples were subjected to clay mineralogical analysis using X-ray diffraction techniques (Whittig and Allardice, 1986). Standard methods were applied to identify smectite/montmorillonite, illite and kaolinite in the clay minerals.

RESULTS

Characteristics of bluff environment

A topographic profile of the lower bluff and nearshore environment of the study area is shown in Figure 2. The total relief of the bluff is approximately 5 m at this site. The nearshore environment maintains a slope of between 0·2 and 0·35 throughout most of the profile. However, small scarp-like features (0·2–0·3 m in height) exist within the nearshore environment. The position of these scarps on the profile suggests that they are formed at very low lake levels (see Figure 2).

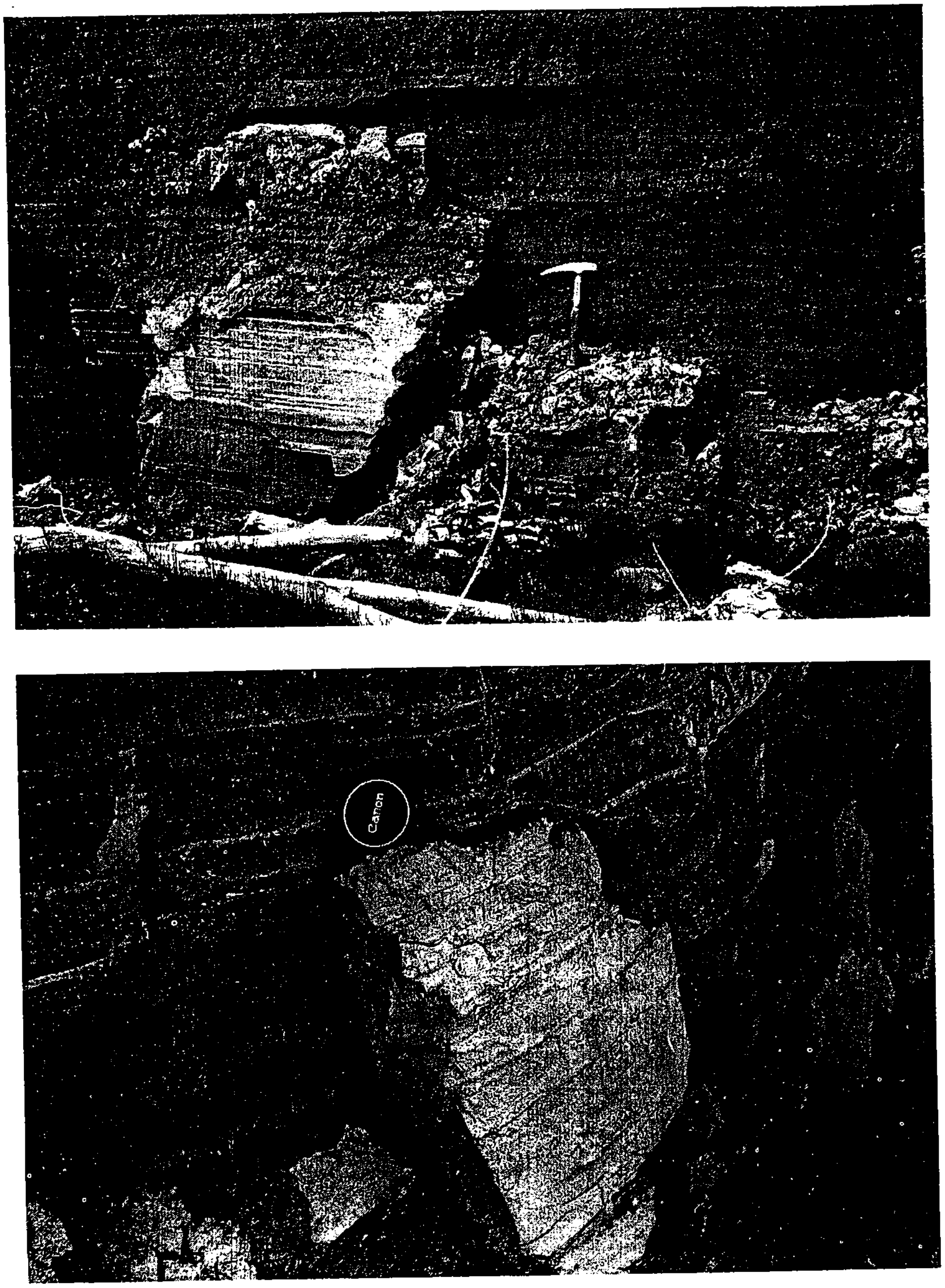

Figure 3. Photographs indicating nature of interbedded sediments and character of bluff environment

Results of textural analysis (Table II) shows that the interbedded sediments have distinct textural properties, such that sand-rich layers are characterized by >50 per cent sand and <10 per cent clay (samples 1 and 3, Table II). By contrast, the clay-rich layers have <10 per cent sand and >20 per cent clay (samples 2 and 4, Table II). Silt content is highly variable in the sand layers but is surprisingly constant in clay-rich layers (see Table II).

Gravimetric moisture content of the nine samples is listed in Table III. Values of θ for four samples taken from intact bluff material exhibit the greatest moisture content (samples 1–4, Table III). Moisture content

Table II. Textural analysis of interbedded sediments

Sample number	% Sand	% Silt	% Clay	USDA classification
1	51	40	9	Loam
2	7	72	21	Silt loam
3	81	14	5	Sand loam
4	4	72	24	Silt loam

for these samples ranged between 30 and 33 per cent. By contrast, values of θ for samples taken from the detaching block were less than 5 per cent (samples 5 and 6, Table III). The two samples taken from behind the detaching block had a moisture content similar to that of *in situ* material (samples 7 and 8, Table III), whereas the final sample taken adjacent to the detaching block had a moisture content roughly midway between *in situ* and detaching block material (samples 9, Table III).

Hydraulic conductivity of the bluff material was determined separately for sand and clay-rich layers. The value of K_s for the horizontal component of clay sediments was $18\,\mathrm{mm\,hr^{-1}}$ whereas that for the vertical component was on the order of metres per hour. The sand layer had a K_s value of $55\,\mathrm{mm\,hr^{-1}}$.

Results of clay mineralogical analyses indicate that clay-rich layers within the bluff environment consist primarily of smectite/montmorillonite clays. The abundance and crystallinity of these minerals were notable. Montmorillonite clays have well documented physical properties including extensive shrinking and swelling in the presence of moisture. By contrast, analysis of sand-rich layers shows much less abundance of clay minerals and less pronounced crystalline structure.

Reservoir dynamics

Recorded water levels for Hyrum Reservoir (U.S. Bureau of Reclamation, 1991) indicate rapid surface draw-down of >10 m, attributable to irrigation withdrawals occurring during the summer. A sample time series of reservoir levels (Figure 4) shows that this phenomenon occurs annually, and is most pronounced during the late summer. Typically, the level of the reservoir drops an average of 2–4 m in a single month of the summer (see Figure 4). The maximum level of the reservoir (shown on Figure 2) reaches the base of the bluff environment during early summer. It falls rapidly throughout the summer reaching a minimum in September (Figures 2 and 4).

DISCUSSION

Capillary fringe and water-table response

The previous section has shown that the bluff environment is never inundated by the reservoir water surface. Nevertheless, the failure site is seasonally affected by saturated conditions. Surveys shown in Figure 2

Table III. Gravimetric moisture content of bluff materials

Sample	Before drying (g)	After drying (g)	% H_2O	Description
1	119·62	91·69	30	Intact bluff
2	166·75	126·60	32	Intact bluff
3	218·92	167·68	31	Intact bluff
4	110·56	83·11	33	Intact bluff
5	151·23	144·21	5	Detached block
6	228·86	222·48	3	Detached block
7	168·40	127·23	32	Behind block
8	270·43	214·28	26	Behind block
9	168·29	149·58	13	Adjacent to block

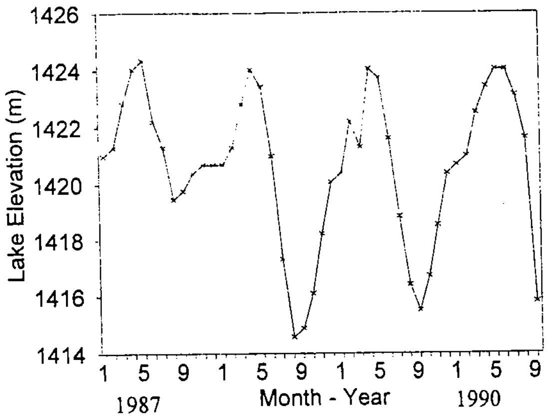

Figure 4. Time series of reservoir levels (1987–1990)

indicate that maximum reservoir elevations reach only the base of the bluff environment. Capillary fringe characteristics of the bluff material (textural characteristics shown in Table II) indicate that the tension-saturated zone may extend 1·2–3·5 m above the water-table, based on literature values presented in Zaltsberg (1986). Figure 5 shows the extent of capillary fringe for different materials, as estimated by the capillary rise formula (Equation 2). The extent of the tension-saturated zone is highly dependent upon the textural and structural characteristics of the reservoir bank material. Gillham (1984) notes that if the radius of Figure 5 is considered to be the largest pore in the bank material, then height of rise (l), can be regarded as the air-entry value $(ha = -1)$ for the material. If it is also assumed that the pore radius is equal to the grain diameter, then Figure 5 shows the extent of the zone of tension saturation that could be expected for bank materials of different texture.

In a layered bluff material, such as that discussed in this paper, there are several assumptions associated with the application of Figure 5. Assuming the radius of the largest pore to be equal to the grain diameter is questionable. However, O'Brien (1982), Gillham (1984), and others have shown that it is safe to conclude that medium- to fine-textured materials can remain saturated under large negative pressures, in the absence of secondary porosity caused by structuring or aggregation. Although the interbedded sediments at the study site exhibit no structuring *per se*, there is structure in terms of the alternation of fine sand and silt/clay. Although the composite material undoubtedly affects the capillary-fringe characteristics of the bluff as a whole, the extent of tension saturation is assumed to be roughly similar to the range for single values shown in Figure 5.

Proposed model for bluff failure

The proposed model for bluff failure is based on the sensitive relationship between sediment characteristics, reservoir draw-down and proximity to upslope sources of water. As reservoir draw-down occurs,

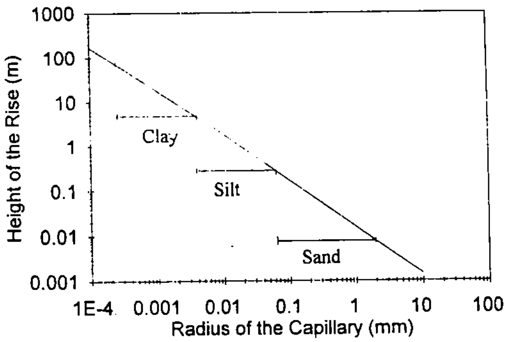

Figure 5. Diagram illustrating the role of capillary fringe in different sediments (after O'Brien, 1982)

Figure 6. Oblique photograph of study site depicting upslope hollow

pore pressure in the bluff sediments remains high due to tension saturation, with some seepage of groundwater from the bluff face. This process is aided and abetted by topographic convergence within an undrained zero-order catchment, upslope from the exposed face (Figure 6). In fact, this upslope convergence appears to control the spatial extent of the failure mechanism described in this paper. The oblique aerial photo in Figure 6 shows that the area of bluff affected by the proposed model is approximately 50 m in width, immediately downslope from the undrained hollow. At the same time as moisture is supplied to the face from below and upslope, the bluff face is subjected to intense drying as a result of high incident solar radiation. Drying is observed to take place along contacts between sand and clay layers, which have distinct textural and hydrological properties, as noted earlier.

As drying progresses in the clay-rich layers, shrinkage occurs, resulting in crack initiation horizontally along the clay/sand interface. Cracks extend inward to the bluff sediment to a depth of approximately 100–150 mm. After the crack is initiated, the moisture supply to the upper part of the detaching block is cut off and horizontal drying is intensified owing to the lack of moisture supplied to the surface (Figure 7).

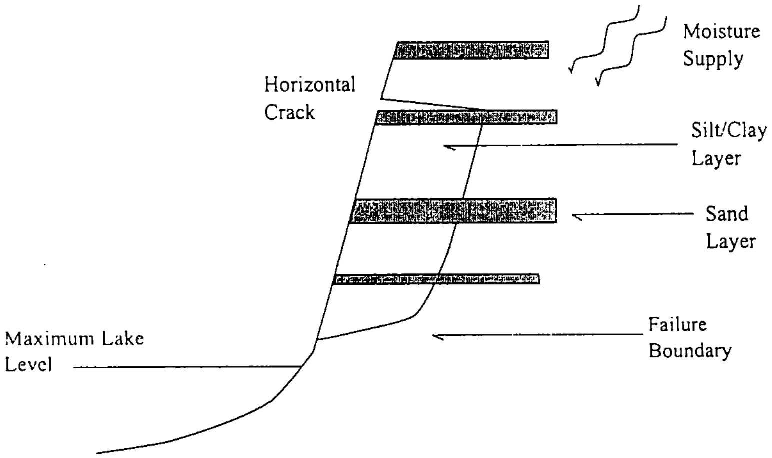

Figure 7. Conceptual model of bluff failure based on interbedded sediments, capillary fringe, and relative lake level

It appears that horizontal penetration determines the inward depth of drying. The dry clay sediments then initiate vertical cracks which enlarge and extend as the drying continues. Because these vertical cracks detach the sediment block from the shoreline bluff, the moisture content of the block diminishes rapidly, from roughly 30–35 per cent to <5 per cent (Table III), as vertical cracking is extended. Finally, the vertical crack becomes so extensive that the shear stress on the surface between the bank and block exceeds the cohesive forces in the bluff, and failure occurs (Figure 7).

This process appears to be limited to only the lowest 2 m of the bluff surface. Above this elevation, effects of capillary fringe appear to be greatly reduced, and few blocks succumb to the mechanism described here. At shoreline sites where upslope hydrology does not produce convergence and bluff sediments do not exhibit the distinctive layered character, other mechanisms (e.g. desiccation and frost action) appear to control bluff recession.

Role of other geomorphic processes

The failure mechanism described here appears to be responsible for bluff retreat at select locations within the study site. However, other notable geomorphic processes play an active role in determining the rate at which bluff recession occurs. Wave activity observed during early summer 1993 (at the highest water level) was directed very near the base of the bluff environment. However, a complete survey of the shoreline revealed little or no direct evidence of undercutting. By contrast, wave activity appeared to be extremely effective at removing failed blocks that had collected at the base of the bluff. This process of removal clearly affects bluff retreat by exposing the base of the bluff surface and maintaining near-vertical bluff slopes.

During the wettest conditions (April to June), some seepage was noticed at the contact between sand and silt/clay layers. Occasionally, this seepage selectively removed sand near the face of the bluff. However, there was no clear pattern relating sapping associated with sand removal and the failure mechanism described here.

Frost activity is an active geomorphic agent in the local climate. Little evidence of frost action was apparent during field inspections of the bluff surface. Nevertheless, it clearly plays a role in expanding existing cracks developed during the previous summer and possibly initiates new cracks in the bluff material, although these were not visible in the field.

CONCLUSIONS

The mechanism of bluff failure described here is driven by high pore pressures in bluff sediments due to reservoir draw-down and subsequent drying of these sediments during low water conditions. Strong capillary forces in the bluff materials act to maintain high moisture content at the base of the bluff where the failure mechanism operates.

The mechanism proposed here was observed at a single study area located within a region of fine-grained deposits of Lake Bonneville. However, it may have more widespread application to fine-grained fluvial or aeolian deposits. This mechanism may also be responsible for stream-bank failure events at flows significantly below bankfull levels. Future research efforts should consider effects of capillary fringe on such erosion events. Additional research is required to establish the magnitude of the mechanism described here relative to that of other active geomorphological forces. Other important issues that need to be addressed include the following:

1. documentation of *in situ* capillary fringe is required to explore the effect of layered media on height of capillary rise in the bluff;
2. *in situ* measurement of bluff moisture and pore pressure are needed to test the proposed conceptual model;
3. development of a water balance model is required for the upslope hollow.

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