Strength and Deformation Characteristics of Redeposited Lahar Derived from the 1991 Mt. Pinatubo Eruption

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1. Introduction

The Mt. Pinatubo Eruption of 1991 produced an estimated total volume of 5 to 7 cubic kilometers of tephra (pyroclastic flow material and ash) filling up valleys and topographic depression around the volcanoes with debris as much as 200 m thick. These erodible pyroclastic fills were later mobilized by rainfalls as lahars carrying appoximately 2 cubic kilometers of materials and burying 400 square kilometers of lowland areas.

Due to the dangers posed by these lahar flows during heavy rainfalls, hydraulic structures (river dikes, dams and levees) were constructed to divert flow away from adjoining towns and to prevent over bank flow caused by the constrictions of river channels. For economic reasons, these hydraulic structures were made from the same lahar material. Unfortunately, most of the structures were observed to experience substantial cracking, excessive piping and, in some areas, complete collapse. The failure maybe attributed to the possible shortcomings in the design and construction and to the lack of understanding on the shear strength characteristics of the material.

To address this issue, a testing program was conducted to determine the shear strength and deformation characteristic of the redeposited lahar using the hollow torsional shear apparatus.

2. Apparatus and Experimental Procedures

2.1 Description of the Apparatus

The hollow torsional shear apparatus was used for shear strength determination. The hollow cylindrical sample with inner radius, r_i = 30 mm, outer radius, r_o = 50 mm, and height H = 195 mm is enclosed laterally by two flexible rubber membranes (inner and outer membrane) and vertically by rigid top and bottom caps. The loading system enables independent control of the torque, the axial load, the effective inner cell and outer cell pressures. Quantities that are measured are the torque, the axial load, the effective inner cell and outer cell pressures, the volume changes of the sample and inner cell, the pore water pressure, and the axial and rotational displacements.

2.2 Sample Preparation

Due to the limitation of the machine, only the portion of the sample passing through the No. 200 (2 mm) sieve was used in the testing.

The samples were prepared by air pluviation. This sample preparation technique was selected in order to ensure uniform samples throughout the whole experimental program.

2.3 Test Procedure

Saturation. At first, carbon dioxide gas was circulated through the sample for about two hours. Then, de-aired water was slowly introduced into the sample. After percolation of a sufficient amount of water under very low static pressure (at most 4 kPa), a back pressure of at least 100 kPa was applied , while keeping the effective confining pressure at 20 kPa. The sample was then left to stand overnight. Following the procedure, a B-value of at least 0.95 was achieved.

Consolidation. In all the tests, the sample was isotropically consolidated to final mean effective stress of either p' = 29.4, 98, or 196 kPa. The consolidation was done for one hour.

Drained Shearing. After consolidation, the samples were sheared under drained conditions by applying torque at a rate of approximately 0.18 % /min. All the normal stress components remained constant during the shearing, i.e. $\sigma_z' = \sigma_r' = \sigma_\theta'$ = constant, consequently, the mean effective stress was constant at p' = 29.4, 98, or 196 kPa. The samples were sheared until a torsional shear strain of about γ = 20 % was attained. The stress state can be summarized as follows:

$$p' = 29.4,\ 98,\ \text{or}\ 196\ \text{kPa}$$
$$q = \tau_{z\theta} = \tau\ , \qquad \Delta q = \Delta\tau_{z\theta} = \Delta\tau$$
$$b = 0.5 = \text{constant}$$
$$\beta = 45^{\circ} = \text{constant}$$

3. Physical Properties

The sample was obtained several hundreds of meters downstream of the caldera and near the towns of Guagua and Bacolor. The location is shown in a map in Fig. 1

The index properties of the material are shown in Table 1 and the grain size distribution is displayed in Fig. 2.

Table 1. Physical Properties of Pinatubo Sample

Sample	Gs	e_{max}	e_{min}	Fines Cont. (%)
Pinatubo	2.668	0.919	0.699	0.38

4. Test Results and Discussion

A testing program was carried out to determine the relationships between the stress ratio (τ/p'), the volumetric strain (ε_v), the mobilized angle of friction (ϕ_{mob}) and the torsional shear strain (γ_{at}) for various effective confining pressures and for various relative density. The results of the tests are presented and discussed in the succeeding paragraphs.

The effects of confining pressure are illustrated by the results of a series of test that was conducted at various effective confining pressures with the relative density almost constant. The series was conducted on samples with relative density Dr = 52 % at effective confining pressure of pc' = 29.4, 98 and 196 kPa. The stress-strain and volume change characteristics observed in this series of tests are shown in Fig 3. (a) and (b). As the data show, the influence of the effective confining pressure is significant both on the deformation and strength of the material. The stiffness of the response decreases with increase in the effective confining pressure, causing a downward shift of the stress-strain curve. The volumetric strain-shear strain behavior at Dr = 52% is predominantly dilative. It can clearly be seen however that the amount of dilation is directly related to the effective confining stress – the higher the effective confining stress, the lesser the dilation.

On the other hand, the effects of relative density are illustrated by comparing the results of a series of tests where the relative densities are varied while the effective confining pressure is held the same. The series was carried out on samples with relative density Dr = 24 %, 53 % and 80 % at the same effective confining stress of pc' = 98 kPa. The stress-strain and volume change characteristics of the series are shown in Fig. 4 (a) and (b). As the relative density decreases the stress-strain response becomes softer and flatter while sample demonstrate lesser dilation.

The strength parameters in the Mohr-Coloumb failure line were derived by constructing the Mohr's circle of stresses for the peak and the residual state of failure. The said parameters are shown in in Table 2.

Table 2. Strength Parameters at Dr = 52 %

Failure Condition	Friction Angle, ϕ	App. Cohesion (kPa)
Peak	39.8	3.0
Residual	39.1	3.0

5. Conclusion

In the forgoing discussion, it can be advanced that the lahar sample conforms to the established behavior of frictional soil, as far as the effects of confining pressure and density are concerned.

A clear knowledge of the strength and deformation characteristics is a very important tool in designing hydraulic structures made from this material. Combining seepage analysis with finite element analysis using a constitutive model reflecting the behavior of the material will be very helpful in discovering potential problems that the structure may encounter.

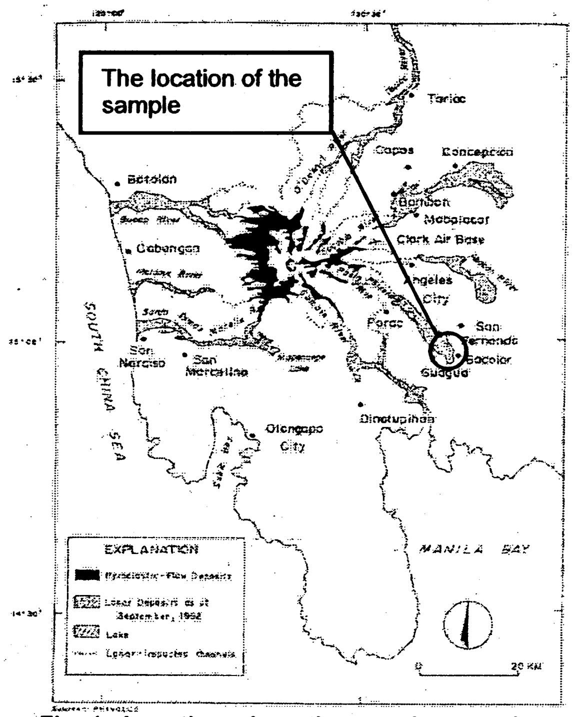

Fig. 1. Location where the sample was taken

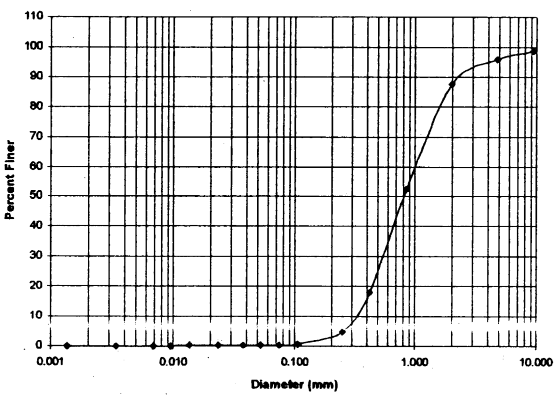

Fig. 2. Grain Size Distribution of Pinatubo Sample

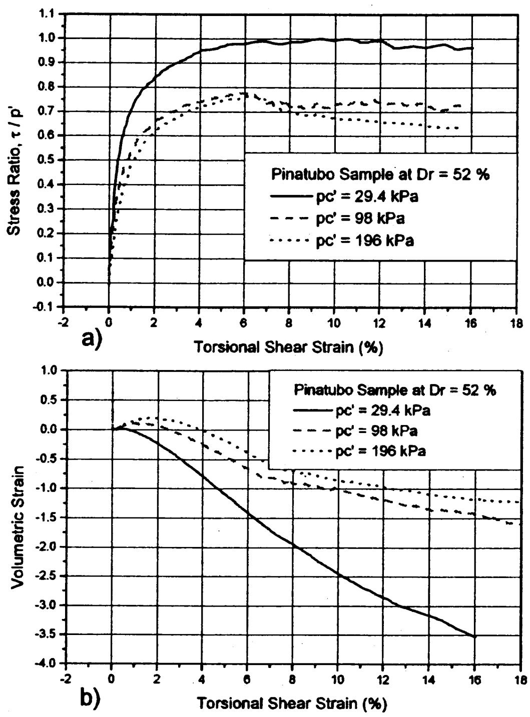

Fig. 3. Influence of Effective Confining Pressure on the Stress-Strain and Volume Change Behavior of Pinatubo Sample at Dr = 52 %

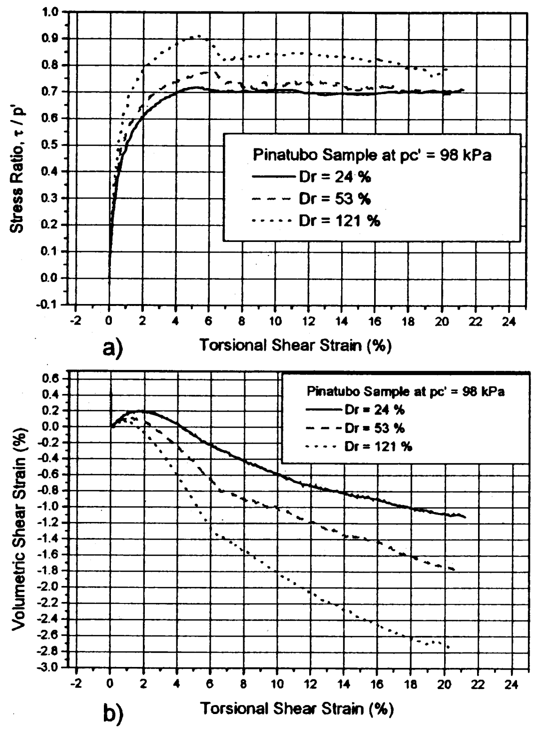

Fig. 4. Influence of Relative Density on the Stress-Strain and Volume Change Behavior of Pinatubo Sample at pc' = 98 kPa