Investigation of the Discharge Mechanism of Hachijo-Fuketsu Lava Tube Cave, Hachijo-jima Island, Japan

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Abstract

Bingham fluid model by using inclined and flat circular tube are applied for the investigation of Hachijo-fuketsu lava tube cave in Japan. From the size and configuration of Hachijo-fuketsu lava tube cave such as tube length, inclination angle, tube diameter(height), the yield strength of the lava was obtained. The obtained yield strength was compared with other lava which formed lava caves and found to have a reasonable value as basaltic.

Introduction

Hachijo-fuketsu lava tube cave is located on Hachijo-jima island south of Tokyo in the Pacific Ocean. Hachijo-jima island, located on the volcanic front of the izu-Ogasawara(Bonin) arc, consist of two stratovolcanoes: Nisiyama and Higasi-yama. Nishiyama is a scarcely dissected cone called "Hachijo-fuji". Nishiyama began its volcanic activities about 10000 years ago. Many lateral volcanoes exist around Nishiyama. Hachijou-fuketsu is believed to have been formed by the eruption of Hachijo-nishiyama volcano 1100 years BP[1]. Its lava flow is basaltic, with silica content of 50.5%[2]. Hachijo-fuketsu is the second longest lava tube in Japan. Despite good accessibility, it is well preserved as shown in Fig. 1. As shown in Fig. 2, its upper and middle sections have moderates slopes and its lower end is flat and horizontal[3].

Modelling, Assumption and Analysis

In modelling the discharge mechanism of this type of lava tube, we used an inclined circular tube model for the sloping section of the cave as shown in Fig. 3. For the flat horizontal section in which the lava flow is driven by hydrodynamic head, we modeled a flat circular tube as shown in Fig. 4. The yield strengths obtained from these two models were similar and comparable to those of other lava flows.

Regarding the inclined circular pipe case, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow[4,5]. A simple model of steady state isothermal laminar flow in inclined circular pipes and in flatten circular pipes were used for analyses. Comparison studies were based on the configuration of Hachijo-fuketsu.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition was determined for the discharge parameters in which the yield strength plays a dominant role. Existing observational data were introduced to the critical condition. This model was applied to lava tube cave of Mt.Fuji, Mt.Etna, Mount St.Helens, Suchiooc volcano, Kilauea volcano and others. Some deduced yield strength of lava of the caves in these areas were found to be in good accordance with yield strength as estimated by other methods[6].

General flow equation of Bingham fluid can be shown as,

$$f(\tau)=(\tau-f_B)/\eta_B \quad (\tau>f_B, \text{ or } r>r_B),$$
$$f(\tau)=0 \quad (\tau<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield stress, η_B is Bingham viscosity, which takes specific value depending on the materials. τ is sharing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For $\tau_w=(\varrho g \sin\alpha)R/2>f_B$,

$$u=(R-r_B)^2(\varrho g \sin\alpha)/4\eta_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\,(\varrho g \sin\alpha)/4\eta_B \quad (r>r_B).$$

For $\tau_w=(\varrho g \sin\alpha)R/2<f_B$, u=0.

Here, α is angle of slope or inclination of tube, ϱ: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B: radius of the flowing position where Bingham yield stress takes f_B.

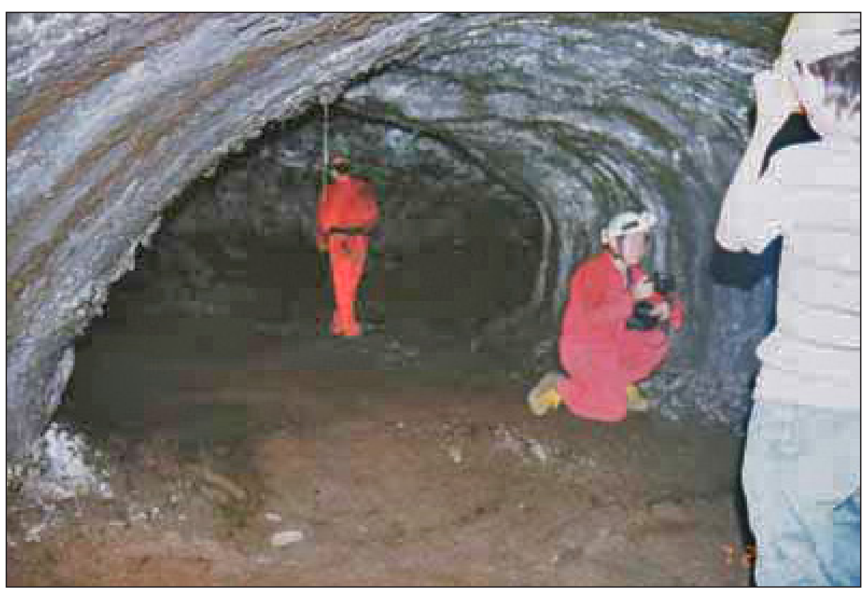

Figure 1. Inside of Hachijou-Fuketsu (photo by T. Honda).

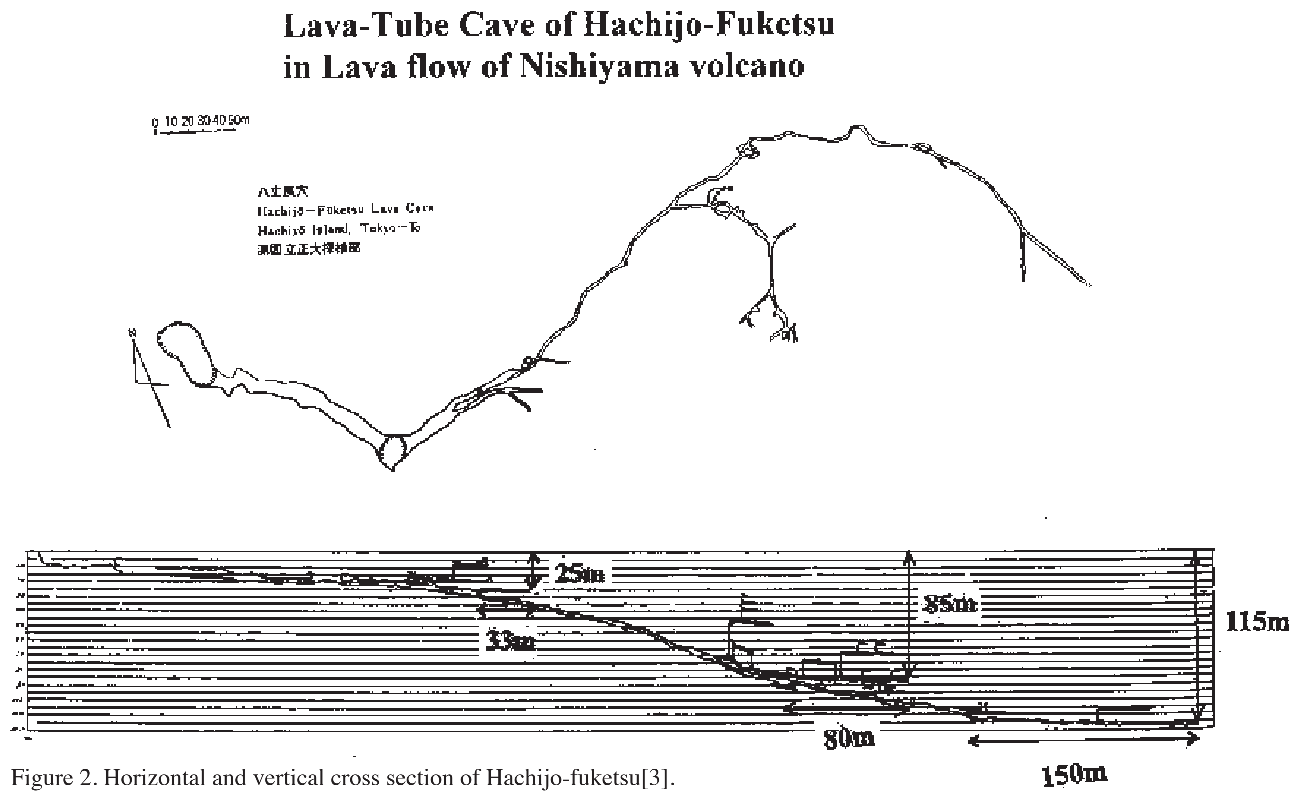

Figure 2. Horizontal and vertical cross section of Hachijo-fuketsu[3].

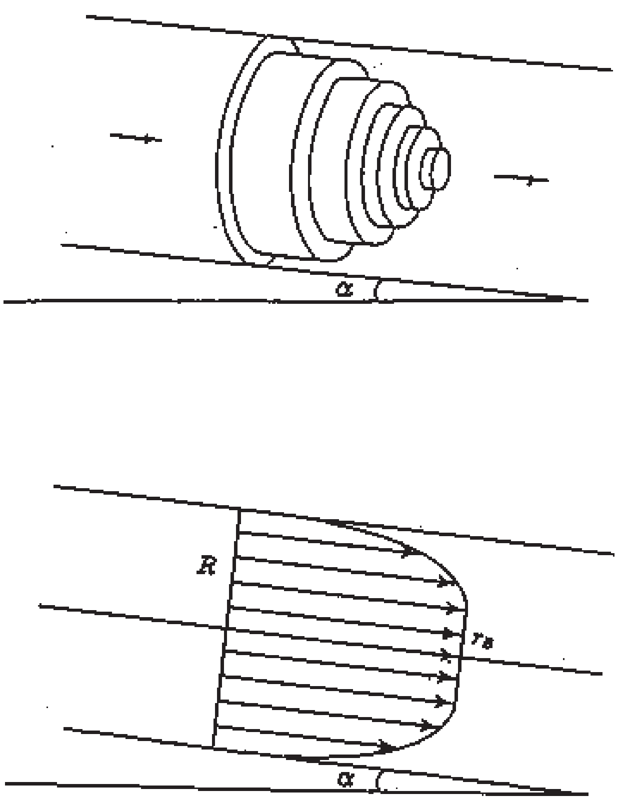

Figure 3. Bingham fluid model of inclined tube.

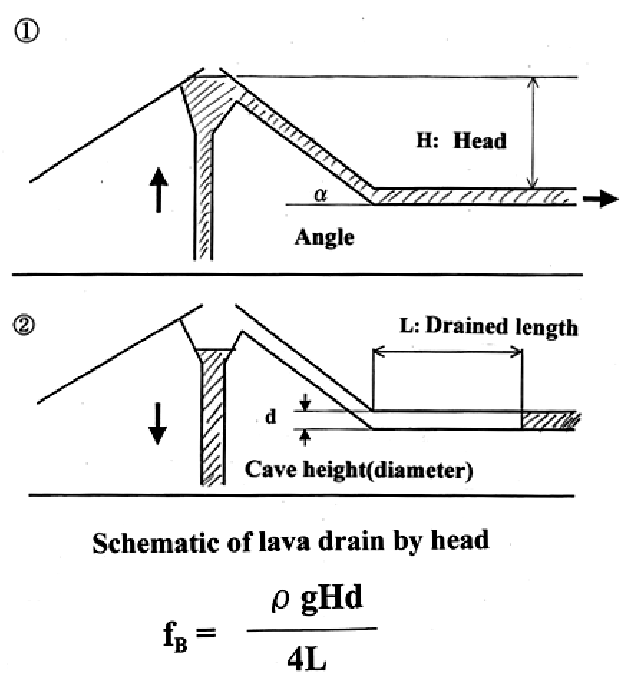

Figure 4. Simplified model of Hachijo-fuketsu.

Table 1. Relation between slope angle and height of Hachijo-fuketsu lava tube cave of sloped configuration.

Location of lava cave	Slope angle(α)	Height(2R)
Upper reaches	4.5 degree	~5m
Intermediate reaches	14 degree	~2m
(Lower reaches)	(0 degree)	(~1m)

Table 2. Relation between head and length at horizontal location of Hachijo-fuketsu lava tube cave of horizontally flat configuration for 2R=1m.

Location of lava cave	Head(H)	Length(L)
Upper reaches	25m	33m
Intermediate reaches	85m	80m
Lower reaches	115m	150m

Table 3. Yield strength obtained from the critical condition.

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Hachijo-nishiyama	50.4~50.5%*	2.0~2.5x10^4dyne/cm^2	*M.Tsukui et al (2002)[2]
Mt.Fuji	49.09~51.3%*	2.5~5.0x10^4dyne/cm^2[5]	*H.Tsuya(1971)[8]

Here, $(\varrho g \sin\alpha)R/2=f_B$ is the limiting condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter(height) of the tube, this critical condition can give the yield strength f_B as shown in Fig. 5. This critical condition means that when the yield strength of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no drainage of fluid from the tube. From Table 1, f_B=2.5x10^4dyne/cm^2 can be obtained for Hachijo-fuketsu.

The above model is, however, valid only for flow in inclined tubes. For perfectly flat lava tube(0 degree), the effect of inertial as driving force due to the head of the flow must be considered, if the flow is continuous together with the inclined tube[7]. Very rough relation between drained tube length and mean head of the flow can be obtained as $(\varrho g R)H/2L=f_B$ by $(\sin\alpha)$ by (H/L). From Table 2, f_B=2x10^4dyne/cm^2 was obtained for Hachijo-jima as shown in Fig. 6.

In summary, obtained basaltic yield stress from slope angle and height of some lava caves(see Table 3)are reasonable values as compared with the yield stress obtained for Mt. Fuji[7].

Conclusions

As a results of this study, Bingham fluid model seems to be well applied for an explanation of formation process of lava tube cave. Further application

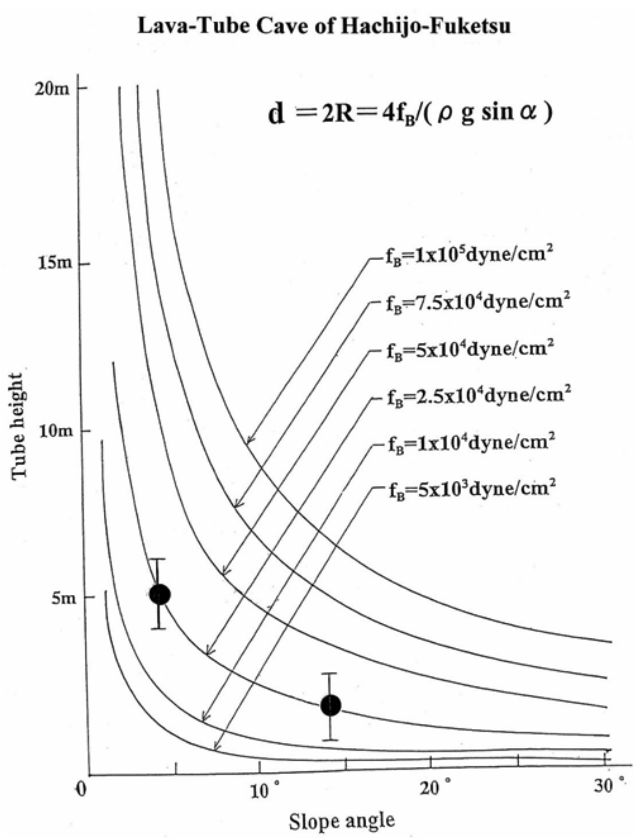

Figure 5. Relation between Slope angle and Tube height in sloped area.

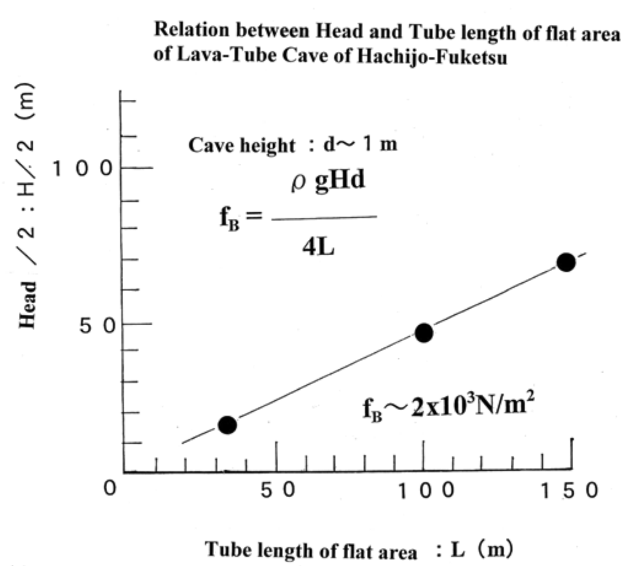

Figure 6. Relation between Head and tube length of flat area.

of this model to other lava tube caves will be necessary and interesting for confirmation. Though the yield strength only plays a main role in this steady state model, for a future study, the analysis by using time dependent transition equation should be performed. In this case, the viscosity of lava will be involved.

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