The Application of 3D Laser Scanning and Unmanned Ship Sounding in the Reexamination of Reservoir Storage Capacity

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Abstract. In order to accurately measure the reservoir capacity after siltation, this paper uses the ground 3D laser scanning system to obtain the topography above the water surface and the unmanned ship sounding system to obtain the topography below the water surface. Then carry out the accurate review of the reservoir capacity through the combination model of water and underwater. The blind area of measurement is caused by the change of water level and detection conditions, which leads to measurement error. Combined with the measured data of surface and underwater topography, the complete reservoir water level-area curve is obtained by water level-area fitting and contour interpolation fitting respectively, the error caused by blind area is minimized, and finally the reservoir capacity review is carried out according to the contour volume method. Practice has proved that the use of contour interpolation fitting method can greatly improve the credibility of the reservoir capacity review results, provide accurate and reliable basic data for reservoir management units, and provide support for reservoir flood control and operation.

Keywords. 3D laser scanning, unmanned ship sounding, reservoir level-area curve, storage capacity review.

1. Introduction

The storage capacity of the reservoir determines the ability of the reservoir to regulate runoff and produce socio-economic effects [1-4]. It is necessary to accurately calculate the reservoir capacity on a regular basis. The main factors affecting the accuracy of reservoir capacity calculation are the calculation method of reservoir capacity and the topographic data of the reservoir area [5-6]. The traditional storage capacity calculation methods include section method, square grid method and triangular grid method. This calculation of storage capacity adopts the contour volume method, which is one of the methods with higher calculation accuracy [7], mainly by pressing the water Different elevation surfaces are differentiated into n-layer trapezoids, and the overall storage capacity is obtained by integrating the n-layer trapezoidal volume. The topographic data of the reservoir area mainly includes water topographic data and underwater topographic data [8]. Traditional topographic surveys on the water are mainly obtained through manual measurements with total stations [9], and underwater topographic surveys are mainly obtained through underwater topographic surveys, such as plumb bob method, probe rod method, etc [6]. The workload is large and the efficiency is low. At the same time, it is easy to cause deviations between the estimated reservoir water level area curve and the actual one.

With the introduction and development of emerging measurement technologies, unmanned ships have the characteristics of small size, good maneuverability, and convenient remote control, which can efficiently and conveniently complete underwater terrain measurement [10-11]. 3D laser scanning
technology uses the acquired spatial point cloud data to quickly establish a complex and irregular three-dimensional model. It has the characteristics of high precision, full digitization, and flexible measurement methods. It can quickly and accurately complete accurate measurements of water terrain [12-15]. This paper takes a reservoir in the west as an example, uses 3D laser scanning technology and unmanned ship sounding system to obtain accurate topographic data of the reservoir, and finally realizes the reservoir capacity review.

2. Instruments and Equipment

2.1. 3D Laser Scanning System
The ground topography measurement uses the Austrian RIEGLVZ-1000 3D laser scanner. As shown in figure 1, the 3D laser imaging system uses full waveform echo technology and real-time full waveform digital processing and analysis technology, which can emit up to 300,000 points per second. The laser beam provides an angular resolution of up to 0.0005°, an effective scanning range of 1000 meters, and a linear error ≤ 1 mm.

![3D Laser scanner and unmanned survey ship](image)

**Figure 1.** 3D Laser scanner and unmanned survey ship.

2.2. Unmanned Ship Depth Sounding System
This underwater topographic survey uses Huawei No. 5 unmanned ship, equipped with a split D230 depth sounder, which can be remotely controlled on the shore, and the software and hardware are separated. It has high measurement accuracy, strong anti-interference, reliable stability and good compatibility and so on.

3. Storage Capacity Measurement
The designed total storage capacity of a large-scale reservoir in the west is 1.55×10⁸ m³, the elevation of the dam site area is 4200~4300 m, the control basin area is 2757 km², the installed capacity of hydropower plant is 20MW, and the annual average power generation is 0.61×10⁸ kW·h. The reservoir is used for irrigation and power generation. Mainly, it has comprehensive benefits such as flood control and tourism. The reservoir was closed for water storage on October 23, 1999. It was completed and put into operation in August 2001. In the past 20 years of operation, there has been no sedimentation and discharge. Due to the high content of cement and sand in the upstream of the reservoir area, in recent years when operating at low water level, it was found that the siltation of the tail of the reservoir was obvious. In order to understand the current capacity of the reservoir, prolong the service life of the reservoir project, and ensure the benefits of normal operation of the reservoir, it is necessary to carry out analysis of reservoir siltation and storage capacity review.

3.1. Water Topography Survey

3.1.1. Field Scanning. The reservoir area of the reservoir is about 2757 km², and the water topography is complicated. If the distance between the measuring stations is too large, it will affect the topography measurement accuracy. Therefore, the measurement accuracy of the water topography is improved by increasing the number of measuring stations. The distance between the stations is 200 m. In order to
ensure that the laser scanning range completely covers the reservoir area, a total of 157 measuring stations were deployed this time. The detailed layout is shown in figure 2.

![Figure 2](image)

**Figure 2.** General layout of water area surveying stations.

3.1.2. **Data Processing.** Import the scanned data and control point data into the point cloud processing software. The point cloud data is preprocessed first. The purpose is to remove irrelevant point cloud and noise interference, while reducing the amount of data to improve the efficiency of data processing. The data is internally spliced to form a 3D point cloud map of the water terrain. The three-dimensional point cloud map of the reservoir area after the splicing is completed is shown in figure 3. Then, a 3D grid model of the water terrain is constructed based on the point cloud map.

![Figure 3](image)

**Figure 3.** 3D point cloud-general map of the reservoir.

3.2. **Underwater Topographic Survey**

3.2.1. **Layout of Control Points in The Survey Area.** As the water surface of the reservoir area is distributed in strips, taking into account the control distance limit of unmanned ships, the reservoir area is divided into 7 areas according to the site conditions, and the area division is shown in figure 4. According to the division of the area and the site conditions, the measurement control point at the right dam head of the dam crest is selected as the reference point of the underwater survey in the reservoir area. The underwater measurement control network is arranged according to the reference point of the right dam head, and a total of 6 measurement control points are arranged according to the actual situation of the site (see the position mark in figure 4).

![Figure 4](image)

**Figure 4.** Layout of underwater topographic survey area and control points.
3.2.2. Unmanned Ship Measuring Trajectory Route. The measurement route of unmanned ships can be divided into two types: planned automatic measurement and on-site manual measurement. For open waters, the route is set to automatic control, and the route spacing is 50m. For the water surface boundary line and its shallower waters, in order to prevent the unmanned ship from hitting the bank slope or being stranded, switch to manual control. The actual measurement trajectory of the unmanned ship is shown in figure 5. The different colors in the figure represent different water depths. Some areas are affected by the shallow water depth and the difficulty of remote control by the unmanned ship. The unmanned ship cannot reach it and will form near the water surface line. A certain depth of “blind zone” leads to incomplete underwater terrain data.

![Figure 5. Distribution of measured trajectories of unmanned ships.](image)

3.3. Reconstruction of Reservoir Model
Use a dedicated software platform for 3D modeling of the water and underwater terrain, and obtain the 3D mesh model of the water and underwater terrain respectively, as shown in figure 6, and then through the meshed DEM reorganization processing, the measured terrain contour distribution of the reservoir is obtained Figure. In the combination of water and underwater terrain, the model data and contour lines at the water and underwater boundaries appear to be discontinuous.

![Figure 6. Three-dimensional mesh model of water and underwater terrain.](image)

After analysis of the cause, it is found that the water level of the reservoir has changed significantly during the actual measurement, and there is no one.

The ship’s sounding system has measurement “blind areas” in shallow water and docking areas, resulting in incomplete underwater terrain data. To solve this problem, we will discuss how to solve the “blind zone” problem of the unmanned ship’s sounding system.

4. Water Level-Storage Capacity Curve Fitting
This time the reservoir storage capacity calculation adopts the contour volume method, by differentiating the water body into n-layer trapezoids according to different elevation planes, and the overall storage capacity is obtained by integrating the n-layer trapezoidal volume. Taking into account
the irregularity of the trapezoid, the formula for calculating the reservoir capacity using the contour volume method is:

\[
V = \sum_{i=0}^{n} h_i \Delta V = \sum_{i=0}^{m} \frac{1}{3} \left( S_i + 2 \sqrt{S_i S_{i+1}} + S_{i+1} \right) \Delta h_i
\]  (1)

In equation (1), \( V \) is the storage capacity, \( m^3 \); \( S_i \) is the area enclosed by the \( i \)-th closed contour, and \( S_0=0, m^2 \); \( \Delta h_i \) is the height difference between the \( i-i+1 \) contours, m.

To fit the water level-storage capacity curve, it is necessary to obtain the water level-area curve first. According to the measured contour distribution of reservoir topography, the contour areas of different water level elevations can be calculated by CAD software, and the reservoir water level-area curve can be drawn (figure 7). The discontinuity in the drawing is due to the blind area of the unmanned ship sounding system, which leads to the missing of the contour line corresponding to the water level of 4234.17 ~ 4242.17 m in the drawing. In order to solve the problem of discontinuity of water level-area curve caused by blind area of sounding system, this paper adopts water level-area fitting method and contour interpolation fitting method to obtain reservoir water level-area curve.

4.1. Water Level-Area Fitting Method
The reservoir water level and area data obtained above are directly fitted by statistical method. This time, the least square method is used to configure cubic polynomial fitting, and the fitting equation of water level and area is as follows:

\[
S = 32.8237H^3 - 4.1632 \times 10^5H^2 + 1.7602 \times 10^9H - 2.4808 \times 10^{12}
\]  (2)

In the equation (2), \( s \) is the reservoir area fitted by curve \( (km^2) \); \( H \) is the reservoir water level elevation (m).

Through the above fitting equation, we can calculate the fitting reservoir area of underwater topography between the reservoir water level of 4234 ~ 4242 m, and the calculation results are shown in table 1. Then draw the water level-area fitting and measured reservoir water level-area curve, as shown in figure 8. Then calculate the corresponding reservoir capacity according to equation (1), and the calculation results are shown in table 1.
Table 1. Comparison of reservoir area and storage capacity.

| Serial number | Water level /m | Contour interpolation fitting | Water level-area fitting | Deviation analysis |
|---------------|----------------|-------------------------------|-------------------------|-------------------|
|               | Reservoir area /km² | Reservoir capacity /km³ | Area /km² | Reservoir capacity /km³ | Area /% | Reservoir capacity /% |
| 1             | 4234.17          | 2080.488                     | 25945.701          | 2093.956           | 25943.291       | -0.643             | 0.00093          |
| 2             | 4235.17          | 2173.571                     | 28069.221          | 2177.334           | 28045.354       | -0.173             | 0.085            |
| 3             | 4236.17          | 2255.430                     | 30278.805          | 2262.16            | 30229.982       | -0.298             | 0.161            |
| 4             | 4237.17          | 2360.664                     | 32574.453          | 2348.633           | 32498.596       | 0.512              | 0.233            |
| 5             | 4238.17          | 2442.339                     | 34956.165          | 2436.949           | 34852.782       | 0.221              | 0.296            |
| 6             | 4239.17          | 2523.577                     | 37423.941          | 2527.304           | 37294.286       | -0.147             | 0.346            |
| 7             | 4240.17          | 2616.790                     | 39977.781          | 2619.897           | 39825.016       | -0.119             | 0.382            |
| 8             | 4241.17          | 2709.755                     | 42617.685          | 2714.923           | 42447.046       | -0.190             | 0.4              |
| 9             | 4242.17          | 2813.960                     | 45343.653          | 2812.58            | 45162.609       | 0.049              | 0.399            |

4.2. Contour Interpolation Fitting Method

Firstly, the 3D laser scanning system is used to obtain the water terrain, extract the corresponding contour area, interpolate and draw the water level-area curve of the contour line of the water terrain, and then combine the curve with the underwater area measured by the unmanned ship sounding system to establish the regression equation of correlation and interpolate the missing underwater area.

(1) establishment of water level-area curve of water topography

According to the above-water terrain data obtained by 3D laser scanning, DEM is used to generate underwater terrain contour lines, and then the corresponding area is calculated, and the water level-area curve of the above-water terrain is drawn, as shown in figure 9.

(2) Complete water level-area curve fitting

Because the unmanned ship sounding system has a blind area in shallow water, the water level-area curve of some underwater reservoirs is incomplete when the water level is above 4234m. The extension of water level-area curve by water terrain interpolation can only reflect the changing trend of reservoir water level-area and cannot be used as a complete reservoir water level-area curve. In order to reduce the interpolation error of underwater terrain data alone, it is considered to extend the contour area above 4234m by combining water terrain interpolation.

Specific methods are as follows:

(1) Using the least square method to fit the regression curve of water level-area extended by interpolation of water topography;

(2) Calculate the reservoir area corresponding to underwater topography at different water levels by using the fitted relationship curve;

(3) Establishing a corresponding correlation function with the measured contour area of underwater topography;

Figure 9. Water level-area curve of water topography.
(4) The regression equation of the correlation between the two areas is as follows:

\[ A_2 = -0.000000030929 \times A_1^2 + 1.1653 \times A_1 - 3.0361 \times 10^5 \]  

In equation (3), \( A_1 \) is the interpolation reservoir area of water topography (km\(^2\)); \( A_2 \) is the fitted reservoir area (km\(^2\)). The correlation coefficient: \( R^2=0.99967 \), indicating a high degree of fitting.

Through the above regression equation of correlation, the fitted contour area of reservoir water level between 4234~4242 m can be calculated, and the calculation results are shown in table 1. A complete reservoir water level-area curve can be obtained by combining the calculated fitted water level-area above 4234m with the above reservoir water level-area results drawn according to the measured data, as shown in figure 10. Then calculate the corresponding reservoir capacity according to equation (1), and the calculation results are shown in table 1.

![Figure 10. contour interpolation fitting method and measured water level-area curve.](image)

### 4.3 Deviation Analysis of Results

Comparison and analysis of the deviations of reservoir area and storage capacity calculated by the two fitting methods are shown in table 1. The results show that the maximum deviations of water level area and storage capacity calculated by the two methods do not exceed 0.65% and 0.4%, indicating that the deviations of the two fitting methods are small. In addition, by comparing some measured terrain data with the above two fitting methods, it is found that the fitting value of contour interpolation method is closer to the measured value. Therefore, this paper uses contour interpolation fitting method to complete the “blind area” data.

### 4.4 Establishment of Reservoir Water Level-Storage Capacity Curve

According to the above analysis, the contour interpolation fitting method is used to complement the reservoir water level-area curve, and then combined with equation (1) to obtain the storage capacity values corresponding to different water levels, draw the actual water level-storage capacity curve, and finally compare the curve with the design water level-storage capacity Compare the curves for siltation analysis (figure 11).

![Figure 11. Comparison of the fitted water level-storage capacity curve and the designed water level-storage capacity curve.](image)
Through fitting and comparison of the design water level-storage capacity curve, it is found that below the dead water level (4235 m), the siltation amount is relatively large, while between the dead water level (4235 m) and the check flood level (4258 m), the siltation amount is relatively small. Combined with the comparison of the topographic map of the reservoir area at the design stage, there is a certain uplift in the elevation value of the reservoir bottom in each area, indicating that the reservoir is more serious.

5. Conclusions and Prospects

(1) Compared with the traditional storage capacity review method, this paper adopts the 3D laser scanning technology with high precision, full digitization, and flexible measurement methods. At the same time, it combines the small size, good maneuverability, and remote control of the unmanned ship depth sounding system to carry out water and Underwater topographic measurement greatly improves the accuracy and efficiency of reservoir capacity measurement, and provides a solution for carrying out accurate storage capacity review.

(2) When using three-dimensional laser scanning and unmanned ship sounding to carry out storage capacity review, the water level-area curve is incomplete due to the blind area of the unmanned ship sounding system in the shallow water area. This paper uses water level-area fitting and contour interpolation. The fitting method discussed two schemes of curve completion. Practice has proved that the contour interpolation method has higher fitting accuracy.

(3) In the process of using three-dimensional laser scanning and unmanned ship sounding system to carry out storage capacity review applications, the reservoir dispatching department should be consulted to reduce or avoid measurement errors caused by changes in the reservoir water level. In addition, the storage capacity measurement should be carried out when the water level is high as much as possible to reduce the measurement “blind zone” of the unmanned ship system.

(4) The use of unmanned ship sounding technology for underwater topographic surveying “blind zone” is inevitable. How to further reduce the error of the curve fitting of the water level of the “blind zone” and how to carry out the accuracy analysis of the storage capacity review is a topic that needs to be studied in the next step.

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