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DEVELOPMENT OF DISCHARGED SOIL MEASURING DEVICE FOR SHIELD TUNNELING MACHINES

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ABSTRACT

It is very important to know the volume of discharged soil for more adequate excavating control of the shield tunneling machines. In confined soil shields and mechanical shields, excavated soil is discharged by belt conveyors and muck cars, so it has been difficult to evaluate the discharged soil volume. In this study we have developed a discharged soil measuring system to evaluate the volume of discharged soil in real time. This system is equipped with (1) an ultrasonic sensor or (2) light section microscope with laser to measure the cross-sectional area of transported soil on a belt conveyor. Using this system, it is possible to evaluate the volume of discharged soil with good accuracy in a very humid environment like a shield tunneling machine. This system is effective not only for volume measurement of soil flow but also for volume measurement of granular material such as coal, and powder such as flour on belt conveyor systems.

1. INTRODUCTION

The method of constructing a tunnel using a shield type tunnel excavating machine, moving forward as it excavates the tunnel mostly through soil and completing both excavation and lining work within the machine itself while preventing collapse of the soil is called the shield tunneling method. In carrying out tunneling work by the shield method, it is necessary to know the volume of the soil excavated at the cutting face in real time, in order for the excavation work not to affect the earth around the tunnel. From this point of view, the slurry shield method is advantageous. It allows comparatively easy measuring of the weight, volume, and specific gravity of the discharged soil as it is handled by a liquidic conveyance system, and the monitoring system relating to soil discharge has generally reached the level of consummation.

However, in the case of the earth pressure balanced shield method, including the use of high density slurry shields, which has been adopted increasingly in recent years, the soil discharged out of the screw conveyor is generally moved by a belt conveyor. Muck cars then remove the soil from the tunnel afterwards. In such cases, the muck cars are used as measures to calculate the volume of the discharged soil.

The purpose of this study is to develop a discharged soil volume measuring system using ultrasonic sound waves and laser lights which measure the cross-sectional area of the continuous soil deposit moving on the belt conveyor. This will improve the excavation control accuracy through real time calculation of the discharged soil volume in the earth pressure balanced shield system.

2. EARTH PRESSURE BALANCED SHIELD MECHANISM AND SYSTEM DEVELOPMENT TARGET

2.1 Earth pressure balanced shield

The shield machines, depending on their front face structures, are roughly classified into the open face type, the partially open face type, and the closed face type as shown in Fig. 1.[1] At present, the closed face shields constitute the mainstream. The closed-face shield, denoting the mechanical excavating shield which has a bulkhead, excavates the soil, fills the cutter chamber space between the excavation face and the bulkhead with excavated soil or slurry, and maintains the stability of the excavated face. An effective restraint pressure is applied to the soil or slurry filling in the cutter chamber during excavation.

The earth pressure balanced shield, one of the closed face types, secures the stability of the excavation face by applying a certain level of pressure to the excavated soil. This shield is equipped with an excavating mechanism to cut the face, a mixing mechanism to stir the excavated soil, a soil discharging mechanism to discharge the soil, and a control mechanism to apply a certain level of restraint pressure to the excavated soil (Fig. 2).

2.2 Development target of discharged soil measuring system

It was determined that the discharged soil measuring device should be installed above the belt conveyor which receives the soil discharged from the screw conveyor (Fig. 2). The material to be measured by the system was assumed to be soil in conditions similar to those of ready-mixed concrete containing sand, clay, gravel, and earth lumps. The maximum measurable soil volume of 100 m^3 with an accuracy of $\pm 10\%$ FS (full-scale) was established as the target of the development effort.

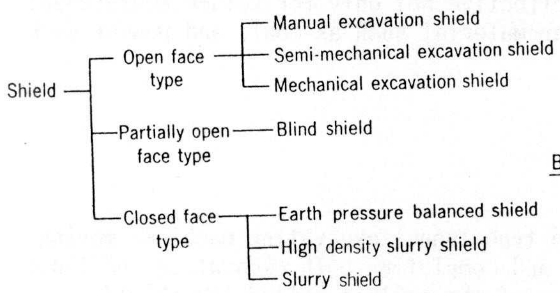


Fig. 1 Classification of shield machines

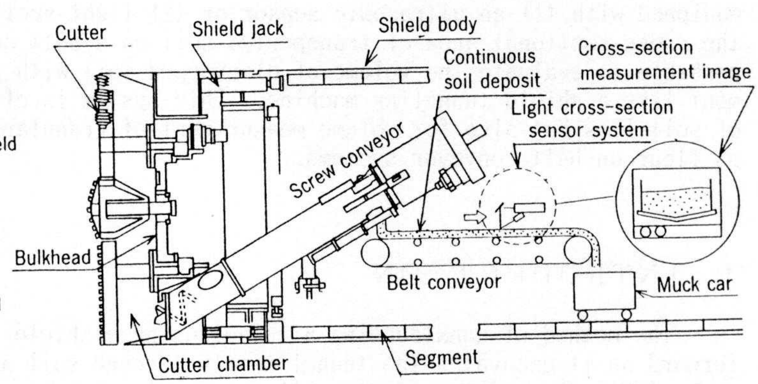


Fig. 2 Constitution of earth pressure balanced shield and outline of discharged soil measuring device

3. ULTRASONIC DISCHARGED SOIL VOLUME MEASURING DEVICE

3.1 Principle of the ultrasonic method[2]

The changing height of the continuous soil deposit moving on the belt conveyor at velocity V is continuously measured by the ultrasonic sensor installed above the belt conveyor (Fig. 3). As shown in Fig. 4, the ultrasonic wave emitted from one or more ultrasonic sensors is reflected on the soil surface, and the distance ℓ between the sensor and the soil surface is obtained from the time required for the reflected waves to return to and to be received by the sensor. The height of the soil deposit h is calculated by the following formula:

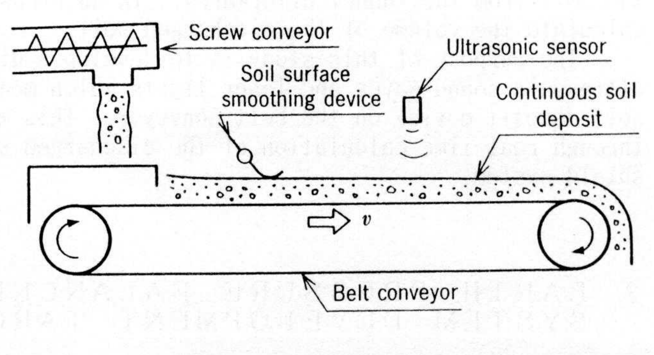


Fig. 3 Principle of ultrasonic measuring method

$$h = H_0 - \ell \quad (1)$$

where, H_0 is the distance from the ultrasonic sensor to the conveyor bottom face.

The cross-sectional area of the soil will be calculated from this height of the soil deposit and the bottom configuration of the belt conveyor.

In this method, it is desirable to smooth the soil surface to improve the accuracy of the measurement. Fig. 5 shows the mechanism and functions of the soil surface smoothing device.

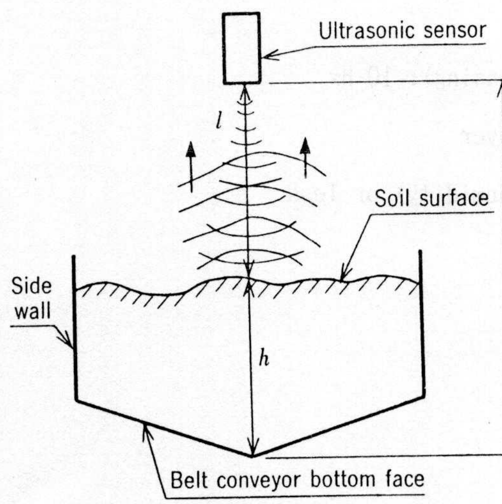


Fig. 4 Corss-section of soil at measurement point

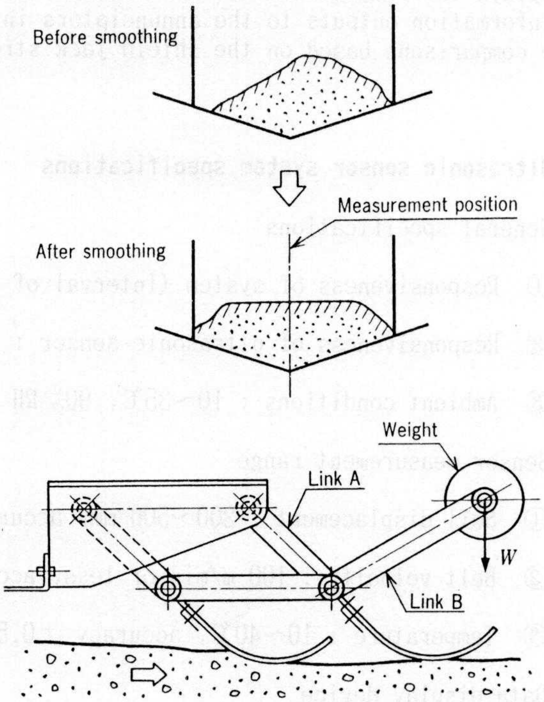


Fig. 5 Soil surface smoothing device

3.2 Ultrasonic sensor system composition

(1) Sensors

The sensors are listed below. As shown in Fig. 6, the signals of each sensor are sent to the pre-processing device and the data display device.

① Ultrasonic distance sensor

② Temperature sensor (thermistor)

③ Belt conveyor velocity sensor (tachometer)

④ Shield jack speed and stroke sensor

(2) Pre-processing device

The pre-processing device receives signals from the ultrasonic distance sensor and outputs the soil cross-section's average height.

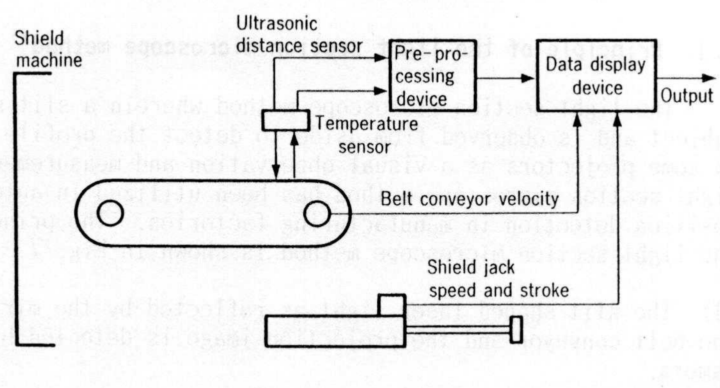


Fig. 6 Ultrasonic system composition

(3) Data display device

The data display device receives signals from the ultrasonic sensor through the pre-processing device, calculates the soil cross-section area, the soil volume, and the soil weight and displays the results of the calculations on the panel of this device. Further, this device sends information outputs to the annunciators in the central control panel and performs soil volume comparisons based on the shield jack strokes.

3.3 **Ultrasonic sensor system specifications**

(1) General specifications

① Responsiveness of system (Interval of total processing): 10 Hz

② Responsiveness of ultrasonic sensor : 200 Hz or over

③ Ambient conditions : 10～35℃, 90% RH (relative humidity) or less

(2) Sensor measurement range

① Soil displacement : 200～500 mm, accuracy ±2 mm

② Belt velocity : 100 m/min or less, accuracy ±1%

③ Temperature : 10～40℃, accuracy ±0.5℃

(3) Data display device

① Functions : Theoretical flow volume calculation, measured flow volume calculation, and display outputs

② Display data : Momentary flow volume, cumulative flow volume, theoretical cumulative flow volume, cumulative weight, momentary soil volume balance, comulative soil volume balance, belt velocity, and excavating distance.

(4) Output signals

Momentary flow volume and cumulative flow volume

4. LASER LIGHT SECTION MICROSCOPIC DISCHARGED SOIL MEASURING DEVICE

4.1 **Principle of the light section microscope method[2)]**

The light section microscope method wherein a slit-shaped light beam is projected upon the subject and is observed from aside to detect the profile of the said subject, has been adopted by some projectors as a visual observation and measurement technique. In recent years, the light section microscope method has been utilized in automatic testing of shapes and automatic position detection in manufacturing factories. The principle of the soil height measurement by the light section microscope method is shown in Fig. 7.

(1) The slit-shaped laser light as reflected by the mirror is projected to the soil surface on the belt conveyor and the projection image is detected by the ITV (industrial television) camera.

(2) Since the light section image displacement plane and the CCD (one type of semi-conductor element) observation plane of the ITV camera have an angle, a geometrical compensation will be made, and the soil cross-sectional area will be sought by the cross-section calculation with the light projection image taking the belt coveyor bottom shape into consideration.

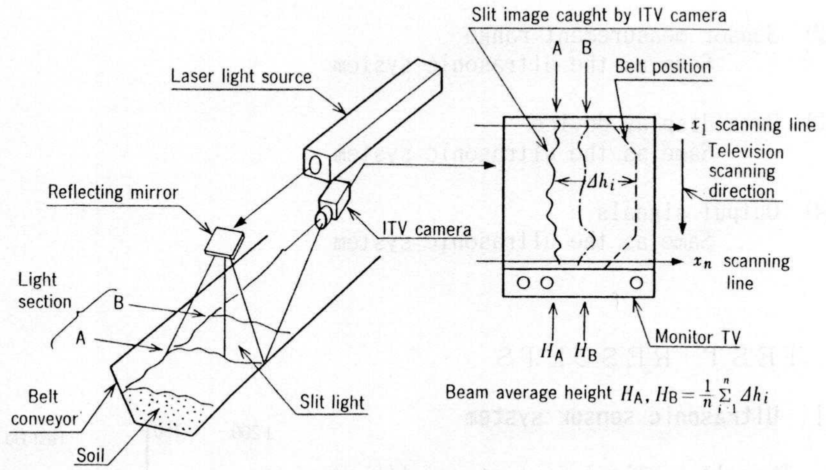


Fig. 7 Principle of light section microscope measuring method

4.2 Light section microscope system composition

(1) Sensors

The optical system equipment and sensors are shown below. As shown in Fig. 8, the video image and the signals from each sensor will be sent to the pre-processing device and then to the data display device.

① Laser light source (slit beam output)

② Reflecting mirror

③ ITV camera (equivalent to CCD 2/3 inch)

④ Belt conveyor velocity sensor (tachometer)

⑤ Shield jack speed and stroke sensor

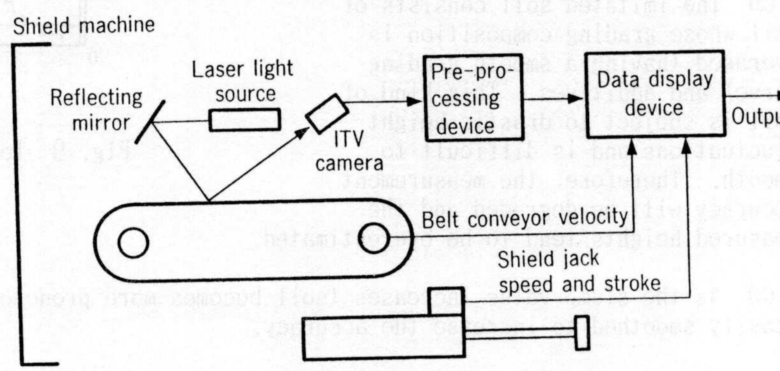


Fig. 8 Light section microscope system composition

(2) Pre-processing device

The beam position (the length appearing on the picture) corresponding to the height will be measured by each raster scanning, calculated as the average value of one picture (field average processed).

(3) Data display device

The same device as used in the ultrasonic system will be used.

4.3 Light section microscope system specifications

(1) General specifications

① Responsiveness of system (Interval of total processing): 60 Hz

② Operating environment : 10～35℃, 90% RH or less

(2) Sensor measurement range
Same as the ultrasonic system

(3) Data display device
Same as the ultrasonic system

(4) Output signals
Same as the ultrasonic system

5. TEST RESULTS

5.1 Ultrasonic sensor system

The ultrasonic type test results are shown in Table 1. Examples of measurement results are shown in Fig. 9.

(1) The soil surface smoothed by the smoothing device makes the measurement effective, and especially in the case of sand, the surface can be smoothed easily to make measurements more accurate.

(2) The imitated soil consists of soil whose grading composition is averaged (having a smooth grading curve) and additives. This kind of soil is subject to drastic height fluctuations and is difficult to smooth. Therefore, the measurement accuracy will be degraded and the measured heights tend to be overestimated.

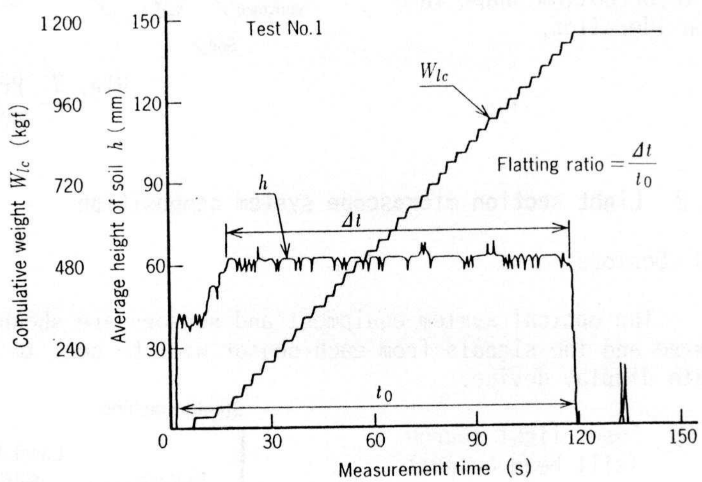


Fig. 9 Test result of ultrasonic system

(3) As the slump value increases (soil becomes more pronetocollapse), the surface can be more easily smoothed to increase the accuracy.

(4) The flattening ratio in Table 1 is defined by the ratio of time during which the soil height was generally constant against the total measurement time and is also the index of the stability of soil against the soil flow in the downstream direction. It was found that an accuracy of ±10% can be obtained if a flattening ratio of approximately 60% or over is secured.

Table 1 Test result of ultrasonic method

Soil conditions			Flow conditions		Measurement
Soil	Slump (cm)	Density $\times 10^3$ (kg/m^3)	Height of soil (cm)	Flattening ratio (%)	tolerance (%)
Sand	—	1.3	4 ~ 7	80 ~ 90	-4 ~ 6
Imitated soil ①	4 ~ 8	1.6 ~ 1.7	4 ~ 10	40 ~ 55	6 ~ 17
Imitated soil ②	9 ~ 11	1.8 ~ 1.9	4 ~ 12	60 ~ 75	-2 ~ 12

5.2 Light section microscope system

The light section microscope system was field tested using a system manufactured for practical use. Therefore, the imitated soil test was omitted, and the bench test was performed using sand only. The surface roughness at random condition was more emphatic than for the imitation soil in Table 4.

The test results are shown in Table 2 and Fig. 10.

(1) No differences were recognized between smoothed soil surface and random soil surface (winding); therefore the smoothing device is unnecessary.

(2) This system has sufficient running performance to meet considerably random soil surfacce fluctuation with good accuracy which satisfies the target accuracy of ±5%.

(3) Generally, depending on the field conditions, protection measures are necessary for the purpose of preventing intrusion of direct outside light.

(4) The effects of the light diffusion on the soil surface caused by the soil water content decrease the strength of the slit light beam reflection but caused no problems as long as it remained partially within the field of vision.

(5) No significance can be recognized in the camera shutter speed, and there is no need for a high speed shutter camera.

Fig. 11 shows the results of the field tests of the light section microscope system manufactured for practical use. It was confirmed that the measured value and the theoretical value correspond well and this system has high performance.

Table 2 Test result of light section microscope method

Soil conditions	Smoothing	Winding	Random	General
Measurement tolerance (%)	-2.4 ~ 2.0	-1.8 ~ 2.4	-3.6 ~ 3.3	-3.6 ~ 3.3

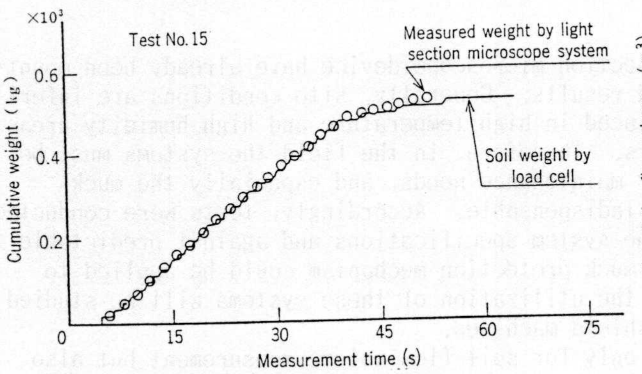


Fig. 10 Test result of light section microscope system

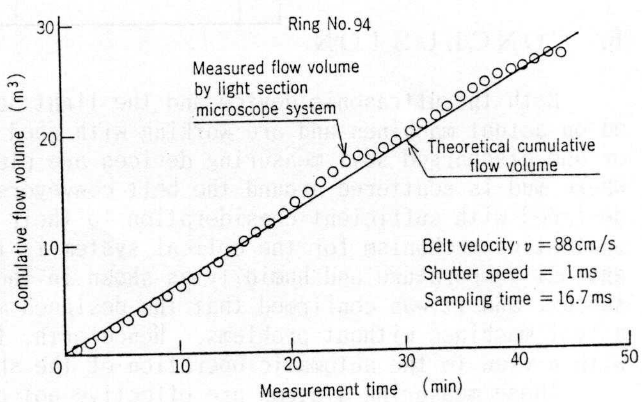


Fig. 11 Field test result of light section microscope system

5.3 Comparison of both systems

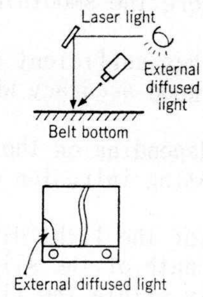
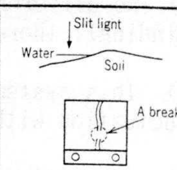
The advantages and disadvantages of two methods or the differences between them are summarized as follows.

(1) In comparison with the measuring device currently in use, it is possible to measure the discharged soil volume continuously, in real time and with high accuracy by using both newly developed systems.

(2) The light section microscope system is superior to the ultrasonic system in measurement accuracy. The smoothing device is not necessary for the light section microscope system.

(3) Table 3 shows some technical problems of each method for use in bad environmental conditions. The smoothing device and the sonic velocity correction by temperature for the ultrasonic system, and the countermeasures against external diffused light and surface water of discharged soil for the light section microscope system, are indispensable respectively.

Table 3 Technical problems and countermeasures for using in bad environmental condition

	ultrasonic system		light section microscope system	
Subject	Sonic velocity change by temperature	Capability of following up soil surface undulation	Countermeasures against external diffused light	Degradation in slit light image sensitivity by surface water
Theme	As the sonic velocity changes by temperature, the distance measured should be compensated.	The necessity for a soil surface smoothing device was studied as there were restrictions relating to the sampling time of the ultrasonic sensor and the number of sensors installable.		 Effects of a blur or a break of the light section image, if any, caused by the water film effect.
Results of studies	The sonic velocity changes at the rate of approximately 1.8% for an ambient temperature change of 10℃. The temperature will be measured by the temperature sensor (thermistor) and the distance (output) shall be compensated accordingly.	Data are to be obtained at intervals of 77mm of the soil on the belt conveyor, and there will be only one or at most a few sensors installed. Therefore, it was determined that a soil surface smoothing device should be installed.	(1) A simple shield mechanism is necessary to intercept the external diffused light. (2) Provided that the surrounding illuminance and the external diffused direct light were segregated from each other, the effect of the latter was determined to be stronger.	It is desirable not to evaluate "breaks" at the time of measuring the beam average height. ⇩ Only the height of the beam whose position can be effectively evaluated will be calculated. The actual effects shall be confirmed by experiments.

6. CONCLUSION

Both the ultrasonic device and the light section microscope device have already been mounted on actual machines and are working with good results. Generally, site conditions are inferior and discharged soil measuring devices are placed in high temperature and high humidity areas where mud is scattered around the belt conveyors. Therefore, in the field the systems must be designed with sufficient consideration to their maintenance needs, and especially the muck protection mechanism for the optical system is indispensable. Accordingly, tests were conducted against temperature and humidity as shown in the system specifications and against predictable shocks, and it was confirmed that the designed muck protection mechanism could be applied to actual machines without problems. Henceforth, the utilization of these systems will be studied with a view to the automatic operation of the shield machines.

These measuring systems are effective not only for soil flow volume measurement but also for volume measurement of granular material such as coal, and powders such as flour on beld conveyor systems.

REFERENCES

1) Tunnel Standard Specifications (Chapter of Shield), Japan Society of Civil Engineers, 1986

2) A. Hatakoshi et al. Measuring Device of Discharged Soil for Tunneling Machines, MHI Technical Review, (1988)