Application of 3D Laser Scanning Technology in Simulating Dam-Breaking Flood Routing

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Abstract: 3D laser scanning technology (3D-LST) is a new measuring technology that has been developed rapidly in recent years, which is characterized by obtaining 3D space coordinates of the object surface with its high speed, high accuracy and high density and the object and without contacting with the measured object. It has been increasingly and extensively applied in a variety of fields of engineering\textsuperscript{[1]}. In this paper, the analysis of 3D-LST in the dam-breaking flood routing analysis and its application in emergency rescue has been discussed. And then, a dam breaking and flood routing model has been established through scanning the dam and its downstream terrain with a 3D laser scanner, so as to provide accurate data basis for dam relief and disaster relief.

1. Introduction

3D laser scanning technology (3D-LST) brings a revolutionary of technology in geomatics. Differing from the previous single-point measurement technology, it can acquire 3D point cloud data on the surface of the measured object in a fast and efficient manner through high-speed laser scanning and geodetic coordinate positioning methods, so as to establish a 3D digital model for the measured object. The 3D-LST has been extensively applied in various fields such as archaeological excavations, 3D modelling of ancient buildings, large-scale terrain measurement, and hydraulic safety monitoring, etc.

Analyzing the dam-breaking flood routing is the essential condition for formulating an emergency plan for reservoir dam breaking, and for providing accurate data support for the emergency plan. Over years, numerous researches have been conducted on dam breaking. However, the real breach situation cannot be reflected by the dimension form of the dam breach in the previous dam breaking analysis. Also, the real terrain change cannot be reflected by the low-accuracy terrain data with sparse measuring points at the downstream dam, thus, resulting in the discrepancy between the actual situation and the real situation. The 3D-LST can effectively compensate for the defects of the inaccurate breach dimension and downstream terrain data in the dam-braking analysis thanks to its high-efficiency measurement method. Therefore, it's of great significance to study the 3D-LST in the dam-breaking analysis.

2. 3D Laser Scanning Technology

2.1. 3D-LST Principle
The terrestrial laser scanning system is composed of a 3D laser scanner, a digital camera, a scanner rotating platform, a software control platform, a data processing platform, a power supply and other accessories.

The principle of 3D laser scanning is that a laser pulse emitter, and two mirrors are rotated in a fast and orderly way in the 3D laser scanner. The measured area has been scanned sequentially by the laser pulse of the emitted narrow beam to calculate the distance through measuring the time required for each laser pulse from impulsing to the surface of the measured object and then returning to the instrument. Meanwhile, the angle of each pulse is measured by the encoder. In this way, 3D true coordinates of the measured object can be obtained. The reflected intensity at the scanning point is utilized to match colors for the reflection point. Points and data on the surface of the measured object can be obtained from a long distance with fast measuring speed and high measuring accuracy via the above steps.

2.2. Comparison with traditional measuring methods
Instruments adopted in traditional measurements involve level gauges, theodolites, total stations, and the commonly-used GPS technology. Limited by various terrain conditions, levels, theodolites, and total stations cannot be erected at complex or steep terrain for measuring. What’s more, measurement personnel have large workloads due to short range of visibility for measurement and heavy topographical scales. Also, because of the excess manual involvement, data accuracy cannot be guaranteed with low working efficiency. Although the GPS technology has been widely applied at this stage, the demands of measuring in the complex and dangerous terrain cannot be satisfied in the large-scale topographic mapping. However, a large amount of time and workload are required for acquiring enough measuring data since GPS is based on the single-point measurement. With the low efficiency, the single-point measurement of GPS cannot truly demonstrate fluctuation changes of terrain in the measurement of complex terrain. Or measuring points cannot be set in some dangerous locations, leading to low measuring accuracy. In comparison, the 3D-LST featuring even data acquisition, automatic operation, and high efficiency, has great advantages in 3D modeling, model accuracy and data processing (Table 1).

3. Application of 3D-LST in analyzing dam breaking
In general, the dam breaking analysis is conducted through simulating the flood routing process after the dam break with the software such as MIKE21, and ArcGIS, etc. The dam breaking analysis is divided into two aspects. The first is the dimensional change of the dam-breaking breach and the calculation of the discharge flow, the dimension of the breach is simulated along with time variation, so as to determine the hydrograph of discharge flow upon dam breaking. And the second is the flood routing analysis. Inundated situations under different breaking conditions are calculated through the hydrograph of discharge flow after dam breaking based on topographic data at the downstream of the dam.

| Table 1 Comparison of the 3D laser scanner with the traditional measurement technology |
|---------------------------------|-----------------|-----------------|
| 3D laser scanner | GPS technology | Total Station |
| Measuring distance | 1300m | The mobile station is 10 to 15 km away from the base station | 500m |
| Measuring speed | 200, 000 points/ second | 150 points/ hour | 20 points/ hour |
| Sampling density | Point cloud interval 5mm | Relatively sparse | Sparse |
| Measuring accuracy | The accuracy of a single point is 5mm within 100 meters, but the accuracy of the point cloud is high. | The accuracy of a single point is 5mm within 1000 meters | The accuracy of a single point is 1mm within 1000 meters |
| Measuring | Fully-automatic scanning | Single-point manual operation | Single-point manual |
The breach form is related to the dam materials and inducing factors, which can be divided into instant break and gradual break in accordance with the time process of dam breaking. It can also be divided into complete break and local break in accordance with the breaking size\textsuperscript{[3]}. Lots of researches have been focused on the breach form. In this paper, the application of the 3D-LST in dam breaking has been primarily studied by means of simplifying the breach into instant and complete break. By doing so, the real-time breach data can be acquired through a 3D laser scanner, once the dam break disaster takes place on at the later stage, once the dam breaks down.

The flow at the dam breaking site can be calculated with the Eq. (3-1)\textsuperscript{[4]}, as shown below:

\[
Q = \frac{8}{27} \sqrt{gh} \frac{b^3}{h_0} \]

Where: 
- Q is discharge flow; 
- g is the acceleration of gravity; 
- b is the width of the breach; 
- \(h_0\) is the depth of flood at the upstream before dam breaking

The dam break form simulated by the above equation may be varied from the actual situation. Therefore, the breach form and its discharge flow are tentatively fixed on the basis of the dam-breaking flood routing model established in this paper. In that case, the real-time breach data of the dam can be obtained through the 3D laser scanner once the dam break takes place. By importing the model, realistic simulation results can be obtained.

### 3.2. inundated analysis

The MIKE21 2D hydrodynamic model adopted in this paper possesses powerful functions in simulating free water flow in 2D, that is, water conservancy elements such as water flow, flow rate, and inundated area, etc. can be well simulated upon determining terrain data, boundary conditions, calculation unit, time step and other factors. Therefore, the dam-breaking flood routing situation at the downstream can be well presented in MIKE 21 in the dam-breaking flood routing model.

The basic governing equation of the hydrodynamic mathematical model of MIKE21 is a 2D shallow water flow equation\textsuperscript{[5]}:

1. Continuous equation:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} &= 0 \\
\frac{\partial hu}{\partial t} + \frac{\partial h u^2}{\partial x} + \frac{\partial huv}{\partial y} + gh \frac{\partial h}{\partial x} - fh - ghc_u \frac{\rho}{\rho_0} w^2 \sin a + \frac{g \sqrt{u^2 + v^2}}{C^2} &= E_x \frac{\partial^2 u}{\partial x^2} + E_y \frac{\partial^2 u}{\partial y^2} \\
\frac{\partial hv}{\partial t} + \frac{\partial hvu}{\partial x} + \frac{\partial h v^2}{\partial y} + gh \frac{\partial h}{\partial y} + fuh - ghc_v \frac{\rho}{\rho_0} w^2 \cos a + \frac{g \sqrt{u^2 + v^2}}{C^2} &= E_x \frac{\partial^2 v}{\partial x^2} + E_y \frac{\partial^2 v}{\partial y^2}
\end{align*}
\]

Where, 
- h is the water depth; 
- x and y represents the horizontal and vertical axis coordinates, respectively; 
- t is the time; 
- g is the gravitational acceleration; 
- u and v are the average speed at a vertical line along the x and y directions, respectively; 
- f is the Coriolis force coefficient; 
- \(\rho\) is the fluid density; 
- \(\rho_0\) is the reference density; 
- w is the real-time wind speed; 
- \(E_x\) and \(E_y\) are the eddy-coefficients in the x and y directions, respectively;

\[
C = \frac{1}{n} \frac{h^{\frac{1}{n}}}{n}
\]
C is the Chezy coefficient; and n is the roughness coefficient.

4. Engineering Examples

4.1. Establishment of a 3D model

By taking a water conservancy project in Jiangxi as an example, 3D digital models of the dam and the downstream terrain have been established through conducting 3D scanning on the dam body and its downstream terrain. Meanwhile, dam-breaking flood routing in the study area have been simulated together with MIKE21. 3D digital models established with the 3D laser scanning technology are shown in Fig. 1 and Fig. 2.

![Fig. 1 3D digital model of the dam](image1)

![Fig. 2 3D digital model of the downstream terrain](image2)

4.2. Data import and mesh generating

The hydrograph of discharge flow at the selected breach is regarded as the inflow boundary when the flood routing model is established in this paper. And the outflow boundary condition is the water level flow relationship curve of a section of the downstream river channel.

Basic data of the dam-breaking flood routing model are topographic data. In order to verify the influence of 3D-LST on the simulation results of dam breaking flood routing, two kinds of topographic data have been adopted in this simulation. The first terrain data that are commonly used in previous studies are extracted and obtained from the 3D data in the 1:100000 topographic map at the dam downstream site. The second terrain data is the point cloud data obtained by scanning the downstream terrain at the dam site using the 3D laser scanner. And then, a ground 3D digital model has been established at the downstream of the dam site. Topographic data have been separately imported into the software to obtain continuous terrain by interpolation. (Fig. 3, Fig. 4).

![Fig. 3 1: 10000 topographic map of the study area](image3)

![Fig. 4 3D laser topographic map of the study area](image4)
Since the dam-breaking flood routing model is calculated with the finite element method, grid partition is conducted on the study area. The finer the grid partition, the more accurate the calculation results. However, as the time for simulation operation is increased with the increase of precise grid partition, grid partition should satisfy the precise requirement of the model while taking the simulation time into account. The terrain mesh of the study area is shown below (Fig.5):

There are a total of 15360 grid nodes. Considering various factors, the time step of grid calculation is 30s; and the total number of calculation steps is 360, that is, the simulation time is 3 hours.

4.3. Simulation results
The flood routing situations at different moments are obtained through simulating the flood routing in the study area. With the model with the basis data of the 1:10000 topographic map as basic data as a case study, starting from the dam breaking, the original river surface area in the study area was 0.8km2. After 2 hours, the inundated area reached stability with the water surface area of 5.09 km2, that is, the inundated area was 4.29 km2. The inundated situations of the study area at 10 minutes, 20 minutes, 30 minutes, 60 minutes, 90 minutes, and 120 minutes are presented as follows.

Fig. 6 (a) The inundated situation in 10 minutes   Fig. 6 (b) The inundated situation in 20 minutes
Fig. 6 (c) The inundated situation in 30 minutes   Fig. 6 (e) The inundated situation in 60 minutes
Fig. 6 (d) The inundated situation in 90 minutes   Fig. 6 (f) The inundated situation in 120 minutes
The areas of the inundated area at different times are calculated separately upon simulating dam-breaking flood routing models with two different kinds of topographic data. Calculation results are summarized in the following table.

| SN | Duration (min) | Inundated area of Model A (m²) | Inundated area of Model B (m²) | Error (B-A) (m²) |
|----|----------------|-------------------------------|-------------------------------|------------------|
| 1  | 10             | 5355                          | 5012                          | -343             |
| 2  | 20             | 7978                          | 7214                          | -764             |
| 3  | 30             | 9628                          | 8553                          | -1075            |
| 4  | 40             | 1092975                       | 1087965                       | -5010            |
| 5  | 50             | 1194685                       | 1192751                       | -1934            |
| 6  | 60             | 1323261                       | 1322589                       | -672             |
| 7  | 70             | 1578473                       | 1578628                       | 155              |
| 8  | 80             | 1850783                       | 1852354                       | 1571             |
| 9  | 90             | 2557624                       | 2563345                       | 5721             |
| 10 | 100            | 3469929                       | 3474538                       | 4609             |
| 11 | 110            | 4340819                       | 4345624                       | 4805             |
| 12 | 120            | 5093595                       | 5096976                       | 3381             |
| 13 | 130            | 4741250                       | 4745055                       | 3805             |
| 14 | 140            | 4345635                       | 4350560                       | 4925             |
| 15 | 150            | 3913067                       | 3917676                       | 4609             |
| 16 | 160            | 3411799                       | 3416208                       | 4409             |
| 17 | 170            | 2849451                       | 2853685                       | 4234             |
| 18 | 180            | 2423487                       | 2428647                       | 5160             |

Note: The topographic data of model A is 1:10000 topographic map; while the topographic data of model B is 3D laser scanning topographic data.

As can be seen from Table 2, precise surface data of the terrain obtained through 3D laser scanning can be obtained with an accurate measurement in small terrain fluctuations at the starting period upon dam breaking. Thus, the inundated area at the early stage of the dam breaking flood in model A is smaller than that in model B. With the inundated routing over time, the inundated range and depth are increased continuously. At this moment, when some complex terrain on the surface are completely inundated, there is a minor difference between the topographic data of model A and model B. Thus, the difference of inundated areas of model A and model B is shrinking along with the extensive inundated range. It can be observed that minor difference in the inundated areas between model A and model B can be observed in the final inundated area although the topographic data scanned by the 3D laser scanner are more accurate. Therefore, the 1: 10000 topographic map can satisfy the simulation requirement of the model for the undemanding dam-breaking flood routing analysis.

The inundated area upon dam breaking at the downstream can be obtained with the help of simulation results of dam-breaking flood routing in the study area, which can provide accurate data support for preparing the dam breaking emergency rescue plan. Moreover, the 3D laser scanner can be used for performing real-time monitoring and scanning on the dam body in the dam breaking emergency rescue. The scanning results can not only provide a basis for rescuers to prepare scientific and reasonable rescue plans, but also import the real-time variation data of the dam breach upon dam breaking into the established dam-breaking flood routing model, so that decision makers can accurately know the losses at the downstream after the dam break, and formulate an emergency rescue plan in a timely and effective manner. What's more, the point cloud data acquired by the 3D laser scanner can be applied to print the dam body and its downstream live model through the 3D printing technology, which can simulate the flood routing situation in a more intuitive way.
4.4. Problem analysis
The topographical measurement at the downstream of the dam break was not conducted completely in this project due to time limitation. About 5km of the river channel was measured. Consequently, the inundated situation of a small section of the river channel after dam break was simulated in the final model results.

In the process of modeling, the finer the grid partitioning, the more accurate the simulation results. Since the finer grid requires longer computer calculation time, the grid partitioning in this project is not fine enough due to the excessive computer load, which might affect the results.

The topographic data acquired by the 3D laser scanner has high measuring accuracy due to the large amount of point cloud data, which can reflect the real change of the terrain. Nevertheless, since large point cloud requires long time to be imported into the model software, the 3D digital model of the terrain has been processed in this project to lower its point cloud density.

5. Conclusion
Compared with the traditional measuring technology, the 3D-LST is characterized by uniform data acquisition, large data volume, no manual operation, and high efficiency.

The topographic data acquired by the 3D laser scanner are more accurate in the dam-breaking inundated analysis, which can accurately reflect the topographic fluctuations at the downstream of the dam site. Hence, the inundated data obtained in the model simulation are more accurate.

By comparing with simulation results of models using different kinds of topographic data, it can be seen that the simulation result of the 1: 10000 topographic map can satisfy the calculation requirements in the dam breaking flood routing analysis with low accuracy requirements or large flood levels since the complex terrain on the surface has been completely inundated with the increase of the inundated area.

In the event of a dam break, the 3D laser scanner can be applied in monitoring and scanning the development of the breach in real time, and import the data of the dimensional change process of the breach obtained over time into the model, which can acquire a true dam breaking flood routing model, providing a more accurate basis for decision makers to develop emergency rescue plans.

About the author
Xiong Fangjin (1987.05-), Male, Master, he is mainly engaged in teaching and research work in the monitoring and safety evaluation of water conservancy projects.

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