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Study of Impact Loads on Retaining Walls

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SUMMARY A large scale physical model of a landslide was developed using dry quartz sand as a flow media. The dry sand was allowed to slide and impact on a wall at a series of slopes (30-40°). Forces resulting from the impact of sand flow were monitored using load cells. High speed photographs facilitated analysis of the motion of the sliding mass. Two waves of sand were observed within each flow slide. An initial wave traveled down the slope and impacted the retaining wall; secondary waves then overtopped the initial sand mass until the angle of repose was reached. Dynamic impact forces exerted against the retaining wall were greater in magnitude than static forces. A linear relationship was observed between the magnitude of the impact force and the slope angle of the container. The location of the force resultant was lower for dynamic loading conditions than static loading. A comparison of test results with existing methods of analysis indicated that the quantitative models underestimated the dynamic forces measure in the model.

1 INTRODUCTION

Landslides and earth movements are complex phenomena resulting from changes in the stability of a soil or rock mass. The cause of landslides and the resulting catastrophic effects have been intensively studied. The dynamic forces produced by such mass movements, however, have received very little attention. Current engineering practice approaches slope stability analyses as a preventative measure. Physical or economic constraints however may dictate that ordinary engineering techniques cannot be used to stabilize the slope and a protective structure may have to be designed to resist impact loads from a mass of moving soil. The purpose of this investigation was to study the forces induced by a flowing soil impacting upon a rigid structure. A simplified model of a landslide was developed consisting of a flow of dry, medium quartz sand. Data on the peak forces and equilibrium forces resulting from the sliding mass of sand impinging upon a model retaining wall were collected and analyzed. The resulting forces were compared with exisiting predictive methods for determining the impact forces developed by a moving mass.

2 FLOW OF GRANULAR MATERIALS

Flows of earthen material range from the completely dry to those which are totally liquid in nature. Morgenstern (1978), and Varnes (1975), provide examples of flows that span the spectrum of water content from dry to saturated conditions. In addition to variation in water contents, different mechanistic models have been shown to exist in nature for a flow of earth materials. The behavior of flows may be described as turbulent, or in a steady state condition (Johnson and Ragle (1964)), behaving as a plastic body in plug flow (Johnson (1970)), channel flow (Royster (1979)) or even travelling as a flexible sheet (Varnes (1975)). It is apparent that the movement of any mass is a complex event with many unknowns.

The forces contained within a sliding mass of material have received little attention. Most previous work has been confined to the evaluation of velocity profiles in open chutes and channels using both mathematical models as well as laboratory tests (Savage (1979), Mandl and Fernandez-Luque (1978), Goodman and Cowin (1971)).

Takahasi (1937) formulated simple velocity equations for the flow of sand through wooded channels. The equations were based on experimental work in chutes of rectangular cross section at various angles of inclination (θ). He found two flow patterns to exist, separated by a critical angle (θ_c). The first at $\theta < \theta_c$ consisted of an upper thin layer of particles flowing over a stationary layer overlying the chute bed. The second at $\theta > \theta_c$ considered each particle to be in a state of chaotic motion corresponding to turbulent flow in fluid mechanics. The velocity of the sand was found to increase more rapidly for the laminar type flow (at $\theta < \theta_c$) than for the turbulent flow ($\theta > \theta_c$). Takahasi found similarities between his work and the motion of avalanches and landslides when comparing his equations to the flow of a liquid. He indicated that further research into the magnitude of the velocities of natural phenomena is needed.

Research by M. Fukuoka (1961) centered around characteristics of landslides in Japan. From a case study he developed equations of motion for a sliding prismatic element of material. The use of retaining walls to impede the movement of landslides was also discussed by Fukuoka at Mt. Chausu, Japan, and at the foot of the Imnouike Valley, Japan.

Scheidegger (1975) discusses in detail the forces transmitted by a sliding mass on a rigid structure. He found similarities between physical properties of snow, ice and landslides. Simple models were developed for the movement of rigid bodies, rock flows, surficial slides, debris flows, and snow avalanches. An analytical equation was developed to determine the coefficient of friction based upon the estimated volume of an imminent landslide. With the coefficient of friction known, the reach and velocity of a landslide could be predicted using a frictional model. The frictional model, however, did not allow the calculation of the distribution of stresses within the snow mass and the resulting impact forces. To accomplish this, Scheidegger utilized the work of Voellemy who considered a fluid model to estimate the impact forces of an avalanche on a structure. Morgenstern (1978) concurs with the fluid flow method of analysis. He stated, "protective structures are often best designed utilizing basic principles of fluid mechanics rather than the more traditional views of soil behavior."

3 MODEL TEST EQUIPMENT, INSTRUMENTATION AND TEST PROCEDURE

The test container consisted of a rectangular box of steel, plywood and plexiglass and measured 2.56 m long, 0.9 m wide and 0.64 m deep. The container was partitioned 84 cm. from one end by a plywood door which pivoted above the top of the box. The partition created a holding bin for the 5.56 kN of quartz sand used to model the dry flow. On the opposite end from the bin was the model retaining wall and force monitoring system as shown in Figure 1. The channel width was acceptable based on the work of Savage (1979) and Passman, et al. (1979). To minimize boundary effects the model was constructed as friction free as possible using plexiglass for the sidewalls. The transparency of the channel walls also allowed high speed photographs to be taken and visual observation of the flow characteristics of the material.

The door release mechanism was constructed so as not to impede the flow of sand upon release. The design consisted of a 3 meter tower adjacent to the box from which a pulley system was attached When the door was released, weights attached to the cable dropped, swinging the door open and allowing the flow of sand to begin.

The retaining wall consisted of three independent sections composed of 12.7 mm thick aluminum plates. The sections were centrally located and did not extend the entire width of the channel to minimize the effect of boundary conditions along the sidewall. Construction of the independent sections also allowed the force recorded by one load cell to be unaffected by the force recorded by another. The three sections enabled a pressure distribution to be determined on the face of a rigid structure for the impact of the dry flow (see Figure 1).

Three different size sets of plates were used to model the retaining wall as a check on the effect of plate size on test results. The sizes used were 387 sq. cm., 206 sq. cm., and 97 sq. cm. Forces resulting from the impact of granular material were monitored using three Strainsert Universal Load Cells. Each was mounted to one of the aluminum plates and rigidly fastened to the steel frame to form the model retaining wall. For each trial a graphical output of force versus time was obtained and the peak (dynamic) and static loads induced by the flow of cohesionless material were determined.

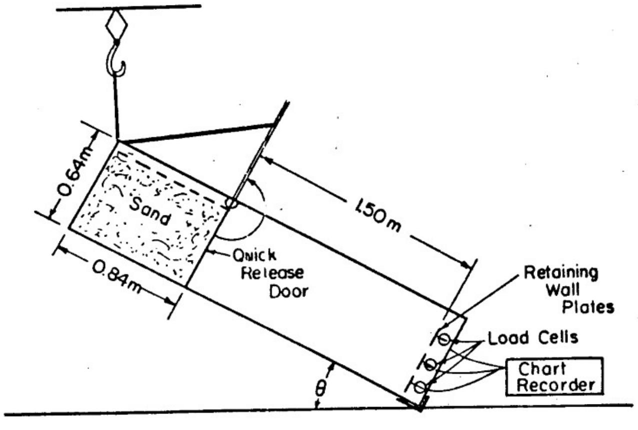

Figure 1

The most critical variable to be considered was the slope of the model dry flow. Preliminary trials of the test apparatus indicated that the best results were obtained at angles from 30° to 40°. The investigation was limited within this range as the angles of repose of most debris material in landslides lie between 30° and 40° (Scheidegger (1975)).

Five test angles were chosen from the trial runs: 32°, 34°, 36°, 38° and 40°. A series of five tests were run at each angle and for each of the three sets of plates. A total of 76 tests were made to acquire the data base. The dynamic and static forces for each plate and for each angle were recorded.

The material used to model the dry flow consisted of a uniformly graded quartz sand. A sand was chosen for its cohesionless properties. Its similarity fo natural flows and the availability of previous research on the flow of granular materials (Savage (1979 and Takahasi (1937)).

Laboratory tests were performed to determine the engineering properties of the sand (Table 1). Testing procedures were adopted from applicable ASTM Standards.

TABLE 1 - PROPERTIES OF QUARTZ SAND

Mineral Type	Quartz
Particle Shape	Subangular to Angular
Maximum Dry Density	14.9 kN/m^3
Minimum Dry Density	12.5 kN/m^3
Specific Gravity of Solids	2.65
Uniformity Coefficient	1.43
Coefficient of Skew	0.98
Angle of Repose	26°
Peak Friction Angle	33°

A standard procedure was developed for the tests. The sand was leveled in the bin section and the volume measured. The test apparatus was raised to the desired angle and the quick release door was opened. A high speed camera recorded the motion of the sand as it moved down the slope and impacted the retaining wall. The load cells monitored the resulting forces and data recorded on the high speed chart recorder.

4 TEST RESULTS

Table 2 summarizes the results and lists the static and dynamic resultants and their location as a function of the angle of inclination. The data indicates the influence that the slope angle has on the magnitude of the forces and their location. As the slope angle increases so do both the static and dynamic loads resulting from the dry cohesionless flow. The location of the resultant is higher for the static condition than for the initial dynamic impact. Also shown in Table 2 is the relative change in the magnitude of the forces that occur between the dynamic load and the static condition. The steeper the angle of the slope the greater the difference between the dynamic and static forces which develop as a result of the dry flow. Figure 2 is a typical plot of force versus time for a test.

5 DISCUSSION OF RESULTS

Flow Development

High speed photographs were taken to examine the model landslide and study the movement of the sand. Two flow regimes were initially expected to exist as suggested by Takahasi (1937). At test runs where the angle of the apparatus was less than the critical angle the flow was expected to be laminar in nature. The flow would be considered turbulent if the test angle was greater than the critical angle. For the quartz sand used in this study, the critical angle should occur at 36°.

Examination of photographs taken at 32, 35 and 40 degrees did not indicate the movement of the sand being laminar or turbulent. A distinctive sequence of flow development was, however, observed to exist. The photographs indicated that the mass of sand moved downward (normal to the slope) and outward

TABLE II

SUMMARY OF TEST RESULTS

Slope Angle	Average Resultant Force		Percent Increase of Static to Dynamic Force	Location of Resultant Above Bottom	
	Dynamic (kPa)	Static (kPa)		Dynamic (cm)	Static (cm)
%			%		
40	160.9	109.8	46.5	16.11	18.08
38	131.8	92.7	42.2	15.12	16.50
36	102.3	78.0	31.1	14.64	15.21
34	80.7	64.4	25.3	13.92	14.14
32	58.2	48.9	19.1	11.33	10.99

(parallel to the slope) as the door was opened. The sand particles which were mobilized accelerated down the slope until impact occurred on the retaining wall. The sequence of photos at both 32 and 40 degrees indicated that in each case at initial impact, a portion of the sand mass was still immobile and another portion was moving only normal to the slope.

Impact of the soil mass on the model retaining wall was observed to occur in a series of waves. The initial wave of sand travelled down the slope and impacted the lower plate. Secondary waves caused by a staged mobilization of the soil mass overtopped the initial flow and struck the middle and top plates in succession. The amount of sand mobilized by each wave was a function of the slope angle.

Inspection of the force versus time output from the strip chart recording also indicated a number of peak responses and wave forms due to the impact of the sand. An initial peak was observed to occur upon impact and subsequent peaks developed as additional sand accelerated down the slope, overtopping the previous mass of sand and reaching equilibrium. As the angle of the test decreased from 40° to 38° the magnitude of the second peak approached that of the first dynamic response. At 36° the two peaks became equal in intensity and at the lower angles of 34° and 32°, the second peak was greater (For an example see Figure 2).

The occurrence of multiple peak responses may be correlated to the various stages of mobilization of the sand mass. At the lower angles (34° and 32°), not all of the sand was placed in motion during the test. For these angles it was not the initial impact that caused the peak dynamic loads, but the second wave of material (Figure 2).

Impact Forces

The initial dynamic impact and subsequent static pressure conditions are evident from the force versus time output obtained for each test. The test data indicated that a major portion of the dynamic force occurred on the lower third of the retaining wall. The dynamic and static pressures are shown in Figure 3 as a function of slope angle and location of impact. The forces developed from the dynamic impact on the bottom section were found to be nearly double those on the middle and more than six times greater than those at the top of the wall.

In nature, impact of a flow slide or landslide would initially be concentrated at the base of any obstacle in its path i.e., a rigid structure such as a retaining wall). After impact, additional material would most likely overtop the initial flow and come to rest against the structure until equilibrium of the sliding mass was reached. Results from this investigation agree with this description for a natural flow slide.

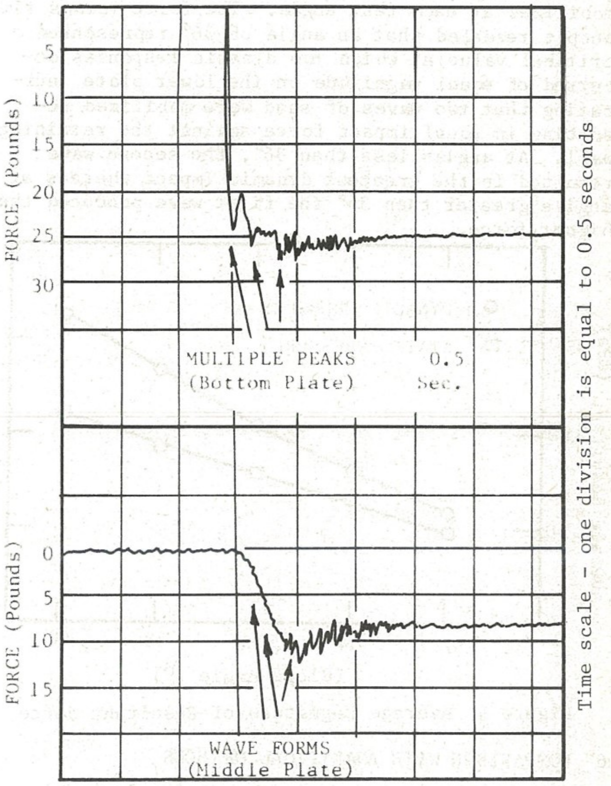

Figure 2 Force Versus Time Output at 32° Slope Angle

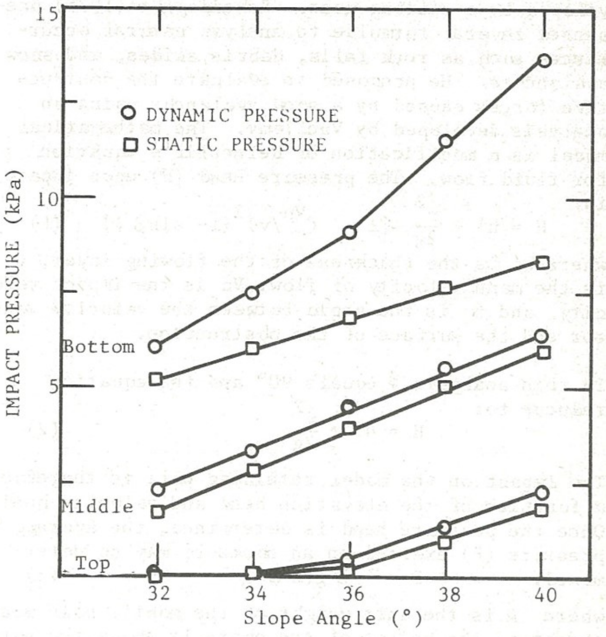

Figure 3 Static and Dynamic Impact Pressure on Wall

The resultant force for the static and impact loading conditions was also measured. The location of the static resultant was higher than that of the impact load for slope angles greater than 33°. At an angle of 33° the location of the dynamic and static resultant were equal. It may be of some significance to note that this angle is approximately the peak angle of friction of the sand.

The resultant of the maximum dynamic forces developed by the sliding mass of sand were found to plot in two linear flow relationships (Figure 4) with a change in slope at 36°. As discussed, a different proportion of the total mass of sand, was mobilized at each test angle. The force versus time output revealed that an angle of 36° represented a critical value at which two dynamic responses occurred of equal magnitude on the lower plate indicating that two waves of sand were mobilized resulting in equal impact force against the retaining wall. At angles less than 36°, the second wave resulted in the greatest dynamic impact whereas at angles greater than 36° the first wave produced the higher force.

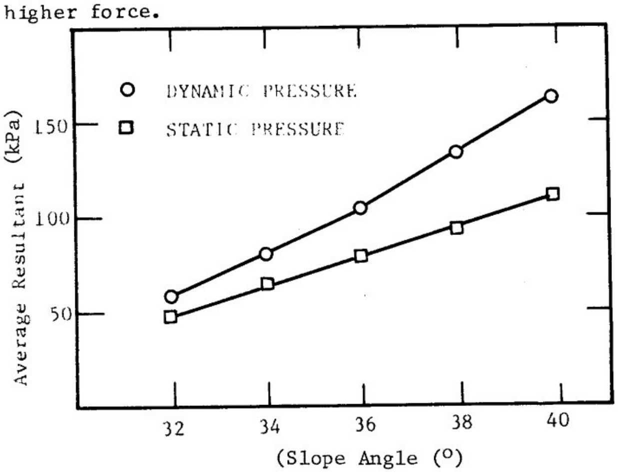

Figure 4 Average Magnitude of Resultant Force

6 COMPARISON WITH ANALYTICAL METHODS

An attempt was made to find a suitable analytical model to compare with the test results. Little information is available on the impact forces developed by a sliding mass. Scheidegger (1975) presented several formulae to analyze natural occurrences such as rock falls, debris slides, and snow avalanches. He proposed to evaluate the destructive forces caused by a snow avalanche using an analysis developed by Voellemy. The mathematical model is a modification of Bernoulli's equation for fluid flow. The pressure head (H) upon impact is:

$$H = h' + \frac{v^2}{2g}\left[1 - (V_n/v)^2(1-\sin\beta)\right] \qquad (1)$$

where h' is the thickness of the flowing layer, v is the mean velocity of flow, Vn is the impact velocity, and β is the angle between the velocity vector and the surface of the obstruction.

In this analysis β equals 90° and the equation reduces to:

$$H = h' + \frac{v^2}{2g} \qquad (2)$$

The impact on the model retaining wall is therefore, a function of the elevation head and velocity head. Once the pressure head is determined, the average pressure (P) exerted on an obstacle may be determined:

$$P = \rho g(H-h^*) \qquad (3)$$

where ρ is the unit weight of the mobile soil mass and h* is the height of the obstacle above the bottom of the avalanche.

Velocity Measurement

Equation (1) developed by Voellemy requires an estimate of the mean velocity of the moving mass. For this case the maximum velocity attained by the sand would seem to be more suitable in evaluating the forces which occur upon impact.

Three methods were used to compute the maximum velocity of the flow slide. The first made use of the high speed photographs to make an estimate of the velocity based on the time between photographs and the measurement of the distance traveled by the sand.

The second method considered an equation presented by Scheidegger to estimate the velocity attained by a rock slide or debris flow. Both occurrences are cohesionless in nature and similar to the dry flow of sand in this study. The velocity equation is:

$$v^2 = 2g\,(\Delta H - f\Delta X) \qquad (4)$$

where v is the velocity upon impact, g is the acceleration due to gravity, f = coefficient of function,ΔX is the movement of the sand mass in the X direction, and ΔH is the vertical distance the mass travels. The origin of X and H was assumed to be the approximate center of gravity of the soil mass immediately mobilized when the door of the test apparatus was opened.

The third method of analysis was based on the research of Goldin and Lyubashavsky (1966) to predict the velocities of mud flows. They proposed an empirical equation as follows:

$$V = 5.15H^{2/3}\ i^{1/4} \qquad (5)$$

where V is the average velocity of the flow in meters and i is the gradient of flow.

The velocities for each test slope angle were computed by the three described methods and plotted on Figure 5. The mean values of velocity as well as maximum velocity values are shown. The empirical mud flow equation gives the lowest velocity. Scheidigger's friction model using maximum velocity gives the highest values. The velocities based on high speed photographic analysis are limited to two slope angles and are plotted as individual points and agree with the mud flow equation and Scheidigger's mean values.

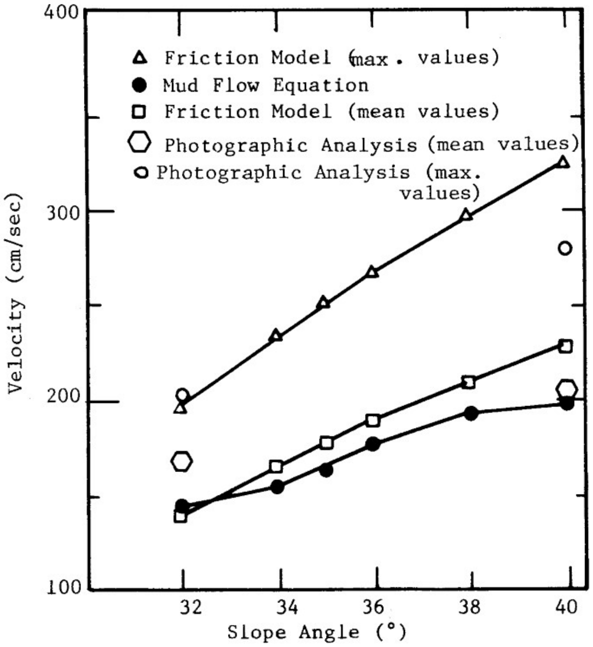

Figure 5 Comparison of Velocity Model Results

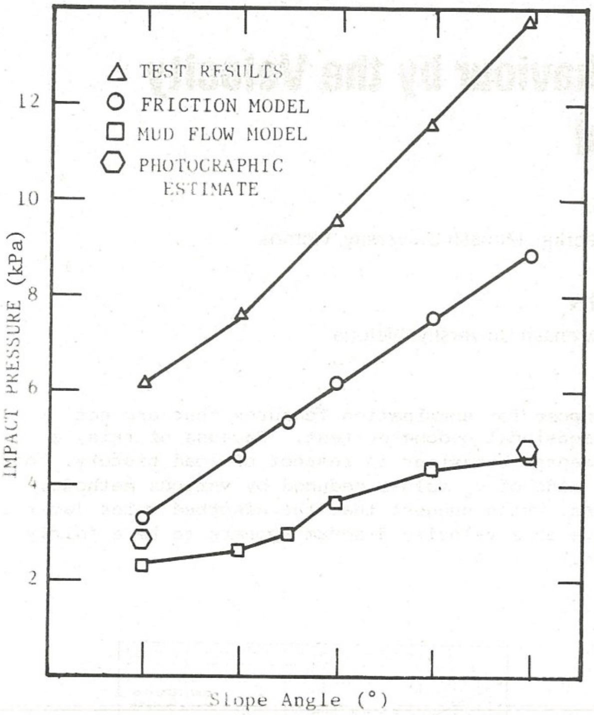

Figure 6 Comparison of Predicted and Measured Impact Pressures

Impact Pressures on the Wall

The calculated values for velocity were used in Voellemy's analysis to predict the dynamic impact pressure on the model wall. These predicted values along with the measure impact pressures are shown on Figure 6. The calculated impact pressures greatly underestimate the actual pressures ranging from 1/3 to 1/2 the actual values.

CONCLUSION

The test results from a large scale physical model of a landslide indicate an increase in load due to the impact of the soil mass as compared to the static or equilibrium condition. A linear relationship was found between the magnitude of the dynamic force resultant and the slope angle. A critical angle was found at 36° after which the slope of the line describing the dynamic forces increased. This critical angle agrees with that of Takahasi (1961) for a dry quartz sand.

The location of the force resultant was found to be lower for the dynamic condition as compared to the static case. The dynamic loads on the lower third of the retaining wall were found to be double those at the middle location and nearly six times those at the top of the wall.

The sand mass was found to travel down the slope in waves. An initial wave of sand traveled down the slope and impacted the retaining wall. Secondary waves overtopped the initial sand mass until the angle of repose was reached.

Frictional, fluid flow, a mud flow model and an analysis based on the photographic record of the tests were used to estimate the velocity and resulting forces generated by the sliding mass. The forces calculated using the mud flow and photographic methods agreed closely, however, they were much lower than the test results. Existing quantitative methods of analyzing the forces developed in the flow greatly underestimate the measured dynamic forces. Further research is required to develop the necessary knowledge from which the forces developed by a semifluid, semisolid flow of material can be calculated.

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