EVALUATING HAZARD OF LANDSLIDE-INDUCED WATER WAVES

By Rudy Slingerland,[1] and Barry Voight[2]

ABSTRACT: Dimensional analysis of the landslide parameters which control dimensionless maximum wave amplitude, η_m/d, when slides impact with a water body, shows that dimensionless slide kinetic energy, E_k, is most important. Data from two site-specific hydraulic studies combine to produce a consistent data set and give a statistically significant linear regression equation of $\log(\eta_m/d) = -1.25 + 0.71 \log(E_k)$, in which $E_k = \rho_s \ell w h V^2 (2\rho g d^4)^{-1}$, ℓ, w, h, ρ_s, and V are slide length, width, thickness, density, and maximum velocity, ρ is water density, g is gravitational acceleration, η_m = maximum wave amplitude at a standard distance $r/d \approx 4$ directly in front of a slide, d = water depth at that site, and r = radial horizontal distance from the point of slide impact. The hydraulic model studies had scale factors of 1:120 and 1:300, with $0.4 < h/d < 0.8$. Landslides were simulated by 1/18–1/3 cu ft (0.002–0.005 m^3) triangular or tabular bags of metal or gravel, with toes initially above water level. η_m/d, back calculated from observed waves and wave run-ups for the 1958 Gilbert Inlet slide in Lituya Bay, Alaska, and the 1905 glacier fall in Disenchantment Bay, Alaska, are accurately predicted by the regression equation in the first case and conservatively predicted in the second.

INTRODUCTION

Large water waves generated by landslides plunging into water bodies are well known from observations in Norway, Italy, Japan, Alaska, and many other localities (6,11,13,16). Their combined human death toll probably exceeds 20,000. Such waves are thus recognized as distinctly hazardous phenomena and the capability of predicting slide-induced wave characteristics for engineering or site hazard evaluation purposes is clearly of importance.

A complete predictive capability would satisfy a wide range of requirements, including the following extreme examples:

1. The detailed specification of waves potentially associated with slide sites in planned reservoirs with large dams. Available funds and time available for analyses are large.

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2. Rapid evaluation of recognized potential slide sites of *immediate* concern. Evacuation of hazardous areas may be necessary in order to prevent loss of life. Available funds may be limited, and time is of the essence. This paper presents a rapid method of analysis to satisfy this latter need.

MODELING PROCEDURE

Attempts at predicting wave characteristics (especially type and amplitude) from slide characteristics (especially size, shape, density, and time-history of emplacement) have proceeded along three lines:

1. Deducing a mathematical model from the physical laws of fluid dynamics.
2. Inductively establishing relationships of variables from dimensional analysis and empirical modeling.
3. Site-specific scale modeling.

Examples of the first approach are found in the work of Noda (12), Garcia (3), Raney and Butler (15), and Koutitas (8), who, respectively, deduced mathematical models from the linearized impulsive wave equations, full two-dimensional Navier-Stokes and continuity equations, vertically averaged two-dimensional wave equations, and St. Venant's equation. Kamphuis and Bowering (7) and Law and Brebner (9) used dimensional analysis and two-dimensional flume data to induce empirical models, whereas Davidson and Whalen (1), Western Canada Hydraulic Laboratories (5), and Eie, et al. (2), created three-dimensional hydraulic models to simulate specific reservoirs and slides of interest.

Deductive models with analytic solutions are restricted in application by assumptions concerning linear versus nonlinear waves, by idealized slide geometries, and by generally being one-dimensional. Deductive models with numerical solutions have fewer restrictive assumptions and are two-dimensional, but require detailed input such as the volume, path, speed, and shape of a slide as it travels through the water, as well as basin shape, bathymetry, and bottom roughness. This approach gives more accurate predictions (16), but also requires complex computer programs for solutions.

Existing inductive models are limited by deriving their relationships from flumes which do not allow radial wave attenuation. Furthermore, relationships are based on the behavior of slides modeled as boxes or trays; these probably do not accurately simulate the shape, porosity, or time history of emplacement.

Three-dimensional hydraulic models, appropriately scaled, eliminate many of these problems. On the other hand, they are site-specific, and such complications as wave refractions and reflections are incorporated into their data. Their experimental arrangement is nevertheless sufficiently realistic to make them also appealing as a data source for predictive equations of a more general kind.

Here, the writers present an empirical regression equation for the prediction of dimensionless first wave amplitude from dimensionless slide kinetic energy induced from two three-dimensional hydraulic studies. This equation is intended to provide a rapid assessment of wave potential from recognized incipient slides in cases where numerical or hydraulic simulations are not feasible. The writers then compare predictions of this relationship with data from prototype events at

Disenchantment and Lituya Bays, Alaska. Finally, the writers present a sample calculation based on a case history from South America.

DERIVATION OF REGRESSION EQUATION

Dimensional analysis of the slide parameters which could control a wave characteristic, A, yields

$$\pi_A = \phi_A\left(\frac{\ell}{d}, \frac{w}{d}, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \theta, \frac{\rho_s}{\rho}, \rho\frac{d\sqrt{gd}}{\mu}, \frac{r}{d}, t\sqrt{\frac{g}{d}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which π_A = a dimensionless characteristic of the wave; ϕ = a function; ℓ, w, h, ρ_s, and V = slide length, width, thickness, density and maximum velocity; θ = the angle of slide entry with respect to the horizontal; μ, ρ, and d = water molecular viscosity, density, and depth offshore from the slide site; r = the horizontal radial distance from the slide; and t = elapsed time. The Reynolds number may be ignored, assuming viscous drag of the slide is much less than pressure drag and simple displacement of the water. θ was shown by Kamphuis and Bowering (7) to be of minimal importance compared with the other parameters and may also be dropped. Thus, dimensionless maximum wave amplitude, η_m/d (η_m = maximum wave amplitude at a particular site as measured from mean water level), at some standardized distance from a slide (say $r/d \approx 4$) is a function solely of parameters which may be combined as a slide dimensionless kinetic energy, E_k:

$$\left.\frac{\eta_m}{d}\right|_{r/d\approx 4} = \phi\left(\frac{1}{2}\frac{\ell wh}{d^3}\frac{\rho_s}{\rho}\frac{V^2}{gd}\right) = \phi(E_k) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

For a first approximation, it is assumed that this relationship is nonlinear. A log-log plot then gives, for $r/d \approx 4$

$$\log\frac{\eta_m}{d} = \bar{a} + \bar{b}\log(E_k) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

and the problem reduces to estimating the coefficients $\bar{a}$ and $\bar{b}$.

GENERATION OF DATA AND REGRESSION ANALYSIS

The data are derived from a U.S. Army Engineer Waterways Experiment Station (WES) model study of Lake Koocanusa, Montana (1), and a Western Canada Hydraulic Laboratories, Ltd. (WCHL) model study of Mica Reservoir, British Columbia. In the WES hydraulic model, the geometric scale factor was 1:120. Model slide material of 1/18 cu ft (0.0016 m^3) bags of iron and lead was allowed to slide down an inclined plane into a model reservoir producing water waves which were recorded at 16 sites. The WCHL model had a geometric scale of 1:300; model slide material consisted of 1/3 cu ft (0.009 m^3) bags of gravel. In both studies, slides typically had toes slightly above water level and were either tabular or triangular in shape. The WES data are from two different slide sites and two different water levels; the range of slide thickness was $0.4 < h/d$

< 0.8. The WCHL data are from one slide with $h/d = 0.37$. In both cases, the velocity term used in the calculation of E_k in Eq. 3 was the maximum velocity of the slide (16) measured directly in the models.

Wave characteristics (Fig. 1) in both studies were taken from three probes in front of each slide, alined parallel to the sliding direction. Previous analysis (16) has shown that in uncomplicated three-dimensional situations, wave attenuation is a simple inverse function of distance from the slide. Therefore, wave decrease with distance measured at these probes was used to estimate the constant, k, in the inverse function, $\eta_m/d = kd/r$. This function was then used to extrapolate a dimensionless wave amplitude to $r/d \approx 4$, an arbitrary reference point.

Fig. 2 is a log-log plot of dimensionless wave amplitude at $r/d \approx 4$ versus dimensionless slide kinetic energy for these data. Regression Eq. 3 has coefficients $\bar{a} = -1.25$ and $\bar{b} = 0.71$, with 97% of variation in log (η_m/d) "explained" by variation in log (E_k):

$$\log\left(\frac{\eta_m}{d}\right) = -1.25 + 0.71 \log(E_k) \quad \text{(4)}$$

Confidence limits at the 95% level are indicated by dashed lines. For comparison, estimates of actual wave amplitudes and associated kinetic energies are indicated for events at Lituya Bay (box) and Disenchantment Bay (line connecting diamonds). The possibility of spurious correlation due to water depth entering into the denominator of both parameters is minimized here because depth variance is much less than the variance of the other variables. The relationship thus seems to be approximately linear over two orders of magnitude of log (E_k). On the other hand, these coefficients are not conservative for broad slides of low dimensionless kinetic energy; possibly a later differentiation of coefficients can be made between point and line sources. Eq. 4 is also quite sensitive to water depths, a troublesome condition for irregular bathymetries in front of a slide.

COMPARISON WITH PROTOTYPE EVENTS

The writers have attempted to back calculate the relevant slide and wave parameters for the 1958 Gilbert Inlet slide into Lituya Bay, Alaska, and the 1905

FIG. 1.—View of Waves Generated in WCHL Model Study. Slide Entered Reservoir at Extreme Right Center along Line from Right to Left

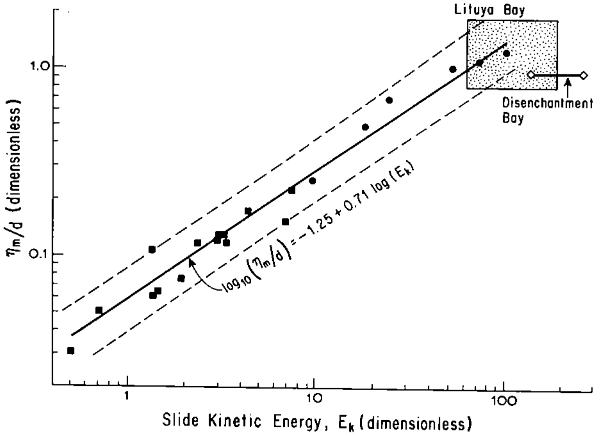

FIG. 2.—Relationship of Maximum Dimensionless Wave Amplitudes (at $r/d \approx 4$) as Function of Slide Dimensionless Kinetic Energy. WES Data Denoted by Squares, WCHL Data by Dots

glacier fall into Disenchantment Bay, Alaska. In the first, an earthquake detached a 40 × 10^7 cu yd (30.6 × 10^6 m^3) rockslide of assumed density, 2.7 g/cm^3, which apparently plunged as a coherent mass down a 40° slope into an arm of Lituya Bay (10). From bathymetric charts, water depth at the slide front was about 400 ft (122 m). Estimates of maximum slide velocity from the basic equations governing sliding of a block on an inclined plane where kinetic friction coefficient is 0.25 are 184 ft/sec (56 m/s) as the slide front hits the water surface, or 226 ft/sec (69 m/s) as the slide front hits the bay bottom (ignoring velocity decrease due to water drag). These values give dimensionless kinetic energies of 60 and 91, respectively. Because the geometry of the slide site allows wave propagation only through 90°, the writers have doubled the higher dimensionless kinetic energy to better bracket the true wave amplitude. (Slide entry at a point along a straight shore line causes wave propagation through a 180° arc, in plan (map) view. This is now considered the "normal" situation. A slide mass entering a water body in a right-angled corner, as viewed in plan, causes propagation of waves through a 90° arc. Such a slide is equivalent to one twice as large entering across a straight shore line. The kinetic energy term in Eq. 4 should therefore be doubled.)

The upper bound of dimensionless wave amplitude was obtained by back calculating a wave amplitude to $r/d \approx 4$ using the previously described inverse wave attenuation function. A stable wave amplitude of 210 ft (64 m) observed at $r/d \approx$ 14–30 was the starting datum. This gives for $r/d \approx 4$, $\eta_m/d = 1.83$. The lower bound of $\eta_m/d = 0.81$ in Fig. 2 assumes wave attenuation is estimated by a function for attenuation in a rectangular channel.

In the 1905 Disenchantment Bay event, the entire Fallen Glacier, approximately 3.8 × 10^7 cu yd (29 × 10^6 m^3) in volume, "shot out of its valley, tumbled a thousand feet down the steep slope, and entered the fjord" (17, p. 68). Using a density of 1.0, water depth at the site as 260 ft (80 m), and a velocity of 197 ft/sec (60 m/s) calculated as before, the dimensionless kinetic energy is 130. If a velocity of 272 ft/sec (83 m/s) is used, representing the velocity when the centroid reaches the water surface and assuming no fluid drag, dimensionless kinetic energy equals 249.

Direct estimates of wave amplitude are not available for this event but amounts of shore run-up are. Therefore, the writers have inverted the Hall and Watts (4) run-up formula to estimate wave amplitudes at sites around the bay. The writers have then back calculated a wave amplitude to $r/d \approx 4$ by the inverse wave attenuation function. By this method, $\eta_m/d = 0.96$.

Regression Eq. 4 conservatively predicts wave amplitudes for Disenchantment Bay and estimates Lituya Bay amplitudes almost exactly, even though these events have dimensionless kinetic energies outside the range of data on which the equation is based (Fig. 2).

EXAMPLE ANALYSIS

In 1971, the Chungar Mining Company (Cia. Minera Chungar, S. A.) operated a mining camp on a narrow, glaciated rock bench along the shore of Yanahuin Lake in the Peruvian Andes (14). On the opposite shore of this small glacial lake, set 1,300 ft (400 m) above a 45° talus slope, was a bedrock cliff of loosely jointed limestone. Sr. Baldón Pablo, a resident at the lake for 17 years, had noted that individual rocks occasionally fell from this cliff face and some even splashed into the lake. Indeed, a small rock fall the previous year had caused a 5 ft (1.5 m) wave but, after a mining company evaluation of the problem, the camp was still considered safe from wave run-up.

About 0700 hours on March 18, 1971, Sr. Baldón Pablo noticed an increased amount of rock fall from the face. An hour later 1.3×10^5 cu yd (10^5 m^3) of rock tumbled down the scree slope and plunged into the lake. The resulting wave traveled across the lake and ran through the mining camp, causing its virtual

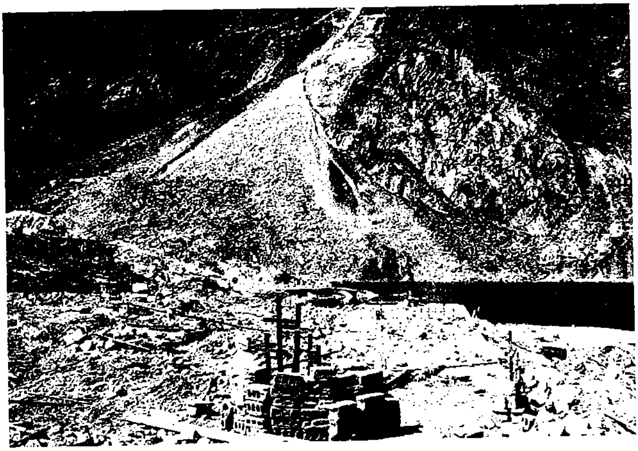

FIG. 3.—View of Rock Avalanche Source Area (Dashed Line) and Talus Debris from Demolished Mining Camp Area on Yanahuin Lake

destruction to an elevation of about 100 ft (30 m) above lake level. An estimated 400–600 mining personnel were killed (Fig. 3).

Although engineering solutions are inevitably enhanced by hindsight, a rapid assessment of slide-induced wave potential, even an hour before the slide, might have been made as follows. First, assume a kinetic friction coefficient, $f_k = 0.25$ (this is an average value for a friction coefficient, based on back-analyses of many slides (16); for a more conservative calculation, set $f_k = 0$). The velocity of the slide, V, at impact with the water surface is given by

$$V = [2gs\,(\sin i - f_k \cos i)]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

in which i = angle of slope; g = gravitational acceleration = 9.8 m/s^2; and s = downslope distance = vertical slope height ÷ sin i. Thus, $V = [2\,(9.8 \cdot 570 \cdot (0.71 - 0.25 \cdot 0.71))]^{1/2} = 77$ m/s.

Assuming that the slide volume could be estimated beforehand and that an average water depth, d, was about 100 ft (30 m), Eq. 2 yields

$$E_k = \frac{1}{2}\left(\frac{10^5}{30^3}\right)\left(\frac{2.7}{1}\right)\left(\frac{77^2}{9.8} \cdot 30\right) \approx 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Directly from Fig. 2, or alternatively by using Eq. 4, at $r/d \approx 4$, $\eta_m/d \approx 1$. If the horizontal distance from the slide site to the mining camp ranged from 300–1,000 ft (100–300 m), $r/d \approx 3 - 10$, we may use $\eta_m/d \approx 1$ directly with no correction for amplitude decrease with distance of travel. Then directly offshore from the camp $\eta_m \approx 100$ ft (30 m). Thus, noting that run up on the gently sloping bench at the campsite could exceed wave amplitude, authorities could have decided to evacuate temporarily the site until the slide hazard was dealt with.

SUMMARY AND CONCLUSIONS

Characteristics of water waves generated by landslides plunging into water bodies are presently predicted by empirical flume models, mathematical models, or site-specific hydraulic models. The first method is limited by unrealistic wave attenuation and slide characteristics, and the second by simplifications and the need for a detailed slide history. However, coupled data from two studies of the last method show a statistically significant relationship between dimensionless maximum wave amplitude at $r/d \approx 4$ in front of a slide, and dimensionless slide kinetic energy (Eq. 4). To test this relationship, maximum dimensionless wave amplitudes directly in front of the 1958 Gilbert Inlet slide in Lituya Bay, Alaska, and the 1905 glacier fall in Disenchantment Bay, Alaska, were back calculated from observed waves and wave run-ups to be 0.81–1.83, and 0.96, respectively. Eq. 4 conservatively predicts dimensionless wave amplitudes from Disenchantment Bay (1.78), and estimates Lituya Bay amplitudes almost exactly (1.03–1.38). The relationship is potentially useful in rapid evaluation of hazards from landslide-induced water waves where more complete modeling is not possible.

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Appendix II.—Notation

The following symbols are used in this paper:

A = wave characteristic;
$\bar{a}$ = regression coefficient;
$\bar{b}$ = regression coefficient;
d = average depth offshore from slide site;
E_k = maximum dimensionless slide kinetic energy;
f_k = kinetic friction coefficient;
g = gravitational acceleration;
h = slide thickness;
i = angle of slope;
k = constant;
ℓ = slide length;
r = radial horizontal distance from slide;
s = downslope distance of travel of slide;
t = time;
V = maximum velocity of slide;
w = slide width;
η_m = maximum wave amplitude at site for particular slide event as measured from mean water level;
θ = angle of slide entry with respect to horizontal;
μ = water molecular viscosity;
π_A = dimensionless characteristic of wave;
ρ = density of water;
ρ_s = slide bulk density; and
ϕ_A = function.