Study of layer sampling method for asteroid probe

–Application possibility of Japanese sword technologyー

By Takeshi SAKAMOTO[1], Takeo WATANABE [2], Shouichirou TAKEHARA [2], Kenji Uchiyama [3], Hironori A. FUJII[3,4] T, Hajime YANO [5], and Genrokurou MATSUNAGA[6]

[1]Kumamoto University,[2]Tokyo Metropolitan University,[3] Nihon University
[4]Kanagawa Institute of Technology,[5]JAXA,[6]Japanese Sword Maker

Abstract

JAXA has planned a sample return mission to sample layers with a certain amount of depth of asteroid in Hayabusa MkII project. The Harpoon & Penetrator method is a new useful method for the sample return mission because of its simple system to use a tethered sampler. On the other hand, the method has possibility in terms of retrieving samples without deformation of layers. We have made effort to clarify the relationship between penetration velocity and penetration depth through experiments using the developed experimental system. It is noted from experimental results that minimum energy for penetration can be taken into account for the design of material and diameter. In the case of the sand and light concrete, the penetration energy is minimum using the corer with 15mm diameter. Experimental results show that the capability for the sampling by employing the Harpoon & Penetrator method. In addition, We are planning to employ Japanese Sword Technology for element of sampler as corer.

Key Words: Sample return mission, Harpoon & Penetrator method, penetration depth, corer, penetration loss, Japanese Sword

小惑星探査における層状採取サンプリング手法について—日本刀技術の応用ー

摘要

現在，はやぶさMk.Ⅱにおける小惑星探査に搭載されるサンプリング機構の研究開発が急務となっている．我々は，筒型のサンプラーを惑星表面に貫入させ，層状の地表サンプルを採取する方式の基礎研究を行い，従来考案されている弾丸型やトリモチ型のサンプリング機構では実現できなかった“惑星の地層サンプルを層状に採取する”ことを目的としている．サンプラーの開発にわが国の伝統技術である日本刀の技術を応用することも検討中であり，貫入深度と採取サンプル量の増加が期待されている．

1. Introduction

For a search of the origin of the life and the inception of the earth, it's necessary that the probe of the asteroid which kept the form of the original solar system without taking space weathering. In sample return mission of the launched asteroid probe Hayabusa by JAXA, the sample was collected from S-type asteroid Itokawa. Hayabusa 2 and Hayabusa Mk2 is planned and examined, as an asteroid probe after the next generation.

In sample return mission of Hayabusa 2, it is planned to collect the samples by Impact sampling and Adhesive-pad sampling. In Hayabusa Mk2, the samples in the depth from 200mm to 300 mm in layer are desired to be collected [1)2)], and because of not satisfying this demand by the conventional sampling method, a new sampling method becomes demand. On the other hand, the circumstances of the surface layer is uncertain to date although the probe to D type asteroid is examined in Hayabusa Mk2. Thus collecting any kind of geological sample needs to consider.

In this paper, in consideration of the possibility of sampling layers, the intrusive examination to various materials assumed as a constituent of the asteroid is done by using the Harpoon & Penetrator method shown in Fig. 1. [3)4)], and the relation between the penetration depth and the penetration velocity is requested. In addition, We are planning to employ Japanese Sword Technology for element of sampler as corer.

2. Experimental methodology

It's defined an asteroid simulated object to use by the penetration experiment. Although using the simulated object of the D-type asteroid is desirable, considering observation results that the surface layer of the Eros (S-type asteroid) is the regolith and that of the Itokawa (S-type asteroid) is the boulder (over a diameter of 256mm) [5)]. By this experiment, penetration objects shown in Table 1. have been used as simulated objects.

Next, it's defined about a corer to use by this experiment. The material of corer is SUS304. Corer shape is hollow cylinder and nose shape is almost flat. Diameters are 5, 10, 12, 15, 20, and 25mm (Fig. 2.). Thickness is 0.5mm. Length is 500mm.

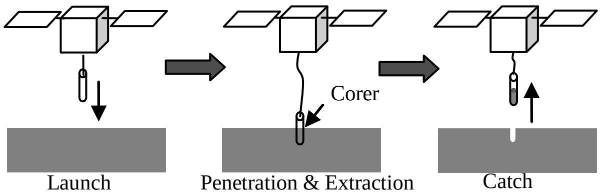

Fig. 1. Harpoon & Penetrator Method

Table 1. Details of penetration objects

Surficial sediment	Penetration simulated object	Density of penetration object [mg/mm^3]
Regolith	Sand	1.70
Boulder	Light concrete	0.60

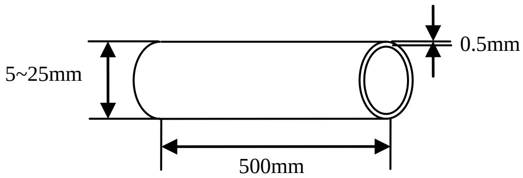

Fig. 2. Schematic View of Corer

Fig. 4. shows the penetration experimental device. The device uses the method that employed the motors equipped with the pulley with 23mm diameter and the corer is pushed out thought the pulley (Fig. 4.). The belt is employed to the pulley in the motor axis in such a way that the energy loss becomes small when the corer is pushed out.

The penetration velocity of the corer was obtained by using the infrared sensor fitted up under this device at the shading time of infrared rays. The number of revolutions of the motor was adjusted, the rotational speed of the pulley was set between 10~17m/s at intervals of 1m/s, and the penetration depth when the corers of five kinds of diameters was driven was measured ten times in each condition.

Fig. 4. shows the results of penetration experiment. The plots shown in Fig. 4. are the average of 10 times at the penetration experiment. The standard deviation of each penetration velocity is small, and the maximum standard deviation at the experiment is 0.12. Although the penetration velocity become small as the corer diameter is large, it is thought that this is because the velocity transmission loss occurs in the contact moment between the corer and this device. Each penetration velocity measured by the infrared ray sensor is proportional to rate of rotation, and then Table 2. shows the penetration velocity range of each corer diameter from the result shown in Fig.4. The penetration velocity is used as the barometer of the penetration depth.

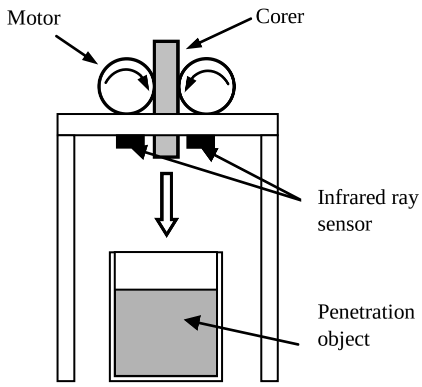

Fig.3. Schematic view of experimental device

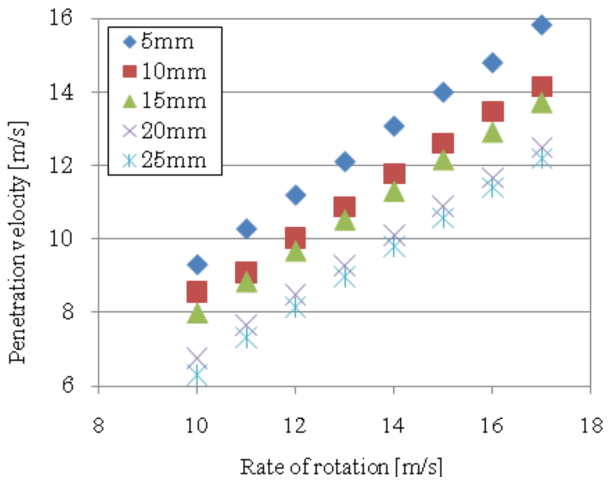

Fig. 4. Result of relation between penetration velocity and rate of rotation

Table 2. Penetration velocity of each corer diameter

Corer diameter [mm]	Penetration velocity [m/s]
5	9.9~15.9
10	8.6~14.2
15	8.0~13.8
20	6.8~12.5
25	6.3~12.2

3. Experimental result

3.1. Sand

3.1.1. Relation between penetration depth and penetration velocity

The penetration depth is measured when the corer penetrates the sand and the corresponding depth is plotted on Fig. 7. for each penetration velocity. The plots are the average of 10 times at the penetration experiment, and though the maximum standard deviation is 12.9. Fig. 7. shows that the penetration depth is proportional to penetration velocity in velocity range of each corer diameter. It is not found whether corer diameter between 5-25mm has effect on penetration depth from this result.

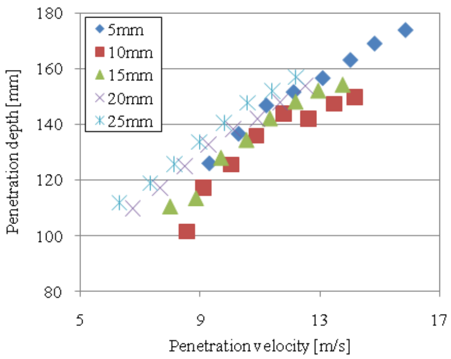

Fig. 5. Result of relation between penetration depth and penetration velocity (sand)

3.1.2. Penetration loss

The penetration depth of the corer has thought equal to the depth of the sampling layers [6)7)]. The possibility that the depth of the actual sampling layers according to the penetration object decreases compared with the penetration depth is thought enough. Then, the depth of the sampling layers has been measured. In addition, the ratio of the depth of the sampling layers to the penetration depth was taken, and the presence of the penetration loss has been examined. Here, in this experiment, the corer and the penetration velocity go on the same condition as the previous experiment. However, the measured depth of the sampling layers in this experiment is the depth of the layers inside the corer of penetration moment, and it is not the depth of the actual sampling layers because sampling system isn't thought in this paper.

Fig. 6. and Fig. 7. show the results of penetration experiment. The depth of the sampling layers is measured when the corer penetrates the sand and the corresponding depth is plotted on Fig. 6. for each penetration velocity measured by the infrared ray sensor. However, 5mm in the diameter of the corer alone has been not able to be measured. Fig. 6. shows that the depth of the sampling layers is proportional to penetration velocity in velocity range of each corer diameter. In addition, the depth of the sampling layers is short compared with penetration depth in velocity range of each corer diameter of this experiment, and it is found there is penetration loss.

Next, Fig. 7. shows the effect of penetration loss. The penetration loss of the vertical axis on Fig. 7. shows that the depth of the sampling layers is equal to the penetration depth, when this value is equal to 0. The penetration loss of the corers of 10 and 15 mm diameter is large with the increase of the penetration velocity in this velocity range, and that of 20 and 25 mm diameter isn't change so much. The larger the corer diameter is also, the smaller the penetration loss is, however, it is found that the corer diameter should be not enlarged in every respect because the value of the penetration loss between 20 and 25 mm diameter isn't change so much.

From this, to secure the desired depth of the sampling layers, it is found that the corer diameter should be large to some degree.

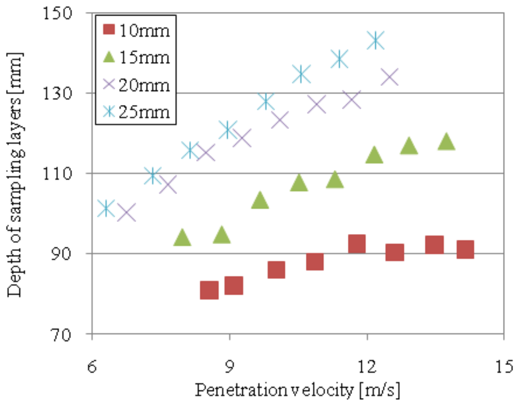

Fig. 6. Result of relation between depth of the sampling layers and penetration velocity

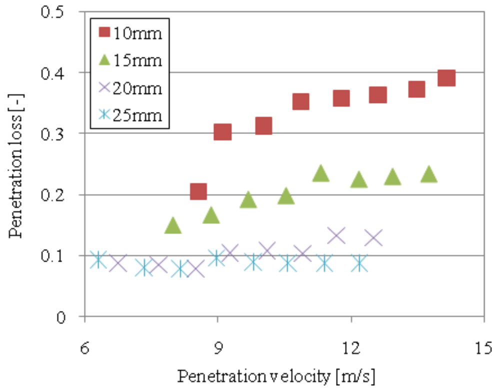

Fig. 7. Effect of penetration loss

3.2. Light concrete

Fig. 8. shows the results of penetration experiment. In this experiment, it has experimented on the condition similar to the sand. The plots shown in Fig. 8. are the average of 10 times at the penetration experiment, and though the maximum standard deviation is 7.17. It is tendency that the values of the penetration depth at driving the same velocity have large width because of the density inhomogeneity and then the standard deviation is large. Fig. 8. shows that the penetration depth is proportional to penetration velocity in velocity range of each corer diameter. It is not found whether corer diameter between 5-25mm has effect on penetration depth from this result. At the light concrete, when the depth of sampling layers is under 15mm depth, the sample doesn't get. However, the depth of sampling layers is equal to the penetration depth, when the sample is over 15mm depth.

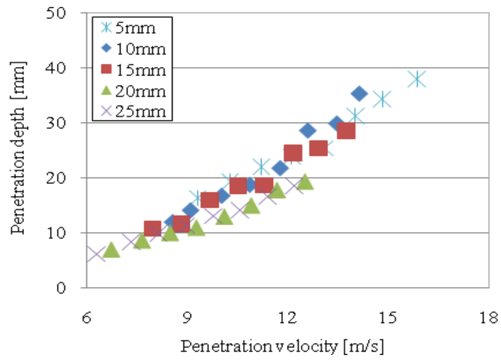

Fig. 8. Result of relation between penetration depth and penetration velocity (light concrete)

4. π number

When the corer strikes a penetration object, the penetration process is normally much shorter than the end of the overall object and the penetration is a local effect. It is thought that the penetration attribute is difference because the sand is the granular material and the light concrete is the solid. Considering parameters which have the effect for two kinds of the penetration object, the dimensional analyses are done using Buckingham π theorem [8].

4.1. Sand

It considers about the sand. There is the bulk modulus as the parameter which has the effect for the sand during penetration [9]. The inside diameter also has the effect because the corer shape is the hollow circular cylinder [8]. The physical quantities which have the effect for penetration depth is expressed by

$$X = f(M, V, d, K) \tag{3}$$

where M, V and d are the mass of the corer, penetration velocity, and inside diameter, respectively. K is the bulk modulus. The nose shape effect of the corer is not included as secondary one, because the corer thickness is thin. And not the outside diameter of the corer but inside diameter of one is used, considering the corer shape is the hollow circular cylinder.

The relations between seven physical quantities are shown by two dimensionless quantities (π_1, π_2) by using Buckingham π theorem [10]. In this paper, as M, V and d are basic physical quantities, a dimensional analysis based on eq. (3) leads to

$$\pi_1 = \frac{Kd^3}{MV^2}, \pi_2 = \frac{X}{d}. \tag{4}$$

It seeks the mutually dependent relations between π_1 and π_2 of eq. (4) based on Fig. 5., because the corer diameter and penetration velocity are parameters in this experiment. Fig. 9. shows the obtained result. The plot set shown in Fig. 9. shows a proportional relationship between π_1 and π_2 without depending on a certain physical quantity.

Here, Li et al. introduced dimensionless quantities $MV^2/f_C d^3$ as impact factor [11]. The reciprocal of π_1 has the meaning similar to dimensionless quantities. The reciprocal of π_1 is used as π_1', instead of π_1. Fig. 10. shows the obtained result. An approximate equation of Eq. (5) is obtained by using the least-squares method from the result.

(5)

$$\frac{X}{d} = 10.972\left(\frac{MV^2}{Kd^3}\right)^{0.4327} \tag{5}$$

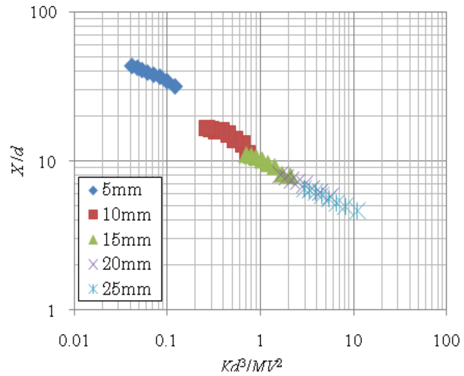

Fig. 9. Relation between $\frac{Kd^3}{MV^2}$ and $\frac{X}{d}$

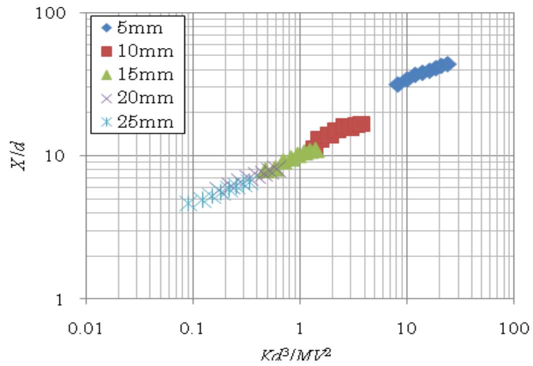

Fig. 10. Relation between $\frac{MV^2}{Kd^3}$ and $\frac{X}{d}$

4.2. Light concrete

It considers about the light concrete. There is the unconfined compressive strength as the parameter which has the effect for the light concrete during penetration [12]. The physical quantities which have effect on to penetration depth is expressed by

$$X = f(M, V, S, f_C) \tag{6}$$

where S is the cross-sectional area of the top of the corer. f_C is the unconfined compressive strength. The nose shape effect of the corer is not included as secondary one, as well as the sand. S is used one of physical quantities for the light concrete instead of d because the destruction is accompanied in the solid when penetrating.

The relations between seven physical quantities are shown by two dimensionless quantities (π_3, π_4) by using Buckingham π theorem [8]. In this paper, as M, V and S are basic physical quantities, a dimensional analysis based on eq. (6) leads to

$$\pi_3 = \frac{f_C\sqrt{S}^3}{MV^2}, \pi_4 = \frac{X}{\sqrt{S}}. \tag{7}$$

It seeks the mutually dependent relations between π_3 and π_4 of eq. (7) based on Fig. 10., because the corer diameter and penetration velocity are parameters in this experiment. Fig. 11.

shows the obtained result. The plot set shown in Fig. 13. shows a proportional relationship between π_3 and π_4 without depending on a certain physical quantity.

Here, the reciprocal of π_3 is used as π_3', instead of π_3 as well as the sand. Fig. 12. shows the obtained result. An approximate equation of Eq. (8) is obtained by using the least-squares method from the result.

$$\frac{X}{\sqrt{S}} = 1.0773\left(\frac{MV^2}{f_C\sqrt{S}^3}\right)^{1.0384} \qquad (8)$$

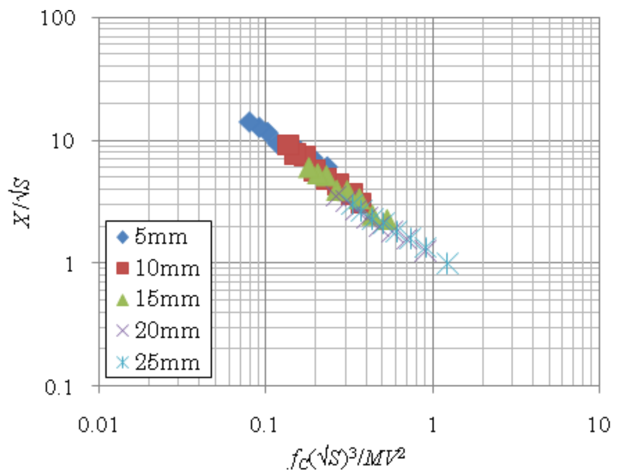

Fig. 11. Relation between $\frac{f_C\sqrt{S}^3}{MV^2}$ and $\frac{X}{\sqrt{S}}$

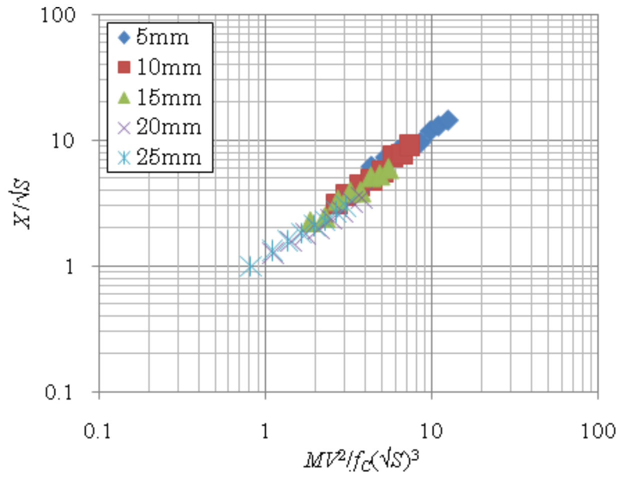

Fig. 12. Relation between $\frac{MV^2}{f_C\sqrt{S}^3}$ and $\frac{X}{\sqrt{S}}$

5. Energy comparison

The requisite velocity and energy to penetrate the object with 300mm depth are extrapolated based on obtained eq. (5) and eq. (8), and then that result is shown in Table 3. and Table 6. Table 3. shows the result of the sand, and Table 4. shows that of the light concrete. To evaluate whether the extrapolated results are possible, the results is compared to the energy of the bullet carried aboard Hayabusa. It has been understood that the penetration tendency differs for the difference of the penetration attribute of the granular material and the solid from Table 3. and Table 4. Here, Fig. 5. shows the result included penetration loss for the sand. The result at the corer with 5mm diameter shown in Table 5. is nothing in order to consider the result of the penetration loss.

At the result of the light concrete shown in Table 4., the requisite velocity and energy to penetrate are small as the corer diameter is small. The minimum value of the extrapolated velocity is 41m/s using the corer with 10mm diameter, and the minimum value of the extrapolated energy is 22N･m using the corer with 5mm diameter. And the requisite energies to penetrate the 300mm depth for all of the corer diameters are smaller than the energy of the bullet. Therefore, the requisite energies for the mission consummation are satisfied in all of the corer diameters used by the penetration experiment of the light concrete.

At the result of the sand shown in Table 5., the requisite velocity and energy to penetrate are small as the corer diameter is large. The minimum value of the extrapolated velocity is 28m/s using the corer with 25mm diameter, and the minimum value of the extrapolated energy is 50N･m using one. This is caused by penetration loss. The requisite energies to penetrate the 300mm depth for all of the corer diameters except 5 and 10mm of the corer diameters are smaller than the energy of the bullet. Therefore, if the corer diameter is over 15mm in the sand, the requisite energies for the mission consummation are satisfied.

From this, the result to meet the desired sample layers with 300mm depth doesn't obtain for all of the corer diameters used by this penetration experiment, however, if the corer diameter is over 15mm, the desired sample layers can be obtained at 300mm depth. In particular, the energy is minimum using the corer with 15mm diameter, and the value is 97N･m.

Table 3. Energy comparison (sand)

	Diameter [mm]	Mass [g]	Velocity [m/s]	Energy [N]
Corer	5	25	30.0	11.4
	10	57	26.4	19.9
	15	86	25.1	27.0
	20	111	24.5	33.3
	25	132	24.3	39.1
Bullet	10	5	300	225

Table 4. Energy comparison (light concrete)

	Diameter [mm]	Mass [g]	Velocity [m/s]	Energy [N･m]
Corer	5	25	42	22
	10	57	41	48
	15	86	42	74
	20	111	42	100
	25	132	44	126
Bullet	10	5	300	225

Table 5. Energy comparison considering penetration loss (sand)

	Diameter [mm]	Mass [g]	Velocity [m/s]	Energy [N・m]
Corer	5	25	-	-
	10	57	163	760
	15	86	48	97
	20	111	32	57
	25	132	28	50
Bullet	10	5	300	225

6. Japanese Sword Technology

Fig.13 Cutting using a Japanese Sword

In the present study, we are proposing to employ Japanese Sword technology for the material and design of corer tip in order to extract deeper and many more sample of the asteroid surface. Fig 13 shows the photo of Test cut by Mr. Matsunaga. The Japanese Sword technology has over 2000 years history, and it is best edged tool in the world. By using the Japanese sword technology, the improvement in coring performance of the sampling can be expected.

7. Conclusion

The device for the penetration experiment was produced, and the relation between the penetration depth and the penetration velocity is requested for the sand and the light concrete. It has been understood that the penetration tendency differs for the difference of the penetration attribute of the granular material and the solid.

If the corer diameter is over 15mm, the desired sample layers can be obtained at 300mm depth. In particular, the energy is minimum, using the corer with 15mm diameter. Experimental results show that the capability for the sampling by employing the Harpoon & Penetrator method.

It is necessary to verify penetration tendency with difference from the attribute of the penetration object for the variety of the grain diameter or the compressive strength. In this paper, the penetration experiment is run using the parameters of the penetration velocity and the corer diameter and the dimensional analyses are done, and then it is necessary to verify the mutually dependent relations of all dimensionless quantities which influence the effective for the penetration depth included others. In addition, employing of Japanese Sword Technology for element of sampler as corer is presented.

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