A Visualization Technology for shield Tunneling; An Example of the Application to a Monitoring System in Cutting Chamber

Hirokazu Sugiyama1, Takehiko Nakaya2, Atsushi Nakaya3, Toshiyuki Iwai4

1) Dr. Eng., Research Manager, Institute of Technology, Shimizu Corporation, Tokyo, Japan. Email: sugiyama.h@shimz.co.jp
2) Manager, Department of Civil Engineering, Shimizu Corporation, Tokyo, Japan. Email: t_nakaya@shimz.co.jp
3) Institute of Technology, Shimizu Corporation, Tokyo, Japan. Email: nakaya@shimz.co.jp
4) Institute of Technology, Shimizu Corporation, Tokyo, Japan. Email: kuwata@shimz.co.jp

Abstract:
A visualization technology can be a very powerful support for our operation during construction process. Particularly with an EPB shield, the technology for monitoring the cutting chamber condition is one of the hottest issues for concerned engineers because a cutting face, the most crucial part of the tunnel, is hidden behind a diaphragm and the condition of the excavated material ahead of the diaphragm is very important for stabilization of the cutting face. In addition, as an EPB type is more applied to tunnels at larger diameters in Japan, demands for the technology are becoming higher.

With such background, Shimizu Corp., is developing “the chamber visualization system.” The system evaluates the condition of excavated material in chamber, i.e. either “soft or hard”, based on the deviation of pressure gauge and then shows the evaluation results in a visual manner.

The system has already been applied to a few construction projects and followed by necessary improvement and advancement. The paper reports about the system during development stages and actual application stages. Particularly with EPB shields at larger diameters, studies were made on evaluation method of the conditions and suitable allocations of pressure gauges for the evaluation. Finally, a report is also included in the paper on an experiment with a 1/10 model which was carried out to verify the appropriateness of the evaluation.

Keywords: an EPB shield, a cutting chamber, a larger diameter shield.

1. INTRODUCTION
It is very important for an EPB (Earth Pressure Balanced) shield to maintain the excavated material in suitable condition within the cutting chamber. For stability of the tunnel face, excavated material has to be maintained in such a condition as moderately liquid-like and watertight as well. Traditionally the condition was monitored by visual observation or hand sensing of human. Recently, it is becoming more and more important to monitor the condition within the cutting chamber as dimensions of shield tunnels are becoming larger.

The authors have developed a monitoring system on the condition inside the chamber. The condition of the excavated material inside the cutting chamber can be guessed through the observation of earth pressure gauges attached at the chamber wall. The gauge fluctuates wider when the material is hard, while it does less when it is well liquidiy. The system evaluates the condition based on the gauges’ fluctuation, then show the results in a visual manner on a computer screen.

![Figure 1. Visualized image of Chamber Evaluation System](image-url)
Fig. 1 is images of system outputs. The one on the left is of a shield at 4.44m in diameter, while the other is of one at 10.83m dia. For the better sensing of the fluctuation by gauges, the influence by mixing blades attached on the cutting head is utilized for evaluation. Their influence to the excavated material inside the chamber as turning around with the cutting head causes such wider fluctuation that the system can evaluate the condition precisely. Number of gauges attached depends on the dimension of the shield, six with the smaller one and sixteen with the larger one. The influence of the mixing blades depends on such conditions as distance to the gauges, rotation speed and so on, but the conditions are not considered in the evaluation system of the two cases.

In the application to another tunnel with a larger shield of over fifteen meter in diameter, twenty-three nos. of pressure gauges are attached. As is seen in Fig. 2, the distance between blades and gauges varies, and the velocity of the blades passing above the gauges also varies depending on their locations. It is this time necessary to consider the variations into the evaluation as the dimension is so large.

In this paper, a report is made on the establishment of an evaluation technique on above mentioned conditions. During the process, a new evaluation technique was proposed through observations on soil mixing experiments, and a downscaled model was used to verify the proposed technique.

2. METHOD

2.1 Soil Mixing Experiment

(1) General Description

Figure 2. Details of cutting chamber with the shield of over 15 m dia.

Figure 3. Soil mixing experiment device
The soil mixing experiment was carried out to observe the different outcomes due to the aforementioned conditions. The mixing chamber is equipped with four pressure gauges, a mixing frame empowered by a motor.

(2) Experiment Conditions

The chamber was filled with materials in various conditions, as shown in Table.1, and mixing conditions are selected as in Table.2 so that the evaluation against the various conditions can be done properly. Thus, the total number of reproduced mixing conditions becomes 48 in one case.

<table>
<thead>
<tr>
<th>Mad sample</th>
<th>Additive rate</th>
<th>CASE #</th>
<th>Slump (cm)</th>
<th>Shear yield stress (Pa)</th>
<th>Plastic viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>10%</td>
<td>C10</td>
<td>7.5</td>
<td>1635</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>C15</td>
<td>8.0</td>
<td>1472</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>C20</td>
<td>10.0</td>
<td>1360</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>C25</td>
<td>12.5</td>
<td>1359</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>C30</td>
<td>12.5</td>
<td>1101</td>
<td>8</td>
</tr>
<tr>
<td>Sand</td>
<td>20%</td>
<td>S20</td>
<td>13.0</td>
<td>588</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>S25</td>
<td>16.0</td>
<td>344</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>30%</td>
<td>S30</td>
<td>19.0</td>
<td>308</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>35%</td>
<td>S35</td>
<td>20.5</td>
<td>237</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>S40</td>
<td>21.5</td>
<td>201</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. Mixing conditions in one case

<table>
<thead>
<tr>
<th>Radius at Gauge’s Position (cm)</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation (rpm)</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Distance between Mixing Blade and Pressure Gauge (cm)</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 A Downscaled Model Experiment

(1) General Description

A soil mixing experiment cannot reflect all the complicated mixing conditions of an actual shield tunneling. Observation on the experiment and the evaluation technique developed from the observation are not necessarily applicable to the actual monitoring. For the verification purpose, another experiment was carried out using a downscaled model of a shield machine chamber.

(2) Law of Similarity

In the model experiment, Reynolds’ number is applied to correspond to the law of similarity.

\[
Re = \frac{\rho ND^2}{\mu}
\]

where \( \rho \); density of liquid[kg/m3],
\( N \); rotation rate[1/s],
\( D \); diameter[m],
\( \mu \); viscosity coefficient[Pa·s]

(3) Method for Experiment

An image of the model is shown in Fig.4. Observation shall be made from the front side of the modeled shield machine.
The shear velocity is defined as $v/d$ where;

- $v$: the velocity of a mixing blade passing above a pressure gauge
- $d$: the distance between the mixing blade and the gauge

The model was set vertical during the experiment and the data of the pressure gauges was collected for ten minutes continuously for each condition cases.

![One-Tenth Downscaled Model](image)

**Figure 4. One-Tenth Downscaled Model**

(4) Experiment Cases

The model was not filled with soil but SAP, Super Absorbent Polymer, so that observation can be made very clearly throughout the chamber. The viscosity of the SAP can be controlled very easily by adjusting the volume of the additive agent. Table 3 shows the material conditions of tested cases. Viscosity of SAP is to be transcalculated to that of soil based on the law of similarity. For example, the viscosity of the examined material in the case # AQ0.2 is close to the material used in the case # C10 in the soil mixing experiment.

<table>
<thead>
<tr>
<th>Case #</th>
<th>Material composition</th>
<th>Viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAP (g)</td>
<td>Water (g)</td>
</tr>
<tr>
<td>AQ0.2</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>AQ0.4</td>
<td>4</td>
<td>1000</td>
</tr>
<tr>
<td>AQ0.6</td>
<td>6</td>
<td>1000</td>
</tr>
</tbody>
</table>

3. RESULTS

3.1 Soil Mixing Experiment

Fluctuation of gauge reading in the soil mixing experiment is shown in Fig.5. The shown graphs are of CASE C10 and CASE S40, the former is with relatively hard material and the latter with liquidly one. The gauge located at the closest position to the mixing blade is showing the widest fluctuation in its reading. In order to quantify the width of the fluctuation, a square average has been calculated with the data obtained from time sixty to time three hundreds, namely RMS value.
Fig. 5. Examples of pressure gauge readings

Fig. 6 shows the plots of the obtained data with the shear velocity at the lateral axis and the gauge fluctuation at the vertical axis. Accordingly, it is shown that the two factors have linear relationship to each other. Additionally, it is also shown that the RMS value gets higher as the viscosity coefficient becomes higher. Application of the relationship may enable the evaluation of excavated materials under different mixing conditions.

Fig. 6. Relationship between shear velocity and RMS value
3.2 Downscaled Model

The data obtained in the experiment of the one-tenth downscaled model is also shown in a same manner as is done in the previous section (Fig. 7). A similar relationship can be observed even though the data has been from a more complicated experiment device.

![Figure 7. Relationship between shear velocity and RMS value](image)

4. APPLICATION TO ACTUAL CASE

The proposed evaluation technique is now to be applied to the data obtained in the actual project, the tunnel of 10.83 m dia., as shown in Fig. 1.

4.1 Description of Application

The shield machine of the project was equipped with pressure gauges of twelve nos. on the outer side of its cutting face and four nos. on inner side. The shear velocities of the mixing blades become 4.7 at outer side and 0.16 at inner side respectively.

![Figure 8. Shield machine of 10.83 m dia.](image)
4.2 Data Processing and Analysis

The data of two pressure gauges, i.e. #EP-1 and #EP-15, out of sixteen nos. were processed chronologically and shown in Fig. 9. The first graphs of the two gauges show the raw data read at the time interval of 0.1 second. The second graphs are about data of averages in thirty seconds. The second one is granted as showing fluctuation influenced by such machine operation as selection of shield jacks or discharge of excavated material. The third ones show the gaps between the first and the second. Thus the exact fluctuation that is required for the analysis, i.e. the fluctuation merely by mixing blades, can be obtained. The forth ones show RMS values calculated from values in the third ones. The same processing was carried out with all the pressure gauges of sixteen nos.

Considering the RMS values of gauges represent the plasticity of the excavated material, their relationships with shear velocity are shown in Fig. 10. The plotted points are of data obtained at the time 1:33.

The field in the graph (Fig. 10) is divided into five regions, ranging from ‘excessively hard’ to ‘excessively soft’. The idea is partly from what was learnt in Fig.6 and Fig.7. Plotting the data obtained, the condition of the excavated material can be evaluated in accordance to the regions the plotted data belongs to. Visualization of the evaluation result by the technique has been further developed for the entire area of the cutting chamber. A comparison in visualized images can be made between the two different evaluations of a same data, one is done in previous evaluation method (Fig. 11) and the other is done in the newly proposed method (Fig. 10).

Figure 9. Chronological data processing samples during one ring advancing
5. CONCLUSIONS

The system has been tested and made necessary improvement through the trial application to actual tunnel constructions. In this paper particularly, development of evaluation technique under various mixing condition was focused and reported. The technique makes evaluation on the plasticity of a material based on the relationship between shear velocity and RMS value. The proposed evaluation includes the classification of the field in the graph. The classification criteria shall be determined in each tunnel project through the actual observation on the material at early stage of the tunneling.

ACKNOWLEDGMENTS

The authors are grateful for the provision of the opportunity for data collection on the project site owned by YOKOHAMA City and Kanagawa Construction Bureau of Metropolitan Expressway Company Limited, as the data significantly contributed to the development of the technique in application to shield tunnels in larger diameters.

REFERENCES