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LANSLIDE-GENERATED WAVE STUDIES

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Abstract. - A serious safety of dams problem is associated with large masses of rock and debris plunging into lakes and causing damaging water waves. This concern prompted the Bureau of Reclamation to study a series of landslides in the canyon upstream from Morrow Point Dam. The problem was studied in a physical model of part of the reservoir and three of the landslides. An empirical prediction method was developed as a result of the physical model studies to predict maximum wave heights (Pugh, 1982, and Pugh and Harris, 1982). A mathematical model was also developed as a part of the studies by Tetra Tech, Inc., under contract with the Bureau of Reclamation (Chiang, et. al., 1981). This paper will briefly describe the physical model study, the empirical prediction method, and the numerical model.

Physical Model Study. - The undistorted physical model simulated 4.8 km (3 mi) of reservoir and 1.3 km (0.8 mi) of the canyon downstream from the dam at a scale of 1:250. Morrow Point Dam is a double-curvature, thin arch concrete dam constructed by the USBR on the Gunnison River 40 km (25 mi) east of Montrose, Colorado. The dam is 143 m (468 ft) high and 4 m (12 ft) thick at the crest. Figure 1 shows the reservoir, the landslides, and the model limits.

The landslide was simulated using a simple wedge shape. Simulation of the exact landslide geometry was not considered necessary since the calculated landslide velocity was less than the wave celerity. The displacement of the water is the major factor creating the wave. The potential dynamics of the landslides were computed according to a method described by Slingerland and Voight (Slingerland and Voight, 1979). The model landslide dynamics of the wedge as it enters the reservoir were designed to match the potential prototype dynamics. The model landslides were equipped with extension springs to slow them as they neared the bottom of the reservoir. The model landslide dynamics could be adjusted to simulate a variety of dynamic slide situations. The simple wedge shape made it possible to accurately measure the landslide dynamics for each test. The rate of change of displaced water and its velocity were measured incrementally for each test. Their product multiplied by water density gives the momentum flux of the water at each instant of time. Since the water waves are primarily a result of the momentum flux, the momentum vs. time relationship for the model tests was used to compare to possible prototype landslides. This method of modeling landslide dynamics

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also provided data to compare to results of the numerical model since the physical model landslide dynamics were accurately known.

Wave data at 14 probe locations shown in figure 1 and landslide dynamics were recorded continuously for each test. Data were recorded for a total of 30 tests for landslides at locations A, B, and C. The maximum height of a bore wave in the canyon downstream from the dam was 7 m (23 ft). The maximum wave heights predicted at the dam for slides A, B, and C, respectively, are 20 m (66 ft), 8.5 m (28 ft), and 6.9 m (22.5 ft). A few examples of wave profiles measured in the physical model study are compared with the math model predictions in figures 2, 3, and 4. The solid circles indicate physical model data.

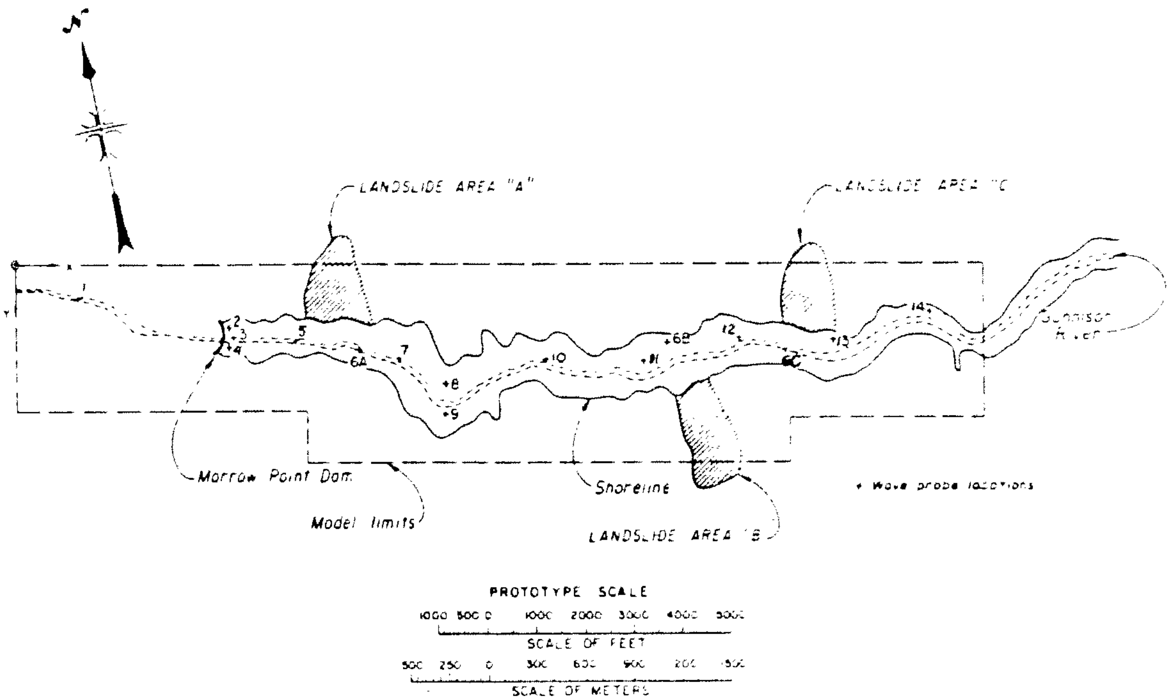

Figure 1. - Morrow Point landslide-generated wave model.

The direction of the landslide momentum was very important to the wave height in the vicinity of the slide. Waves directly in line with slide direction were two to three times higher than waves not in line with the slide. Figures 2, 3, and 4 are time histories of the water surface at probes 6A, 3, and 12, respectively, due to a landslide at location A. The zero time is the instant the slide releases. Waves close to the landslide are very steep and sharp. As the wave moves away from the landslide it lengthens and smooths out.

All electronic measurements of the landslide position, velocity, and wave heights were taken and recorded with a microprocessor and data acquisition system. The microprocessor had an internal clock. The instant the slide was released the microprocessor began recording data from the 14 wave probes, the landslide instruments, and the clock. Twelve readings per second were taken from each of the instruments and stored on magnetic disk for later plotting and analysis.

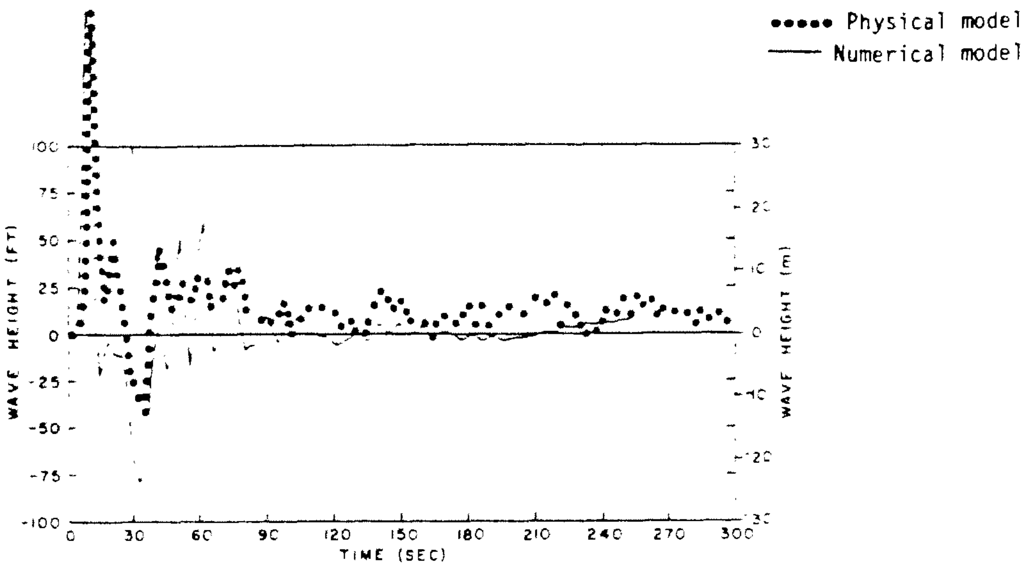

Figure 2. - Physical and numerical model wave profiles at probe No. 6A.

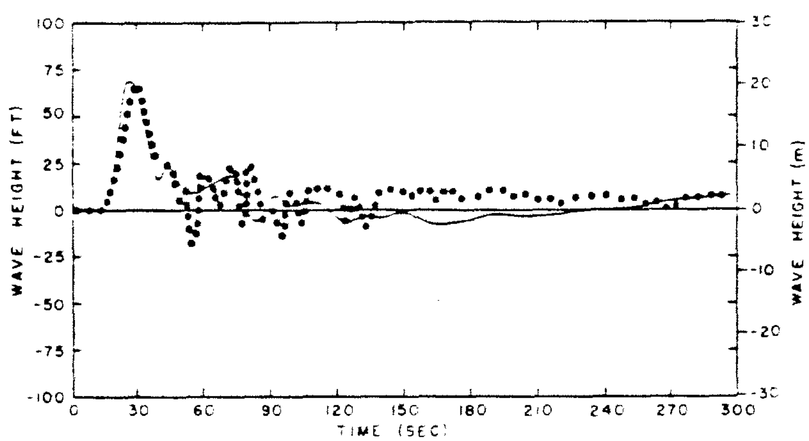

Figure 3. - Physical and numerical model wave profiles at probe No. 3.

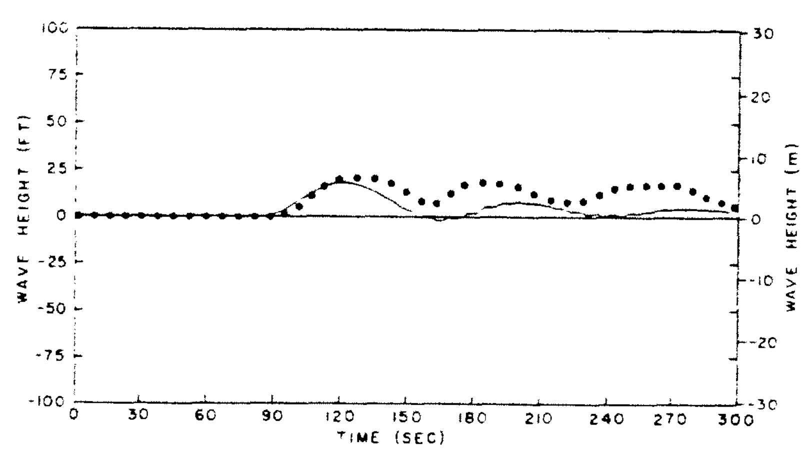

Figure 4. - Physical and numerical model wave profiles at probe No. 12.

Empirical Prediction Method. - A dimensional analysis [4] was performed on the continuity equation (2) and momentum equations (3), (4). From this analysis it was determined that the main parameters affecting the wave height and propagation are the slide Froude number, $F_r = V_s / \sqrt{gD}$, a distance parameter ℓ/D, and the time rate of change of water displacement.

A series of data plots were made relating the maximum initial wave height (η/D) to a displacement parameter (V/D^3), the slide Froude number, and the distance from the slide. For slide Froude numbers above 0.6, increases in velocity of the landslide produce only minor increases in wave heights.

An equation was fitted to the data in the original study using a logarithmic form. The wave height was found to decay with distance from the slide according to a power law.

An independent study (Huber, 1982) conducted at about the same time in Switzerland resulted in many of the same conclusions reached in this study. Huber also concluded that a displacement parameter, a slide Froude number, and a distance parameter were the primary factors influencing the wave height. The main difference between Huber's study and the Morrow Point study was the range of the displacement parameters. Historic rockfalls into Swiss lakes have displacement numbers around 0.02, while the displacement parameters for the Morrow Point study ranged from 2.0 to 4.0.

Huber developed a technique for estimating wave height based on displacement parameter, direction of propagation, slide Froude number and distance. This method was developed from a series of two-dimensional flume tests and three-dimensional wave basin tests.

It is realized that the logarithmic equation developed from the original physical model study of Morrow Point Reservoir is not valid for displacement numbers smaller than 1.0. Rockfalls into the Swiss lakes are in this range. Therefore, a power equation was developed as an alternative. The power equation still gives good estimates for the Morrow Point model waves and the Vaiont landslide case (see figure 5) and also gives reasonable estimates for smaller landslides and rockfalls. Figure 5 is a plot of the equation.

$$\frac{\eta}{D} = \frac{0.14\ (V/D^3)^{0.50}}{10^{\frac{\ell/D}{58}}} \qquad (1)$$

Equation 1 gives estimates for maximum wave heights at the dam with the wave propagating at a 90° angle to the direction of the landslide. Waves in the direction of the landslide are much higher and initially decay at about twice the rate with the distance until ℓ/D is about 20, then the decay rate stabilizes and is the same in all directions. The wave height at the dam is increased in amplitude due to the partial reflection of the dam. This increase is included in equation 1.

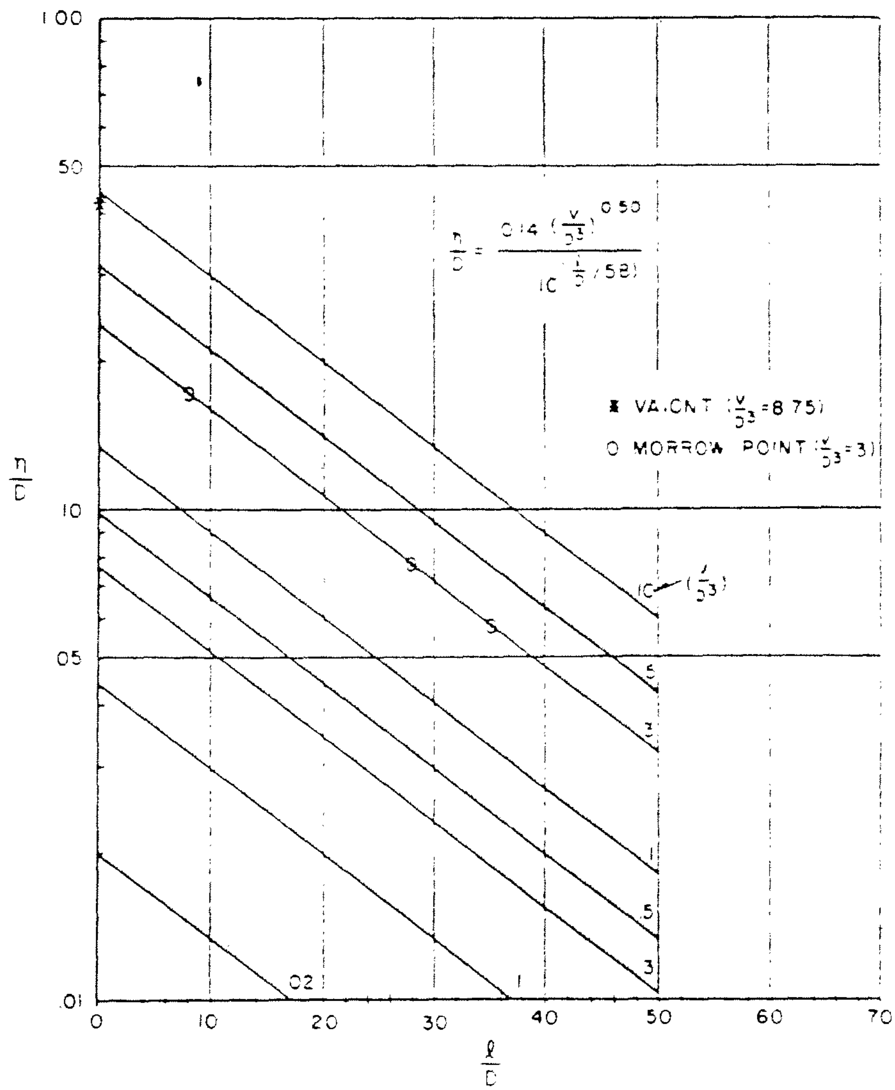

Figure 5. - Maximum wave height vs. displacement parameter and distance from the landslide.

Numerical Simulation. - A mathematical model was developed to study the generation, propagation, and dissipation of rockfall or landslide-generated water waves in bays, lakes, reservoirs, fjords, and rivers (Chiang, et. al., 1981). The mathematical model was used to simulate the laboratory tests of landslide-generated waves in Morrow Point Reservoir. The numerical results agree very well with the laboratory results. The mathematical model was also verified with several historic events and model studies reported in the literature.

The mathematical model is a set of nonlinear, depth-integrated equations to be applied to a variable depth basin. Hydrostatic pressure is assumed. Coriolis force is neglected due to the small area of application. The major forcing function is the squeeze of the water column due to the intrusion of a landslide mass. The squeeze action is represented by a change of water depth or a raise of the bottom of the basin. The lateral velocity produced by the squeeze action is simulated by the velocity due to the elevation gradient which is produced by the raise of the water column at the location of the landslide. The effects of drag due to the landslide are included in the momentum equations. The resultant set of equations is (see also Chiang and Lee, 1982, and Raney and Butler, 1975).

$$\frac{\partial \eta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = -\frac{\partial D}{\partial t} \tag{2}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} = -F_x \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial y} = -F_y \tag{4}$$

The terms on the right-hand sides of momentum equations (3) and (4) include effects of bottom friction and drag due to a landslide. At a location outside of the landslide area, the resistance force is equal to that due to bottom stress:

$$F = \frac{n^2 g\ (u^2 + v^2)}{1.486^2\ H^{4/3}} \tag{5}$$

At a location covered by the moving landslide, the resistance is represented by the drag induced by the slide [1].

$$F = -\frac{1}{2}\frac{V_r^2}{HA_s}\left(C_{Dp}A_p + C_{Dv}A_v\right)\cos\alpha \tag{6}$$

A central difference formulation is used to transform the aforementioned partial differential equations into a set of finite difference equations in an explicit form. Three kinds of boundary conditions were used in addition to the time history of the slide intrusion. At the far upstream boundary, a radiation condition allows the wave to propagate through the boundary without reflection. At the downstream boundary a dam allows overtopping if the water level is higher than the specified elevation. Other parts of the boundary are partially reflective on which part of the wave energy is dissipated.

The mathematical model was used to simulate the landslide waves generated in Morrow Point Reservoir. The model consists of 14 by 64 grid points. The grid spacing is 76 m (250 ft) in either direction. The bathymetry was obtained from the appropriate topographic maps published by the U. S. Geological Survey. Landslides at three locations (A, B, and C in figure 1) were studied.

The time history of the computed wave heights at the grid point nearby each probe is stored and plotted. Figure 2 depicts the prototype time history of the wave amplitude nearby probe No. 6A which is located in front of slide A (figure 1). The solid line represents the computed results while the solid circles indicate the laboratory data. The first peak of approximately 52 m (171 ft) prototype height is caused by the sudden push of the slide mass on the water. This peak later breaks on the south shore with part of its energy propagating both downstream and upstream. Although there appears to be a phase difference of a couple seconds (prototype), the calculated maximum height is amazingly close to the laboratory measurement. The negative wave and the reflective wave also match reasonably well. The later fluctuations due to multiple reflections and refractions in the irregular bathymetry are small and of no significant meaning.

The wave measured by probe No. 3 indicates a peak of 20 m (65 ft) in front of the dam. The results from the numerical model again show very good matching with the experimental data (figure 3).

At probe No. 12, the wave is reduced to about 6 m (21 ft) due to multiple reflection losses and dispersion effect along the path of more than 3 km (2 mi). The computed peak is slightly lower (figure 3). The phase matches with the data very well.

Conclusions. - Landslide-generated water waves were studied in Morrow Point Reservoir using a physical model. An empirical prediction method was developed from the data to estimate maximum wave height at a dam (η/D) based on a dimensionless displacement parameter (V/D^3) and the distance from the landslide (ℓ/D).

Waves are two to three times higher directly in line with a landslide than beside the landslide. For slide Froude numbers above 0.6 only minor increases in wave heights result. The wave height attenuates according to a power law with distance from the landslide.

A mathematical model was developed which accurately predicts the amplitude and phase of waves both in the vicinity of the landslide and several kilometers from the landslide. The numerical model can be used to predict waves resulting from possible landslides, rockfalls, and fault displacements in the bottom of a basin. Landslide data can be input into the model, or the model will generate an assumed landslide to produce the waves.

Acknowledgments. - The technical contributions of Dr. Henry Falvey to the physical model studies and Mr. David Divoky to the mathematical model development are greatly appreciated. Dr. David Harris was the primary coordinator for all of the studies.

Appendix 1. - References

1. Chiang, W. L., Divoky, D., Parnicky, P., and Wier, W., "Numerical Model of Landslide-Generated Waves," Report T3427, Tetra Tech, Inc., Pasadena, California, November 1981.

2. Chiang, W. L., and Lee, J. J., "Simulation of Large-Scale Circulation in Harbors," Journal of the Waterway, Port, Coastal and Ocean Division, ASCE, Vol. 108, No. WW1, Proc. Paper 16841, February 1982, pp. 17-31.

3. Huber, A., "Impulse Waves in Swiss Lakes as a Result of Rock Avalanches and Bank Slides, Experimental Results for the Prediction of the Characteristic Numbers for These Waves," Paper, Int. Comm. on Large Dams, 14th Congress, Q54, R29, Rio de Janeiro, Brazil, May 1982.

4. Pugh, C. A., "Model Studies of Landslide-Generated Water Waves, Morrow Point Reservoir," U. S. Bureau of Reclamation, REC-ERC-82-9, January 1982.

5. Pugh, C. A., and Harris, D. W., "Prediction of Landslide-Generated Water Waves," Paper, Int. Comm. on Large Dams, 14th Congress, Q54, R29, Rio de Janeiro, Brazil, May 1982.

6. Raney, D., and Butler, H. L., "A Numerical Model for Predicting the Effects of Landslide-Generated Water Waves," Research Report H751, U. S. Army Engineering Waterways Experiment Station, Vicksburg, Mississippi, February 1975.

7. Slingerland, R. L., and Voight, B., "Occurrences, Properties, and Predictive Models of Landslide Generated Waver Waves," Rockslides and Avalanches, Vol. 2, Elsevier Science Publishing, N. Y., 1979.

Appendix 2. - Notations

A_p, A_v, A_s	cross-sectional areas
C_{Dp}, C_{Dv}	pressure drag coefficient and viscous drag coefficient
D	water depth
F	resistance force
$F_r = V_s/\sqrt{gD}$	slide Froude number
F_x, F_y	total friction along x and y directions, respectively
g	gravitational acceleration
$H = \eta + D$	total water depth relative to instantaneous water surface
ℓ	distance from the landslide
ℓ/D	distance parameter
n	Manning's roughness coefficient
t	time
u, v	water velocities along x and y directions, respectively
x, y	coordinates
η	surface elevation relative to initial water surface (positive upward)
η/D	maximum initial wave height
α	angle between the instantaneous slide direction and the horizontal
V	volume of water displaced by the landslide
V/D^3	displacement parameter
V_r	horizontal landslide velocity, relative to far field water velocity
V_s	maximum landslide velocity