Experimental study of shear behavior of soil-geosynthetic interface by large scale direct shear test

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ABSTRACT: Geosynthetics are extensively used in building bases and liner systems in landfills. In engineering practices, geosynthetics are usually paved on top of compacted soils, forming soil-geosynthetic interfaces. Large scale direct shear tests are widely adopted to investigate the shear behavior of the interface. In existing researches, the relative displacement of the shear boxes is usually taken as the relative displacement between soil and geosynthetics, which is different from the real scenario. The reason is that soil undergoes a certain extent of creep deformation during the shearing process. In the present study, a new direct shear testing technology, including a newly designed apparatus and corresponding testing method, was developed to measure the shear behavior of the soil-geosynthetic interfaces between soft clay and textured geomembrane. A soil-grabbing apparatus was designed to accurately acquire the displacement of soil at the soil-geosynthetic interface. A series of interface direct shear tests were performed with large scale specimen (600×200 mm), under a constant normal stress of 100 kPa, with a shear displacement of 70 mm and shear rate of 1 mm/min. The results indicate that the developed apparatus is a powerful tool to investigate the shear behavior of the soil-geosynthetic interface.

Keywords: Geosynthetic interface; Direct shear apparatus; Geomembrane; Creep deformation

1 INTRODUCTION

Owing to its favorable anti-seepage performance, geomembranes (GMs) are used as liquid and vapor barriers in a wide variety of engineered facilities, especially waste disposal landfills. Furthermore, to serve the function effectively, geomembranes are universally used in conjunction with bentonite or compacted clay liners (CCLs) as composite liners to prevent the toxic leachate generated in landfill from entering the groundwater system.

However, due to the relatively low shear strength, the interface between geosynthetic and soil is often the potential weak interface of a liner system. The failure due to displacement along the interface between GM and soil within the liner system in Kettleman Hills Landfill is a typical example (Zania et al. 2008; Mitchell et al. 1990), which has drawn increasing concern in engineering practice. After the Kettleman Hills landfill failure, quite a few researchers have made an effort in measuring shear strength of the interface between geomembrane and soil with different methods (e.g. Mitchell et al., 1990; Koutsourais et al., 1991; Seed and Boulanger, 1991; Fishman and Pal, 1994; Gilbert and Bryne, 1996; Jones and Dixon, 1998; Dove and Frost, 1999; Gomez and Filz, 1999; Esterhuizen et al., 2001; Ling et al., 2001; Briancon et al., 2002; Hsieh and Hsieh, 2003; Narejo, 2003; DeJong and Westgate, 2005; Zabielska-Adamska, 2006; Zania et al. 2008; Ross and Fox, 2015).

Especially, Fishman and Pal (1994) give a comprehensive review of soil – geomembraneinterface testing procedures, where the effects of testing procedures on measured interface strength parameters were analyzed also. Generally, direct shear apparatus with some modification to facilitate shearing at the geomembrane–soil interface under normal stress is appropriate to study shear strength of geomembrane–soil interface. A comprehensive overview of different direct shear apparatus and testing procedures is given by Stoewahse, et al. (2002). Mostly, one of the shear box contains tested soil and the other contains a geomembrane mounted on a rigid block to perform the tests. A large range of shearing rates from 0.3 mm/h or slower (e.g. Fishman and Pal, 1994; Jones and Dixon, 1998) to 50 mm/h or faster (e.g. Seed and Boulanger, 1991; Fishman and Pal, 1994; Esterhuizen et al., 2001) are included in previous studies, while the effect of shearing rates on shear strength of geomembrane-soil interface seems to be insignificant (Zabielska-Adamska, 2006).

Due to difference in testing apparatus, procedures and targets, conclusions of previous studies on shear strength of geomembrane-soil interface differ from each other, which is insufficient to guide prac-tical design of liner systems of landfill. As pointed out by Fox and Stark (2004), the shearing test results is dependent on many factors including but not limited to: product manufacturer, shearing device, grip-ping surfaces, specimen size, displacement rate and normal stress. Therefore, standard test methods are needed in order to decrease the variability of shear test data. ASTM D 5321-02 provides a standard test method for determining the coefficient of soil and geosynthetic or geosynthetic and geosynthetic friction by the direct shear method. Specifically, a leading and comparatively mature large-scale shear apparatus was developed by Fox et al. (2006) and quantity of shear tests on geosynthetic interfaces were reported (Fox et al. 2007, 2010, 2011, 2015a, 2015b). However, no standard large-scale shear test on geomem-brane-clay interface has been performed, which demonstrates the necessity to carry out relevant investi-gation.

This paper presents a newly developed large-scale shearing apparatus to measure the monotonic shear characteristics of the interface between a textured HDPE GM and compacted clay obtained from Laogang municipal solid waste (MSW) landfill, Shanghai, China. Experimental investigations of the monotonic shear strength of the GM/CCL interface were conducted under constant normal stresses (σ_n = 100 kPa), displacement rate of 1.0 mm/min and amplitudes of 70 mm to reach the residual shear strength, with large scale specimens (600 mm × 200 mm). Particularly, 3 soil-grabbing apparatus with LVDT sensors were installed on the apparatus to detect the deformation of compacted clay in the shear box during the shearing process.

2 TEST DEVICE

2.1 *Large geosynthetic interface shear apparatus*

A geosynthetic interface shear apparatus powered by two high pressure oil pumps and controlled by a set of server systems was developed. The mainframe of the geosynthetic interface shear apparatus is exhibited in Figure 1. As seen in Figure 1, the apparatus is consisted of three main subsystems: (1) the shear test system on the right, (2) the control system on the bottom left and (3) the oil power system on the upper left.

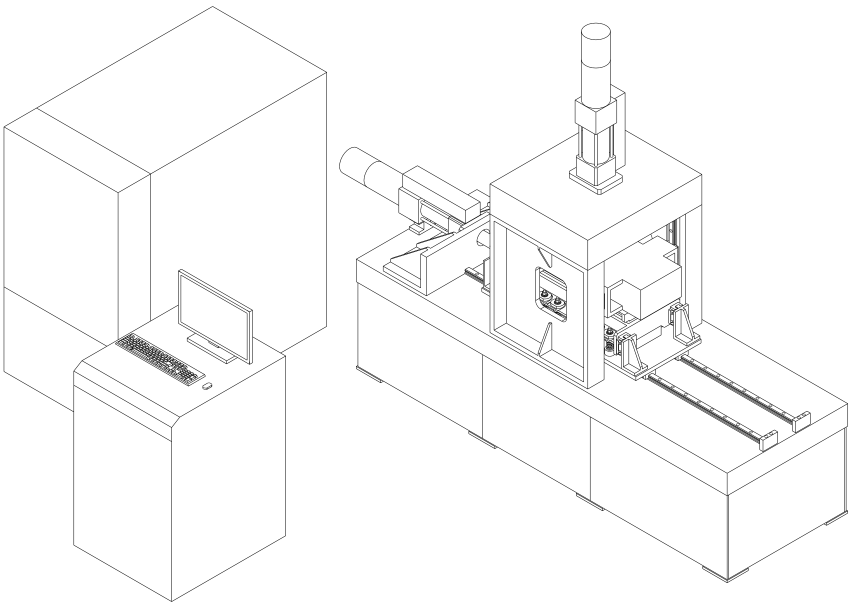
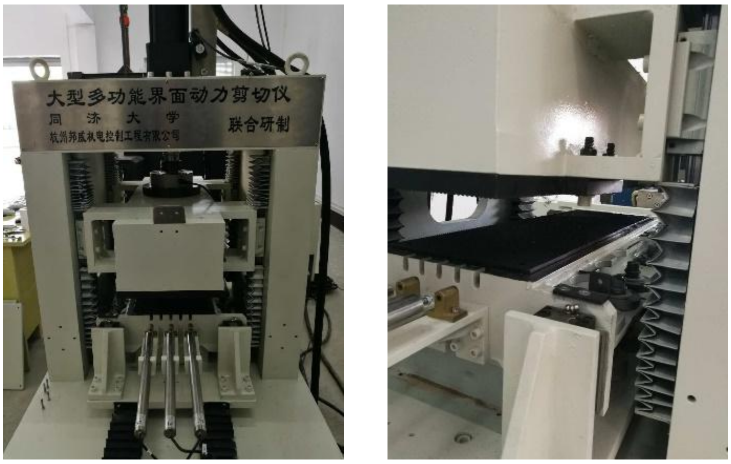


Figure 1. Mainframe of the geosynthetic interface shear test apparatus.

The upper and bottom shear boxes were designed to model the shear process between the geomembrane and the soil, as shown in Figure 2(a). The black upper gripping plate with acute 1 mm high steel teeth is fixed on the upper shear box, as shown in Figure 2(b).



(a) Upper and bottom shear boxes (b) Upper gripping plate

Figure 2. Geosynthetic interface shear test apparatus.

The size of the tested specimen is 600 mm × 200 mm, which is a quite large scale one compared with traditional apparatuses. The normal stress varies from 0 to 1000 kPa, and the maximum shear stress is 700 kPa. For static shear test of the soil – geosynthetic interface, shear displacement rates of 0.1 ~ 100 mm/min are feasible. More specifications of the shear apparatus are listed in Table 1.

Table 1. Geosynthetic interface shear apparatus specifications.

Feature	Specification
Specimen size	600 mm × 200 mm
Maximum normal stress	1000 kPa
Maximum shear stress	700 kPa
Maximum specimen thickness	100 mm
Maximum horizontal displacement	120mm
Specimen gripping system	Steel gripping plate, teeth spacing distance: 2 mm
Minimum displacement rate	0.1 mm/min
Maximum displacement rate	100 mm/min
Maximum sinusoidal frequency	5 Hz

Apart from the static shear tests, the developed geosynthetic shear apparatus is capable of conducting dynamic shear test of several geosynthetic interfaces, such as the GM/GCL and GM/Soil interfaces.

2.2 *Soil grabbing sensor system*

The shear mechanism of the geosynthetic – soil interface static shear test is exhibited in Figure 3. The upper shear box is fixed, with a gripping plate fixing the geomembrane specimem, and the bottom shear box is pushed by the oil pump actuator, so the soil – geosynthetic interface forms by contact between a surface of fixed geomembrane and a surface of tested soil in the moving shear box.

By rethinking and analysis of the internal deformation of the tested soil in the bottom shear box, the hypothesis of internal creep deformation of tested soil in large scale shear tests was established. During the shear process, the upper geomembrane surface is very likely to drive a specific part of the tested soil to move with the surface for a certain distance, which may be very small and is limited, and the creep deformation of this specific part soil will occur. This specific part of soil is named as creep deformation layer as shown in Figure 3, and the creep deformation layer could be divided into three different areas: the loose area, the moving area and the compacted area. The order of these three areas is mainly due to the moving direction of the shear test, under the proposed hypothesis. The rest soil in the bottom shear box apart from the creep deformation layer is named as the undisturbed area.

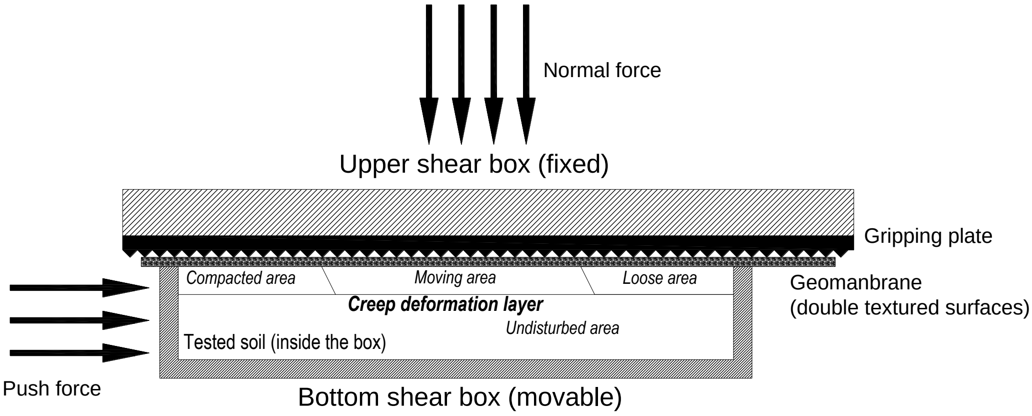


Figure 3. Creep deformation of tested soil during large scale shear test

A newly designed soil grabbing sensor system was developed to investigate the creep deformation of the soil during shear tests. The system is consisted of three main units: (1) deformation acquisition unit (soil grabbing spoon), (2) displacement transmission unit (displacement transmission rod, protecting pipe and bending elimination joint) and (3) digital sensor unit (the LVDT senor).

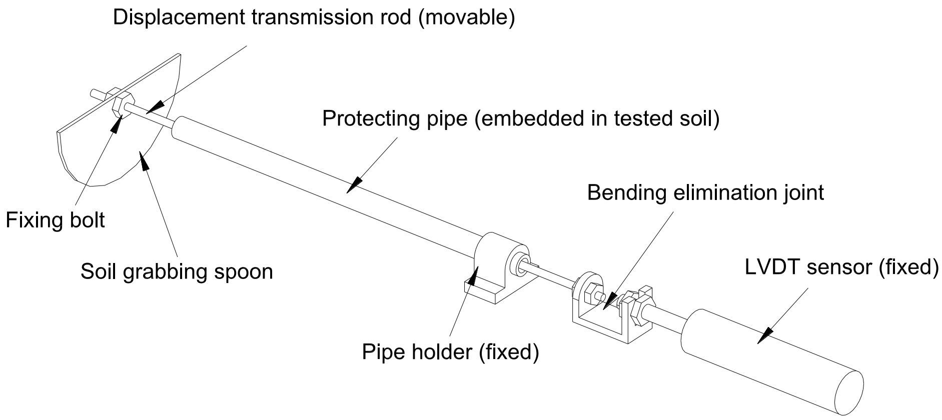


Figure 4. Diagram of the soil grabbing sensor system

A soil grabbing spoon was designed to acquire the minor deformation of the creep soil layer, as shown in Figure 4, and method of a displacement transmission rod through a protecting pipe, which is embedded in the soil during tests, was developed to avoid the friction of surrounding soil with the aim of transmitting accurate creep deformation in the form of horizontal displacement of soil particles.

(a) Three parallel LVDT sensors

(b) Three embedded pipes and the soil grabbing spoons

Figure 5. Soil grabbing sensor system in the shear test

Three soil grabbing sensor systems were parallel installed, with different lengths as shown in Figure 5(a) and (b). This specific experimental design was meant to measure the creep deformations of three different areas. If the certain deformations were detected by the sensor systems, the proposed hypothesis of creep deformation layer of shear tested soil is proved. So, a static shear test of soil – geosynthetic interface was conducted.

3 MATERIAL AND PROCEDURE

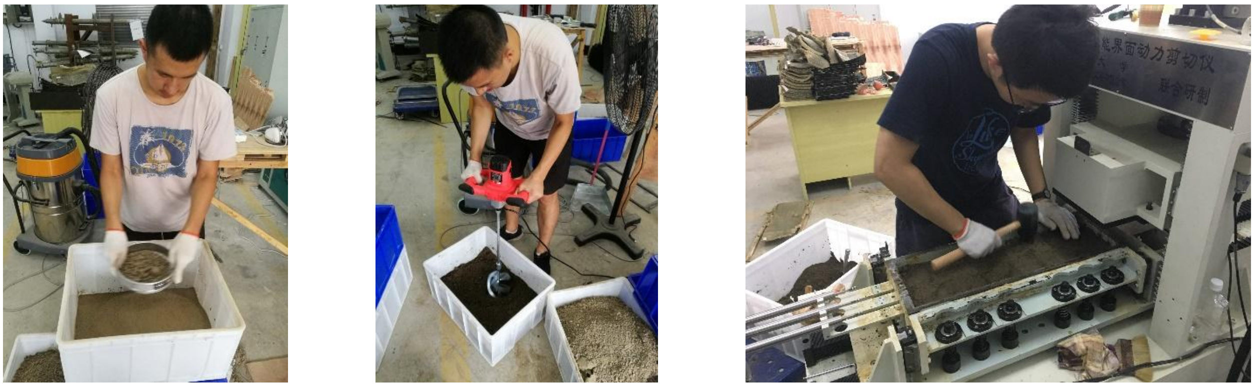
3.1 *Test materials*

Two types of materials, geomembrane and clay, were utilized in the static shear test of the soil – geosynthetic interface. The geomembrane is high density polyethylene (HDPE) microspike liner manufactured by GSE (Suzhou, Jiangsu, China). It consisted of a constant thickness of around 1.53 mm, with two textured surfaces. The soil was obtained from Laogang landfill at Pudong district of Shanghai, with the permission and kind help of the Laogang MSW disposal cooperation. The Laogang clay is the very material utilized in the construction of the compacted clay layer of the landfill composite liner system.

The liquid limit and plastic limit of Laogang clay were determined as 27.6 % and 18.5 %, respectively by laboratory geotechnical tests. The optimum moisture content of the Laogang clay was determined as 20.8 % by compaction tests. For the convenience of test, moisture content of 20% was chosen as the tested moisture content.

3.2 *Test procedures*

A consistent testing procedure was used for the shear test of soil – geosynthetic interface. The detailed outline of the methods was first provided by Nye et al. (2007). Each test involved a multi-step process. It started with cutting the geomembrane specimens from large rolls. The specimen size of geomembrane was 700 mm × 240 mm, larger than the interface size of 600 mm × 200 mm, to guarantee an adequate shear distance.



(a) Sieving the air-dried soil (b) Blunging the sieved soil (c) Compacting the tested soil

Figure 6. Test preparations.

The Laogang clay was firstly air-dried for several days and sieved through 2.5 mm sieve for the preparation of blunging with water. Figure 6(a) and (b) exhibit the operation procedures of sieving and blunging. After the tested soil specimen was prepared, the soil was then compacted into the shear box with rubber hammer, as seen in Figure 6(c).

Before the test, a preload stage was run to impose the tested normal stress of 100 kPa for 2 hours to reach a steady thickness of the specimens. The tested shear displacement rate was 1 mm/min, the shear distance is 70 mm, and the static shear last for 70 min. The long shear distance was to ensure the observation of steady shear strength of the soil – geosynthetic interface.

4 EXPERIMENTAL RESULTS

4.1 *Visual Inspection of the tested specimens*

As shown in Fig.7(a) and (b), there were clear veins in surface of clay caused by the spikes of geomembrane, which demonstrates that the geomembrane and clay are bonded together during the shearing process. Notably, a thin layer of clay was adhered to the geomembrane when the geomembrane was taken out. Therefore, it could be inferred that part of failure occured within the compacted clay because of the existence of spikes on geomembrane, while failure of the soil - geosynthetic interface is the main mode.

(a) Geomembrane specimen after test (b) Clay surface after test

(c) Soil grabbing spoon in tested soil (d) Lateral squeezed soil of the bottom shear box

Figure 7. Visual inspection of the specimens after test.

In Fig. 7(c), the soil grabbing spoon in tested clay could be observed and it moved with the superficial clay together during the shearing process. The lateral extrusion of clay, in Fig. 7(d), indicates that the top thin layer of clay was not well confined in lateral direction. Hence, the amount of clay in the shearing box should be controlled with more caution in future studies.

4.2 *Shear strength of the soil-geosynthetic interface*

Figure 8 displays the relation between shear stress and shear displacement of the tested interface. At the very first stage of the loading process, the shear stress increased swiftly to about 20 kPa, which could be deemed as a elastic stage. After that, a stable process of hardening is detectd until peak shear strength. The peak shear strength is around 76.2 kPa and it was reached at the shear displacement of about 23 mm.

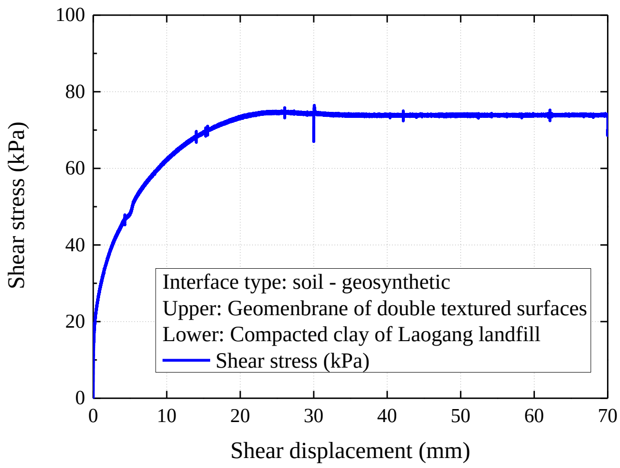


Figure 8. Curve of shear stress vs. shear displacement of tested interface.

A slight softening phenomenon of the interface is observed after the peak at 23 mm. When shear displacement exceeded 35 mm, the shear strength of the interface reached a stable level of about 74 kPa. The limited difference between peak and residual shear strength indicates that the softening property could be taken no account in to the engineering design practice of this type of soil – geosynthetic interface.

4.3 *Thickness reduction of tested soil*

Figure 9 displays the process of thickness reduction of the testdd clay. The rate of reduction of thickness drops during the shear process. Thickness reduction of 2.93 mm is the final state reached at the end of the test, which is mainly ascribed to the redistribution of stress within the compacted clay.

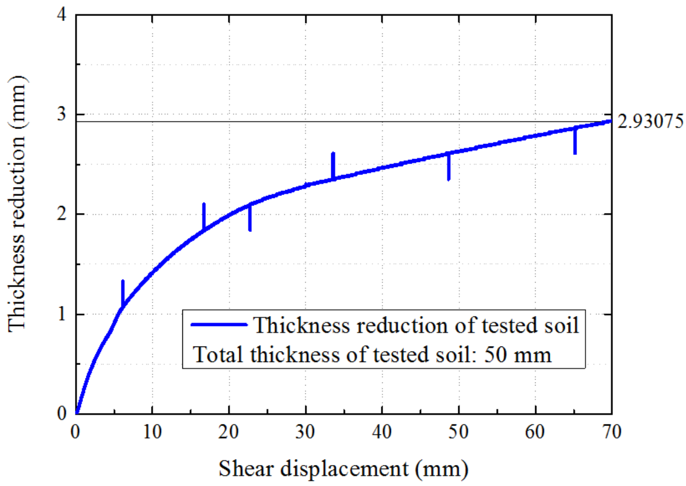


Figure 9. Curve of thickness reduction vs. shear displacement.

4.4 *Creep deformation of tested soil*

The recorded creep displacement of three typical positions by LVDTs is displayed in Figure 10 and all the three curves show typical two-segment characteristic. The increasing rate of creep displacement at the first segment is apparently larger than second segment. Interestingly, the divide of the two segments is the peak shear strength of the interface since the abscissa of the divide is consistent with the shear displacement of peak shear strength of the interface shown in Figure 8. This phenomenon proves the hypothesis of creep deformation within the tested soil. The creep displacements recorded by sensor 1# and 2# are similar, while the displacement recorded by sensor 3# is lower than half of the displacement of 1# and 2#, demonstrating that the distribution of creep deformation within clay is not uniform.

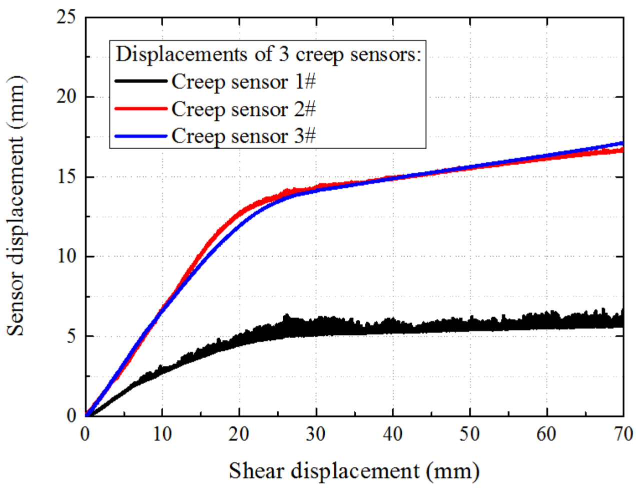


Figure 10. Curves of sensor displacement vs. and shear displacement of the interface.

5 CONCLUSIONS

The test results on shear strength of clay – geomanbrane interface verify that the newly developed apparatus is a powerful tool to investigate shear mechnism of the soil – geosynthetic interface. The shear strength of the interface between textured HDPE geomembrane and compacted clay is characterized by typical elastoplasticity, and the displacement-softening property is of little importance. Creep displacements obtained by the soil grabbing sensor system demonstrates the existence of creep deformation layer within the tested clay, which is crucial for soil-geosynthetic interaction.

Furthermore, the discoveries in this paper is drawn based on single test and more investigations on the effect of normal stress, displacement rate and water content of clay are expected. Especially, the analysis of creep deformation layer and shear zone is of vital importance for revealing the mechanism of soil-geomembrane interaction, worthing further deep researches.

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