APPENDIX.—REFERENCES

21. Burcharth, H. F., "Full Scale Trials of Dolosse to Destruction," Institute of Civil Engineering, Aalborg University, Denmark, May, 1980.
22. The Dock and Harbour Authority, "Rubble Mound Breakwaters," Apr., 1980.
23. Zwamborn, J. A., "Analysis of Causes of Damage to Sines Breakwater," *Proceedings of Coastal Structures 79,* ASCE, Mar., 1979.

EVALUATING HAZARD OF LANDSLIDE-INDUCED WATER WAVES[a]

Discussion by Andreas Huber[3]

On the basis of two specific hydraulic model studies and the reconstruction of two natural events the authors found the following dimensionless relationship between maximum wave height and dimensionless slide kinetic energy

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

in which $E_k = \frac{1}{2} \frac{l \cdot w \cdot h}{d} \frac{\rho_s}{\rho} \frac{v^2}{g \cdot d} \quad (7)$

Further, wave height was related to the quantity r/d, where r is measured from the location of impact. Thus, at any distance the wave height can be extrapolated from the simple function

$$\frac{\eta_m}{d} = k \frac{d}{r} \quad (8)$$

The proposed method predicts wave height within an order of magnitude.

The writer also performed model tests on the topic of slide-induced water waves, but considered the actual physical processes of plunging landslides (18,19). Eq. 4 may be written in a more detailed form:

$$\log \frac{\eta_m}{d} = -1.25 + 0.71 \left(\log \frac{1}{2} + \log \frac{l \cdot w \cdot h}{d^3} + \log \frac{\rho_s}{\rho} + \log \frac{v^2}{g \cdot d} \right) \quad (9)$$

Here the dimensionless slide kinetic energy is equal to the product of slide volume, density ratio and impact Froude number. These are the most important parameters influencing wave height. Since landslides are rarely square in shape, it is more appropriate to specify their volume

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[a] November, 1982, by Rudy Slingerland and Barry Voight (Paper 17487).

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directly. Eq. 9 may then be rewritten as

$$\log\frac{\eta_m}{d} = -1.46 + 0.71\left(\log\frac{V}{d^3} + \log\frac{\rho_s}{\rho} + \log\frac{v^2}{g\cdot d}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The following comments may be made in the light of the writers' tests with respect to the individual terms in Eq. 10.

Maximum Wave Height.—In the authors' study the maximum wave height is reckoned in the main momentum direction of the slide. Consequently, assuming the slide crosses the lake shore at right angles, waves attain a maximum height in a direction perpendicular to the shore line. Waves propagating in semicircles from the impact site in other directions have smaller elevations, assuming that they are not influenced by reflection or refraction effects due to lake contours and topography. The three-dimensional model tests aforementioned involved gravel slides travelling down a smooth ramp into a rectangular pool of constant depth. This enabled a relationship between sliding mass, propagation distance, propagation direction and wave height to be developed. The results of one such test are shown in Fig. 4. The writer's model tests demonstrated that three dimensional waves are smaller and attenuate more quickly in the main momentum direction than two-dimensional waves.

Dimensionless Slide Volume.—In Eq. 10, the term V/d^3 does not take into consideration the shore length along which the slide volume plunges into the lake. But wave height essentially depends on this factor. If the slide is concentrated over a short section of the shore line, then waves will be higher than if the slide was greater in lateral extent. The writer suggests that the parameter V/wd^2 (which could be called a displacement number) be substituted for V/d^3.

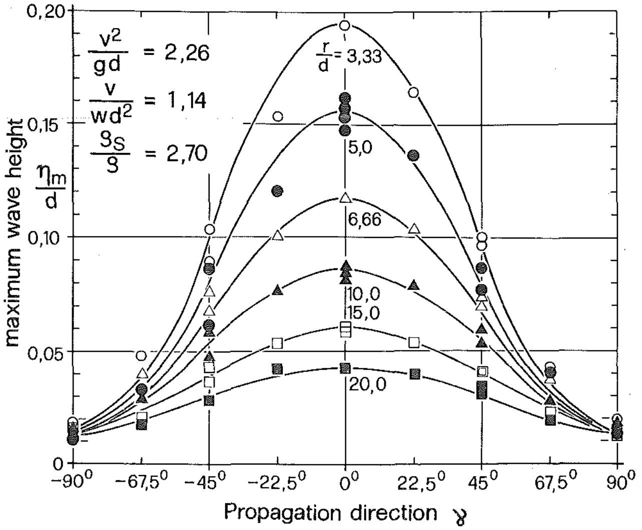

FIG. 4.—Wave Height Against Propagation Direction; Propagation Distance at Given Displacement Number; Impact Froude Number and Density Ratio

Density Ratio ρ_s/ρ.—The density ratio determines whether the slide will plunge or float. With ice slides, once the velocity of the slide has been decreased sufficiently, buoyancy lifts the ice mass to the water surface. Kinetic energy is partially converted into wave energy and partially dissipated by turbulence. In contrast to this, rock masses slide further below the water surface, and a considerable part of the slide's energy is dissipated by bottom friction. At impact velocities equal to those of ice slides, the proportion of energy converted into waves and turbulence is minor. Thus, if no ice-layer is present to attenuate waves, ice-slide induced waves are higher than rock-slide induced waves. On principle the two cases $\rho_s/\rho < 1$ and $\rho_s/\rho > 1$ must be distinguished.

Impact Froude Number v^2/gd.—This quantity corresponds approximately to the square of the ratio of impact velocity to wave propagation velocity. In analogy to the flow into a basin two different cases exist: $v^2/gd < 1$ (no hydraulic jump) and $v^2/gd > 1$ (generation of a hydraulic jump). According to the second case, slides with a rapid velocity will convert less energy into waves because of the increase in energy dissipation with Froude number, i.e., increased turbulence. Thus, as the writer's tests showed, wave height is not proportional to the impact velocity and wave energy is not proportional to the slide energy.

APPENDIX.—REFERENCES

18. Huber, A., "Impulse Waves in Swiss Lakes as a Result of Rock Avalanches and Bank Slides," *14th Congress on Large Dams*, Rio de Janeiro, 1982, Vol. III, Q 54, R 29, and Vol. V, pp. 500, 501.
19. Huber, A., Schwallwellen in Seen als Folge von Felsstürzen, Mitteilung Nr. 47 der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Eidg. Technische Hochschule Zürich, 1980.

Closure by Rudy Slingerland[4] and Barry Voight[5]

The writers agree with Huber's comments and thank him for pointing out various restrictions on the terms comprising a dimensionless kinetic energy of landslides. As the discusser notes, three dimensional waves attenuate more quickly in the main momentum direction than two dimensional waves. The writers have shown in Ref. 16 that three dimensional waves attenuate as $1/r$, where r is the radial distance from the source, whereas two dimensional waves attenuate as $1/\sqrt{x}$, where x is the rectilinear distance from the source. The writers' method uses $1/r$ in the calculations and therefore is restricted to uncomplicated three dimensional situations.

As a matter of interest the writers' have used the data in Fig. 4 to test their model. Eq. 4 predicts for this E_k an $\eta_m/d = 0.14$; the discusser's data show $\eta_m/d \cong 0.17$ at $r/d = 4$, a value within the 95% confidence interval of Eq. 4. Despite the complications noted in the discussion, the

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