Research and Application of 3DGIS Burst Analysis Algorithm Based on Urban Water Supply Network

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Abstract. To address the issues of insufficient information technology in the water supply network and how to quickly develop effective valve closure plans for travel in the event of pipe bursts, the visualization management of the water supply network has been achieved, the layout of the water supply network pipeline has been optimized, and the problem of graphic information asymmetry has been solved. By using the principles of graph theory, the water supply network is abstracted as a two-dimensional directed network graph; Establish a three-dimensional network model of water supply network based on GIS technology, and create a spatial database to store graphic data; This article's algorithm is applicable to the analysis of complex water supply pipe bursts in circular pipe networks. It studies and implements an algorithm for quickly locating the upstream/downstream valves that need to be closed, the range of affected areas after downstream pipe bursts occur, and a comprehensive valve closure analysis algorithm.A solution for the burst analysis algorithm of 3DGIS based on real pipeline network data scenarios has been demonstrated and developed, realizing functions such as dynamic graphic burst analysis, connectivity analysis, and valve closure analysis. GIS services have been published, and users can connect front-end and back-end graphic data and attributes and update them dynamically in real-time.After testing data verification, the system can not only visually manage the data information of the city's water supply pipeline network, but also quickly and effectively confirm the optimal valve position, reducing the time and impact of urban water supply pipeline explosion accidents. It has strong application value and economic value.

Keywords: GIS; Burst analysis algorithm; Graph theory; BFS; DFS; Recursive SQL

1 Introduction

In 2022, there were 1418 underground pipeline accidents in China, with an average of 4 incidents per day, resulting in direct economic losses of billions of RMB per year. In 2022, the main pipeline of the water supply network in the urban area of Shiyan City from Hubei Province exploded 22 times, with an average of three times per month. With the aging of water supply pipeline materials and the impact of construction damage, underground pipeline explosion accidents are inevitable.Urban water supply networks are generally underground. In the event of sudden incidents such as pipe bursts, traditional drawings and manual search

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(a) (b)

Fig. 1. (a) Water Pipe Break Photograph, (b) 3DGIS based on the water supply network in BS

methods are used to conduct surface inspections. Not being able to see the underground water pipes not only consumes a lot of time and energy, but also further expands the affected area due to untimely repairs. How to solve the problem of burst pipes in underground water supply pipelines is an urgent problem in municipal engineering management [1].

Contributions We established a GIS(Geographic Information System) spatial database for the urban pipeline network, and then designed a burst analysis algorithm for the urban underground pipeline network in Figure 1. The effectiveness was verified through various experiments. Finally, we conducted data publishing services for 2DGIS /3DGIS. There are a number of innovative ideas employed in the development and application of these algorithms ; these include: 1) This article designs and implements a method for finding target valves in a directed graph with loops using deep first DFS(Depth First Search) algorithm using recursive SQL statements in spatial databases; 2) From the perspective of graphical expansion of business data, this article designs an effective comprehensive burst analysis performance optimization algorithm for real urban underground pipeline network data; 3) This article studies and designs a complete set of underground pipeline GIS solutions for 2DGIS/3DGIS, covering data collection, conversion, and publishing.

2 GIS Method

2.1 GIS technology

GIS is a spatial information system that integrates different disciplines such as geography science and computer science. The urban underground pipeline network management system based on GIS can gain the following advantages:

- Accurate positioning of valves and pipelines for convenient and rapid fault location. The GPS positions of pipeline points and pipelines are collected through instruments, and the accuracy of using GIS coordinate positions can reach centimeter level, with very small measurement errors in GIS.
- Temporal and spatial visualization: Through GIS systems, underground pipeline network data can be displayed in a graphical manner, allowing users to intuitively understand the distribution and coverage range of the pipeline network. This can avoid information leakage or errors caused by the complexity of a large amount of graph data [3].

- Fast fault localization: Traditional fault localization relies on manual search and troubleshooting, which is time-consuming and prone to errors. The underground pipeline management system based on GIS can quickly locate fault points through a map interface, improving the efficiency and accuracy of fault handling.
- Data update and maintenance: GIS systems can achieve real-time updates and maintenance of underground pipeline network data. Once new pipelines or equipment are updated, they can be promptly reflected in the GIS system to ensure the accuracy and timeliness of data.

The original drawing data of the water supply pipeline network is usually a CAD file. We can set up a coordinate system, perform vector registration, and convert CAD file to shape file of GIS file format and then import shape file to spatial database.

2.2 Spatial Database

This article selects PostgreSQL, abbreviated as pg, which is an open-source and the object-oriented database. PostGIS is an open-source pg extension plugin that adds the ability to store and manage spatial data on pg. Pg+PostGIS can store the graphic and attribute data of pipe points/pipelines in a table, and directly publish the graphic data on the web by Geoserver.

The data sources of water supply network have diversity characteristics, which includes both geographic spatial data (surface road data, terrain data, etc.) and water supply equipment data (including pipeline, valve data, etc.). The multi-source data has also caused a series of problems in the system integration process, such as poor data standardization, and the lack of unified standards for information storage formats and structures between different systems. To meet the demand for data information integration in the water supply network, the system will import standardized and structured basic data after cleaning and at last a water supply network system integrating diverse data will be formed [2].

2.3 Graph theory

The water supply network is a dynamic nonlinear network based on the water supply transmission path. The topological relationship between pipeline segments and nodes can be dynamically simulated and represented using graph theory [10]. To analyze the impact of pipe bursts on the pipeline and develop valve closure strategies, the system abstracts the water supply network into a directed network diagram based on the principles of graph theory on the basis of GIS. The water source is the source point(S) of the graph, the water supply pipe is the directed weighted edge(E), the pipeline connection point is the node(V) of the directed graph, and so G=(V, E). A data model of the water supply network is constructed. Regarding the analysis of burst tubes, this article studies and implements BFS(Breadth First Search),DFS,Dijkstra, a burst analysis algorithm for massive urban pipeline databases. We will use pgrouting to design these algorithm ,which is is a path planning extension plugin integrated into POSTGIS.

2.4 BIM+3DGIS+Sensor Technology

The GIS model of water supply network has been widely promoted and applied in the industry due to its effective integration of underground pipeline network model and spatial attribute model of GIS, which can achieve three-dimensional simulation of pipeline network

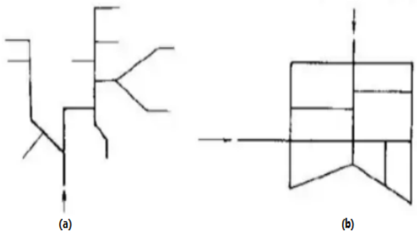


Fig. 2. (a) Tree shape, (b) Circular shape

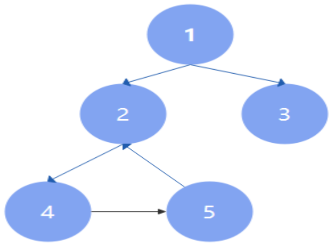


Fig. 3. Traversal graph of directed pipeline network

and associate internal attribute features, especially the building model combined with BIM(Building Information Modeling).With web technology as the core and support, utilizing the interactive ability of the browser, providing query and retrieval functions for water supply network equipment and water supply information, achieving visual display of spatial data.

3 Algorithm Model

The water supply network is divided into tree shaped network and circular network according to the layout form, as shown in Figure 2. The city water supply network is a general circular pipeline with loops inside [4]. After a water supply pipeline explosion accident occurs, it is necessary to first determine which section of the entire water supply network the point of failure is located in. Then, close the valve that controls the incoming water path of this section of the pipeline and dispose of the burst pipe section. It can be achieved using BFS algorithm.

3.1 BFS Algorithm of Directed Graphs in the water supply network

The water flow in the pipeline is directional and the water supply network controls the direction of water flow based on the supply pressure. When an urban water supply pipeline explosion occurs, the valve to be closed that needs to be searched for should be the control valve upstream of the burst pipe section. BFS algorithm for directed graphs is similar to the hierarchical traversal of trees, and is implemented based on the queue data structure. The most commonly used storage structures for graph storage are adjacency matrix and adjacency table and we choose the latter [11]. Traversing a graph is the process of accessing each vertex in the graph one and the BFS algorithm idea is as follows:

① Firstly, select a vertex v in the graph as the starting point, and after accessing it, queue it up and mark it as visited;

② Access the vertices adjacent to v sequentially, that is, when the queue is not empty, check all adjacent vertices of the queue vertex, access the adjacent vertices that have not been accessed and queue them, and repeat this process;

③ When the queue is empty and a loop is exited, that is, all adjacent vertices of the visited vertices are accessed, then the traversal is completed;

Referring to this algorithm, with v_1 as the root node in Figure 3, the vertex traversal order is (v_1,v_2,v_3,v_4,v_5). When using the adjacency table of a directed graph, the time complexity is

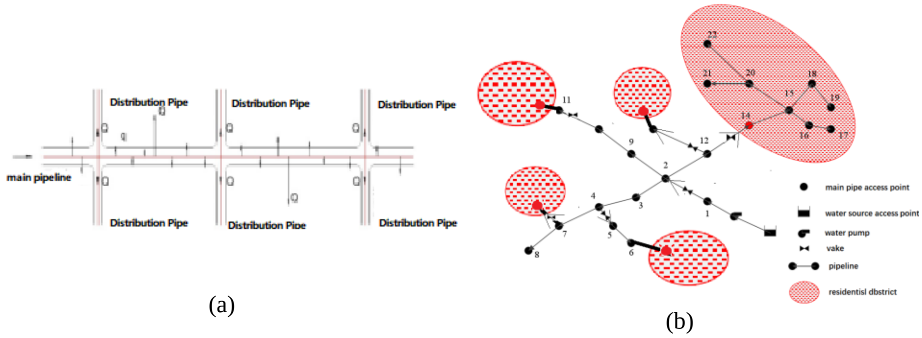


Fig. 4. (a) Main pipes and distribution pipes, (b) Residential community pipeline network

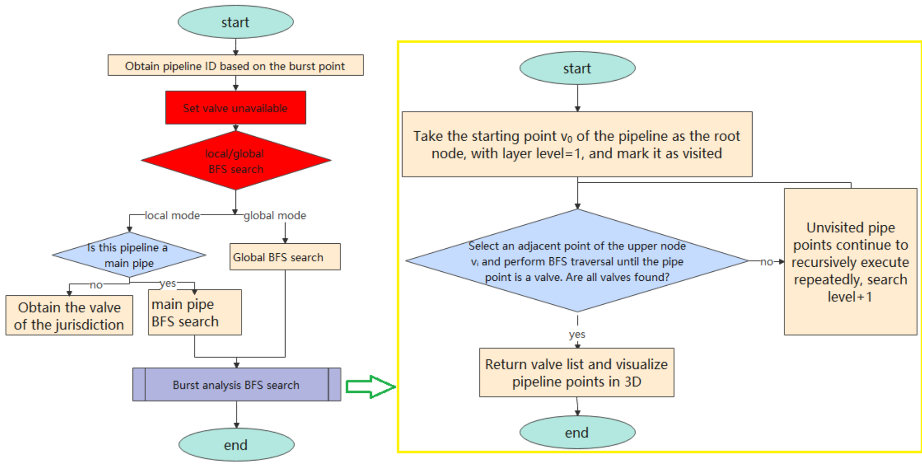


Fig. 5. A custom interactive burst analysis method based on the BFS algorithm

O(V+E) because each edge is only accessed once and will not be repeated; The time complexity of the adjacency matrix is $O(V^2)$. The spatial complexity is O(V).

3.2 A comprehensive burst analysis algorithm in city water suply network

3.2.1 Definition of Local mode and Global mode

Urban pipelines are divided into main pipes and distribution pipes based on their importance and diameter size in Figure 4. A valve on a main pipe can control the water supply of several residential areas. Local mode is a subnet that only includes all main pipes and Global model is the current network, which includes all pipelines [5].

3.2.2 A custom interactive burst analysis method Based on BFS

The BFS algorithm traverses to avoid the influence of the loop in the circular structure of the water supply network [6]. This article creates a custom interactive burst analysis method based on the BFS algorithm as follows:

①Based on the GPS location of the reported explosion pipe, obtain the edge attached to the pipeline table from the spatial database, and determine whether it is a main pipe or a distribution pipe based on its isTrunk property;

② Interactive selection of algorithms:

- User can choose local/global search modes for iterative search. Fast local mode speed, searching for critical valves causing accidents within the backbone network subnet; The global retrieval path is more comprehensive and detailed, and upstream valve retrieval can start from the management points of each building in the residential community.
- User can freely set the specified unavailable valve. During the implementation process, maintenance workers may find that some upstream valves cannot be closed due to equipment failures. Therefore, it is necessary to continue upstream traversal and search for available valves.

③ Mode selection:

- If global mode is selected, go to ④ ;
- In local mode, if the main pipe is turned to ④ ; If the distribution pipe directly finds the end of the valve in the distribution jurisdiction through attributes.

④ By traversing the root node depth first from the starting point of the pipeline, a list of valves that need to be closed and their paths are obtained, and the process ends. All algorithm steps refer to Figure 5.

4 Experimental Result

We use recursive SQL(Structured Query Language) to conduct BFS experiment in pg.

4.1 Experiment on Burst Analysis Algorithm

4.1.1 The grammar statement of recursive algorithm

Common Table Expression(CTE) can be thought of as defining temporary tables that exist just for one query.The optional RECURSIVE modifier changes WITH from a mere syntactic convenience into a feature that accomplishes things not otherwise possible in standard SQL. Recursive SQL code is below:

```
WITH RECURSIVE t(n) AS (
  VALUES (1)
  UNION ALL
  SELECT n+1 FROM t WHERE n < 100)
SELECT sum(n) FROM t;
```

4.1.2 Recursive SQL testing of table with no spatial data

We use the sys_cbp_test table, which has a parent-child relationship between records. First, we constructed an acyclic directed graph, and then added a record on it to implement a directed graph which has one cycle. The table structure and insertion records are shown in Table 1. Root node must be specified in recursive SQL ,and you have to use array[id] as path and ANY(path) in order to use BFS in Table 2. To create a breadth-first order, Level column of SQL can track the depth of the search.

Table 1. Parent-child relationship table with no spatial data

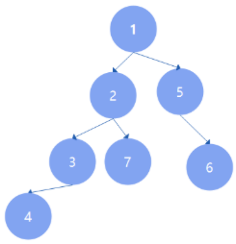
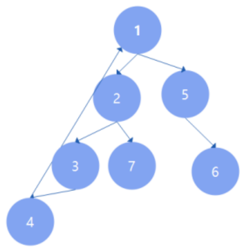
DML	Graph(no cycle)	Graph(cycle)
CREATE TABLE sys_cbp_test (id INT,parent_id INT);INSERT INTO sys_cbp_test VALUES (1 , NULL) ,(2, 1) ,(3 , 2) ,(4 , 3) ,(5 , 1) ,(6 , 5) ,(7 , 2) ,(20 , NULL) ,(21 , 20) ,(22 , 21); For Graph(cycle) **INSERT INTO sys_cbp_test VALUES (1 , 4)**		

Table 2. Recursive SQL experiment for cycles with no spatial data

SQL(cycle)

```
WITH RECURSIVE x ( id , prior_id , parent_id , level , path , root, cycle) AS
( SELECT id , NULL::INT AS prior_id , NULL::INT AS parent_id , 1 ,array[id] , id as root, false
   FROM sys_cbp_test
  WHERE parent_id IS NULL
  UNION ALL
 SELECT b.id , x.id AS prior_id , b.parent_id , level +1 , x.path || b.id , x.root, b.id = ANY(path)
   FROM x, sys_cbp_test b
  WHERE x.id = b.parent_id
    AND NOT cycle
)
SELECT id , prior_id , parent_id , level ,'/' || array_to_string( path , '/' ) AS path, root, path, cycle FROM x WHERE NOT cycle ORDER BY id;
```

Return results

id	prior_	parent	level	path	root	path(1)
1	(Null)	(Null)	1	/1	1	{1}
2	1	1	2	/1/2	1	{1,2}
3	2	2	3	/1/2/3	1	{1,2,3}
4	3	3	4	/1/2/3/4	1	{1,2,3,4}
5	1	1	2	/1/5	1	{1,5}
6	5	5	3	/1/5/6	1	{1,5,6}
7	2	2	3	/1/2/7	1	{1,2,7}
20	(Null)	(Null)	1	/20	20	{20}
21	20	20	2	/20/21	20	{20,21}
22	21	21	3	/20/21/22	20	{20,21,22}

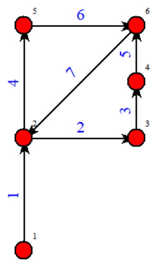
4.1.3 Recursive SQL testing of table with spatial data

(1) Build a pipeline network graph with cycles

In the right of Figure 6, the blue line with an arrow represents the pipeline, and the red solid sphere represents the pipe point. The numerical value on the middle left side of the pipeline represents its ID , and the small black number on the upper right side of the pipeline point represents its ID. In the left of Figure 7, we have created a pipeline table edge_table_c2, each record is a pipeline segment, where its field group (x1, y1) is the coordinate starting point, and the field group (x2, y2) is the coordinate ending point. The_geom is the geometric data field of pipelines. pgr_createTopology can automatically generate a point table and automatically update numerical values of the source and target fields in the edge table [7].

(2) Searching for cycles in the pipeline network

```
CREATE TABLE edge_table_c2(
    id BIGSERIAL,
    dir character varying,
    source BIGINT,
    target BIGINT,
    cost FLOAT,
    reverse_cost FLOAT,
    capacity BIGINT,
    reverse_capacity BIGINT,
    category_id INTEGER,
    reverse_category_id INTEGER,
    x1 FLOAT,
    y1 FLOAT,
    x2 FLOAT,
    y2 FLOAT,
    the_geom geometry
);
INSERT INTO edge_table_c2 (
    category_id, reverse_category_id,
    cost, reverse_cost,
    capacity, reverse_capacity,
    x1, y1,
    x2, y2) VALUES
(3, 1,    1,  1,  80, 130,   2,   0,    2, 1),
(3, 2,   -1,  1,  -1, 100,   2,   1,    3, 1),
(2, 1,   -1,  1,  -1, 130,   3,   1,    3, 1.5),
(2, 4,    1,  1, 100,  50,   2,   1,    2, 2),
(1, 4,    1, -1, 130,  -1,   3,   1.5,    3, 2),
(2, 1,    1,  1, 100, 130,   2,   2,    3, 2),
(2, 1,    1,  1, 100, 130,   3,   2,     2, 1);
UPDATE edge_table_c2 SET the_geom = st_makeline(st_point(x1,y1),st_point(x2,y2));
SELECT pgr_createTopology('edge_table_c2',0.001);
select * from edge_table_c2;
```



id	source	target	cost	reverse_cost	x1	y1	x2	y2	the_geom
7	6	2	1	1	3	2	2	1	0102000000020000000000
1	1	2	1	1	2	0	2	1	0102000000020000000000
2	2	3	-1	1	2	1	3	1	0102000000020000000000
3	3	4	-1	1	3	1	3	1.5	0102000000020000000000
4	2	5	1	1	2	1	2	2	0102000000020000000000
5	4	6	1	-1	3	1.5	3	2	0102000000020000000000
6	5	6	1	1	2	2	3	2	0102000000020000000000

Fig. 6. DML, graph and table data of a pipeline network graph with cycles

Table 3. Recursive SQL experiment for Searching for cycles of spatial data in the pipeline network

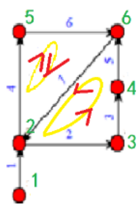
SQL(cycle) | Return results | Graph

```
WITH RECURSIVE x ( id, parent_id, path, cycle) AS(
 SELECT target as id, 0 as parent_id, array[target] as
path, false FROM edge_table_c2 WHERE id=1
 UNION ALL
 SELECT b.target as id, b.source, x.path || b.target,
b.target = ANY(path) FROM x, edge_table_c2 b
WHERE x.id = b.source AND NOT cycle
)
SELECT id, parent_id, array_to_string( path , '->' ) AS
path, cycle FROM x WHERE cycle
ORDER BY id;
```

Return results:

id	parent_id	path	cycle
2	6	2->5->6->2	t
2	6	2->3->4->6->	t

Graph:



When working with recursive queries it is important to be sure that the recursive part of the query will eventually return no tuples, or else the query will loop indefinitely. The standard method for handling such situations is to compute an array of the already-visited values.This query will loop if all relationships contain cycles [12]. Instead we need to recognize whether we have reached the same row again while following a particular path of links. We add two columns(cycle and path) and judging condition(AND NOT cycle) to the loop-prone query in order to remove those cycles in Table 3.

(3) Table design optimization

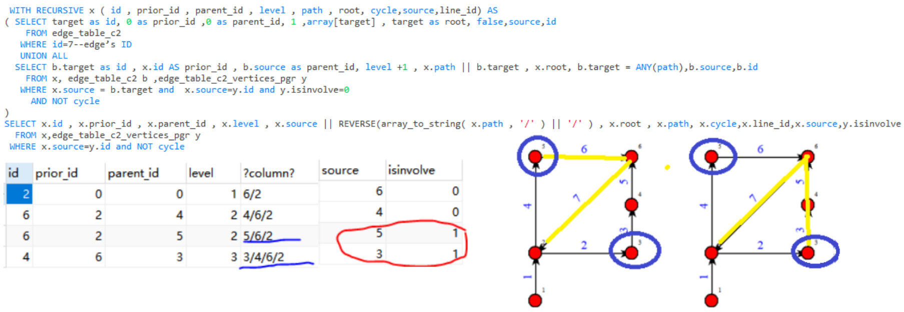


Fig. 7. BFS SQL for upstream valve closure

Table 4. Table design optimization

Table Type	Field Name	Field Type	Description
pipeline	isTrunk	boolean	If true it is the main pipeline network; If false it is the distribution network
	sectionID	Int	ID of the valve which governs his territory
Pipeline point	isInvolve	boolean	If true is a valve; If false is a common pipeline point.
	involveLevel	Int	Importance level of valves (only 0 for main pipeline)

Considering the use of the algorithm in 3.2, we only supplement the fields in the pipeline table and the pipeline point table in in Table 4. Not only considering the three normal form principles of database table design, but also considering reusability and SQL performance, the redundant field sectionID of the pipeline table has been added in Table 4 [8]. We can create some views based on the latest table to simplify SQL statements.

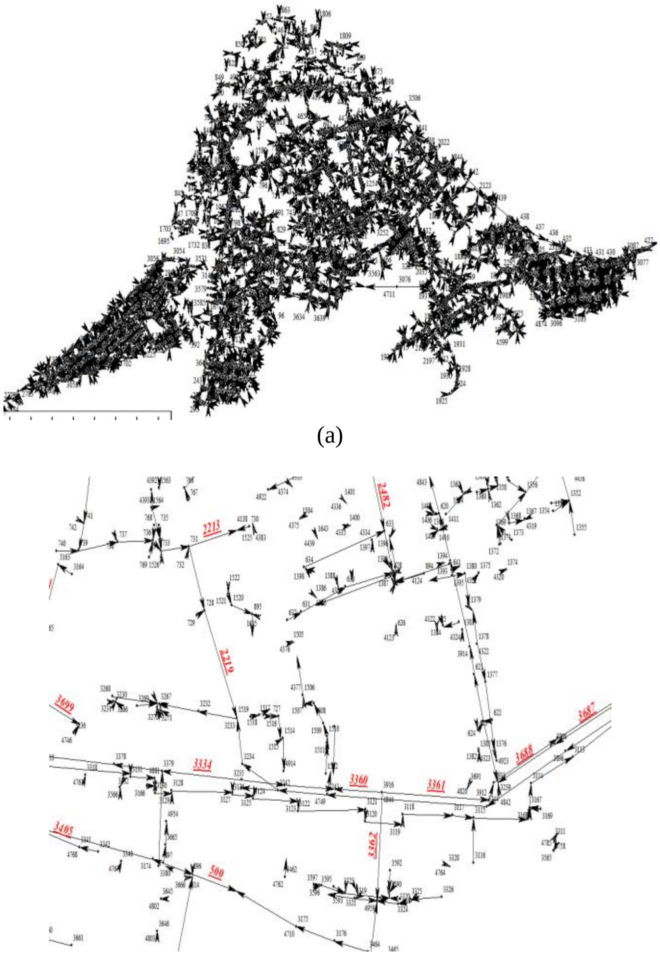
(4) Upstream valve closing algorithm and valve closing algorithm experiments

The recursive SQL for upstream valve closure is shown in the Figure 7, where IsShut is true.Set isInvolve=1 for id=3 and id=5 in the pipe point table to perform upstream traversal. The feedback is that the upstream valves that need to be closed are pipe points 3 and 5, with paths of 5/6/2 and 3/4/6/2, respectively,as shown in Figure 7.

4.2 Experiment on Burst Analysis Algorithm

The function uses upstream valve search, with the same SQL restriction of 10 levels of hierarchical search, and the results are shown in Table 5 and Figure 8. The performance comparison between the algorithm in this article and similar algorithms shows the following advantages: ① The use of BFS retrieval in main pipeline network is faster than similar algorithms; ② The interaction ability in specifying the availability of valves is better [9].

4.3 Existing issues and Expand discussion



(a)

(b)

Fig. 8. (a) GIS data in the experiment, b) 10 levels of hierarchical search of valves in upper stream

Table 5. Performance evaluation of burst tube analysis algorithms under different data volumes

Dataset	Table record Number	Search Level	Task	SQL	time
edge_table_c2	7 pipeline, 5 pipeline points	10	upstream valve search	BFS	0.007s
Real data	4220 pipeline, 4979 pipeline points	10	upstream valve search	BFS	0.009s

4.3.1 Existing issues

- The real urban water supply network has multiple water sources, which means there are multiple root nodes. This must be adjusted in conjunction with the actual application scenario for table design.
- The implementation of the circle breaking method for the minimum spanning tree of a directed graph will accelerate the speed of BFS retrieval. The research and implementation of this algorithm is still in progress.

4.3.2 Expand discussion

- Expand the application of burst pipe analysis to scenarios such as power, telecommunications, gas, and oil pipelines;
- The current focus of this article is on real-time analysis of explosive tubes. It is necessary to create a data warehouse to store historical explosive tube information data, and then conduct spatial data mining to discover potential unknown patterns.

5 Conclusions

In order to promote the information and digitization process of water supply management, this article uses GIS technology to establish an interactive integrated logical algorithm model for water supply pipeline zoning based on the characteristics of urban underground pipeline data and the needs of pipe burst analysis. On this basis, a depth first algorithm based on graph theory is completed to search for upstream and downstream valves. In order to achieve logical and spatial pipeline equipment queries along the selected area, analyze the impact of pipe bursts, develop effective valve closure strategies, and seize valuable time for emergency repair work, minimize losses caused by pipe bursts.

Acknowledgments. We would like to express our gratitude to the net friends who provided data of the water supply network in this article. Based on the industry data, we put up the new design ideas, new data structures, and new burst analysis algorithm. We also practiced the algorithm in the business data of the spatial database for underground pipelines and confirmed that it is feasible.

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