

AN EVALUATION OF BOAT WAKE ENERGY ATTENUATION BY A TULE
STAND ON THE SACRAMENTO RIVER

by

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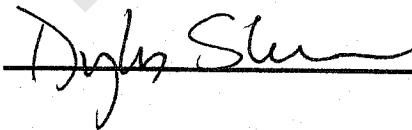
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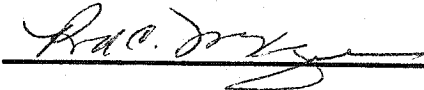


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PREVIEW

Variables

b = y intercept of the regression line

C_D = drag coefficient ≈ 1.0

D = still water depth

density = $\frac{n}{area}$

D_s = grass stalk diameter

D_t = tule spacing in meters

E = wave/wake energy

g = gravitational constant (9.81 m/s^2)

h = water depth

H = wave height

$H_{Kp(z)}$ = depth correct index wake height

$H(x)$ = wave height onshore of the vegetation

H_{in}^* = wave height (m) in vegetated sections

H_{out}^* = wave height (m) in front of vegetation

H_1 = wave height offshore of the vegetation

H_2 = wave height offshore of the vegetation

H_i = index wake height

H_o = wave height offshore of the vegetation

H_{in}^o = wave height (m) in un-vegetated sections

H_{out}^o = wave height (m) in front of vegetated berms

H_{PT} = water depth above the PT in meters

H_{rms} = root mean square wave height

k = wave number, $\frac{2\pi}{L}$

$K_p(z)$ = pressure response factor

l = length of stand through which wave propagates

L_∞ = deep water wavelength

l_a = length of linear array in meters

M = multiplier

m = slope of the regression line

N = correction factor equal to unity

n = number of tule stalks within area

p = data points in the PT record representing the pressure signal

P = hydrostatic pressure

P_D = dynamic pressure

Q_x = total flow in the x direction

RHR = wave extinction with vegetation / wave extinction without vegetation

s = average stalks spacing (assumed on centers)

T_1 and T_2 = successive values in the PT record

T_i = wave period

T_s = smoothed data point after the average

U = orbital velocity

u = water flow in the x direction

U_i = index orbital velocity

v = water flow in the y direction.

V_{EM} = current meter voltage output

V_{PT} = pressure transducer voltage output

x and y = Cartesian coordinates within the “c” rack

z = water depth from the free water surface or instrument elevation above the bed

η = water free surface displacement

η_n = Nielsen-corrected water surface elevation

ρ = water density

π = Pi assumed to equal 3.14

δ = sampling interval

σ = standard deviation

ω = radian frequency $\frac{2\pi}{T}$

Abstract

Boat wake energy attenuation by a tule stand on the Sacramento River was estimated with a linear array of electromagnetic current meters and pressure transducers as a function of differing tule density. A boat was used to produce consistent wakes focused on during data analysis. Dean's (1979) model predicting wave attenuation by vegetation was also utilized to test its validity when applied to tule vegetation. Trends of H_{rms} wake heights were used to estimate the attenuation of wake energy, which showed a decrease of 15.8% over the length of the array. Dean's model was applied to measured values obtained at PT1 and predicted a reduction in wake energy of 12.1 %. Regression analysis did show the results were significant. Based on these findings it was determined that tule does attenuate incoming wake energy and that Dean's model does predict wake attenuation by tule however predicted wake heights are inaccurate.

1. Introduction

The Sacramento Delta is located in California, approximately 80 miles east of the San Francisco Bay area. The delta is an area of extreme importance to California for its agricultural production, flood control and especially as a source of fresh water to approximately two-thirds of California's residents (CALFED 1999). The delta is also important for its natural gas deposits, wildlife habitat and recreation, as well as commercial shipping and transportation (Sacramento-San Joaquin Delta Atlas 1987, CDWR 1992, CALFED 1999). Most of the delta is protected by earthen, artificial levees. That isolate agricultural tracts from daily tidal and yearly flood flows. The isolated tracts of land have become one of the most productive agricultural areas in the world. The levees are also important hydraulic barriers that keep saline San Francisco Bay waters out of the delta, allowing a clean source of fresh water to remain (CALFED 1999).

Since their construction, the delta levees have been under constant attack from natural processes as well as those attributable to man. In the delta, erosion by river currents, wind and boat generated waves are all important factors that induce levee erosion. Due to the extreme importance of these levees, research into processes affecting them both positively and negatively have been ongoing. Studies into the effects of plant species on the levees (Thompson 1982) as well as those into the effects of river currents, wind and boat wave induced erosion, Collins and Noda (1971), Limerinos and Smith (1975) and Bauer, Lorang, Sherman (2000) have been

done. Research into the abilities of different plant species to attenuate wave and current energy along the banks of lakes and rivers have also been undertaken, Dean 1978, Knutson 1988, Asano et. al., 1992, Kobayashi et.al., 1993, Coops et. al. 1994, Coops et.al., 1996 and Massel et.al., 1999. However, there has been minimal research into the attenuation of boat wave/wake energy by vegetation. This thesis attempts to quantify the attenuation of boat wake energy by tule in the Sacramento / San Joaquin Delta. These results will provide knowledge that may provide insight into possible management strategies for protecting the delta levees from physical processes of erosion.

1.1. Delta geography

The Sacramento-San Joaquin Delta consists of approximately sixty reclaimed islands with an area of 738,000 acres, approximately 1153 mi² (2986 km²). Within this region there are approximately 700 miles of waterway and 1100 miles of levee (Limerinos and Smith 1975, CALFED 1999). These levees are extremely important to the delta region because of the protection they provide to the reclaimed islands - many of which lie as much as 20 feet (6 m) below sea level - from inundation by storm and yearly spring runoff (Limerinos and Smith 1975, Hart 1999).

Five major rivers feed the delta: the Sacramento, San Joaquin, Mokelumne, Cosumnes and Calaveras. This system of rivers and sloughs drains more than 61,000 mi² of drainage basin, or 37 percent of the state, which equates to 47 percent of

California's total runoff (Limerinos and Smith 1975, Tyner, Bauer, Sherman 1995, CALFED 1999).

Up to a century ago most of the delta was a freshwater tidal swamp underlain by peat. The continuity of the peat, like that of its vegetation cover, was broken up by the deep master channels and distributaries and by many of the sloughs and inland swampy islands throughout the delta area (Thompson 1982). The abrupt banks of these channels and sloughs were narrow natural levees, only a foot or two above the floor of the tule swamp and progressing into the adjacent marshland. These natural levees consisted of the fine sedimentary materials deposited during previous floods that overtopped the riverbanks (Thompson 1992).

Early in California history the delta was recognized as an area of rich organic peat soils with easily accessible water for irrigation (DWR, 1992). Due to these delta soils, land was reclaimed by the construction of additional levees atop the natural levees to provide arable land for agriculture (DWR 1992). More than 80 percent of the former marshland of the delta was reclaimed and developed for agriculture from the mid 1800's to the early 1900's (Sacramento-San Joaquin Delta Atlas 1987, Arreola 1975, Thompson 1992).

1.2. Levee construction and failure

Levees in the delta have been problematic, at best, since the first were constructed in the 1850's. When delta reclamation started, the main levee construction materials consisted of the delta's peaty soils due primarily to their close

proximity. These soils are organic and extremely fertile but as construction materials and as a levee base are extremely poor. These peaty soils have low densities, are highly compressible and are very weak (DWR 1982). This peat soil, after being set into the levee as blocks or for fill, shrank as it dried. Cracks and surface irregularities developed fairly rapidly on the early delta levees (Arreola 1975). Constant river current and wave attack on the levees has shown that the easily eroded peat is unreliable as a levee construction material; mixtures of mineral and organic soils placed on the levees since their initial construction have proven stronger. These mineral soils were removed from the channel bottoms and deposited on the levees. This increased levee reliability by creating deepened river channels that helped convey larger river flows. This reduced the failure rates but did not solve levee problems (Arreola 1975).

Erosion by both river and tidal currents causes erosion on the waterside of the levees (Limerinos and Smith 1975, DWR 1982, Bauer, Lorang, Sherman 2000). River water, as it flows through the river channels and sloughs, applies tractive shear stress to the adjacent levee banks. Since the sand silt and peat used in the construction of the levees possess minimal resistance to this shear, they are eroded by the river flow (Limerinos and Smith 1975). This erosion of levee materials weakens the levees by gradual deterioration and reduces their ability to resist the force of tidal and flood flows (CALFED 1999)

Waves, both wind and boat-generated, are also known to erode the weak soils used to construct the levees. These waves are important energy-transfer agents where

the wave motions themselves constitute a transfer of energy over water surfaces. The displacement of the water surface away from the flat still-water condition gives the waveform potential energy. At the same time, the orbital motions of the water under the wave constitute kinetic energy. Integrating both potential and kinetic energies along the full length of the wave yields the total wave energy and can be related directly to the wave height. These waves can be a primary cause of erosion or may generate a variety of nearshore currents and sediment-transport patterns (Komar 1998). Waves also cause levee erosion by applying shear stresses to the levees (Limerinos and Smith, 1975). Wind and boat-generated waves are common and are known to cause levee erosion in the delta area (Limerinos and Smith 1975, Hart, 1999, Yaari 1999, Bauer, Lorang, Sherman 2000, Ellis 2001).

1.3. Research into levee erosion

1.3.1. Collins and Noda (1971)

Collins and Noda (1971) focused on levee erosion in an attempt to quantify the relative percentages of erosion generated by river and tidal current, wind-generated and boat-generated waves. Collins and Noda's, 1971 research focused on two major North-South boating channels, one along Georgiana Slough and the other along the North Fork of the Mokelumne River. The site along Georgiana Slough was considered a natural channel with seasonal and tidal influence where as the site along the Mokelumne River was chosen due to the lack of tidal influence.

Historical flow and tide data were used to calculate the shear stresses imposed on the levee banks including steady river discharge and oscillating flow due to tidal fluctuations. Erosion was estimated by computing the shear stresses directly from velocity measurements within the channels over the course of a year where the shear stresses were converted to energy dissipation along the banks of the river channels. The energy dissipation estimations for the site within Georgiana Slough were $3.97 \times 10^7 \text{ J yr}^{-1}$ at the Mokelumne River site flow varied depending on whether the delta cross channel was open or closed. Energy dissipation was calculated, as before, with an estimated energy dissipation of $8.81 \times 10^6 \text{ J yr}^{-1}$.

Levee erosion due to boat-generated waves was also estimated. Since they determined that boat wakes were too difficult to properly measure, Collins and Noda utilized data on boat resistance and partition of resistance based on a boat's power requirements to obtain a quantitative measure of energy transfer from a boat's hull to the wave system. These measurements were used to determine energy that propagates away from a boat toward the levee bank. In order to quantify this energy Collins and Noda focused on three different size boats. The energy transfer from each type of boat was calculated by relating boat hull, size and speed. Estimations of wake energy propagating from each type of boat coupled with the number of boat passes for each type of boat sizes traveling up the channel provided estimated yearly energy dissipation along the levee banks, $2.49 \times 10^5 \text{ J yr}^{-1}$ for Georgiana Slough and $5.38 \times 10^5 \text{ J yr}^{-1}$ for the Mokelumne River sites.

Levee erosion by wind-generated waves was estimated as well. Collins and Noda used the Sverdrup, Munk and Bretschneider (1947) relationships to calculate the wave characteristics within the study channels. Wind data was obtained for both sites from data collected at Travis Air Force Base. The potential erosive energy was estimated for each site by relating the wind speed, fetch and duration which produced estimated erosion potential. These estimations were termed the mean annual wind wave energy dissipation. Energy dissipation was given for several channel characteristics from straight channels to channels with bends and ranged between $1.8 \times 10^4 \text{ J yr}^{-1}$ to $1.25 \times 10^8 \text{ J yr}^{-1}$ in Georgiana Slough and $3.3 \times 10^4 \text{ J yr}^{-1}$ to $1.93 \times 10^8 \text{ J yr}^{-1}$ at the Mokelumne River site.

Conclusions from Collins and Noda's (1971) report were that boats were not an important source of levee erosion in the delta where the greatest source of erosive energy corresponded to floods. Wind waves were also determined important factors in levee erosion on the outside of river bends, particularly if the bend is exposed to the southwest. Collins and Noda believed that the levee erosion from river and tidal conditions were so overwhelming, when compared to boat wave erosion, that they expected their results to hold true even for large increases in boating.

1.3.2. Limerinos and Smith (1975)

Limerinos and Smith (1975) were keenly aware that erosion problems with the deltas levees were caused by the peat foundations of the levees, weak materials used in the levee construction and the increased hydraulic pressures applied to the

levees from subsidence of the inner islands. Their field observations focused on the effect that natural phenomenon such as river current and wind-generated waves in addition to boat-generated waves had on delta levee erosion.

Limerinos and Smith chose two river channels in the delta to undertake their research. One site was along a section of Georgiana Slough and the other was along a section of the False River. The sites were chosen because of the heavy boat traffic that each regularly experienced and because of the contrasting natural forces at work in each channel. The site in Georgiana Slough is influenced mainly by flood flows where as the False River site is mainly influenced by tidal flows.

Limerinos and Smith focused on the increased shear stresses imposed on the levees by water movement through the channels and the additional stresses imposed by wind and boat-generated waves. They assumed that if there was a connection between levee erosion and boat-generated waves there would be a correlation between increases in levee maintenance and increases in boat traffic in the selected study channels, assuming that the natural forces which cause levee erosion including subsidence, weak levee construction materials or river current during yearly flood events were constant. During their study they used float-type wave gauges to determine the heights of tidal flows and wave heights.

Limerinos and Smith found that channels that receive large yearly flood flows, similar to Georgiana Slough, experience most erosion from tractive shear stresses imposed by the river currents during annual floods. The energy dissipated on the banks by floods is about two thirds that of combined wind and boat-generated

waves, with boat-generated waves comprising about twenty percent of the total energy dissipated against the levee banks. However in channels similar to the False River, that are little effected by yearly flood flows, the relative contribution of wind and boat-generated waves is from forty to eighty percent of the erosion imposed on the levee banks. Their general conclusion was that in channels similar to False River, erosion caused by boating is a more significant factor than erosion from yearly flood flows.

1.3.3. Bauer, Lorang, and Sherman (2000)

Bauer, Lorang, and Sherman (2000) attempted a different approach to the assessment of boat wake erosion in the Sacramento San-Joaquin delta. They developed analytical methods to assess the relative impacts of boat-induced erosion to a site in Georgiana Slough. In the experiment, instrumentation was employed to determine if boat waves were an important forcing agent in levee erosion. A 23-foot boat was used to create boat waves at the site.

Results from this research did show that boat-wakes of $H_{\max} < 0.25$ m, when the water depth was approximately 0.5 m or less, do have enough energy to erode the fine-grained cohesive sediments that make up the levee bank materials. Although the boat's waves were sufficient to erode and suspend sediments at their site, the removal of this sediment relied on the background flow of the river to carry the suspended materials away. This confirmed that incoming boat wakes removed

material each time the boat passed the site, proving that boat waves are an important force responsible for erosion of the delta levees.

1.4. Possible solutions to levee failure

In the previously cited literature, river and tidal current and wind and boat-generated waves are included as forces that erode the delta levees. To protect the levees from erosion, barriers have been used to slow the erosivity of currents and waves. Several approaches which included caps of heavier sediment, mats of brush or plants (willow trees, Bermuda grass and alfalfa) have been used. These plants were either placed or planted on the waterside of the levees in an attempt to stop erosion, but the practice of planting grasses or alfalfa was abandoned because it encouraged burrowing animals to call the levees home (Thompson 1982).

1.4.1. Bank Armoring

Armoring the banks with some form of stone (riprap) has been widely implemented to protect the levees by dissipating incoming wave energy as it reaches the shore. This riprap increases the strength of the bank materials as well as the resistance to the tractive shear stresses that the river flow imposes on the shore. This riprap also protects against incoming waves by dissipating wave energy enough so that materials are not eroded from the levee. Although riprap is generally effective in protecting the banks from damage, it is unsightly, expensive to employ and needs regular maintenance.