Application of Underwater Robot in Safety Monitoring of Sluice Gates

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Abstract

This study focuses on a key hydraulic structure in China - the sluice gate - and explores the application of underwater robots equipped with optical imaging technology in safety monitoring. Given that the underwater structure of sluice gates is constantly exposed to water, making them susceptible to corrosion and erosion, the study underscores the necessity of regular safety inspections. The technology of underwater robots utilized in this research effectively addresses disturbances caused by water flow and conducts thorough analysis using high-definition video and image data. The findings reveal that this technology can accurately identify a range of structural defects such as sedimentation, concrete erosion, and cracks, even in low-visibility underwater environments. This discovery confirms the significant potential of underwater robots in enhancing the efficiency of safety monitoring for sluice gates. Overall, the study not only proves the practicality of underwater robots in inspecting the structure of sluice gates but also provides profound insights into the advancement of underwater detection technology and the maintenance and safety assessment of hydraulic facilities.

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1. Introduction

In China, sluice gates, as crucial hydraulic structures, are numerous and play a pivotal role. Statistics reveal that there are approximately 100,000 sluice gates in China, with control gates constituting 56.5% of them [1][2]. These control gates are essential for maintaining the safety of hydraulic projects, as well as protecting surrounding farmlands and residential areas. However, due to prolonged exposure to harsh underwater environments, these control gates' underwater structures are prone to soaking, corrosion, and erosion, thereby posing safety hazards. Consequently, regular safety inspections and assessments of these sluice gates are of utmost importance.

In recent years, with the rapid development of robotics and computer technology, significant advancements have been made in underwater robotic inspection techniques [3][4]. Research on underwater robots began internationally in the 1950s and was introduced to China in the late 1970s, where it has since rapidly evolved [5][6]. Currently, various types of underwater robots have been developed and are widely used in ocean exploration and inspection of underwater facilities [7][8]. Among these, underwater wall-climbing robots can perform structural inspections in complex underwater environments; robots equipped with high-definition underwater cameras are used for detecting cracks on the surfaces of bridge concrete structures; remotely operated vehicles (ROVs) have proven their worth in large hydropower dam inspections; and robots equipped with sediment removal and replacement modules have enhanced detection capabilities in murky water conditions [9][10].

In summary, although underwater robotic inspection technology is relatively mature, application research on the inspection of control gate underwater structures remains limited. This paper aims to explore the application of underwater robots based on optical imaging technology in the inspection of underwater sluice chambers and stilling basins of control gates. The research involves using underwater optical imaging technology for video inspection, recording and saving video image data, and conducting a detailed analysis of the inspection results to verify the feasibility of using underwater robots for inspecting control gate underwater structures.

1. Method and Experiment

1.1. Underwater Detection Based on Optical Imaging Technology

The core of this study is underwater detection based on optical imaging technology. This technology uses high-resolution optical images to capture details of underwater structures, thereby assessing their appearance quality and operational status [11][12]. Optical imaging technology relies on the reflective and absorptive properties of light, using changes in the intensity and wavelength of reflected light to reveal surface characteristics of objects. The reflected light intensity model can be represented as:

$$I = I_0 \cdot R \cdot cos(\theta)$$

where I is the intensity of reflected light, I_0 is the initial intensity of incident light, R is reflectivity, and θ is the angle between the incident light and the reflective surface. This method provides true color and texture information, which is crucial for accurately detecting the surface state of underwater structures [13][14].

Regarding equipment, this paper employs the Auto 200E ROV underwater robot system. This system is connected to the surface control center via a cable, enabling remote control and energy supply. Although the cable may be affected by factors such as water currents, the robot is equipped with eight thrusters arranged in a vector distribution, effectively overcoming these challenges and achieving precise multi-directional movement, providing a stable platform for optical imaging.

Fig.1. Auto 200E ROV Underwater Robotic System.

1.2. Experimental Design for Underwater Detection

This study employs underwater robots for optical imaging inspections of sluice chambers and stilling basins to assess their structural integrity. In the sluice chamber inspection, the underwater robot moves along a predetermined route and speed, systematically scanning the floor and piers. Detected defects are recorded through video shooting and screenshots. To ensure comprehensive coverage, the robot's trajectory lines are designed to be parallel to each other, ensuring a thorough inspection of every part of the sluice chamber (Fig 2).

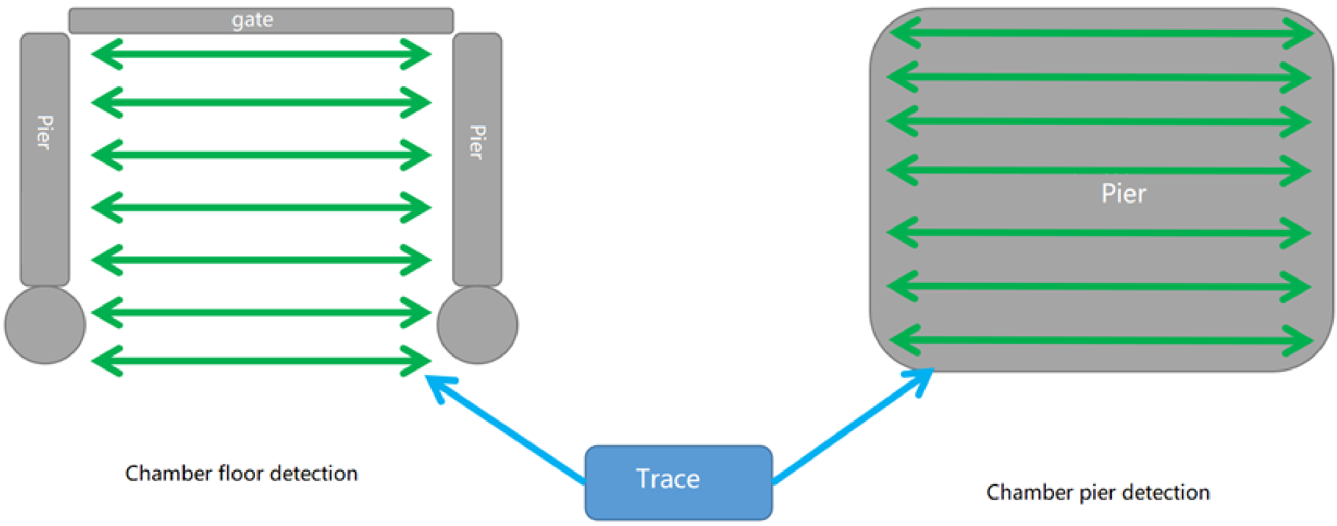


Fig.2. Schematic diagram of gate chamber inspection.

For the inspection of the stilling basin floor, considering its slope surface characteristics, the layout of the robot's trajectory is adjusted to accommodate different depths and slopes. Similarly, during the inspection, the robot records areas with defects while maintaining parallelism and spacing in its trajectory lines, ensuring a comprehensive inspection of the stilling basin floor (Fig 3).

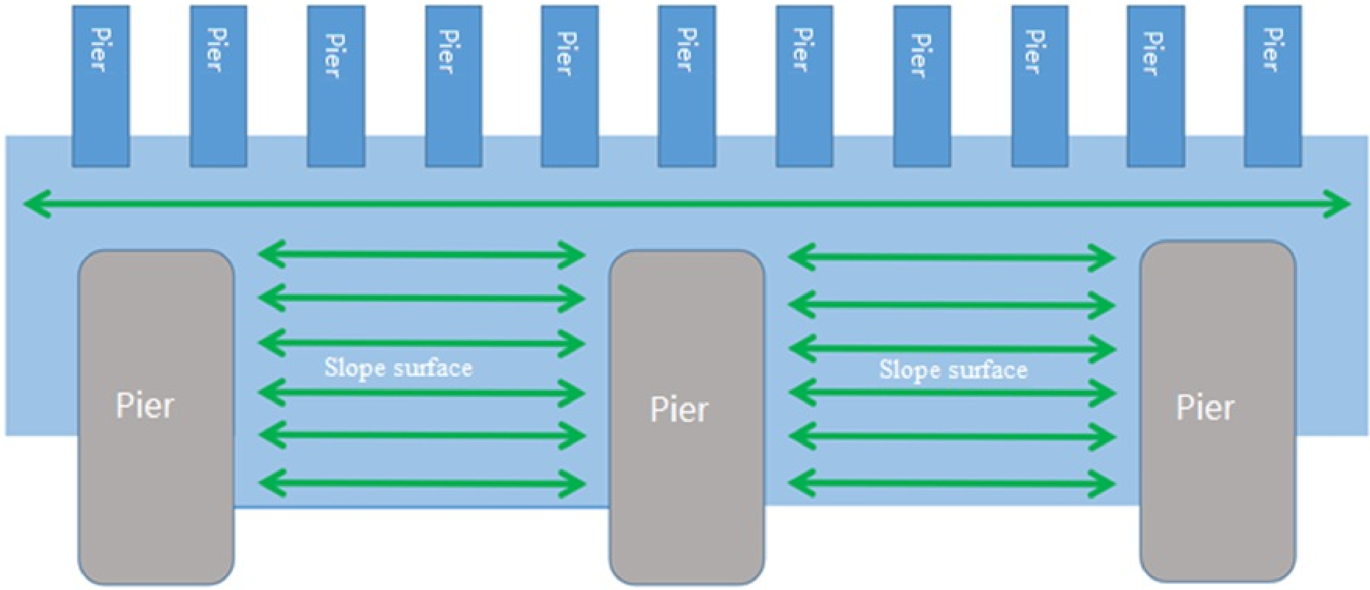


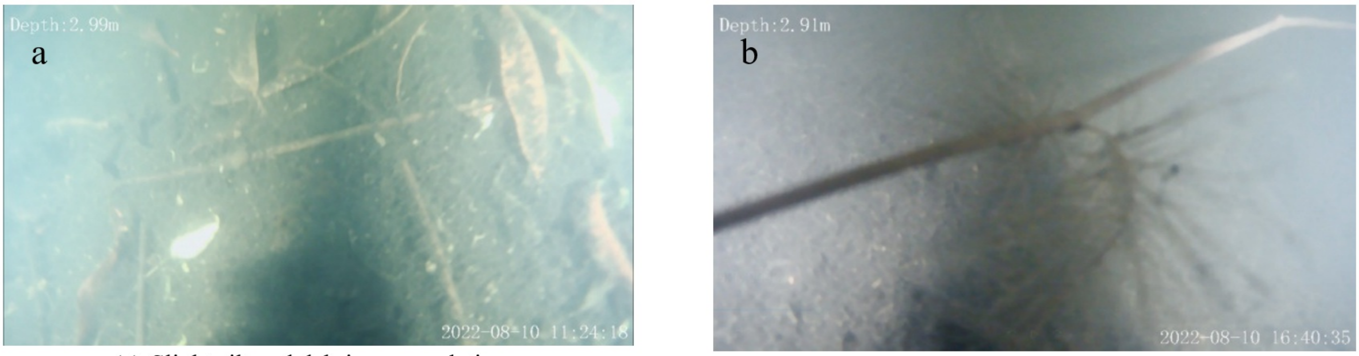
Fig.3. Schematic diagram of dissipative pool inspection.

The design of the above detection strategies aims to optimize the precision and efficiency of underwater structure inspection, while also ensuring the integrity and reliability of the data.

2. Results and Analysis

2.1. Sedimentation Level

After conducting optical imaging inspections of sluice chambers and stilling basins, varying degrees of sedimentation and debris deposition were observed on the floors of each sluice chamber. Fig. 4a shows minor sedimentation, visible with fragments such as leaves and twigs, but the floor remains fairly clear, indicating a thin layer of sediment and effective detection by the underwater robot. Fig. 4b, however, depicts severe sedimentation. The view becomes blurred due to a thicker layer of sediment, seemingly covering the entire floor surface. The dense pattern of cracks and mud indicates that the sediment layer might interact with structural defects or potentially conceal some.



(a) Slight silt and debris accumulation;

(b) Severe silt accumulation

Fig.4. Siltation detection images.

Comparing the two Fig 4.s, it's apparent that under severe sedimentation conditions, the imaging capability of the underwater robot is impacted due to reduced visibility. Despite this, it still provides crucial information about the extent and pattern of sedimentation, vital for maintenance and safety assessments. The detection effectiveness largely depends on the clarity of the water, available light, and the level of sedimentation.

2.2. Concrete Erosion

Underwater robot inspections revealed various degrees of erosion and spalling in the concrete structures of sluice chambers and stilling basins, as shown in Fig. 5 [15].

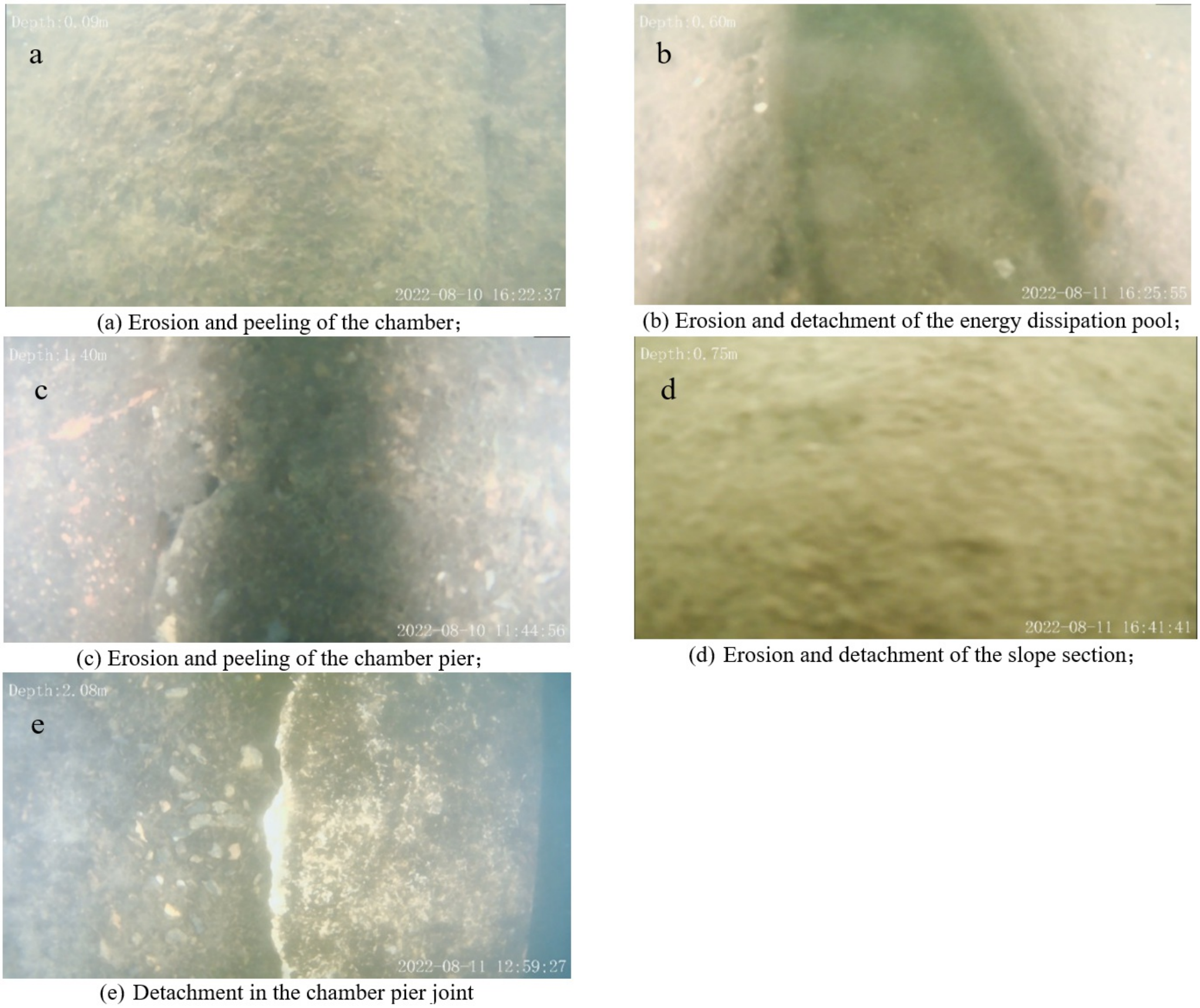


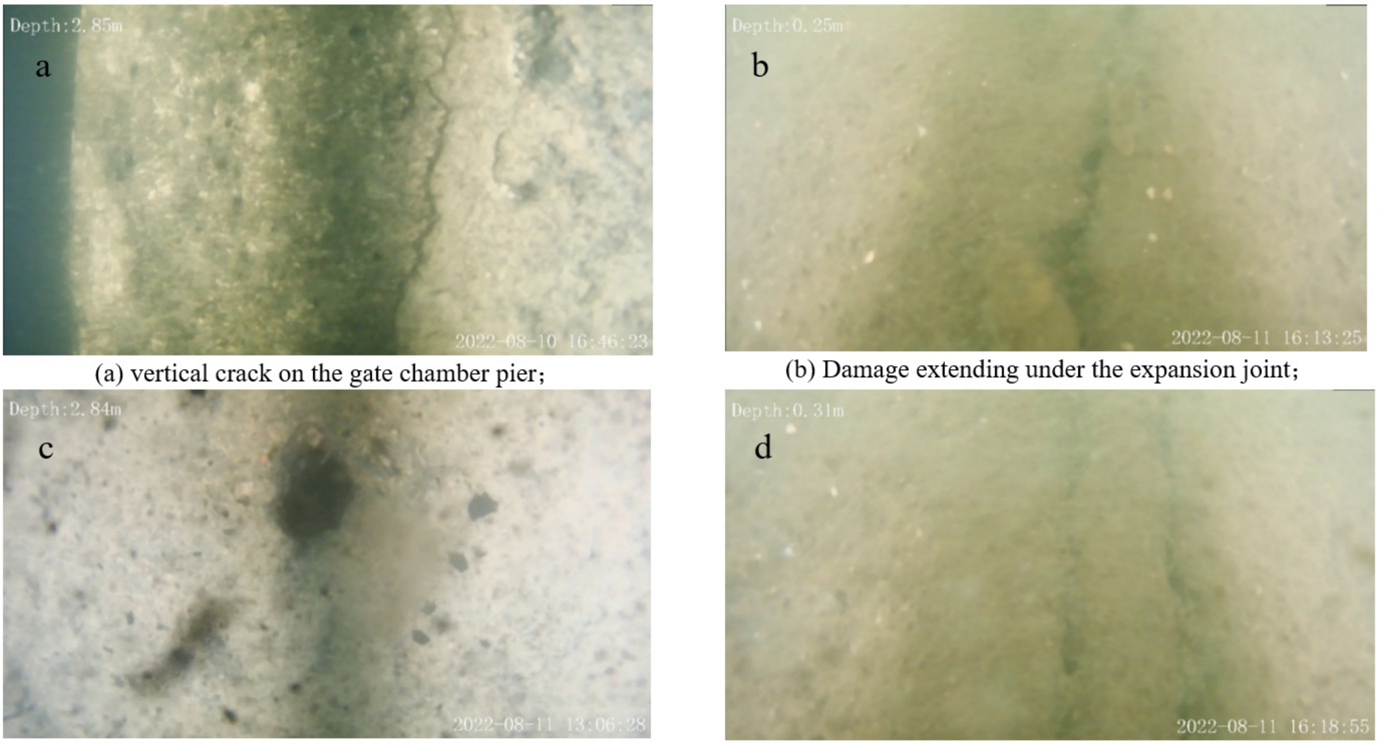
Fig.5. Concrete erosion detection images.

Fig. 5a displays erosion and spalling on the surface of sluice chamber piers, indicating long-term water flow effects on the concrete structure, leading to surface material loss. Fig. 5b portrays the erosion and detachment of the concrete layer on the floor of the stilling basin, showing relatively severe concrete damage, possibly due to the more direct impact of water flow on the basin floor. Fig.5c and 5d respectively show the scouring and spalling of the concrete layers on sluice chamber piers and the sloping section, with varying degrees of damage to the concrete surface observable. Fig. 5e, depicting the sluice chamber pier expansion joint filler detachment, indicates that even the structural joints are affected, with joint filler detachment posing long-term risks to structural integrity.

Overall, the effectiveness of underwater robot detection is influenced by underwater visibility and lighting conditions[16]. However, these Fig 5.s demonstrate that even under limited visibility, underwater robots can capture different degrees of concrete erosion damage.

2.3. Crack Defects

Utilizing underwater robots for detecting concrete crack defects, Fig. 6 showcases the effectiveness of this approach[17].



(a) vertical crack on the gate chamber pier;
(b) Damage extending under the expansion joint;
(c) Small hole on the gate chamber pier;
(d) Crack parallel to the expansion joint

Fig.6. Crack defect detection images

Fig. 6a reveals a vertical crack at the bottom of the upstream end of a sluice chamber pier. The crack edges are clearly visible, indicating the underwater robot's precision in capturing such defects. Fig. 6b shows damage beneath an expansion joint on a sloping section. Although the Fig. is somewhat blurred, the direction of the crack and damaged area is still discernible. Fig. 6c captures a small hole, approximately 25mm in diameter, on a sluice chamber pier. Despite its small size, the underwater robot is able to identify and clearly display the defect. Fig. 6d depicts a crack parallel to an expansion joint on the sloping section. This Fig. shows the linear nature of the crack, which, although thin, is still clearly visible on the concrete surface.

Overall, these Fig 6.s indicate that underwater robots are effective in identifying and recording different types of crack defects in concrete structures, even in underwater environments with limited visibility. These detection results are very useful for assessing structural integrity and formulating maintenance plans.

3. Discussion

This study demonstrates the application of underwater robots in the safety monitoring of underwater structures in control gates, particularly in detecting sedimentation, concrete structural damage, and crack defects. Even in low-visibility underwater environments, underwater robots accurately identify key structural issues, which is crucial for the early identification and prevention of potential safety hazards.

Due to the variability and complexity of underwater environments, research in this field continually points towards improving the adaptability of underwater robots and the precision of detection technologies [18]. The results indicate that regular monitoring can timely detect problems and initiate appropriate measures, effectively avoiding potential safety risks. Future research should further explore the autonomous navigation capabilities and environmental adaptability of underwater robots, and develop more advanced image processing and analysis algorithms to enhance the detection of subtle defects and extract more useful structural health information from the data.

Considering the specificity of underwater environments and the diverse requirements of technological development, future work should focus on interdisciplinary collaboration, combining knowledge from engineering, robotics, and data science, to further propel the development of underwater detection technology and improve the accurate assessment and maintenance of underwater structural safety.

4. Conclusion

This study thoroughly investigates the application of underwater robots equipped with optical imaging technology in the safety inspection of control gates. The research emphasizes the complex environment of underwater detection and the need for high-precision detection technology for diverse structures. Key findings highlight the effectiveness of these robotic systems in identifying potential safety risks, such as erosion and cracks. Through the analysis and research of control gate safety inspections, the following conclusions are drawn:

1. Underwater robots equipped with optical imaging capabilities successfully capture detailed images of underwater components of control gates, enabling comprehensive assessment of their condition.
2. The research reveals various degrees of damage in control gates, including erosion and cracks, highlighting potential safety hazards within these structures.
3. The study makes a significant contribution to the advancement of underwater detection technology, demonstrating the practicality and accuracy of robotic inspections in challenging environments.
4. The results provide key insights for the maintenance and safety assessment of hydraulic projects, emphasizing the importance of regular and thorough inspections.

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