Evaluation of Drainage Gradient using Three-dimensional Measurement Data and Physics Engine

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Abstract –

The shape of a building can be recorded through various technologies, such as three-dimensional (3D) laser scanners and photogrammetry. The 3D measurement technology facilitates the mensuration of unevenness of a reinforced concrete structure, horizontality of the floor, and drainage gradient. In particular, measuring devices with a tilt sensor (e.g., 3D laser scanners) allow the evaluation of the horizontality of buildings using point cloud data. In this study, a method is introduced to evaluate the drainage gradient using 3D polygon data and a physics engine. The point cloud data were acquired via a 3D laser scanner and converted into polygon data. The polygon data were imported into a virtual space through the physics engine. Subsequently, the drainage capacity was evaluated by placing water particles on the polygon data and observing their movement according to the physics engine. The aim of this procedure is to evaluate the inclination angle of all parts of a building (e.g., rooftop) and develop a method for identifying the locations where puddles can frequently occur. Our simulation software was created using Unity and NVIDIA FleX. In this research, a simulation was conducted in which the polygon data were imported into the developed software, and the drainage situation was predicted.

Keywords –

3D laser scanner; Point cloud; 3D surface; Drainage gradient; Physics engine

1 Introduction

1.1 Background and Related Work

Point cloud data are composed of a set of points containing information related to three-dimensional (3D) coordinates and colors. However, because the data are only composed of points, they are usually converted into 3D models and building information modeling (BIM) data. Alternatively, data analysis is applied to point cloud data, for example, comparing the horizontal plane information with the point cloud data to analyze floor flatness. Accordingly, several researchers have examined evaluation methods using 3D point clouds, shape recognition of point clouds, and automatic conversion of point clouds into BIM data.

In the construction industry, approximately half of the studies on the application of point cloud data are based on 3D model reconstruction [1], and a quarter involve geometry quality inspection [1].

The automatic segmentation of point cloud data into building parts (e.g., walls and columns) acquired by a laser scanner has been investigated [2]. Research on reconstructing point cloud data into a 3D model has been performed by creating BIM data for buildings [3] and other civil engineering structures, such as tunnels [4]. Studies on creating BIM data according to the level of development (LOD) specification using point cloud data have also been explored [5]. In some studies, point cloud data and parametric modeling are combined [6]. For example, one study performed a dimensional quality assessment of the rebar of a reinforced concrete element based on point cloud data. [7]. In recent years, methods for directly performing structural calculations from point cloud data have been explored [8]. A system implemented for floor flatness compliance control given a set of point clouds and a 3D BIM model has also been proposed [9].

1.2 Research Aim

Point cloud data contain considerable amounts of information. For example, surface dirt and deterioration of buildings can be observed based on point cloud data. Furthermore, because the accuracy of 3D laser scanners has improved, it is possible to analyze the drainage gradient using the data acquired by the scanner. A 3D laser scanner can measure even the slightest unevenness in an actual building.

In several recent studies, methods for automatically converting point cloud data into a 3D model or BIM data have been investigated. The general BIM data exhibit a smooth shape of walls and floors. Therefore, the 3D shape information of the building included in the point cloud data is typically lost after conversion into BIM data. Point cloud data contain the exact shape and color information in the real world; hence, these data include richer information than the BIM data of the LOD 500 level.

The purpose of this study is to utilize the shape information contained in point cloud data. Our research aims to devise a mechanism to evaluate drainage performance by combining a 3D surface converted from point cloud data and a physics engine.

The objectives of this study are summarized as follows:

(1) Devise a procedure to create a 3D model for analyzing drainage capacity
(2) Verify water particle movement on a 3D surface model using the physics engine
(3) Conduct validation of the drainage capacity analysis results by comparing against actual measurement data

2 Drainage gradient evaluation method using 3D measurement data and physics engine

2.1 Drainage Gradient Evaluation Procedure Using Point Cloud Data and Physics Engine

The evaluation method for the drainage gradient using point cloud data and the physics engine involves the following three steps:

(1) Measurement using a 3D laser scanner
(2) Creation of a simulation model based on point cloud data
(3) Evaluation of the drainage gradient using a physics engine

The point cloud data of a building that are obtained using a 3D laser scanner cannot be employed for simulation that uses a physics engine. Accordingly, we have formulated a procedure for converting point cloud data into information that can be applied to such a simulation.

The procedure for converting point cloud data is shown in Fig. 1. Two 3D models are used to evaluate the drainage gradient using point cloud data and a physics engine. The first type of 3D model is a surface model converted from point cloud data; the second is a 3D model of a sewer created from point cloud data and field surveys.

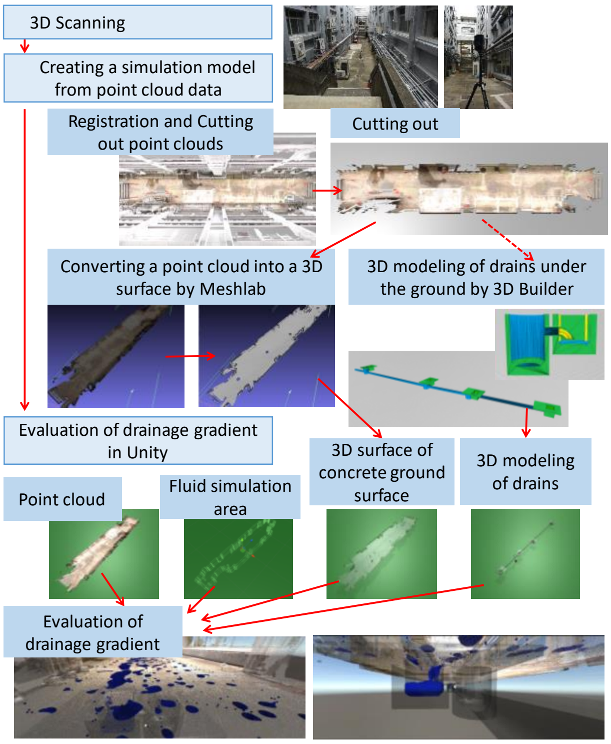


Figure 1. Evaluation procedure of drainage gradient using 3D measurement data and physics engine

2.2 Level of graphical information acquired from point cloud data

Point cloud data contain rich information; to utilize this information, the data are usually analyzed and converted into another data format. In this study, we categorized the level of graphical information acquired from point cloud data. This classification is summarized in Table 1.

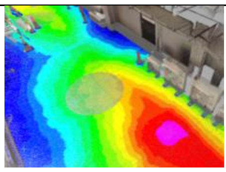
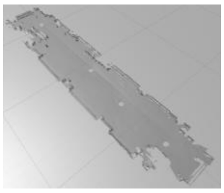
A point cloud is composed of 3D coordinates, color, and brightness. We can observe the shape and color of a building as well as the stains and wet spots on its surface based on the color of the point cloud.

The data containing the information extracted from the point cloud data for analysis are derived by examining the 3D coordinates of the point cloud data. For example, there are certain amounts of data containing information on the distance of a point from a horizontal plane that represent this distance in terms of color.

The 3D surface is composed of data obtained by converting point cloud data into polygon data. In this study, objects in motion were used based on the physics engine.

The simulation model is a 3D model that implements various simulations. It is composed of a 3D surface converted from point cloud data, a simulation area, point cloud data, and 3D models. The simulation model is employed to estimate the drainage capacity using actual measurement data.

Table 1. Level of graphical information acquired from point cloud data

Level definition	Image
Point cloud data Point cloud data is composed of 3D coordinates, color, and brightness.	
Point cloud data analyzed to extract information These are data created by analyzing the 3D coordinates of the point cloud data.	
3D surface These data are obtained by converting point cloud data into polygon data. In this study, the data are used for moving objects based on the physics engine.	
Simulation model This is a 3D model that can be employed in various simulations.	

2.3 Creation of the Simulation Model from Point Cloud Data

2.3.1 Procedure for Creating a Simulation Model from Point Cloud Data

To create a model for simulation, we organized three types of 3D data by analyzing and converting point cloud data. These three types consist of "point cloud data analyzed to extract information" and "3D surface," as summarized in Table 1. Additionally, we created "a 3D model of drains under the ground." However, underground drains cannot be measured using a 3D laser scanner. Therefore, after examining the point cloud, we estimated the position of these drains and created a 3D model to represent them.

Four positions were scanned with the 3D laser scanner; Fig. 2 presents a photograph of these measurements. The acquired point cloud data of the campus building are shown in Fig. 3. These data were used to create the simulation model employed in this study.

The procedure for creating a 3D surface from the point cloud data is detailed below:

(1) Register several scanning data
(2) Cut out the point cloud data on the floor
(3) Convert the point cloud data into a 3D surface model

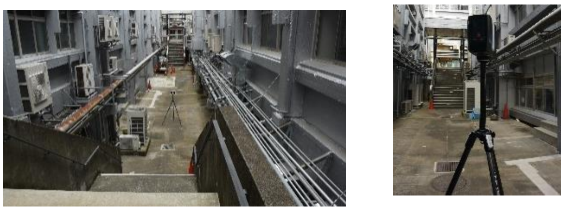


Figure 2. Measurement scheme in experiment

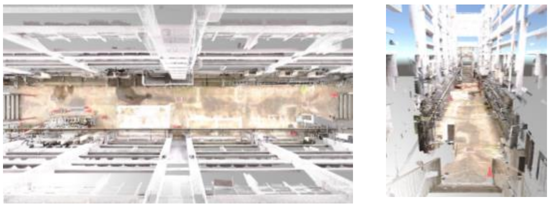


Figure 3. Acquired point cloud data of campus buildings

2.3.2 Registering and Cutting Out Point Clouds

We registered the point cloud data and removed the floor point cloud data to convert them into a 3D surface model; the cutoff point cloud data are depicted in Fig. 4. The installation positions of the 3D laser scanner are denoted as A, B, C, and D. The point cloud data captured from these four positions are illustrated in Fig. 5. The data were classified into four colors (i.e., red, blue, yellow, and green) corresponding to the point cloud data acquired from these four locations.

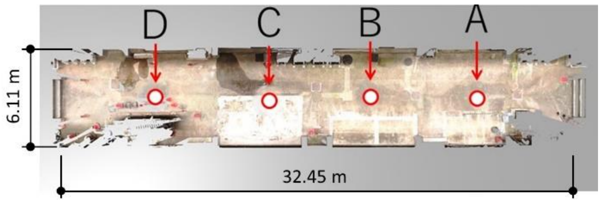


Figure 4. Installation positions of 3D laser scanner

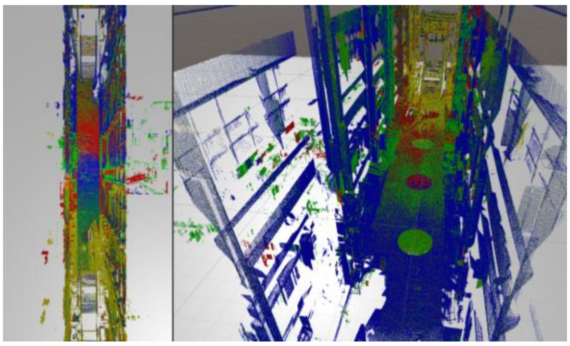
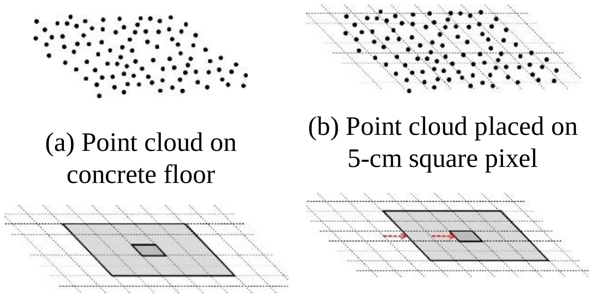


Figure 5. Point cloud data captured from four measurement positions

2.3.3 Measurement of Concrete Floor Flatness Using a 3D Point Cloud

The slope of the concrete slab is obtained from the point cloud data, and the location of the local minimum point is then analyzed, as presented in this section. Water accumulates in locations with low elevation. Therefore, it is essential to analyze the position of the local minimum point to compare the Z-coordinate values with the surroundings.

The analysis of the position of this minimum point was performed according to the procedure shown in Fig. 6. First, as shown in Fig. 6(a), the point cloud on the floor is extracted. The point cloud is placed on the XY plane in a 5-cm square grid, and the average value of the Z coordinate of the point cloud in the grid is calculated. Next, one grid is selected, as shown in Fig. 6(c), and the elevation based on the Z coordinate is compared with the surrounding grids of 11 × 11 cells. If the Z coordinate of the selected grid has the smallest value in the 11 × 11 cells, then that position is defined as the local minimum point.



(a) Point cloud on concrete floor

(b) Point cloud placed on 5-cm square pixel

(c) Comparison of Z-coordinate values with surrounding pixels

(d) Moving the pixel to be calculated

Figure 6. Calculation procedure of local minimum point position on concrete slab surface by point cloud data

The analysis results of the flatness of the concrete floor slab are presented in Fig. 7, which illustrates the inclination of the concrete slab towards the four drain covers. The positions and elevations of the local minimum point on the concrete slab are shown in Fig. 8.

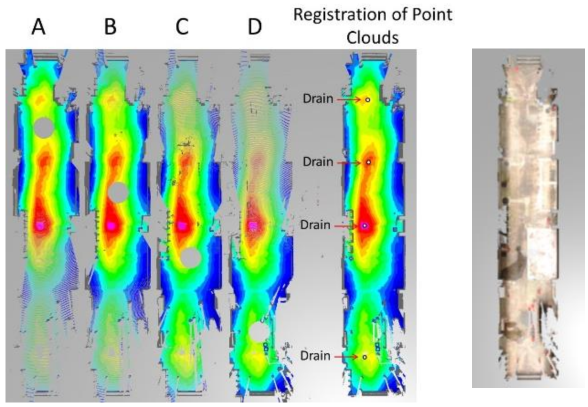


Figure 7. Measurement of concrete floor flatness using 3D point cloud data

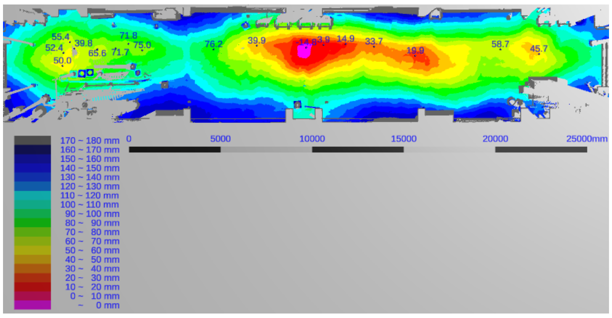


Figure 8. Positions and elevations of local minimum points on concrete slab extracted by point cloud data analysis

2.3.4 Point cloud data conversion into 3D surface model

The point cloud data shown in Fig. 4 were used to convert the point cloud into a 3D surface model through MeshLab [10]. The point cloud data consist of 6.67 million points, which were reduced to a density of point clouds at intervals of 2 cm. Thereafter, the point cloud data contained 525,000 points. Subsequently, the point cloud data were converted into mesh data. Furthermore, hole filling was performed using mesh data. Finally, the data compression process was conducted until the number of faces in the mesh data was 50,000.

2.3.5 3D Modeling of Underground Drains

We were unable to measure the shape of the drainage and sewer under the concrete slab using a 3D laser scanner. Therefore, the drain cover position from the point cloud data was extracted, and the shape of the drainage and sewer was estimated. Subsequently, a 3D model of the drainage and sewer was created using "Microsoft 3D Builder," as shown in Fig. 9.

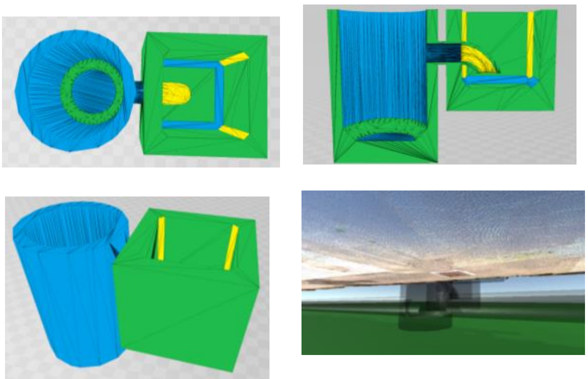


Figure 9. 3D modeling of underground drains by 3D Builder

2.3.6 Simulation Model for Analyzing Drainage Capacity

We created a 3D model and a simulation model to evaluate the drainage capacity. The 3D model contains four types of 3D shape data, as shown in Fig. 10.

(1) color point cloud
(2) fluid simulation area
(3) 3D surface of concrete floor surface
(4) 3D model of underground drains

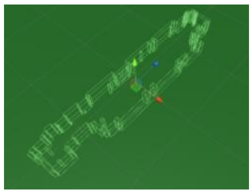
In this study, fluid flow simulations were performed using the NVIDIA FleX for Unity [11]. Therefore, a 3D object, which can engage with the fluid "particles", was used to convert the point cloud on the concrete floor into a 3D surface.

The 3D model of the drain was placed below the 3D surface of the concrete floor. Four holes on the 3D surface were created according to the position of the drain cover. Water particles flow through the holes in the drain cover into the 3D surface and move inside the 3D model of the drain.

The fluid simulation area is defined as a wall-shaped object. A 3D model with the wall-shaped object of the fluid simulation area is presented in Fig. 11. This area can prevent the flow of water particles from the periphery of the 3D surface.

In addition, a colored point cloud was employed to observe the dirt and water wet spots on the concrete floor.

(a) 3D point cloud



(b) Fluid simulation area

(c) 3D surface of concrete floor surface

(d) 3D modeling of drains

Figure 10. Four types of 3D shape data for evaluating water flow

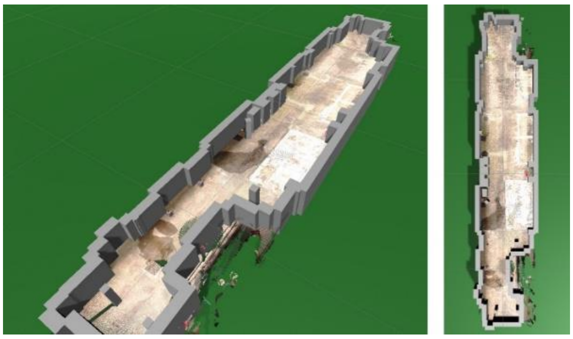
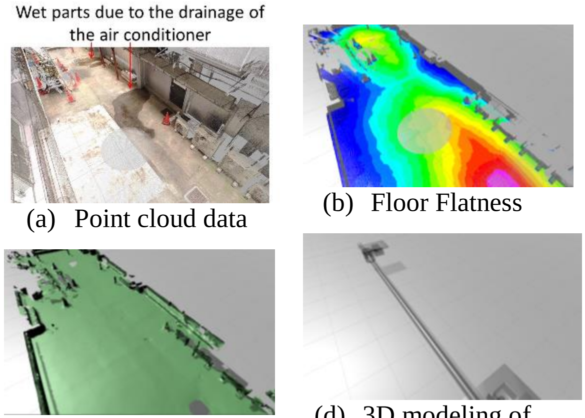


Figure 11. 3D shape data for analyzing drainage capacity

2.4 Verification of water particle movement on 3D surface model using a physics engine

The simulation model demonstrated in Fig. 11 was used to evaluate whether the water particles moved according to the principles of the physics engine. A part of the concrete slab measured in this study was wet due to water draining from the air conditioner, as illustrated in Fig. 12 (a). The water particles were generated according to the positions of the drainage of the air conditioner, thereby evaluating the water particle movement.



(a) Point cloud data

(b) Floor Flatness

(c) 3D surface

(d) 3D modeling of drains

Figure 12. Simulation model for verification of water particles movement using physics engine

The simulation was performed in Unity, and NVIDIA FleX was used to achieve water movement. The simulation for generating water particles in Unity and moving them onto the 3D surface is shown in Fig. 13. The water particles created by NVIDIA FleX for Unity in the 3D measurement model are shown in Fig. 14. The diameter of the simulated water particles is 0.03 m.

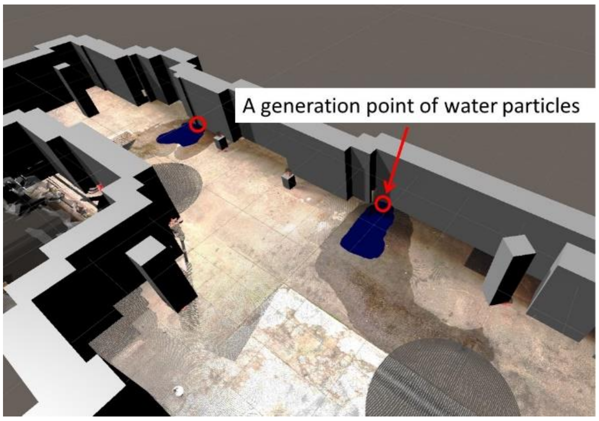


Figure 13. Simulation for predicting drainage flow

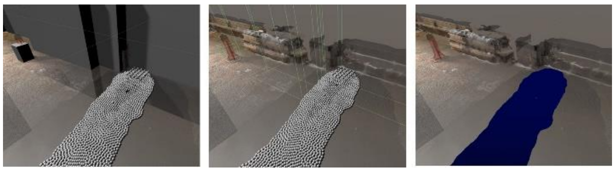


Figure 14. Water particles generation by NVIDIA FleX for Unity on 3D measurement model

The evaluation results of the drainage gradient using 3D measurement data and the physics engine are presented in Fig. 15. We confirmed that the water objects flowed on the wet parts of the concrete floor. Using the visualization data that analyzed the distance of each point from the horizontal plane and represented the distance in color, we confirmed that the water objects were flowing along the low positions of the concrete floor rather than on the surrounding area.

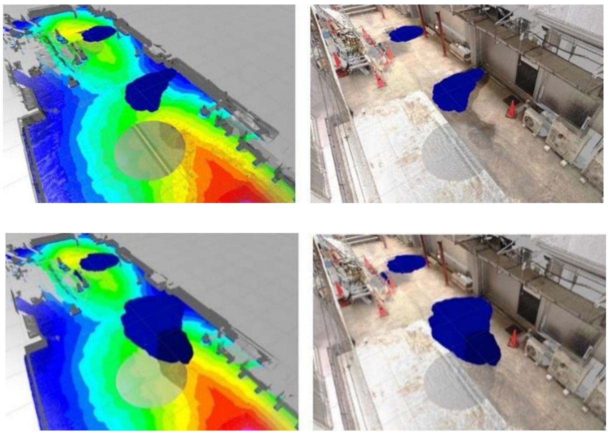


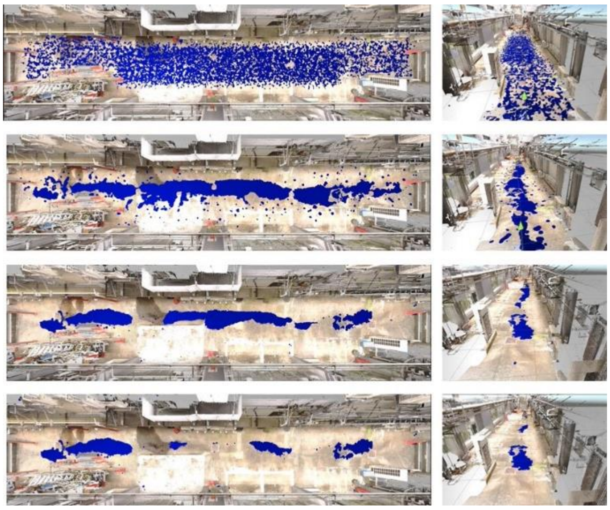
Figure 15. Drainage gradient evaluation result using 3D measurement data and physics engine

3 Results and Discussion

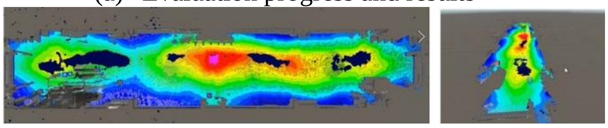
3.1 Evaluation of drainage capacity when water is uniformly generated.

A 3D measurement model was used to evaluate the drainage capacity. The results are presented based on a uniform distribution of water particles. Water particles with a diameter of 0.03 m are uniformly generated on the upper surface of the simulation model. The movement of these particles, according to gravity and their flow from the drain, was observed. The image in Fig. 16 (a) indicates that our system uniformly generated water particles.

These uniformly generated water particles on the concrete floor moved to a location with a lower elevation than the surrounding area. Thereafter, the water dropped into the drainage channel, reducing the amount of water on the floor. However, some water particles did not drain and instead remained on the concrete floor. The image in Fig. 16 (b) illustrates the accumulated water particles in the section where the gradient is low.



(a) Evaluation progress and results



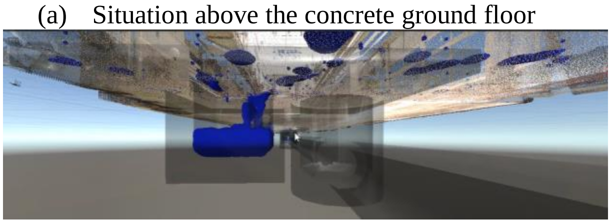
(b) Evaluation results and concrete floor flatness

Figure 16. Evaluation of drainage capacity when water is uniformly generated

3.2 Situation of drains and sewers under concrete floor slab

In the simulation (Fig. 16), it was observed that water particles flowed into the drain and through the sewer. As shown in Fig. 17 (a), the water particles flowed to the drain located above the concrete ground floor. Moreover, Fig. 17 (b) shows that the water particles flowed into the drain and sewer under the concrete floor slab.

(a) Situation above the concrete ground floor



(b) Situation of water particles flowing through drains and sewers under concrete floor slab

Figure 17. Water objects falling into drain

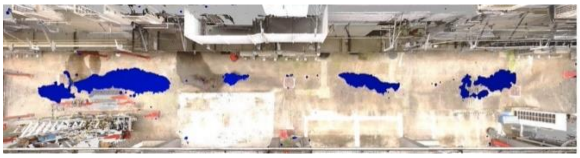
As shown in Fig. 18, the water particles were stored in a storm drain consisting of a catch basin and sand traps. It was confirmed that the water particles flowed into the sewer through the outlet trap when the catch basin was full.

Figure 18. Water particles accumulating in drainage drain and flowing into sewer pipe

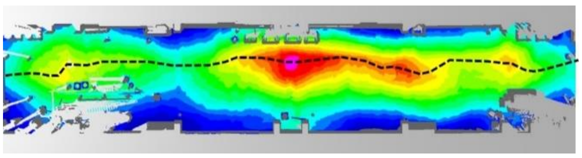
3.3 Verification of Drainage Capacity Analysis Results Using Actual Measurement Data

The simulation results of the drainage gradient were investigated using 3D measurement data and a physics engine. These were compared with the actual situation of floor drainage. First, the locations of the remaining water objects were compared with the unevenness of the concrete floor. The dotted line in the image in Fig. 19 (a) denotes the position of the valley line on the concrete floor. The figure shows that the water objects remain near the valley line of the concrete floor with a small slope value.

The locations of the minimum point elevation on the concrete slab are shown in Fig. 20. If the elevation is minimum at a 55 × 55 cm area, then this can be defined as the minimum elevation point. Considering the results shown in Figs. 19 and 20, it can be observed that water tends to remain at a point relatively lower than the surroundings.



(a) Drainage gradient evaluation results with point cloud data



(b) Concrete floor flatness and position of the valley line

Figure 19. Location of remaining water objects and valley line of concrete floor

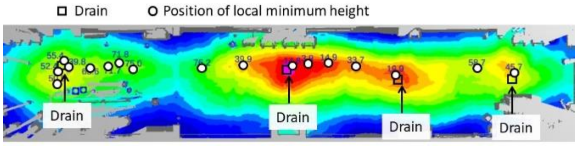


Figure 20. Position of local minimum elevation

The image on the left side of Fig. 21 depicts the condition of the actual concrete floor after the rain. The image on the right side represents the condition of the virtual concrete floor after the water particles have been drained. In observing the concrete floor state after the rain in the actual world, and based on the simulation results, it can be confirmed that water accumulates along the valley line portion, as shown in Fig. 19.

From Fig. 21, it was confirmed that the simulation results based on the measurement data were accurately analyzed to a certain extent.

Figure 21. Conditions of concrete floor after rain in actual world and after water particles are drained in virtual world

4 Conclusion

In this study, a 3D surface was created from the data obtained by converting point cloud data. The data representing the concrete floor contained 6.67 million points. However, the use of 3D surfaces reduced the number of faces to 50,000. The size of the concrete floor measured by the 3D laser scanner was 32.45 × 6.11 m, as depicted in Fig. 4. We reproduced the concrete floor, of an area of approximately 200 m², with a 3D surface composed of 50,000 faces. This 3D surface with a reduced data size was used to verify that the drainage gradients could be evaluated.

Furthermore, we reproduced the drainage and sewage channel under the concrete slab using a 3D model, which was used in combination with the 3D surface in the drainage simulation. It was confirmed that the water particles properly flowed inside the drains and sewers.

Ultimately, this study verified that the drainage gradient could be evaluated using a 3D measurement model and physics engine.

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