Development and Field Application of an Automated Pipe Jacking Friction Resistance Identification and Warning System in Construction

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Abstract: Minimizing frictional resistance is crucial for ensuring the safety and smooth progress of pipe jacking construction. However, due to the unpredictability of geological conditions, it is difficult to grasp the frictional resistance during construction, which poses challenges to safe and smooth construction. In order to reduce the frictional resistance during the process of pipe jacking, an automated pipe jacking friction resistance identification and warning system is thus innovatively proposed. This system uses jacking resistance sensors to identify resistance during the jacking process. When the jacking resistance exceeds a certain threshold, the system will send alerts, which could prompt construction workers to adjust the rheological slurry ratio according to the on-site soil conditions. This system includes the following major components: (1) an analysis of primary factors influencing pipe frictional resistance and a model for resistance calculation, (2) the examination of forces exerted on disturbed soil during pipe jacking construction to determine the optimal placement of resistance sensors, (3) the design and operational principles for an automated resistance identification and warning system, and (4) the application of a slurry shield construction method for resistance reduction. The research has practical significance in providing a reference for developing intelligent pipe jacking and contributing to the improvement in construction safety levels.

Keywords: slurry pipe jacking; construction; friction resistance; sensors; geology conditions; early warning; thixotropic mud

1. Introduction

With global urbanization, the adoption of pipe jacking technology has become widespread in the creation of diverse urban infrastructures [1–5]. Compared with the conventional open-cut method, pipe jacking, which requires a much smaller job site area, could avoid utility diversions, mitigate the risks of damaging existing infrastructure, and reduce traffic disruptions [2–4]. Yet, the jacking distance, to a great extent, restricts the application of pipe jacking because of friction resistance [1]. When the jacking distance is increased, the jacking force keeps rising, and when the friction resistance increases, more jacking force is also required. As a result, excessive jacking force might damage the pipe segments, reaction walls, and adjoining buildings [1–4]. In the field of engineering, friction resistance is commonly mitigated using two prevalent strategies: the strategic placement of intermediate jacking stations within pipe segments at regular intervals, and the injection of lubricants into the annular gap that exists between the pipe strings and the rock–soil mass [5,6]. Of these two methods, lubrication is preferred, since intermediate jacking stations are expensive, environmentally unfriendly, and cumbersome [5–8].

Thixotropic slurry, a lubricant traditionally based on bentonite, has earned extensive utilization owing to its outstanding efficacy, broad-spectrum suitability, and negligible
ecological impact [9]. Scholars and engineers have conducted extensive research on rheological mud [10]. In Ref. [11], in the field of civil engineering, various methodologies have been implemented for the measurement and modeling of thixotropy in fresh concrete. In Ref. [1], a laboratory test was set up to simulate pipe jacking to identify the effects of bentonite pressure on the lubrication, finding that the continuous injection of bentonite slurry can reduce the friction coefficient significantly [1]. In Ref. [12], the dynamics of coarse particle suspensions within a thixotropic cement paste were examined. In Ref. [13], the lubrication performance was evaluated via the reduction in the friction coefficient, and the impacts of the injection type, soil, and lubrication type were investigated on the lubrication performance in a pipe jacking project.

However, a change in mud performance alone cannot achieve effective resistance reduction. The contact between the pipe and soil and between the pipe and mud also yields large amounts of friction [14]. Scholars have conducted relevant research on the frictional force generated by contact pressure. In Ref. [15], Protodyakonov’s arch model, in its original form, was adapted to facilitate the computation of the vertical pressure exerted on deeply embedded pipes. In Ref. [16], the average friction coefficient (AFC) was obtained in the residual phase for the contact surface under seven contact conditions. In Ref. [4], the frictional mechanism of pipe–soil–slurry and the jacking force prediction of rectangular pipe jacking were studied. Moreover, the frictional properties of the outer pipe interface under various contact conditions were studied along with a direct shear test [8]. In Ref. [7], a novel approach was suggested for estimating friction resistance in the context of rectangular pipe jacking. An experiment on how the slurry concentration and standing time influence the friction characteristics was conducted [6], and it was found that both the contact pressure and pipe stress exhibit significant asymmetry during the jacking process; the magnitudes of contact pressure at the crown and the bottom exhibit relative proximity [17]. Comparisons of the calculation models have been made in terms of the pipe friction resistance and application conditions, resulting in a simplified calculation model to estimate the pipe friction resistance in the rock stratum [18]. In Ref. [19], the grouting pressure was analyzed in slurry pipe jacking in terms of the mechanical characteristics of the surrounding soil stability.

To date, numerous researchers have implemented studies using shear tests, numerical simulations, model box tests, field jacking force monitoring, and lubrication records [9]. Yet, research in regard to an automated identification system for pipe jacking grouting that is applicable to different formations is lacking. In Ref. [20], the future of intelligent tunnel construction technology was envisioned in China: on-site intelligent assembly combined with digital management will become the trend for intelligent tunnel construction. It has been found that human–machine collaboration is an important research trend for the interaction between humans and intelligent construction machinery [21]. Digital construction technology for urban underground spaces has been analyzed, and construction methods (auxiliary methods) with intelligent pre-control have been proposed for construction safety [22].

Although the aforementioned studies mentioned the application of intelligent technology to tunnel excavation, specific designs or research on intelligent technologies in pipe jacking are still lacking. This paper develops an automatic pipe jacking friction resistance identification and warning system for pipe jacking construction. In Section 2, we comprehensively analyze the influence of the pipe jacking–soil pressure–mud relationship on the friction force in concrete pipe jacking construction, describe friction resistance models, and provide the formula for friction resistance calculations. In Section 3, we describe the automated pipe jacking friction resistance identification and warning system along with identification sensors for pipe jacking construction. Furthermore, we explain the construction method in Section 4. Finally, we demonstrate the practical application of this system in pipe jacking construction using a specific engineering case.
2. Friction Resistance Analysis and Calculation

2.1. Resistance Analysis during Pipe Jacking Construction Based on a Literature Review

Through literature research, the frictional resistance of slurry pipe jacking was analyzed and summarized. Six main factors affecting the frictional resistance of pipe jacking were identified: lubrication, pipe–soil contact, soil type, design parameters, soil pressure, and the interaction between the pipe and slurry. For clarity, they are displayed as follows:

1. Lubrication: Lubrication is a key factor in reducing frictional resistance; therefore, lubrication has a significant impact on frictional resistance [1,23,24].
2. Pipe–soil contact: Pipe–soil contact increases frictional resistance, but the specific proportion depends on the degree and conditions of the pipe–soil contact [7,16,24,25].
3. Soil characteristics: The soil’s internal friction angle, cohesion, and void ratio affect frictional resistance, but the specific proportion depends on the soil’s characteristics and engineering conditions [2,3,15].
4. Design parameters: Design parameters, including burial depth, pipe diameter, and overcut, exert influence on the frictional resistance; however, the specific weight depends on the specific design conditions [3,24,26,27].
5. Mud pressure: Mud pressure affects the contact between the pipe and soil, thereby affecting frictional resistance [14,17,18,28].
6. Pipe–soil–slurry interaction: The interaction between the pipe, soil, and slurry affects friction resistance. The specific gravity depends on factors such as the pipe–soil contact angle and contact area [9,14,29,30].

The injection of bentonite significantly complicates the interaction between the pipe and the surrounding soil, thereby increasing the complexity of analyzing the frictional resistance during jacking. Therefore, detailed engineering analysis and calculations are required to determine the specific weight for each factor.

2.2. Models of Friction Resistance

Numerous studies have been conducted to investigate friction resistance. Some hypotheses have been proposed to establish prediction models. Three basic scenarios are set up, as follows:

Scenario 1: The angular space created resulting from overcut is entirely filled with lubricant slurry, and the excavated tunnel remains stable under the slurry pressure [23–26,31,32].

Scenario 2: The instability of the excavated tunnel induces the subsidence of the surrounding soil mass, resulting in its complete coverage over the surface area of the jacking pipes [25,29–32].

Scenario 3: The excavated tunnel retains its stability under slurry pressure, with only part of the pipe making contact with the surrounding soil [23–26,31,33].

In slurry pipe jacking, the ideal scenario is that there is no mutual infiltration, or termination of the mutual infiltration between the slurry and the pipeline is surrounded by a cavity formed by the slurry layer (see Figure 1a). However, pipe–soil contact could occur because of various factors, such as the design, amount of grouting slurry, jacking speed, pipeline deviating from the intended line and level, irregular surrounding soil deformation, and interpenetration between the soil and slurry. Hence, a more common occurrence is when the excavated bore is stable, and part of the pipe inevitably comes into contact with the soil (see Figure 1b).
Figure 1. (a) Full contact schematic diagram and (b) pipe–soil partial contact model in grouting.

The black arrows, in Figure 1, indicate the rough range and direction of the pressure of the surrounding soil on the pipe. And in Figure 1b, the black cross signs indicate the points of contact between the pipe and the soil. As shown in Figure 1b, in the case of grouting, some predictive friction resistance models are proposed. The Persson model, established by Ciavarella and Decuzzi, is suitable [18,31,33], as illustrated in Figure 2.

Figure 2. Persson contact plane strain model.

The dashed lines and the black arrows marked in Figure 2 indicate the axis of the two non-concentric circles. The blue arrows indicate the range and direction of the pressure of the soil on the pipe when the pipe is in contact with the soil.

The central force, denoted as \( P \), is primarily focused at the arc of contact between the pipe and the soil. As shown in Figure 1b, in the case of grouting, some predictive friction resistance models are proposed. The Persson model, established by Ciavarella and Decuzzi, is suitable [18,31,33], as illustrated in Figure 2.

![Persson contact plane strain model](image)

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of the two contact bodies, respectively, and parameter $b$ is related to the pipe–soil contact angle [18]. The computation of the associated parameters is delineated in Equation (3):

$$\begin{cases}
\alpha = (1 - \eta)/(1 + \eta) \\
\beta = \lambda/(1 + \eta) \\
\eta = E_p(1 - v^2_s)/(E_s(1 - v^2_p)) \\
\lambda = (1 - v_p/(1 - v_p)) - \eta(1 - v_s/(1 - v_s)) \\
\Delta R = R_s - R_p \\
e = \tan(\theta/2) \\
b = \tan(\varepsilon/2)
\end{cases}$$

(3)

where $v_s$ denotes the Poisson’s ratio pertinent to the soil, $E_p$ is the elastic modulus of the pipe (kPa), and $R_p$ is the radius of the pipe. $p(\theta)$ represents the contact pressure at location $\theta$. Equation (1) can be determined by applying numerical analysis techniques [18,30]. $P$, the contact pressure, can be obtained by taking it into Equation (2). In Ref. [32], it was assumed that the angle of contact ($2\varepsilon$) between the pipe and the soil can be approximated as a fixed value of 180 degrees, and the aggregate contact pressure is approximately 1.35 times the intrinsic weight of the pipeline.

It can be seen from Equations (1) and (2) that the pipe–soil contact characteristics mainly depend on the elastic modulus and Poisson’s ratio of the pipe and soil. Taking into account the contact pressures at the interfaces of the pipe–soil and pipe–slurry [32], the frictional resistance per unit length $f$ of the pipe can be calculated as follows:

$$f = k_c\mu_s + 2\varepsilon R_p C_s + 2(\pi - \varepsilon) R_p P_m u_m$$

(4)

where $k_c$ represents the amplification coefficient of the contact pressure, which arises due to the uneven distribution of said pressure [32], and $P$ represents the contact pressure exerted per linear meter between the pipe and soil [31,33], which is 1.35 times the dead weight of the pipe, so $k_c$ is 1.35. $\mu_s$ is the friction coefficient of the pipe–soil. $C_s$ is the pipe-soil cohesion. $P_m$ is the mud pressure. $u_m$ is the friction coefficient between the pipe and the mud. This seems to be an appropriate method for forecasting the frictional resistance of pipes within layers of soft soil. Then, the calculation formula shown in Equation (4) is used to calculate the friction resistance per meter, combining the friction resistance between the pipe and soil and the pipe and slurry [18,30].

3. Automated Pipe Jacking Friction Resistance Identification and Warning System

3.1. Resistance Sensor Distribution

Mechanical analysis was conducted on the soil disturbed during the construction of the jacking pipes, particularly focusing on areas where significant frictional resistance occurs between the jacking pipe and the surrounding soil during the jacking process. This ensures the effectiveness of the resistance sensor installation locations. The disturbance analysis of the soil during pipe jacking is shown in Figures 3 and 4.

![Figure 3](image-url)
The soil disturbed during pipe jacking construction can be divided into seven distinct disturbance zones, as shown in Figures 3 and 4. These are the compression disturbance zone, shear disturbance zone (front/back), unloading disturbance zone (top/bottom), grouting shear disturbance zone, and consolidation zone. During the jacking process, the frictional resistance between the pipe jacking shell and the surrounding soil generates a force that results in a shear disturbance zone in the soil surrounding the tunnel boring machine. This zone has a relatively smaller range than other zones [25,34,35]. When no grouting is applied, the soil in the grouting shear disturbance zone experiences shear friction resistance between the pipeline and surrounding soil, leading to a movement back and forth along the pipeline axis during the construction process [36]. After grouting, the slurry transforms the dry friction between the pipeline and soil into wet friction, thus reducing the frictional resistance and supporting the surrounding soil, and reducing the soil deformation caused by pipe jacking construction. Taking all of these factors into consideration, the installation positions of the sensors were determined, as shown in the sensor location diagrams in Figures 3 and 4.

3.2. Design of an Automated Pipe Jacking Friction Resistance Identification and Warning System

The automatic resistance identification and warning system, as depicted in Figure 5, comprises several key components.

The sensors, which are primarily employed to gauge the pressure during the pipe jacking construction process, form the first line of data collection. These raw data are then harvested by the data acquisition unit, which uses digital converters and microcontrollers to transform the sensor signals into a digital format.

The digitized data are subsequently transmitted to the monitoring and analysis system via the communication module, which employs various communication technologies. The monitoring and analysis system, equipped with specialized software, performs real-time monitoring and analysis of the collected data, processing and visualizing it for further use.

The warning system, a crucial component of the setup, sets thresholds based on the data from the construction site. It employs statistical analysis, machine learning, or artificial intelligence technology to identify any anomalies in resistance.

The user interface serves as a visual representation of real-time data, resistance identification situations, and warning information, presenting it to the operator in an easily interpretable format.
Resistance sensors are capable of the real-time monitoring of resistance during the jacking process. The collected resistance is then transmitted to the detection host through a resistance collector via a communication line. The detection host receives the resistance signal, stores it, and plots the complete resistance curve. The resistance display visually reflects the resistance distribution during pipe jacking. The shape of the resistance sensor and the architecture of the automatic resistance identification and warning system are shown in Figure 6.

![Diagram of the automatic resistance identification and warning system.](image)

**Figure 6.** Diagram of the automatic resistance identification and warning system.

The working principle for the resistance sensor is that the elastic component undergoes elastic deformation under external force, causing conversion elements, such as the resistance transducer attached to its surface, resulting in a change in the resistance value. This resistance change is then converted into an electrical signal through the corresponding measurement circuit, completing the process of converting the external force into an electrical signal. The jacking resistance during the construction process of pipe jacking is calculated according to resistance calculation Equation (4). The resistance sensors, developed by the Wauteco company, consist of soil pressure sensor modules that have undergone LGA packaging and assembly with the pressure modules. This design enables the sensors to provide calibrated output signals at a predetermined ratio. The resistance collector, also developed by the Wauteco company, then receives the signals from sensors.

The resistance data are transmitted in real time to the indoor monitoring terminal through a communication line. In the monitoring host, the resistance pre-alarm warning value is set through the warning system. Once the detected resistance exceeds the threshold, an automatic alarm is triggered to promptly notify the operators and maintenance personnel to analyze and understand the resistance status of the pipe jacking machine. This allows for timely maintenance and grouting adjustment. The control process is illustrated in Figure 7.
3.3. Construction Methods with a Resistance Identification and Warning System

The construction processes for the automated friction resistance identification and warning system and for pipe jacking are listed in steps, as follows:

1. The installation of resistance sensors on the outer wall of the jacking pipe according to the designated positions, and their connection, with data cables, power cables, a monitoring host, and their display.
2. Near the tunnel entrance, removal of the steel sheet piles when the jacking machine is 200 mm away from the tunnel entrance wall, and quick advance of the tunneling machine into the working face.
3. Completion of the following steps: installation of guide rails—installation of infrared alignment devices—installation of reinforced backrest—fixing of jack feet and installation of jacks—connection of hydraulic cylinders—hoisting of the tunneling machine as well as pipe sections—hoisting of the crown plate—pipe jacking and other related procedures.
4. Performance of actions to ensure pressure grouting and displacement of the variable slurry. Determination of the slurry ratio based on the initial plan and determination of the grouting pressure based on the depth of the pipeline and the groundwater level.
5. The total grouting volume should not be less than 2% of the volume of the annular space outside the pipe. To consider slurry losses, continuous grouting must be performed regularly to ensure the integrity of the slurry jacket.
6. Monitor the jacking process, including preliminary, jacking, and completion measurements. Measurements must be taken every 50 cm of jacking, with frequent adjustments. The correction angle should be kept within 10’ to 20’, not exceeding 1°. Measurements should be promptly recorded and submitted for review at the end of each pipe jacking section.
7. Identification and control of jacking resistance. Sensors in the jacking process automatically identify the jacking resistance. The pressure sensor automatically detects pressure during pipe jacking construction. According to formula (4), the frictional resistance during the jacking process is calculated, resulting in the actual resistance

![Diagram of the resistance threshold pre-alarm control process.](image-url)
value. When the resistance value exceeds the pre-alarm threshold, the system automatically triggers an alarm, reminding construction personnel to adjust the resistance by improving the variable slurry. At this point, soil condition analysis at the construction site is required to optimize the slurry ratio and modify it, accordingly, reducing frictional resistance to achieve smooth jacking.

4. Engineering Case
4.1. Project Background and Geological Conditions

The construction site of the third section of the Black and Odorous Water Body Comprehensive Treatment Project is situated within the Han River Economic Development Zone in Hubei Province, China. The project construction is segmented into different zones, and construction is conducted in the corresponding zones. The project duration is set at 180 calendar days. The project comprised sub-projects such as ground pipeline excavation, masonry valve chambers, and road restoration. The amount of work required for the project is immense, while the project duration is rather short, which makes top pipe construction challenging.

Furthermore, top pipe construction is divided into two sections: WX2–WX13 and WX23–WX24, with a total length of approximately 480 m. The overall project investment amounts to CNY 1,790,571.6. The WX2–WX13 section lays approximately 432 m of \( \varphi 1000 \) third-grade reinforced concrete socketed pipes, and the WX23–WX24 section lays approximately 48 m of \( \varphi 800 \) third-grade reinforced concrete socketed pipes. The terrain along the pipeline passage slopes mildly from northwest to southeast over a plain lake area characterized by low-lying topography and silty soil.

The soil parameters were determined through direct shear tests on soil samples obtained from the construction site. The strata of the WX2–WX13 section comprise clay, sandy soil, and silt soil, as depicted in Table 1 and Figure 8. Figure 8 shows the strata conditions, and the red line and arrow indicate the jacking direction.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Natural Unit Weight (Kn·m(^{-3}))</th>
<th>Cohesion (kPa)</th>
<th>Internal Friction Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>20.1</td>
<td>45.6</td>
<td>18.52</td>
</tr>
<tr>
<td>Sandy soil</td>
<td>19.3</td>
<td>4</td>
<td>17.15</td>
</tr>
<tr>
<td>Silty soil</td>
<td>19.4</td>
<td>21.1</td>
<td>18.32</td>
</tr>
</tbody>
</table>

The geological layers from top to bottom are as follows: clay (3.5 m thick), sandy soil (0.5 m thick), and silty soil (0.5 m thick). The pipe jacking passes through clay, sandy soil, and silt at elevations between \(-7.5\) and \(-11.5\) m.

![Figure 8. WX2–WX13 stratigraphic section.](image)

The unevenness and rheological thixotropy properties of the clay therefore make pipe jacking construction risky. The pipe might sink or deform because of the poor stability of
The main equipment for this construction method includes resistance sensors, resistance collectors, resistance displays, detection hosts, and a grout buffer tank. The specific models and specifications are presented in Table 2.

### Table 2. Key equipment and technical parameters table.

<table>
<thead>
<tr>
<th>No.</th>
<th>Quantity</th>
<th>Equipment Name</th>
<th>Model and Specifications</th>
<th>Construction Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>Resistance Sensor</td>
<td>High-strength steel</td>
<td>Pipe Jacking</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Resistance Collector</td>
<td></td>
<td>Pipe Jacking</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Grouting Pipe</td>
<td>Outlet diameter 50 mm</td>
<td>Grouting</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Grout Buffer Tank</td>
<td>50 L capacity</td>
<td>Grouting</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Resistance Display</td>
<td></td>
<td>Control Console</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Monitoring Host</td>
<td></td>
<td>Control Console</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Slurry Balance Pipe Jacking Machine</td>
<td>NPD1000</td>
<td>Pipe Jacking</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>Spiral Grouting Machine</td>
<td></td>
<td>Grouting</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>Wheeled Crane</td>
<td>25 T</td>
<td>Pipe Jacking</td>
</tr>
</tbody>
</table>

### 4.3. Calculation of Frictional Resistance and Grouting Adjustment

Based on the equipment, soil parameters (shown in Table 1) at the construction site, and pressure sensor data, the jacking construction resistance value \( f \) can be calculated using the calculation formula shown in Equation (4). Based on general experience from the construction site, the resistance warning value is initially set at 20 kN. The monitored resistance values during the construction process are shown in Figure 9.

As presented in Figure 9, the analysis of the resistance values reveals that the design and implementation of the automated pipe jacking friction resistance identification and warning system can effectively monitor resistance in real time during the jacking process.
The frictional resistance gradually increases from the starting point to a point 24 m away. The situation in which this resistance continuously increases at the beginning of the construction phase is consistent with reality. When the resistance value reaches the preset warning value of 20 kN, an alarm is triggered to indicate increased resistance. At this point, it is necessary to timely adjust field construction conditions, such as the rheological properties of the slurry mix. As seen from the graph above, after adjusting the rheological properties of the slurry, the resistance value during pipe jacking decreases continuously, effectively promoting long-distance jacking.

5. Conclusions

This paper introduces an innovative automatic resistance identification and warning system specifically designed for pipe jacking construction. First, an analysis of the resistance-impacting factors during the pipe jacking construction process was conducted, drawing upon a review of the existing literature. Considering the varied factors influencing pipe jacking resistance, it was suitable to choose the Persson calculation model based on Persson theory from several existing resistance calculation models. On the basis of the Persson model, the calculation formula for pipe jacking friction resistance was given. Second, an automatic resistance identification and warning system was proposed that encompasses several key aspects:

1. Sensor placement is strategically determined by analyzing the stress patterns in the soil surrounding the pipe jacking.
2. The foundational structure of the resistance identification and warning system is constructed.
3. The control process for the resistance warning is provided.
4. A construction approach during pipe jacking is presented, which integrates with the resistance identification and warning system.

Third, the resistance identification and warning system was tested through a practical application in the Hubei Han River Black and Odorous Water Body Comprehensive Treatment Project in China. It was found that at the beginning stage of pipe jacking construction, as the jacking distance increases, the jacking resistance continuously increases, which supports the findings of a study conducted by Ye et al. [23,24,30]. When the friction resistance value reaches the preset warning value, an alarm is triggered. After adjusting the proportion of thixotropic mud, the resistance value starts to decrease.

In summary, the development of an automated pipe jacking friction resistance identification and warning system can provide a reference for the development of intelligent pipe jacking and contribute to improving construction safety levels. Because the warning value is established from construction experience data, further research is needed to study the application of artificial intelligence algorithms, such as deep learning, for the identification and prediction of resistance thresholds.

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