PREDICTION OF RESERVOIR SHORELINE EROSION

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Abstract. This paper describes the development and application of a new method for predicting wave-induced shoreline erosion on a reservoir. A method that relates erosion rates to winds, water levels, fetch distances, and a simplified representation of the shape of beach profiles was developed and applied to the shores of Hartwell Lake, South Carolina/Georgia, a U.S. Army Corps of Engineers (USACE) hydropower and flood control reservoir. Historical shoreline change rates were quantified by comparing available digital aerial photos from different years, and the erosion prediction model was calibrated using these computed erosion rates.

This paper also discusses the differences between the newly developed method and the existing approaches in the literature. Application of the shoreline erosion methodology to the Western Carolina Sailing Club in Anderson County, SC is also described in this paper.

INTRODUCTION

In lakes and reservoirs there are several physical processes acting on the shore that can influence erosion rates, including surface runoff, groundwater seepage, movement of lake ice, lake currents, wind action, wave action and slumping of the bluff. The Shore Protection Manual (USACE, 1984) states that water waves are the dominant force in determining the geometry and geologic composition of beaches in coastal environments. Surface waves generally derive their energy from the winds. A significant amount of this wave energy is finally dissipated in the nearshore region and on the beaches.

Parameters including offshore bathymetry, beach slope, elevation of toe of the bluff and dynamic factors including incident wave climate and water level affect the amount of wave energy reaching the shore. The incident wave climate depends on winds and fetches and controls wave energy approaching the shore. The water levels in the lake are affected by hydrological and meteorological conditions and reservoir operation.

Shoreline erosion was predicted by an approach that relates erosion rates to wind wave forces. A simplified representation of the shape of the beach profile is employed. Shoreline erosion prediction method was calibrated using historical shoreline change rates inferred from available digital aerial photos.

METHODOLOGY

The erosion prediction methodology is derived based on the equation by Thorn et al. (1980) that quantifies the erosion rate for cohesive sediments under water.

$$\frac{dm}{dt} = M\left(t - t_c\right) \quad (1)$$

where m is the mass of sediment eroded from the bed (kg/m^2), t is time (s), t and t_c are the bottom shear stress and the critical shear stress (pascals), M is an empirical coefficient ($M = 9.73\times10^{-8}$ s/m).

A schematized beach profile with uniform sediment properties, as shown in Figure 1, is considered. Also it was assumed that monochromatic, linear waves

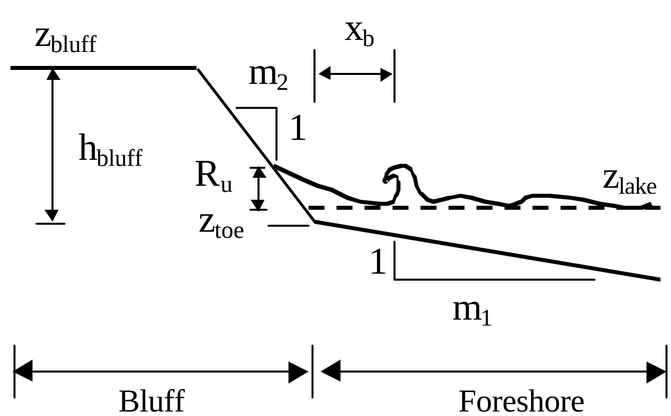

Figure 1. Simplified geometry of shoreline. Parameters defined in Table 1.

approach the beach. A reservoir is likely to feature deepwater waves over much of its surface area, because of the relatively short wave periods resulting from short fetches. Wave runup and recession rate are calculated in terms of influencing parameters such as: simplified profile shape, water level, wind direction and magnitude, and sediment characteristics. Assuming waves will break before reaching the shore, three cases, as shown in Figure 2, are considered.

The following list summarizes the steps for the erosion rate prediction methodology (Elci and Work, 2002):

1. Wind speed, wind direction, and water level data are obtained. Fetches are measured on a map for each location and wind direction.
2. Geometry of the shoreline of interest is surveyed or estimated from a topographic map and values of z_{bluff}, z_{toe}, z_{lake}, h_{bluff}, m_1, and m_2 are measured or estimated.
3. Wave runup (R_u) is calculated by the following equation as a function of beach slope, m_1, wave height, H, and wave period, T.

$$R_u = 1.24 H^{0.5} T m_1 \qquad (2)$$

4. The time t (in seconds) required for waves crossing a fetch of length X for a wind speed u is calculated:

$$t = 77.23 \frac{X^{0.67}}{u^{0.34} g^{0.33}} \qquad (3)$$

If calculated time, t is less equal to 1 hr then waves are assumed fetch limited. If calculated time, t is greater than 1 hr waves are duration limited.

Table 1. Definition of Parameters Used to Define Simplified Beach Profile Geometry

Parameter	Definition
z_{bluff}	Elevation of the top of the bluff
z_{toe}	Elevation of the toe of the bluff
z_{lake}	Elevation of the lake water surface
h_{bluff}	Height of the bluff measured between z_{bluff} and z_{toe}
R_u	Wave runup, a local maximum or peak in the instantaneous water elevation at the shoreline
m_1	Slope of the foreshore
m_2	Slope of the bluff
x_b	Distance from the toe of the bluff to the breakpoint
l	Wetness (submergence) ratio defined by: $l = (z_{lake} + R_u - z_{toe}) / (z_{bluff} - z_{toe})$

Calculate new fetch, X_{new}, using the following equation.

$$X_{new} = 1.523 * 10^{-3} \left(u_* t^3 g\right)^{1/2} \qquad (4)$$

5. Wave runup is added to the water level and compared with the elevation of the toe of the bluff:

a) If the water level + wave runup is below the toe ($z_{lake} + R_u < z_{toe}$), recession rate is assumed proportional to the erodibility of the cohesive shore. Erodibility is calculated in terms of excess shear applied to the soil, assuming a quadratic relationship between the bed shear stress and near bed velocity defined by linear wave theory. Then recession rate R (m/s) is calculated as a function of foreshore slope, m_1, wave period, T, distance to the breaker line from shore, x_b, friction factor under waves, f_w (=3.4×10^{-3}), density of water, r, sediment density, r_s, an empirical factor describing the eroding effect of wave runup on the bluff, n (=3), wetness ratio, l (=0) and k (=0.78).

$$R = \left(\frac{A m_1^2 x_b^2}{T^2 \sinh^2(kh)} - B \right)(1 + n\, l) \qquad (5)$$

where

$$A = \frac{1}{6} M \frac{r}{r_s} f_w k^2 p^2 \qquad (6)$$

$$B = \frac{M t_c}{r_s} \qquad (7)$$

b) If the water level is below the toe ($z_{lake} < z_{toe}$) but the water level + wave runup is above the toe

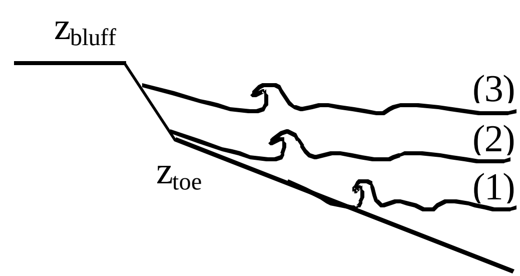

Figure 2. Cases considered for erosion prediction methodology. Case (1): mean water level is below the toe of the bluff, and runup does not rise above the toe of the bluff. Case (2): mean water level is below the toe of the bluff, but the runup rises above the toe of the bluff. Case (3): mean water level is above the toe of the bluff.

($z_{lake} + R_u > z_{toe}$) then recession rate R (m/s) is calculated using Equation 5 (l is nonzero).

c) If the water level is above the toe ($z_{lake} > z_{toe}$), then erodibility of the cohesive soil is related to wave power that can be calculated as a function of wave height. Hence, recession rate R (m/s) is given as a function of a calibration constant, C, wetness ratio, l, wave height, H, wave period, T, beach slope, m_1, and slope of the bluff, m_2.

$$R = C l H^2 T m_1 m_2 \quad (8)$$

6. Recession rates (in meters) are integrated in time for the given period of interest and a final recession distance is calculated.

APPLICATION OF THE SHORELINE EROSION PREDICTION METHODOLOGY

Hartwell Lake, a U.S. Army Corps of Engineers (USACE) reservoir, is located on the Savannah River, between Anderson, South Carolina, and Hartwell, Georgia, USA. The reservoir was built between 1955 and 1963, with joint goals of flood control, power production, water supply, and recreation.

Hartwell Lake has a shoreline length of 1548 km, and erosion of lakeshores has been a significant problem for homeowners. As of September 2002, there were 1123 permitted riprap installations, and 393 permitted retaining walls, for a total of 1516 erosion control structures along the lakeshores (source: USACE Hartwell Office), an indication of the magnitude of the erosion problem.

The erosion prediction methodology was applied to the Western Carolina Sailing Club located in Anderson County, SC. This site was chosen because of a noticeable erosion problem and the availability of survey data (Figure 3). Values of the beach profile parameters obtained from a survey are used in this application (Table 2). The fetches were measured in 36 directions. The lake level data (daily) obtained from USACE, National Oceanic and Atmospheric Administration (NOAA) provided the wind data (hourly).

A numerical model was developed to predict shoreline erosion at the tip of the island. The model was run from 1981 to 1987 using a time step of one hour, to match the sampling rate of the wind data. These two dates were selected based on the availability of the aerial photos that were used to calibrate the numerical model. At the northern tip 60 cm/year

Table 2. Parameters Describing the Beach Profile at the Western Carolina Sailing Club Peninsula

Parameter	z_{bluff} (m)	z_{toe} (m)	h_{bluff} (m)	m_1	m_2
Northern	203.65	201.70	2	0.06	0.08
Southern	203.65	201.70	2	0.12	0.10

erosion was estimated with a calibration constant (C = 0.00022). Using the same calibration constant erosion rate was estimated as 100 cm/year at the southern tip of the island.

The aerial photos from March 8th, 1981 and April 1st, 1987 of the Western Carolina Sailing Club, located in Anderson County, were chosen for shoreline erosion analysis. Both images had to be rectified by comparison to an image from 1994, which is in a known projection. This was done using the ImageWarp extension of ArcView. Since water levels on different dates differ, the erosion rates inferred from digital photos were modified accordingly using the slopes.

The shoreline change rates are calculated from the two images using ArcView. Figure 4 shows the average shoreline change rates (erosion) per year of the island. The image shown is from 1987 and the polygon is drawn based on the image from 1981. Maximum erosion rate calculated was 1.8 m/year. Erosion rate at the northern tip of the island was 0.6 m/year, and 1.1 m/year at the southern tip. Each pixel in the images represents 1 meter $\times$ 1 meter of earth. Therefore erosion rates obtained from aerial photo analysis may present 1 meter per analysis duration (6 years in this analysis) error, corresponding to ± 16 cm of error. Considering this possible error, and neglecting other potential sources of error, associated with water level, and slope, erosion rates inferred from digital aerial photos can be rewritten as 60 ± 16 cm/year and 110 ± 16 cm/year at the northern tip, and at the southern tip of the island respectively.

The methods by Penner (1993) and Kamphius (1986) were also applied to the island using their respective best-fit calibration parameters. The same values of wind data and fetch parameters were used for both north and south part of the island since two locations were very close. Therefore the estimated erosion rates were same and equal to 60 cm/year for both south and north parts of the island. However they did not agree well with the erosion rate of 110 ± 16 cm/year inferred from aerial photos.

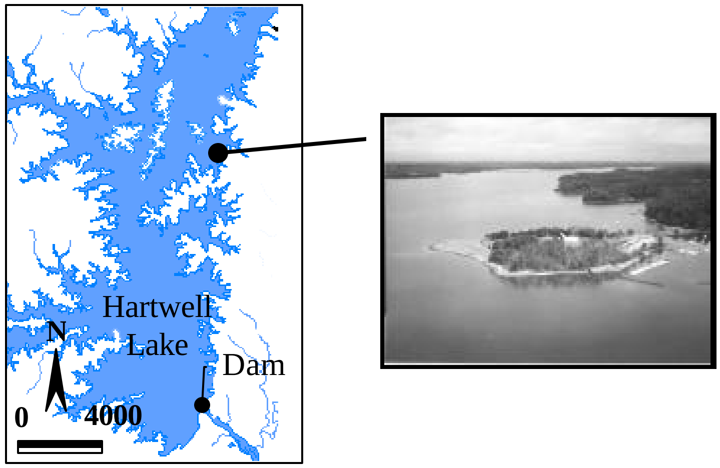

Figure 3. Location of the Western Carolina Sailing Club in Anderson County, SC.

SUMMARY

The shoreline erosion prediction methodology described in this paper quantifies erosion in terms of recession rate, which is calculated as a function of lake levels, wind direction and magnitude, fetch and beach profile slopes. This method accounts for the variability in slopes along the shoreline of a reservoir and spatial variations in sediment characteristics. The erosion prediction methodology was applied to an eroding peninsula within the lake.

The new erosion prediction methodology was calibrated at the northern tip, and was validated at the southern tip of the peninsula. Predicted erosion rate of 100 cm/year at the southern tip agreed well with the value obtained from aerial photo analysis, 110 ± 16 cm/year. Two other approaches by Kamphius (1986) and Penner (1993), were also applied to both parts of the peninsula, however erosion rate at the southern part of the island could not be estimated correctly, in part because the variability of the beach profile slopes are not included in these methods. Since erosion rates may differ from one location to another even if the climate conditions are same, it was concluded that specification of the beach shape profile is essential for an accurate estimation of shoreline erosion.

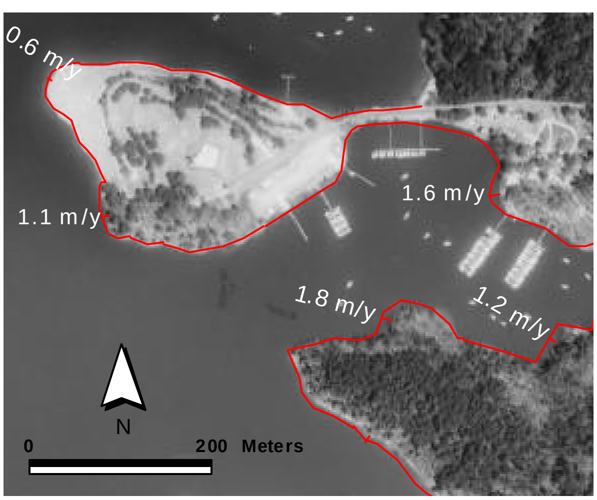

Figure 4. Average shoreline change rates (erosion) per year at the sailing club. The image shown is from 1987 and the polygon is drawn based on the image from 1981.

ACKNOWLEDGMENT

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LITERATURE CITED

Elci, S. and Work, P.A., 2002. Prediction of shoreline erosion and sedimentation in Hartwell Lake, SC/GA. *Technical Report No. GTREP-CEE/2002-1*.

Penner, L.A., 1993. Shore erosion and slumping on Western Canadian lakes and reservoirs. *Environment Canada*, Regina, Saskatchewan.

Kamphuis, J.W., Davies, M.H., Nairn, R.B., and Sayao, O.J., 1986. Calculation of littoral sand transport rate. *Coastal Eng.* 10(1), 1-21.

Thorn, M.F.C. and Parsons, J.G., 1980. *Erosion of cohesive sediments in estuaries: an engineering guide.* Proc. of the Int. Symp. on Dred. Technol., 349-358.

U.S. Army Corps of Engineers, 1984. *Shore Protection Manual*. Dept. of the Army, Washington, DC.