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Research Article

Study of the Instantaneous Water Level Measurement Method on Unsteady Flow Based on Single Camera and Fixed Scale Compensation in the Tunnel Model

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The shape of instantaneous water surface profiles for the unsteady flow in the tunnel model can be determined by measuring the instantaneous water levels at multiple points synchronously. However, the measurement accuracy of the ultrasonic method is affected greatly because of the complex state of the water surface when water level changes rapidly. Using an optical method, multicamera synchronous measurement is difficult to control, and the cost is high. For single camera measurement, the reading of the steel ruler in the image cannot be clearly seen when the distance between the measuring point and single camera is far. When the distance is short, all steel rulers cannot be captured at the same time. Hence, in this paper, a single camera and fixed scale compensation method for instantaneous water level observation in unsteady flow is proposed. A series of fixed scales is placed with the same height and width near the water surface to be measured. In order to capture dynamic images of all fixed scales with a clear water surface, a single camera is set at a far position to continuously record the water level change process within the model range. According to the height of the fixed scale, the image accuracy is compensated and the effect of the wide-angle image distortion is automatically avoided. The water level elevation is obtained according to the relationship between the fixed scale and the water surface. In this paper, the unsteady flow model measuring test is applied to the Southern Main Tunnel and the Water Distribution Pool of the Huangchigou Water Diversion Project. The accuracy of this method in measuring the dynamic water level is 1–2 mm, which meets the accuracy requirement and greatly reduces the observation cost of the model test. The proposed method may also be suitable for measuring the instantaneous water level of the unsteady flow in other similar hydraulic model tests.

1. Introduction

The instantaneous water surface profile of unsteady flow reflects the water flow state and the water-passing capacity of the hydraulic structure, and it is an important basis for determining the structure size and the operation mode of the control gate. In the tunnel model test, the instantaneous water surface profile needs to determine multipoint simultaneous water levels. At present, the main methods for measuring unsteady flow surface profiles include the tracking water level meter method, ultrasonic method, and optical method.

Zhang and Cui [1] analyzed the structure and principle of the water level measuring instrument in the Yangtze River flood control model. In the water level instrument, resistance is used as an arm of the measuring bridge, but it could not get rid of the bridge output drift caused by the change in water temperature and water quality. Since the inertia in the rotating part of the instrument cannot be completely eliminated, it is still unable to track the situation where the water level changes rapidly. When multiple water level meters are adopted to work at the same time, it becomes difficult to realize synchronization, and the cost is very high.

Qu et al. [2] verified the reliability of the instrument by installing an ultrasonic water level gauge at the Zhuangzi station. After 4 months of comparative observation, the instrument can meet the requirement of water level observation, but temperature has a great influence on the sensor.

Khuntia et al. [3] studied turbulence characteristics in a rough open channel under unsteady flow conditions, and three-point gauges with a Vernier scale were fixed to measure the flow depth from different positions along the centerline of the flume. Hu et al. [4], Liu et al. [5], and Song and Graf [6] have carried out indoor experiments on unsteady flow wave propagation characteristics, sediment transport capacity, flow velocity, and vortex in channel models. The authors have used the ultrasonic water level meter to measure the water level, and the corresponding cost is high. Jalili Ghazizadeh et al. [7] studied characteristics of water surface profiles over rectangular side weirs for supercritical flows. Water surface profiles were measured at different sections in the longitudinal and transverse direction of the main channel next to the side weir using piezometers and a movable point gauge with 0.1 mm accuracy.

Optical measurement is a method to measure water level using a camera to capture the water gauge reading image. This method has the advantages of noncontact measurement, no temperature drift, traceable results, and low system cost.

Zhong [8] proposed a method using a camera to capture a video containing a water gauge and intercepted the water level image from the video in real time. After grayscale conversion, median filtering, and edge detection, the image containing the scale calibration is obtained. According to the water gauge readings identified, the water level is calculated in the subsequent process. The method for calculating the water level results, compared with the manually direct reading of the water gauge, has an accuracy of 0.6 cm. This method is suitable for remote measurement of water level in lakes, reservoirs, and culverts. Ruan et al. [9] proposed an observation method for measuring the tidal water level by working together with an artificial noncalibration water gauge and a ruler with a standard scale, which can measure the dynamic water level at a fixed point. In this method, the pixel height in the image is determined by using the ruler. The water level is obtained proportionally according to the distance from the baseline of the noncalibration water gauge to the water surface, that is, the number of pixels. The idea of this method is novel.

Aiming at the water level operation control mode of large-scale water transmission open channels, Cui et al. [10] studied the constant water level operation control mode in front of the gates on a large-scale water transmission open channel in the Trunk Canal at the middle route of the South-to-North Water Diversion Project in China. Fang et al. [11] studied the water level variation lawcaused by the flow changes at the water outlet in the main canal in the middle water transfer channel of the South-to-North Water Diversion Project. Li et al. [12] took a canal section in the middle water transfer channel of the South-to-North Water Diversion Project as a typical example and studied the hydraulic characteristics of the open channel water delivery system under the control of the gate. Litrico and Fromion [13], Bautista and Clemmens [14], and Clemmens et al. [15] used the method of feedforward control and storage compensation to simulate the operation scheduling of irrigation channels. In the above research studies, the numerical simulation method was adopted, and in contrast, the multipoint water level measurement for the unsteady flow in the open channel hydraulic model has an important reference value to test the rationality and objectivity of the unsteady flow water level simulation results.

Therefore, in this paper, considering the synchronous measurement and image resolution of multipoint water levels in unsteady flow instantaneous water levels, an observation method based on a single camera and fixed scale compensation is proposed. The method will be applied to the open channel water level measurement in the Southern Main Tunnel of the Hanjiang-to-Weihe Valley Water Diversion Project. The instantaneous water levels at multiple points of the Water Distribution Pool and the Southern Main Tunnel are measured when the inflow from the Qinling Tunnel is 0.0173 m^3/s, and the inlet gate of the Southern Main Tunnel is quickly opened or closed. Through the measurement and research, the instantaneous water surface profiles of unsteady flow are obtained in the Water Distribution Pool and the Southern Main Tunnel at any time. Moreover, the measurement accuracy and feasibility of the method are verified by comparing with the measurement results using a steel ruler with a single camera and close-up shot.

2. Engineering Background and Problems

2.1. Engineering Background. The Hanjiang-to-Weihe Valley Water Diversion Project is a water diversion project from the Yangtze River to the Yellow River drainage, which is a cross-basin water transfer project in Shaanxi province, China. It consists of two major parts: the water transfer project (the first stage) and the water transmission and distribution project (the second stage).

The Huangchigou Water Distribution Project, as the connection center of the water transfer project and the water transmission and distribution project, is a core water distribution structure. It plays a decisive role in the safe and rapid water distribution in the whole project.

According to the characteristics of linear distribution of water-receiving objects, two main water delivery routes are arranged. The Southern Main Route is an open channel flow tunnel. The section of the Southern Main Tunnel model has a horseshoe shape with a size 0.398 m × 0.239 m. How to measure the instantaneous water level in the model tunnel becomes a key issue.

Based on the hydraulic physical model of the Huangchigou Water Distribution Project, considering the sudden rise and fall of the inlet gate in the Southern Main Tunnel due to various operating conditions, it will cause a significant change in the water level at the Water Distribution Pool and the Southern Main Tunnel model. Therefore, it is necessary to conduct a real-time observation on the water level in the Water Distribution Pool and the Southern Main Tunnel model.

2.2. Problem of Measuring the Instantaneous Water Level at Multiple Points with a Single Camera. Figure 1 shows the original scheme for measuring the instantaneous water level of the Southern Main Tunnel model with a single camera.

In order to obtain the instantaneous water level of each measuring point at the Water Distribution Pool and the Southern Main Tunnel, a steel ruler was erected at the Water Distribution Pool, and several steel rulers were erected at multiple measurement points in the Southern Main Tunnel. Because the model of the Southern Main Tunnel is long (about 20 m), in order to display all measuring points in a single camera, it is necessary to ensure that the camera and the model have a sufficient distance. Under this condition, since the camera is too far from the water surface to be measured, the reading of each steel ruler in the image cannot be seen clearly, causing difficulty to implement this measurement scheme.

2.3. Principle of Measuring the Instantaneous Water Level Using the Single Camera and Fixed Scale Compensation Method. In order to overcome the problem that the single camera is too far from the point to be measured and the reading of each steel ruler in the image cannot be seen clearly, naturally, the multicamera and multipoint measurement method can be considered. That is, a camera is set up in front of each steel ruler. All frames of images are extracted from the video collected by using the camera and saved, and the instantaneous water level of each measuring point at the same time is obtained according to the extracted images. However, this method requires multiple cameras, and its synchronization is difficult to control with high cost.

To solve the problem, considering that the water surface profiles in the polymethyl methacrylate model is clearly visible within a certain distance, an instantaneous water level observation method for unsteady flow based on the single camera and fixed scale compensation is proposed. First, we erect multiple noncalibration fixed scales with the same height at each point to be measured. Second, the water surface profile is photographed. Third, the instantaneous water level is calculated according to the relative position relationship between the water surface profile and the bottom edge of the fixed scale in the intercepted image. The fixed scale plays a vital role in compensating image accuracy and automatically avoiding the effect caused by wide-angle image distortion.

3. Test Procedure

3.1. Installation of Fixed Scales and Camera Equipment. The specifications of the fixed scales are unified as a red polymethyl methacrylate plate with a height of 60.0 cm and a width of 5.0 cm. All scales are sequentially set at the measuring position with the numbers clearly visible in the image. The distance between adjacent fixed scales in the model is about 0.80 m.

We used Canon 5DIII professional digital camera + Canon 16–35 mm, f/2.8 lens as a single camera to conduct panoramic photography in the test process. Figure 2 shows the relationship between the single camera and the position of the fixed scale. The wide-angle mode camera can capture 2–14 fixed scales in the photo at a close distance, and the telephoto mode camera can capture 1–24 fixed scales in the photo at a long distance. The wide-angle mode measurement scheme is adopted in this study.

In order to check the measurement accuracy of this method, a steel ruler is set beside the No. 12 fixed scale, as shown in Figure 3. Another Canon EOS70D + EFS18-200 mm camera was set up to take a close-up photo of the water surface profile near the steel ruler, and the instantaneous water level measurement results of the two methods were compared.

3.2. Calibration of Relative Elevation at the Bottom of the Fixed Scale. When installing each fixed scale, we use the hanging hammer method to ensure the verticality of the fixed scale. Since relative elevation at the bottom of each scale is unknown, it needs to be calibrated. When the outlet gate of the Qinling Tunnel and the inlet gate of the Southern Main Tunnel of the model are fully opened, the water is in flow condition. Closed the outlet gates of the Qinling Tunnel andthe SouthernMain Tunnel of the model, the Water Distribution Pool and the Southern Main Tunnelmodel reaches static water condition. The needle is used to read the static water surface relative elevation in the Water Distribution Pool and the static water level is denoted as H0 . The single camera fixed scale measurement method was used to take photos of the fixed scales under the static water condition, as shown in Figure 4. The height $H_{\text{fixedscale}}$ of each fixed scale and the height $h_{\text{fixedscale}}$ between the water surface and the bottom of the fixed scale in the image were measured using CAD software. The actual distance H_{water} from the water surface to the bottom of the fixed scale can be calculated according to formula (1). The relative elevation of thebottom of each fixed scale can be obtained by H0-Hwater.

$$\frac{H_{fixed\,scale}}{H_{water}} = \frac{60}{h_{fixed\,scale}}. \tag{1}$$

The relative elevation of thesteel ruler bottom can be obtained by H0-Hruler.Hruler is the measuring depth fromwater surface to the steel ruler bottom, which can be obtained through reading the steel ruler scale. In this way, the instantaneous water level at the No. 12 fixed scale measuring point can be obtained by the single camera and fixed scale measurement method or can be read from the image captured using the camera at a close range with the steel ruler, so as to verify the accuracy of this method.

The calibration results of the bottom edge relative elevation of the fixed scale are shown in Table 1, in which the geometric scale of the model is 1 : 15. It should be noted that the relative elevation of the water level and the bottom edge

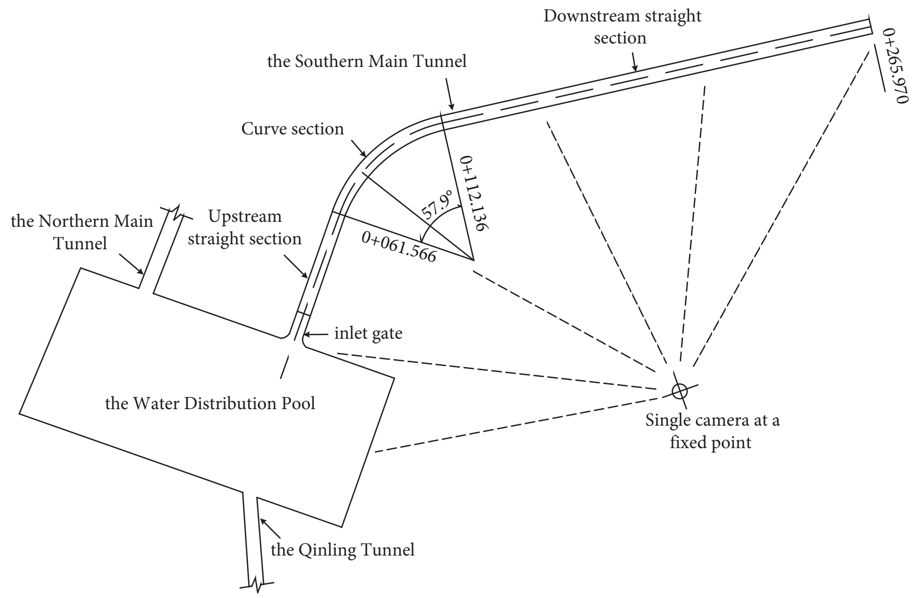


Figure 1: The original scheme for measuring the instantaneous water level by erecting steel rulers at multiple points using a single camera.

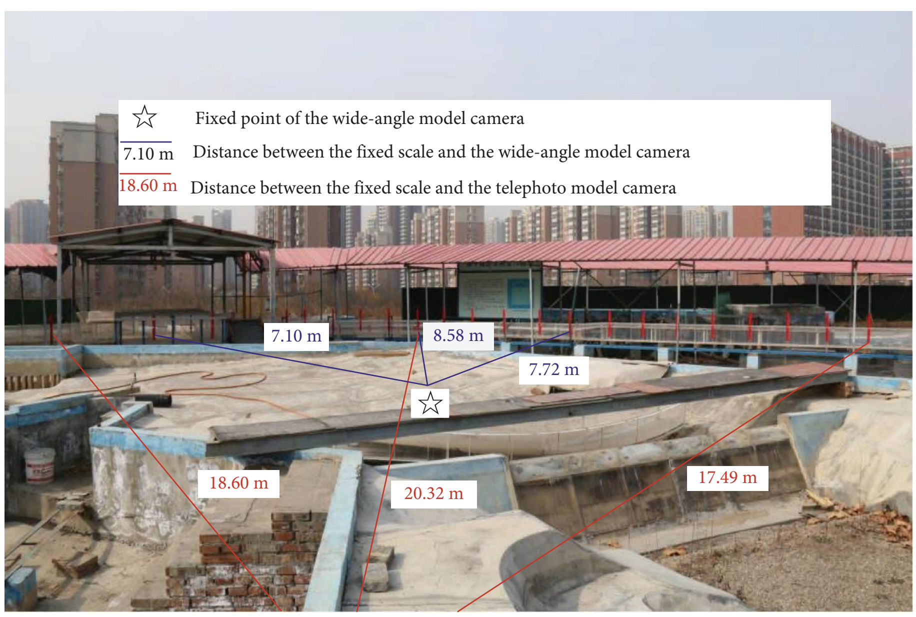


Figure 2: The position relationship between the single camera position and the fixed scale (two options).

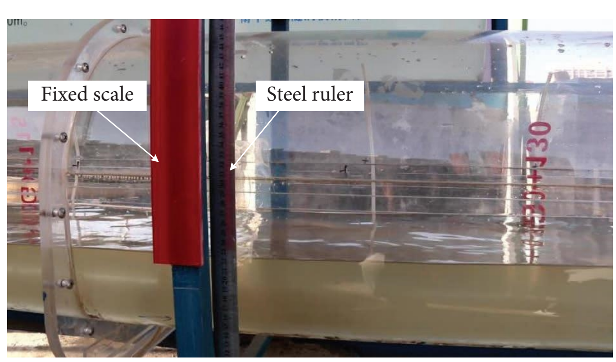


Figure 3: The position relationship between the No. 12 fixed scale and the steel ruler.

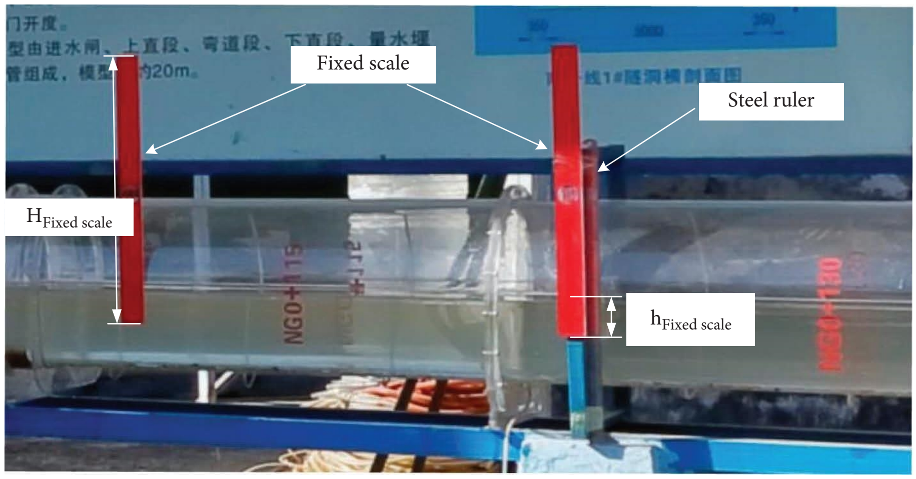


Figure 4: A schematic diagram of water level measurement.

Table 1: The position number of each fixed scale and the elevation of the bottom edge of the scale.

Fixed scale no.	Pile no.	Bottom edge elevation of the fixed scale (m)
3	NG0-012.300	661.266
4	NG0+027.175	661.228
5	NG0+035.275	661.235
6	NG0+046.459	661.180
7	NG0+059.101	661.339
8	NG0+071.519	661.391
9	NG0+084.461	661.333
10	NG0+098.038	661.259
11	NG0+109.948	661.283
12	NG0+123.718	661.318
13	NG0+137.743	661.451
14	NG0+149.623	661.383

of the fixed scale adopts the relative elevation of the prototype, and the other parameters adopt the model parameters in this paper. This makes it easy for the reader to understand design characteristic parameters of the prototype.

3.3. Measuring Process of the Instantaneous Water Level. When the inlet gate of the Southern Main Tunnel model is suddenly closed or opened, an unsteady flow process will occur in the Water Distribution Pool and the Southern Main Tunnel model. The instantaneous fluctuation of the water surface is large, and the influence range is wide. Therefore, the water surface change process can only be recorded by a video.

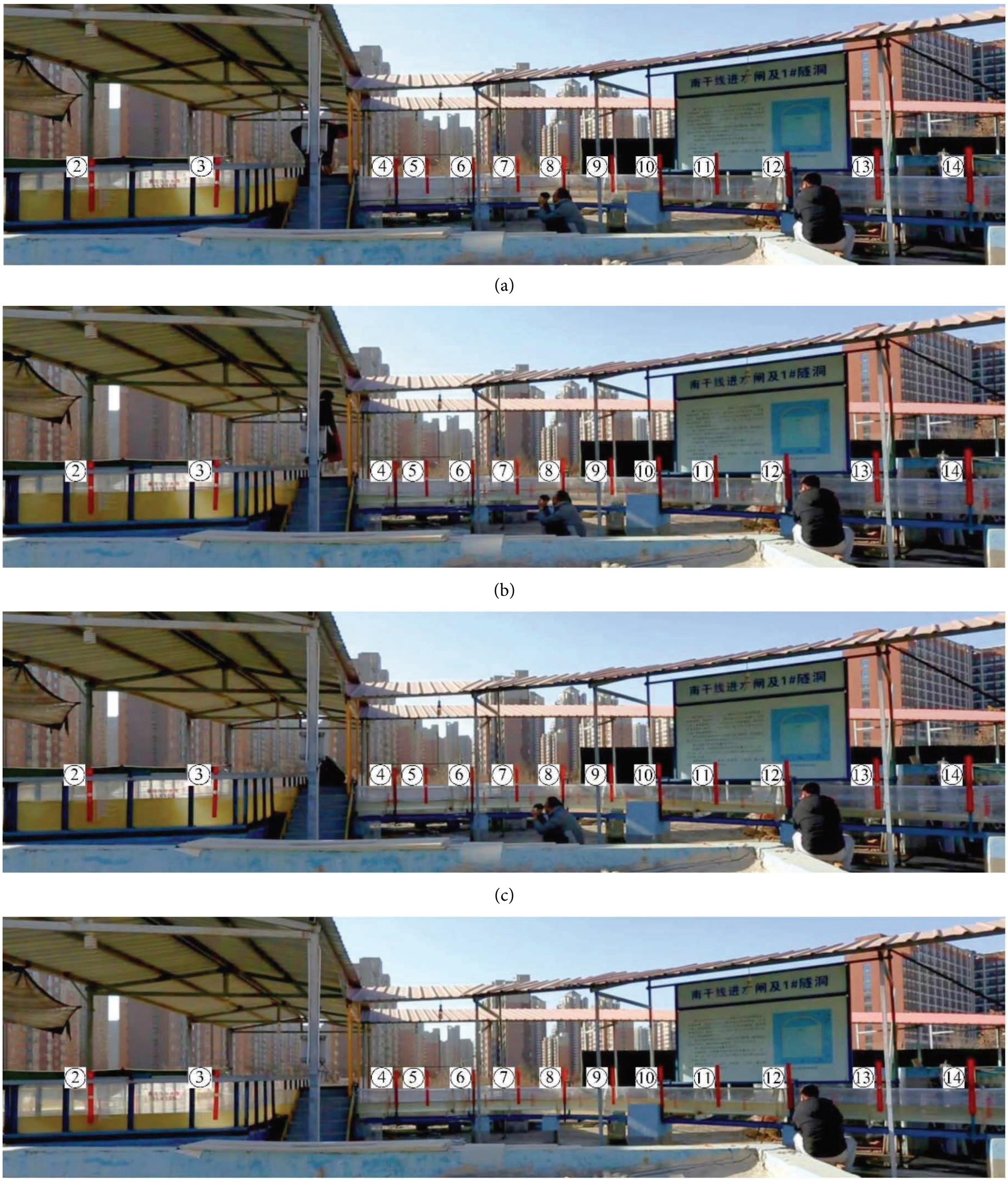
A series of pictures of the water level on fixed scales at multiple measuring points is intercepted from the video at an interval of 0.5 s. The height from the water surface of each measuring point to the bottom edge of the fixed scale at different times is read out in turn using CAD software, and the relative elevation of the water level at each measuring point is obtained by H0-Hwater. At the same time, the relative elevation points at the water level from the Water Distribution Pool to each measuring point in the Southern Main Tunnel model are connected in turn to form the instantaneous water surface profile at that time.

By repeating the above steps, the entire change process of the unsteady flow surface profiles can be obtained.

4. Application Research Measuring Instantaneous Water Levels of Unsteady Flow Using the Single Camera and Fixed Scale Compensation Method

4.1. Qualitative Analysis of the Instantaneous Water Level in the Water Distribution Pool and the Southern Main Tunnel Model. Considering Qinling Tunnel's model inflow of 0.0173 m^3/s, the inlet gate of the Southern Main Tunnel model is initially closed. The gate is suddenly opened when the water level of the Water Distribution Pool rises to 664.88 m, and the change process at the instantaneous water level in the Water Distribution Pool and the Southern Main Tunnel model is analyzed. Typical instantaneous water surface photos taken from the video using a wide-angle camera are shown in Figure 5.

Figure 5(a) shows a picture of the water flow state of the Water Distribution Pool and the Southern Main Tunnel model at 2.0 s before opening the inlet gate. The water surface of the Water Distribution Pool is calm at a water level of 664.88 m. Figure 5(b) shows a panoramic view at 1.0 s after opening the inlet gate of the Southern Main Tunnel



(a) (b) (c) (d)

Figure 5: A panoramic view of the instantaneous water surface in the Water Distribution Pool and the Southern Main Tunnel model (a) A panoramic view at 2.0 s before opening the gate. (b) A panoramic view at 1.0 s after opening the gate. (c) A panoramic view at 3.0 s after opening the gate. (d) A panoramic view at 204.0 s after opening the gate.

model suddenly. The water surface of the Water Distribution Pool close to the inlet gate drops obviously, and the water surface fluctuates obviously. There is an open channel flow behind the gate of the Southern Main Tunnel model, which fluctuates greatly, and the front peak of the water wave reached the No. 8. fixed scale. Figure 5(c) shows a panorama view at 3.0 s after opening the inlet gate. The water level of the Water Distribution Pool fluctuates obviously. The water level close to the inlet gate has a greater decrease and greater fluctuation. The water coming reaches the No. 11~12 fixed scale in the Southern Main Tunnel model. The water level close to the wave forehead gets lower and lower. Figure 5(d) shows a panoramic view at 204.0 s after opening the inlet gate. The water level of the distribution hub has a greater decrease, and the Southern Main Tunnel model has the same level as the Water Distribution Pool, while water reaches a constant flow state.

4.2. Quantitative Analysis of the Instantaneous Water Level in the Water Distribution Pool and the Southern Main Tunnel Model. Using the single camera and fixed scale compensation method to measure the instantaneous water level at different positions in the model, the water levels in the Water Distribution Pool and the Southern Main Tunnel model were obtained. The instantaneous water levels are sorted out at No. 3, 7, 8, 10, and 14, respectively, as shown in Figure 6. It can be seen that the water level of the Water Distribution Pool continued to decrease, and the water level of each measuring point in the Southern Main Tunnel model increased sequentially from upstream to downstream and gradually stabilized after 9.5 s.

The instantaneous water surface profiles at different times are shown in Figure 7. It can be seen that the water level at the Water Distribution Pool is 664.88 m before opening the inlet gate and that there is no water in the Southern Main Tunnel model. At 0.5 s after opening the inlet gate, the front peak of the water wave in the Southern Main Tunnel model reaches the No. 6 scale, and the water level difference between upstream and downstream is very large. At 1.5 s after opening the inlet gate, the water front reaches the No. 11 scale, and the water level changes relatively little between the 4th and 8th scales, while the water level drops rapidly in downstream. At 3.5 s after opening the inlet gate, the water flow reaches the No. 14 scale. At 9.5 s after opening the inlet gate, the water level in the Southern Main Tunnel model is close to the highest.

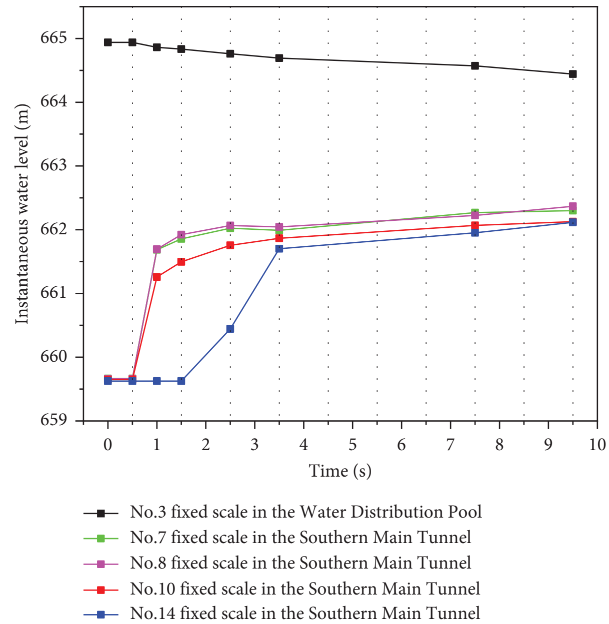


Figure 6: Instantaneous water level at each measuring point.

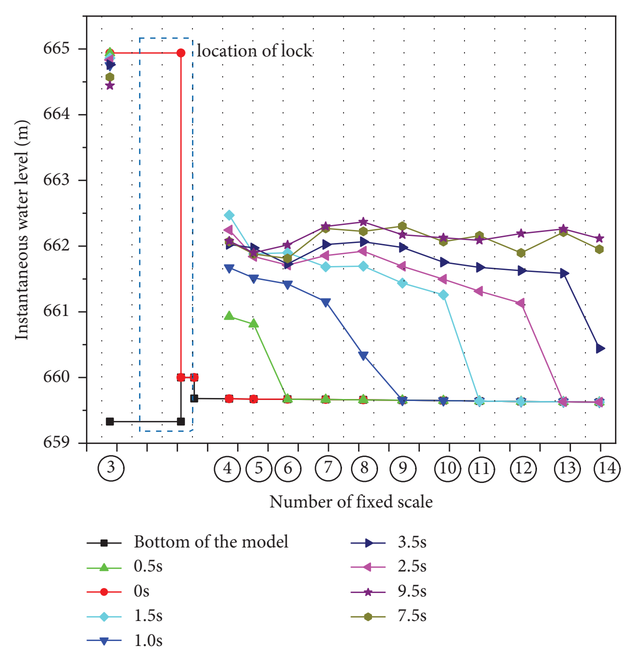


Figure 7: Instantaneous water surface profiles at different times.

4.3. Image Distortion Analysis. In the panoramic image obtained using the wide-angle camera, the measured height of each fixed scale is shown in Figure 8. It can be seen that the fixed scales with the same height obviously have different heights in the panoramic image due to the influence of the camera view field. The ratio of the maximum height to the minimum height is 1.599. The panoramic image distortion shows that the middle fixed scale is smaller and that at two sides is larger. Consequently, the height measured directly in the image needs to be corrected, and setting a fixed scale can avoid this distortion influence, which reflects the superiority of the method in this paper.

5. Accuracy Analysis of the Instantaneous Water Level by the Single Camera and Fixed Scale Compensation Method

The instantaneous water level at the No. 12 fixed scale measuring point can be obtained by the single camera and fixed scale measurement method, or it can be read from the image taken by using the camera at a close distance with a steel ruler. The specific results are shown in Figure 9. It can be seen that the instantaneous water levels obtained by the two measurement methods are in good agreement. At 8.0 s, 10.0 s, 16.0 s, 29.0 s, and 41.0 s, the water surface fluctuates obviously. The biggest difference between the results by the two methods is 0.7 cm in the model. The reason is that the position at the instantaneous water level read by using the steel ruler is slightly different from that at the No. 12 fixed scale. When water flow is unstable and the liquid level fluctuates greatly, the instantaneous water levels have a large difference. When water flow tends to be stable, that is, at 310.0 s, 320.0 s, and 328.0 s, it can be seen that the water level difference measured by the two methods is 1~2 mm in the model.

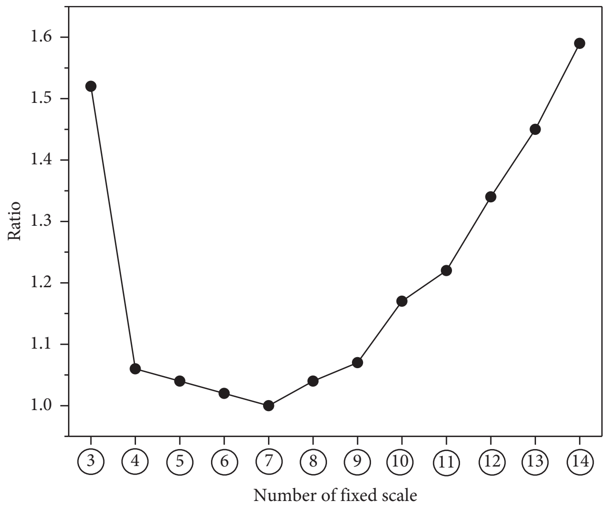


FIGURE 8: The ratio of each fixed scale height to the minimum height of the fixed scale in the image.

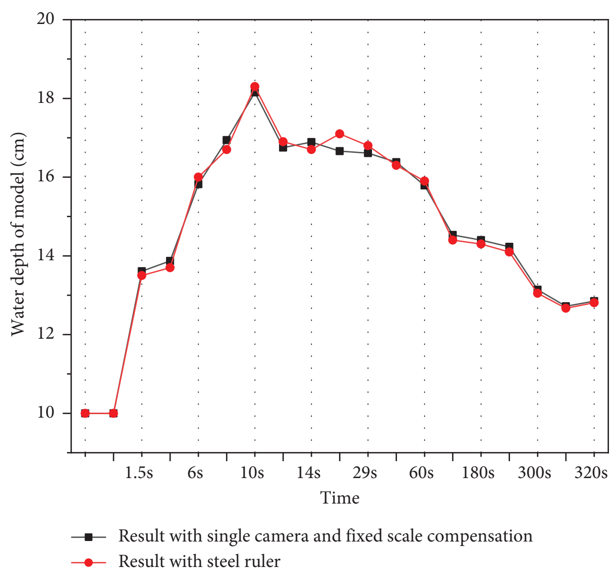


FIGURE 9: The instantaneous water depth at the unsteady water level at the same position by two measuring methods.

From the above analysis results, the single camera and fixed scale compensation method proposed in this paper can be implemented to measure the instantaneous water level accurately and meet measuring accuracy requirements of the hydraulic tunnel model.

6. Mechanism Analysis of Instantaneous Water Level Measurement by the Single Camera and Fixed Scale Compensation Method

Since a panoramic image needs to be obtained including all the fixed scales at the measuring points and the camera is far from the water surface to be measured, the readings of all fixed scales in the image cannot be seen clearly. Therefore, it is not feasible to obtain the instantaneous water level by shooting all fixed scales using a camera.

The core of the proposed method in this paper is to make the fixed scale very high so that the image including all the fixed scales at the measuring points captured by using the wide-angle camera is clearly visible. The image height of the fixed scale can be accurately measured in the image, and the water surface level can be read and corrected. Image distortion effects can be avoided by erecting a huge fixed scale at each measuring point. The fixed scale can be subdivided in the image, and the precise water level can be read.

This method compensates the measurement resolution, and the idea of this paper is innovative. To the best of our knowledge, it has not been reported in all previous hydraulic model tests.

7. Conclusion

Aiming at the simultaneous water level measurement and image resolution at multipoint water levels in unsteady flow, a single camera and fixed scale compensation method is proposed. This method is applied to the open channel flow model test in the Water Distribution Pool and the Southern Main Tunnel of the Huangchigou Water Distribution Project, and the instantaneous water surface profile of unsteady flow at any time is obtained. The measurement accuracy of the method in this paper is verified. The specific conclusions are as follows:

(1) The principle and implementation process of the single camera and fixed scale compensation method to measure the instantaneous water level are proposed. This approach solves synchronization problems at multipoint measuring. The installation of a patternless fixed scale is equivalent to setting a magnification in the image. A clearly visible scale acts as a ruler, which objectively compensates or improves the image resolution. At the same time, it can avoid the geometric distortion influence caused by using the wide-angle camera in the captured image.

(2) When the results of measuringinstantaneous water level at the same point are compared with those of directreading steel ruler, the single camera and fixed scale compensation method has very high measurement accuracy. The 1~2 mm measuring accuracy meets the requirements of the instantaneous water level measurement in the unsteady flow model test.

(3) The method proposed in this paper was applied to the hydraulic model test in the Water Distribution Pool and the Southern Main Tunnel of the Huangchigou Water Distribution Project. The multipoint instantaneous water level research in the tunnel model was carried out, and the variation law of the instantaneous water level was analyzed. The quantitative water level measuring results are consistent with the macroscopic observation and water level analysis of unsteady flow, indicating that the method proposed in this paper is feasible for the unsteady flow tunnel model test.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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