CHAPTER 35

IMPULSE WAVES GENERATED BY LANDSLIDES

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ABSTRACT

A study programme has been initiated to investigate the impulse waves generated by landslides originating entirely above the water surface It may be seen that the characteristics of this wave depend mainly on the slide volume and the Froude number of the slide upon impact with the water The resulting wave goes through a transition period For the highest wave (usually the first), the wave height becomes stable relatively quickly and decays exponentially during the period of transition, the wave period continues to increase for a long time, the velocity of propagation may be approximated very closely by solitary wave theory

INTRODUCTION

Impulse waves generated by landslides have long been a menace in certain localities and the study of this phenomenon has been carried out at an accelerated rate in the 1960's, perhaps as a result of disasters of major proportions such as at Vaiont (2) In coastal areas, these slides are also not uncommon and Miller (4) gives a number of examples

An attempt is made in this paper to determine the relation between the generated impulse waves and the various parameters of the slide and the receiving body of water Some studies of underwater slides and of slides under simplified conditions have been performed, Wiegel (9), Prins (5,6) and Wiegel et al (10), but little is known about slides originating above the water surface, sliding into the body of water at various angles

Theoretical work has also been done for simplified generating conditions e g Unoki and Nakano (7), Kranzer and Keller (3) and Ursell (8) In this paper no attempt has been made to express the results on a theoretical basis

The purpose of the present paper is to approach a highly complex, non-linear problem entirely experimentally, invoking as little simplification as possible The test series is yet incomplete and the analysis is part of a continuing program

EXPERIMENTAL TECHNIQUE

Experiments were carried out in a 45 m long flume, 1 m wide, with water depths, d, ranging from 23 to 46 cm [1]. The landslides were modelled using a tray (Fig 1), loaded with a varying number of units of constant specific gravity and of zero porosity. The tray was placed at various distances above the water to roll down a roller ramp. In Fig 2 this ramp is shown with the tray in position at the top of the ramp. The angle of the ramp with the water surface, θ, was adjustable, as was the front slope of the tray, α. The tray was released using a quick release mechanism and the velocity of impact with the water, V, was measured using a combination of stroboscope illumination and prolonged photographic exposure of a series of lines on the top of the tray.

The resulting waves were measured continuously at three locations, 3.35, 9.45 and 17.1 m from the point of impact. These locations are called a, b, and c respectively.

The record from the first wave probe (a) was also squared and integrated by analogue methods. The wave energy was calculated, using a digital computer programme, by a combination of

$$E_o = \rho g \, C_a \int \eta^2 \, dt \tag{1}$$

and

$$E_s = \frac{8}{3\sqrt{3}} \, H^{3/2} \quad d^{3/2} \tag{2}$$

where E_o is the energy contained in a deep water wave using oscillatory wave theory, E_s the energy by solitary wave theory, ρ the water density, g the acceleration of gravity, C_a the phase speed of the wave at location a, η the wave record, t the time and H the maximum wave height. The phase speed C_a, was measured using the elapsed travel time between probe a and an on-off probe, located at still water level, very close to probe a.

DIMENSIONAL ANALYSIS

For the experimental study, any property, A, of the wave may be stated as a function of the following parameters

$$A = f(l, w, h, V, \beta, \theta, p, \rho_s, \rho, \mu, g, d, x, t) \tag{3}$$

where l, w and h are the length, width and thickness of the slide, β is the angle between the front face of the slide and the horizontal ($\beta = \theta + \alpha$), ρ_s is the density of the slide, μ is the dynamic viscosity of the water, x is the distance from the point of impact and t is the elapsed time.

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1 A summary of the notation may be found at the end of the paper

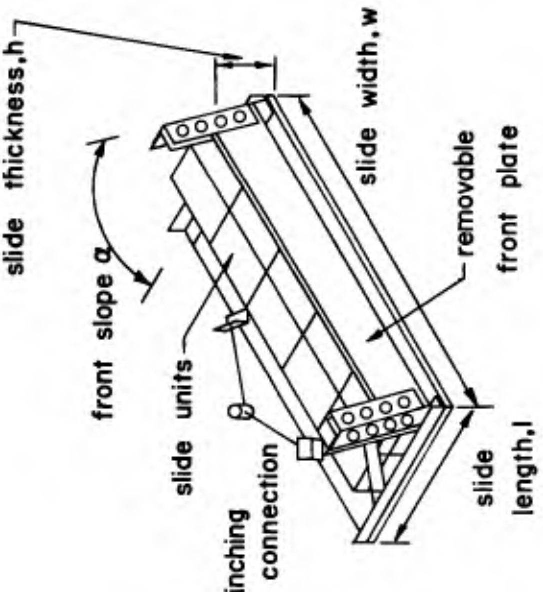

Fig. 1: Model Slide

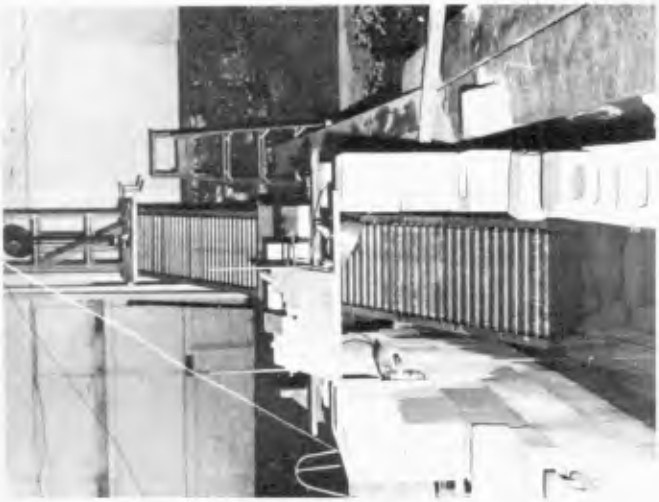

Fig. 2: Roller Ramp

Eq 3 may be written in dimensionless form as

$$\pi_A = \Phi_A \left(\frac{l}{d}, \frac{w}{d}, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}, \frac{\rho d\sqrt{gd}}{\mu}, \frac{x}{d}, t\sqrt{\frac{g}{d}}\right) \qquad (4)$$

Because the tests were performed in a two dimensional flume, the term w/d becomes irrelevant Early in the tests it became evident that the slide volume and the related kinetic energy of the slide upon impact with the water are very important terms and therefore l/d has been replaced by the two-dimensional slide volume per unit width expressed in dimensionless form as

$$q = \frac{l}{d} \times \frac{h}{d} \qquad (5)$$

The kinetic energy upon impact can be obtained by the following combination

$$k = \tfrac{1}{2} \left(\frac{\rho_s}{\rho}\right) \left(\frac{l}{d}\right) \left(\frac{h}{d}\right) \frac{V^2}{gd}$$

Because shear was negligible throughout, the Reynolds number can be neglected and Eq 4 becomes

$$\pi_A = \phi_A \left(q, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}, \frac{x}{d}, t\sqrt{\frac{g}{d}}\right) \qquad (6)$$

where π_A represents the dimensionless form of any dependent quantity A

Thus for maximum wave height at any probe

$$\frac{H}{d} = \phi_H \left(q, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}, \frac{x}{d}\right) \qquad (7)$$

and for the wave energy at the first probe

$$\frac{E}{\rho g d^3} = \phi_E \left(k, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}\right) \qquad (8)$$

Here q has been replaced by k, a more relevant parameter

For the speed of propagation of the waves

$$\frac{C}{\sqrt{gd}} = \phi_C \left(q, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}, \frac{x}{d}, t\sqrt{\frac{g}{d}}\right) \qquad (9)$$

and for the wave period

$$T\sqrt{\frac{g}{d}} = \phi_T \left(q, \frac{h}{d}, \frac{V}{\sqrt{gd}}, \beta, \theta, p, \frac{\rho_s}{\rho}, \frac{x}{d}, t\sqrt{\frac{g}{d}}\right) \qquad (10)$$

Throughout the tests, except for one isolated test series, p and ρ_s/ρ were not varied ($p = 0$, $\rho_s/\rho = 2.7$). Further work needs to be done to test the effect of these parameters. The work also needs to be extended to higher values of slide volume, q or kinetic energy, k.

The test results therefore only apply to relatively small rock slides, originating above the water level.

TEST RESULTS

The wave records obtained were very much as expected. At probe a, the wave train consisted of one large wave followed by a short train of smaller, trailing, oscillatory waves. At probe b, the large leading wave had lengthened considerably and decreased in height. It had passed some of its energy to the following wave train. The train of oscillatory, following waves had also lengthened. At probe c, the wave height appeared to have reached a stable or almost stable value. The wave train was now very long, the large wave itself having attained a wave length of the order of 20 to 30 times the depth of water.

The first wave was always the highest in the train except for test series 52 where θ is 90°.

Maximum Wave Height. The test results indicate the dimensionless parameters in Eq. 7 that exercise the greatest influence on the wave height are q, the volume per unit width of the slide and $\mathbb{F} = V/\sqrt{gd}$ the Froude number of the slide upon impact with the body of water. The other parameters only introduce variations to the basic relationship. All test results have been plotted against q.

Typical test results are shown in Fig. 3 and it may be seen that H_c/d varies directly with log q. This is not true for H_a/d, the wave height nearest the point of impact. From comparison of wave heights at a, b and c, it appears that H_c/d is stable, i.e. the wave height does not decrease significantly beyond probe c. The subsequent figures focus on this stable wave height and the other two measured wave heights are related to it by a wave height attenuation function discussed later in this section.

The effect of the slide thickness on the stable wave height is indicated in Fig. 4. For thick slides, defined as $h/d > \frac{1}{2}$, the relation between H_c/d and q is relatively constant. For thin slides, defined as $h/d < \frac{1}{2}$, a decrease in h/d results in smaller wave heights.

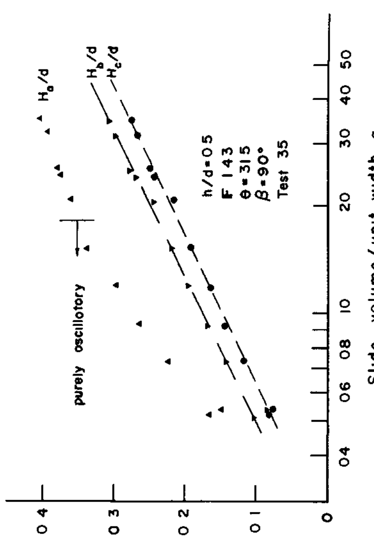

Fig 3 Wave Height as a Function of Slide Energy

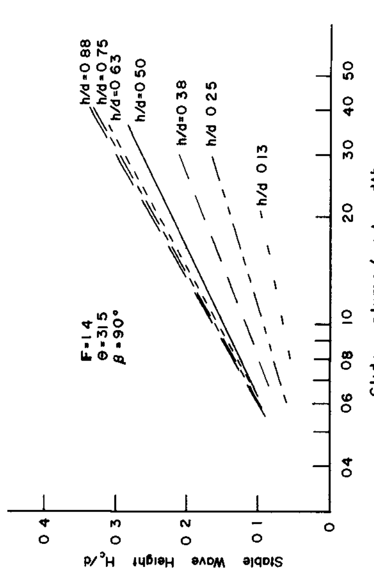

Fig 4 Effect of Slide Thickness on the Stable Wave Height

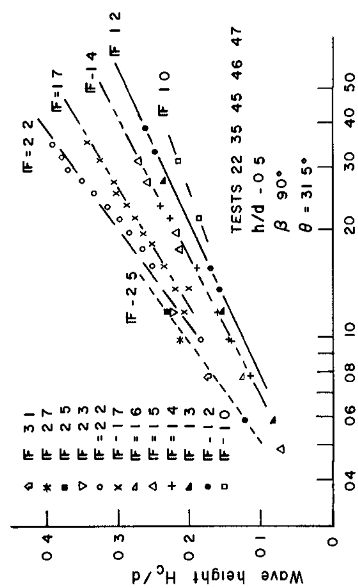

Fig 5 Effect of Impact Froude Number on the Stable Wave Height

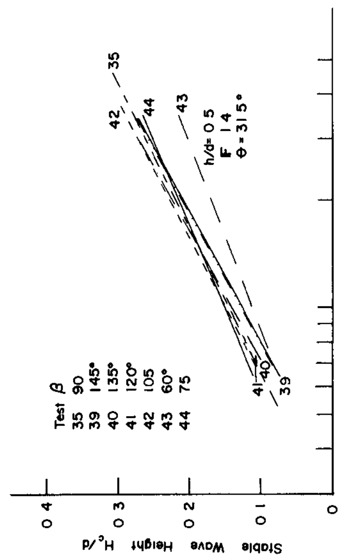

Fig 6 Effect of Front Slope of the Slide on the Stable Wave Height

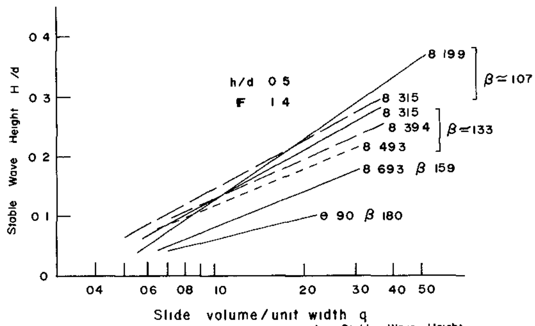

Fig 7 Effect of Slide Slope on the Stable Wave Height

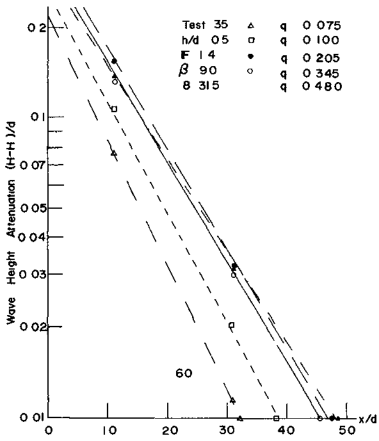

Fig 8 Example of Decrease in Wave Height with Distance

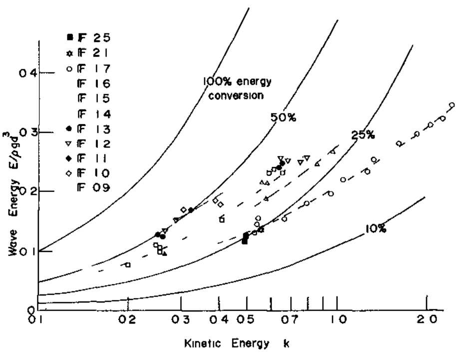

Fig 9 Effect of Impact Froude Number on Wave Energy

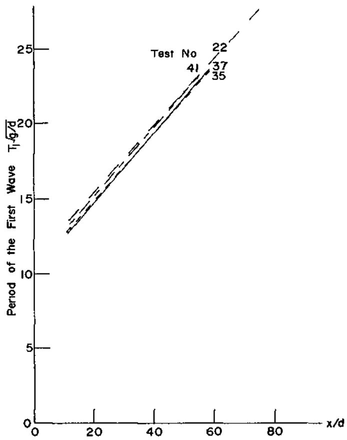

Fig 10 Period of the First Wave vs distance

For the range of Froude numbers tested (Fig 5) it may be seen that the stable wave height increases significantly with the Froude number of the slide upon impact

An increase in the front slope of the slide, β, appears to increase the slope of the relation between H_c/d and q For large slides the resulting wave height increases with β, for small slides, it decreases with β In addition, for $\beta < 90^o$ there is a general reduction in agitation An example of the effect of β on H_c/d has been plotted in Fig 6

As θ increases, the generated wave is decreased slightly except for small slides - Fig 7 The results of test series 51 and 52 have also been plotted - not to indicate the effect of θ but to represent a possible overlap with the results of Prins (5,6) and Wiegel (9,10)

In Fig 3 it may be seen that $H_a > H_b > H_c$ This can be attributed mainly to dispersion, i e the passing of energy from the highest wave to the trailing train and the lengthening of the whole wave train Experimentally it was found that the decrease in wave height is exponential and that the wave height for most tests decreased little beyond probe c An example is shown in Fig 8 The slope of the lines is almost constant for all tests and the intercept varies as a function of q

Wave Energy The test results involving wave energy may be plotted similar to Figs 3 to 7, but it is more convenient to plot them as a function of k, the dimensionless kinetic energy As an example - Fig 9 - the effect of Froude number has been plotted and on the same graph the lines of constant % energy conversion have been shown

Velocity of Propagation The velocity of propagation, between probes b and c, of the highest wave in the wave train was found to be within 1% of the following theoretical approximation for a solitary wave

$$\frac{C}{\sqrt{gd}} = 1 + \frac{\eta_{max}}{2d} \tag{11}$$

This corresponds to Eq 9 because $\eta_{max}/2d$ is simply another function of the right hand side of Eq 9

Wave period $T_1\sqrt{g/d}$, the dimensionless period of the first wave in the wave train has been plotted against distance along the flume in Fig 10 It may be seen that the wave period increases linearly with distance along the flume It was found that all the other parameters of Eq 10 exercised a negligible influence on the relation between $T_1\sqrt{g/d}$ and x/d

DISCUSSION

The wave forms obtained from the tests varied from a pure oscillatory wave train to a wave approaching solitary wave configuration, followed by an oscillatory wave train Comparison with Prins (5, Fig 10) would indicate his experience to be similar At no time during the tests were bores generated and therefore the results presented here can only be viewed as partial, also in this respect

Under these conditions the test results indicate that a stable wave height is generally obtained within 80 depths from the point of impact

Maximum Stable Wave Height A definite relation exists between the stable wave height and the volume of the slide This relation can be expressed as

$$\frac{H_c}{d} = C_1 + C_2 \log q \qquad (12)$$

where both C_1 and C_2 are functions of the remaining dimensionless parameters of Eq 7 But Fig 5 indicates that the wave height is also highly dependent on Froude number Taking this into account, the relationship which approximates the test results most closely is

$$\frac{H_c}{d} = \mathbb{F}^{0\ 7} (0\ 31 + 0\ 20 \log q) \qquad (13)$$

This can be used as a good estimate of the stable wave height for $0\ 05 \leq q \leq 1\ 0$, as long as the slide is thick, i e $h/d \geq \frac{1}{2}$, the front angle of the slide is 90° or greater and the angle of the slide plane is about 30° Eq 13 can also be used as a conservative estimate for slides where $\beta < 90^{\circ}$, or $\theta > 30^{\circ}$ and an estimate of the built in factor of safety may be obtained from the figures presented in this paper For the case $\theta < 30^{\circ}$, Eq 13 could be unsafe

Eq 13 is purely empirical Unoki and Nakano (7) conclude that theoretically $\eta \sim$ initial impulse Since for each test series V was kept almost constant, this reasoning should lead to $\eta \sim$ slide volume for each test series However, this appears not to be the case, indicating that the system is highly non-linear and that the theoretical approach of (7) overestimates the generated wave height The theoretical approach of Kranzer and Keller (3) could perhaps be applied as an approximation, if the "initial" water surface, immediately after impact of the slide, were known This is virtually impossible because of splash and because the slide takes a finite time to enter and travel through the body of water

The changes in the relation of H/d on q for the parameters treated in Figs 4 to 7 can be explained from the physical phenomenon It must be remembered that in all cases with the exception of Fig 5, the Froude number is constant, therefore slide volume is synonymous with kinetic energy on impact

Referring to Fig 4, as the slide becomes thinner, it imparts less energy to the water, dissipating more of the remaining energy by bottom impact

As the impact Froude number increases, Fig 5, the kinetic energy upon impact increases for the same slide volume This results in greater wave heights as well as greater splash and bottom impact

Fig 6 indicates that a decrease in β beyond 90° causes the front of the slide to become more streamlined The slide then imparts less energy to the water

As θ decreases, the distance of travel of the slide through the water becomes greater and therefore it is expected that a greater amount of the energy of the slide goes into wave generation Also, the generation mechanism changes to more of a pushing action

Wave Height Attenuation Fig 8 is an example of the pattern of wave height attenuation found generally Because the attenuation is represented by straight lines of constant slope, the decrease in wave heights can be expressed as

$$\frac{H}{d} = \frac{H_c}{d} + C_3 e^{-C_4 \left(\frac{x}{d}\right)} \tag{14}$$

where C_3 is a function of the other parameters in Eq 7, C_4 appears to be constant at 0 08 For values of $0\ 1 < q < 1\ 0$, Eq 14 can be approximated by

$$\frac{H}{d} = \frac{H}{d}(\text{stable}) + 0\ 35 e^{-0\ 08 \left(\frac{x}{d}\right)} \tag{15}$$

Wave Energy For the range of values tested the wave energy is generally from ¼ to ½ the kinetic energy of the slide upon impact For test 52, the vertically falling slide only 10 to 20% of the kinetic energy was converted into wave energy Thus the slide at an angle appears to be considerably more efficient than the vertical one The kinetic energy of the slide at the time of impact is a rather difficult term to assess in the field An easier estimate is the potential energy of a slide and this figure has been used by Johnson and Bermel (1) and Wiegel (9) for laboratory generation of impact waves and by Miller (4) in assessing slides in the field The conversion from potential energy to kinetic energy upon impact is entirely different in all three cases, however, and the complex mechanism in the field slides cannot be adequately simulated by simplified laboratory models For that reason, kinetic energy upon impact was used which leaves the transfer function of field potential energy to kinetic energy only to be determined, circumventing an additional, similar function for each particular laboratory situation

Velocity of Propagation With wave lengths of the order of 20 to 30 times the depth, the waves are by definition shallow water waves and their characteristics can be approximated by the solitary wave theory, once the waves become of constant form Therefore the velocity of propagation should be approximated by the expression for the phase velocity of a solitary wave (Eq 11) The close comparison between actual values and theoretical values was indeed surprising

Wave Period The various dimensionless parameters, other than the distance from the point of impact had very little influence on the wave period of the first wave and this wave period may be defined from plots similar to Fig 10 as

$$T_1\sqrt{\frac{g}{d}} = 11 + 0\ 225\left(\frac{x}{d}\right) \tag{16}$$

This indicates that, although wave height and velocity of propagation of the first wave have reached a stable value at probe c, the wave period and wave length have not Therefore the first wave continues to stretch out, tending to become a true, solitary wave, of infinitely long period, with no or only slight decrease in wave height The periods of the trailing waves exhibit the same tendency although their increase in period is not linear with x/d through the range of x/d tested

PRELIMINARY COMPARISON WITH FIELD RESULTS

Properly monitored field data are difficult to obtain because of the unexpected and disastrous nature of the slides In an attempt to see how relevant the model tests are and as an indication of the applicability of formulae such as Eq 13, the slides listed by Miller (4, p 66) were used as field examples

The model tests are two-dimensional and therefore can be expected to give a conservative indication for the three-dimensional field results

Most of the slides listed by Miller are rock slides and all originated above the water surface The volume and width of the slide front are only mentioned simultaneously in three cases thus reducing the list to only three examples For one of these, the Shimabara Peninsula slide, the slide volume was greater than the range of q tested For the other two, the Loen Lake slide of 1936 and the Tafjord slide of 1934 Eq 13 gives a reasonably close estimate wave height

A great deal more work needs to be done in this area

CONCLUSIONS

The impulsively generated waves resulting from the sliding of a rock mass into a body of water have been investigated

A series of tests has been performed to determine the effect of various parameters describing the slide and the receiving body of water on the generated impulse waves In this test series all slides were impervious and of rock density The volumes of the slides were kept relatively small and so the test results are only applicable to small and medium sized slides of rock which originate above the water surface and slide into relatively large bodies of water

For these conditions it was found that the wave height stabilized very quickly and can be described as a function of the slide volume and Froude number on impact (Eq 13) All other parameters appear as relatively small modifications to this function The wave height attenuation between a location close to the site of impact and the point where the wave height has stabilized can be described by an exponential function (Eq 15)

The wave energy varies for these tests from ¼ to ½ of the input kinetic slide energy The velocity of propagation of the highest wave can be described adequately by solitary wave theory Its wave period increases linearly with distance for the distance range tested Some very preliminary work on field data indicates that Eq 13 can be used to predict or hindcast field wave heights

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NOTATION

A = general dimensional expression for wave parameters,
a = location of first wave measuring probe,
b = location of second wave measuring probe,
C = velocity of propagation of the wave,
c = location of third wave measuring probe,
d = depth of water,
E = wave energy,
E_o = wave energy in deep water from oscillatory wave theory,
E_s = wave energy by solitary wave theory,
$\mathbf{F}$ = Froude number,
f = dimensional function,
g = acceleration of gravity,
H = maximum wave height,
h = thickness of the slide,
k = dimensionless kinetic energy of the slide,
l = length of the slide,
p = porosity of the slide,
q = volume per unit width of the slide,
T = wave period,
t = time,
V = velocity of impact of the slide,
w = width of the slide,
x = distance from the point of impact of the slide,

α = angle between the bottom and the front face of the slide,
β = angle between the front face of the slide and the horizontal, ($= \alpha + \theta$)
η = wave record,
θ = angle between the slip plane (roller ramp) and the water surface,
μ = dynamic viscosity of the water,
π = general dimensionless expression for wave parameters,
ρ = density of water,
ρ_s = density of the slide material,
Φ = dimensionless function,
ϕ = dimensionless function,