

# Field Implementation of an Automated Hydraulic Excavator Using ROS2-TMS for Construction and OPERA

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**Abstract**— We are developing a Cyber-Physical System (CPS) for earthwork sites, called ROS2-TMS for Construction, utilizing OPERA, an autonomous construction platform under development by the Public Works Research Institute. In this paper, as a case study of the system’s field implementation, we automated the loading of cohesive soil into a hopper during soil improvement work using a hydraulic excavator. Experimental results demonstrated that the system was able to dynamically determine excavation positions and achieve continuous operation for more than one hour. Furthermore, we conducted an additional slope-collapsing experiment using a hydraulic excavator, which demonstrated the applicability of the proposed system to diverse earthwork tasks.

## I. INTRODUCTION

The construction industry is one of the sectors with the highest number of occupational accidents, with fatal accidents also remaining at a high level. At the same time, in many developed countries, the number of construction workers is decreasing due to an aging workforce and insufficient inflow of new workers, leading to a serious shortage of skilled labor.

To address these challenges, we are developing a cyber-physical system (CPS) platform for earthwork operations, called ROS2-TMS for Construction [1][2][3], which aims

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to improve both efficiency and safety. ROS2-TMS for Construction is designed based on an informationally structured environment, and it can be regarded as an application of the Town Management System (TMS) [4] to construction domains. In this platform, various types of information from earthwork sites are collected and recorded through sensors installed on construction sites and machinery. Based on this collected environmental information and the construction plan, operation commands are generated for earthwork robots and construction machines, thereby enabling autonomous operation.

However, most construction machines do not disclose their internal specifications, which makes it difficult to ensure ROS (Robot Operating System) /ROS 2 compatibility. To address this issue, the Public Works Research Institute (PWRI) has been developing the Open Platform for Earthwork with Robotics and Autonomy (OPERA) [5]. OPERA standardizes control signals and adopts ROS/ROS2 as middleware to facilitate autonomous construction.

In this paper, as an example of field implementation integrating ROS2-TMS for Construction with OPERA, we report on the automation of cohesive soil loading into a hopper during soil improvement work using an OPERA-compatible hydraulic excavator based on the Hitachi Construction Machinery ZX200 (hereinafter referred to as “ZX200”). Using a 3D LiDAR installed at the site, excavation positions were dynamically determined, and continuous operation was successfully demonstrated.

In addition, we conducted a separate experiment in which the ZX200 was used to excavate a slope, demonstrating the applicability of the proposed system to diverse earthwork tasks.

## II. RELATED WORK

Research on construction automation has demonstrated the effectiveness of utilizing robots in construction sites [6], and its progress spans different levels, including overall site management as well as excavation planning and autonomous excavation focusing on hydraulic excavators.

Regarding overall site management, relatively few studies have been conducted in the robotics field. One example is Schöberl et al. [7], who integrated collaborative robots into a BIM-based digital construction management process and reported reduced construction time and improved safety

through cooperative work with excavators and vibration plates.

In terms of excavation planning, Zhao et al. [8] proposed a neural network-based task planner (Tasknet) that hierarchically decomposes excavation regions and operations to generate efficient task sequences, demonstrating near-human loading efficiency in real-world experiments. Furthermore, Terenzi et al. [9] proposed a hierarchical excavation planning framework that integrates navigation and soil handling, and demonstrated autonomous excavation planning under real-world site conditions. These studies can be regarded as efforts to enhance efficiency and autonomy by hierarchically planning and executing excavation tasks.

Meanwhile, research on autonomous excavation has also progressed. Egli et al. [10] proposed a reinforcement learning-based bucket-filling controller, which, after being trained in simulation, was applied to a real hydraulic excavator and demonstrated adaptability to varying conditions and performance comparable to skilled operators. Mori et al. [11] introduced human-in-the-loop reinforcement learning, where human feedback was incorporated to achieve site-ready path tracking within a short training time. These studies focus on improving the efficiency of excavation operations and enhancing adaptability to site conditions.

Based on these studies, excavation planning and autonomous excavation have made active progress, whereas research from the perspective of construction management remains limited. Moreover, studies that bridge both aspects and demonstrate the effectiveness of autonomous excavation in actual civil construction sites are still scarce. This study is characterized by structuring the entire site based on information collected from environmental sensors, and integrating task management through ROS2-TMS with machine control via the OPERA platform, thereby demonstrating autonomous excavation of soil mounds in real construction sites (soil improvement work). Furthermore, the CPS developed in this study can be applied to other tasks, such as slope excavation, by switching sensing processes, thus providing a versatile and practical foundation for earthwork operations.

### III. ROS2-TMS FOR CONSTRUCTION

#### A. Overview

ROS2-TMS for Construction is a CPS platform based on the concept illustrated in Fig. 1, and it manages construction sites by repeatedly executing the following cycle:

- 1) **Measure** – Collect environmental information from sensors installed on the construction site and on construction machinery.
- 2) **Analyze, Plan** – Construct a virtual representation of the site in cyberspace based on the collected sensor data, analyze the current state, and generate an action plan for the construction machinery.
- 3) **Control** – Compute the control commands required to execute the action plan and send them to the construction machinery.

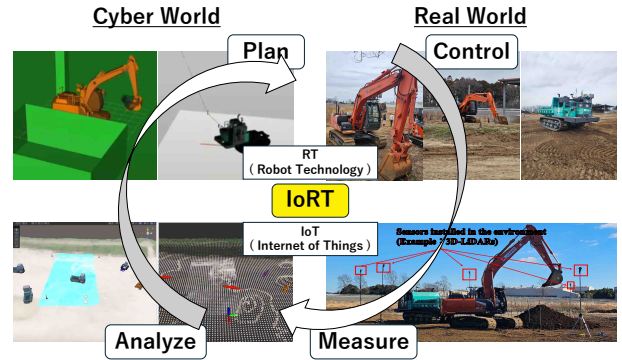


Fig. 1: Conceptual overview of ROS2-TMS for Construction.

ROS2-TMS for Construction has the architecture shown in Fig. 2. Each function is modularized as follows, and the overall system is formed through their interactions:

- **Database (TMS\_DB):** Responsible for writing to and retrieving from the database.
- **User Request (TMS\_UR):** Provides the interface with the user.
- **Task Scheduler (TMS\_TS):** Manages construction tasks.
- **Robot Planning (TMS\_RP):** Plans the motions of construction machinery (in this study, this corresponds to OPERA).
- **Robot Controller Module (TMS\_RC):** Computes the control commands for construction machinery (in this study, this corresponds to OPERA).
- **Sensing Processing (TMS\_SP):** Processes sensing data obtained from sensors.
- **Sensor Driver (TMS\_SD):** Sends sensor data to TMS\_DB.
- **Sensor System (TMS\_SS):** Preprocesses sensor data and transfers it to TMS\_DB.

For more details of ROS2-TMS for Construction, please refer to [2].

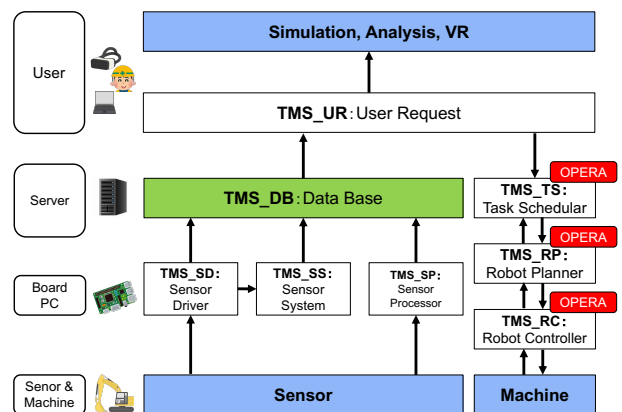


Fig. 2: Architecture of ROS2-TMS for Construction.

### B. Task Scheduler(TMS\_TS)

The Task Scheduler (TMS\_TS) is responsible for managing construction tasks. For task composition and execution, a behavior tree is employed, where the sequence of operations is represented as a tree-structured task sequence. An example of such a task sequence is shown in Fig. 3. The task sequence consists of multiple nodes called *subtask nodes*, which represent the smallest unit of a task.

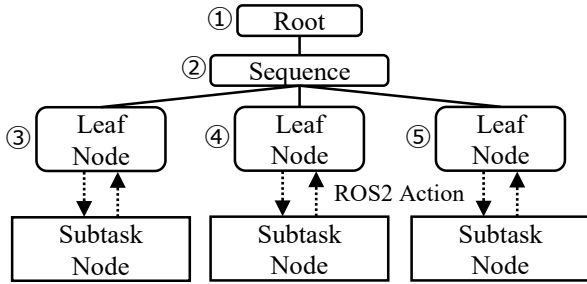


Fig. 3: Example of a task sequence created using a behavior tree, where numbers indicate the execution order.

## IV. THE OPEN PLATFORM FOR EARTHWORK WITH ROBOTICS AND AUTONOMY (OPERA)

The *Open Platform for Earthwork with Robotics and Autonomy (OPERA)* is an open platform being developed by the Advanced Technology Team of the PWRI to promote the development of autonomous construction technologies. OPERA is an open platform being developed by the Advanced Technology Team of the PWRI to promote the development of autonomous construction technologies. The system architecture of OPERA is shown in Fig. 4. OPERA consists of common control signals, real environments (electronically controlled construction machinery and experimental fields), simulators (virtual construction machinery and virtual experimental fields), middleware (ROS/ROS2), and applications such as self-localization. These components can be used to verify the operation of applications implemented on OPERA.

In this study, we used the ROS2 package set “zx200\_ros2” [12] for operating the ZX200.

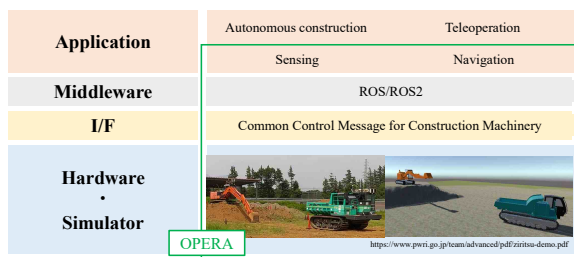


Fig. 4: Architecture of OPERA

## V. EXCAVATION AND RELEASE SUBTASKS FOR HYDRAULIC EXCAVATOR

In this study, the experiments with the ZX200 utilized four subtasks, as listed in Table I.

TABLE I: Manipulation subtasks for ZX200

Name	Operation
ChangePose	Move the excavator to the target pose.
Excavate_Plan	Perform only the planning of the soil excavation operation.
Excavate	Perform the soil excavation operation.
Release	Perform the soil releasing operation.

### A. ChangePose subtask

We define a virtual plane extending from the cutting edge to the bucket root, which we refer to as the *bucket cutting plane*. It receives either the target joint angles or the target position  $(x, y, z)$  together with the angle between the bucket cutting plane and the ground, and moves the excavator to the specified pose.

### B. Excavate\_Plan subtask

Since the excavation poses are primarily provided by the 3D LiDAR-based sensing, the motion planning may fail when an unreachable excavation pose command is given. Such failures need to be reported to the Behavior Tree, which manages the tasks, in order to modify the excavation pose and perform replanning. Therefore, a dedicated subtask is introduced that performs only the motion planning.

### C. Excavate subtask

The *Excavate* subtask, which performs the soil excavation, receives the excavation pose as a parameter.

Based on the operation of the excavator observed in manual operation by a human operator, the subtask was implemented as follows, as shown in Fig. 5a. This implementation enables a scooping excavation motion, which is expected to stabilize the excavation volume regardless of the shape of the soil mound:

- 1) For a given excavation pose:
  - +0.5 (m) forward in the horizontal  $(xy)$  plane relative to the excavator,
  - -0.5 (m) in the vertical  $(z)$  direction,
  - with the bucket tip angled toward the ground.
- 2) Move the arm and bucket in the closing direction to perform excavation.

### D. Release subtask

The *Release* subtask, which performs release operations such as loading soil into a crawler dump, takes the final bucket angle after release as a parameter.

When only the bucket angle is opened, the motion results in a throwing action that scatters soil not only at the specified location but also around it. Therefore, based on the operation of the excavator observed in manual operation by a human operator, the subtask was modified as follows, as shown in

Fig. 5b, in order to ensure that the soil is released only at the specified location:

- 1) Move only the bucket angle in the opening direction until the bucket tip faces downward toward the ground.
- 2) Move both the arm angle and the bucket angle simultaneously in the opening direction.

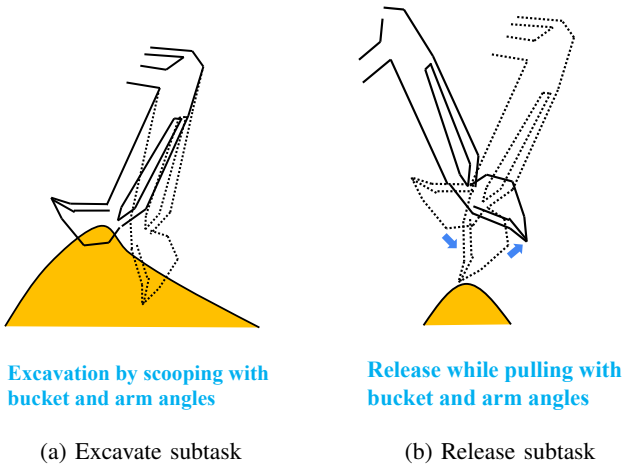


Fig. 5: Examples of the expected operation of the subtasks.

## VI. 3D LiDAR-BASED SENSING FOR EXCAVATION POSITION AND POSE DETERMINATION

In soil mound excavation using a hydraulic excavator, the excavation method varies depending on the shape of the mound. In this study, the shape of the soil mound was measured using a 3D LiDAR, and different excavation methods were implemented for the following two types of mound shapes.

### A. Soil mound excavation[13]

When performing soil mound excavation, a height map of the mound is generated from the point cloud measured by 3D LiDAR, and the highest point is calculated as the excavation point. In this process, the reachable range of the ZX200 is taken into account, and the calculation is performed within a cropped spherical region.

### B. Slope excavation

When performing slope excavation, the excavation pose is calculated from the point cloud measured by 3D LiDAR through the following procedure, as illustrated in Fig. 6.

- 1) Extract the point cloud corresponding to the ground region and only in the excavation direction from the ZX200.
- 2) Extract slope regions with an inclination greater than a predefined threshold.
- 3) (Only at the beginning or when the ZX200 has moved) Divide the excavation range laterally by half the bucket width and determine the excavation areas.
- 4) According to the priority of excavation areas, sequentially compute next excavation area from the unexcavated areas.

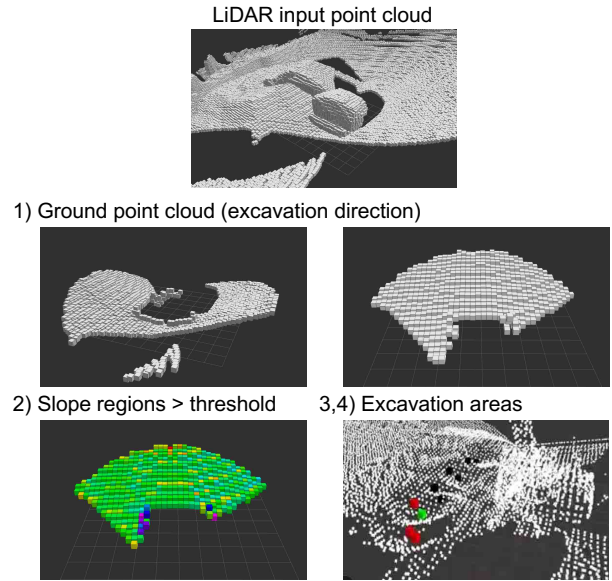


Fig. 6: Processing pipeline for slope excavation. Starting from the LiDAR input point cloud, excavation areas are computed through sequential processing. According to priority, the next excavation area (green) is selected from the unexcavated areas (black), while excavated areas (red) are continuously updated based on completion judgment. The slope inclination is stored in the intensity field and visualized for representation. For illustrative purposes, this figure also includes data obtained in a simulation environment.

At this stage, the area is judged to have been excavated based on (i) the change in the average height of the excavation area compared with the initial point cloud, and (ii) the disappearance of the point cloud in the excavation area for a certain period of time. After this judgment, the region is regarded as an excavated area. The latter condition is introduced to avoid false detection due to point cloud disturbance during excavation by the ZX200.

Furthermore, based on the calculated slope angle, the bucket angle relative to the ground is also adjusted, and the excavation pose is determined. Similar to soil mound excavation, the reachable range of the ZX200 is taken into account, and the calculation is performed within a cropped spherical region.

## VII. EXPERIMENT

### A. Field experiment for soil improvement work

1) *Field Environment:* The field experiment was conducted at a soil improvement site, as shown in Fig. 7. At this site, cohesive soil and sandy soil were mixed in a ratio of 0.29:0.71 to produce improved soil, which was then transported to another site. A series of operations were performed by multiple excavators and dump trucks working in cooperation. In Fig. 7, cohesive soil is loaded into the hopper at point (a), and sandy soil at point (b), by separate excavators. These soils are conveyed by belt conveyors, and at point (c), the improved soil is produced. The mixing ratio

of the soils is controlled by the speed of the belt conveyors. Therefore, to ensure efficient operation, it is necessary to keep the hoppers from running out of soil.

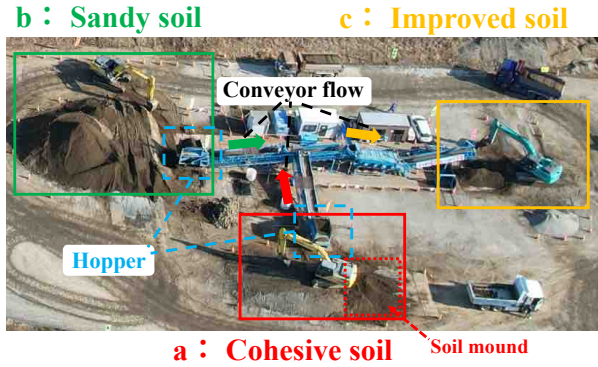


Fig. 7: View of a soil improvement site

2) *Experimental overview*: In this field implementation, automation was applied to the excavator responsible for loading cohesive soil into the hopper at point (a). The overall sequence of operations was as follows:

- The ZX200 excavates cohesive soil from the soil mound and loads it into the hopper.
- Dump trucks asynchronously supply cohesive soil to the mound (the ZX200 is stopped for safety during this process). Gathering and leveling of the soil are performed manually by another excavator under manned operation.
- Since the position and shape of the soil mound change each time due to the above processes, the excavation position is adaptively adjusted using 3D LiDAR.

In this experiment, as shown in Fig. 8, two 3D LiDARs (HAP, LIVOX) were installed to recognize the shape of the soil mound. Using the soil mound recognition described in Sec. VI-A, the excavation position was dynamically assigned to the ZX200, as shown in Fig. 9.

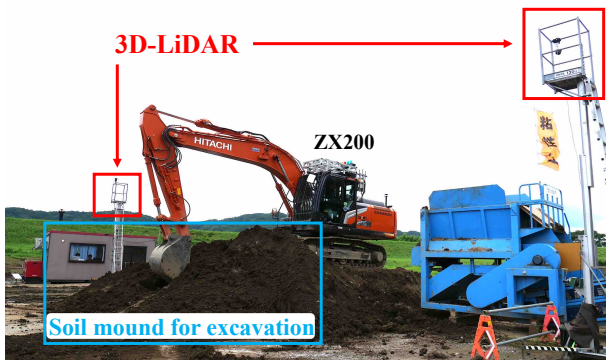


Fig. 8: View of the 3D LiDAR setup

3) *Task sequence based on construction plan*: In this field implementation, the following requirements had to be satisfied:

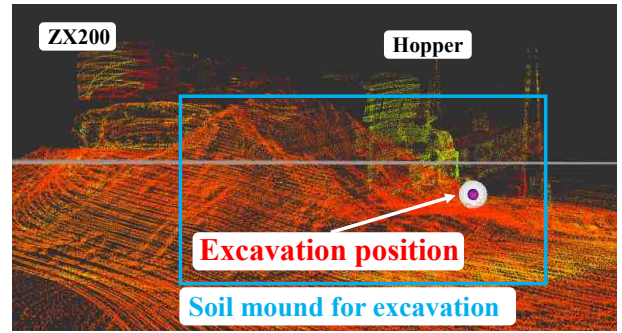


Fig. 9: Detection of soil mound and estimation of apex position

- When release soil into the hopper, the release timing must be adjusted depending on the soil volume inside the hopper.
- From a safety perspective, the ZX200 must stop its operation if crawler dumps or manually operated excavators move within its slewing radius.

Based on these construction requirements, a task sequence was designed as shown in the behavior tree of Fig. 10, which was used for automation. The flags utilized in the task sequence are defined as follows:

- **Continue flag**: Manages the continuation of construction work.
- **Excavation flag**: Manages the execution of excavation.
- **Release flag**: Manages the execution of release.
- **Bucket loading flag**: Manages the detection of soil loaded inside the bucket.

4) *Trajectory planning considering obstacles*: In this experiment, trajectory planning had to be performed to avoid static obstacles, such as the hopper. The hopper was set as an obstacle, and trajectory planning was carried out using MoveIt 2, enabling the ZX200 to operate while avoiding the hopper.

5) *Experimental results*: The operation sequence is shown in Fig. 11. As a result of the experiment, continuous operation for 1 hour was successfully achieved while dynamically changing excavation positions. During the total working time of five hours on the day of the experiment, including this one-hour continuous operation, the excavated soil amounted to 84 t, corresponding to a volume of 44.76 m<sup>3</sup>. For safety and experimental reasons, continuous operation for the total working time of five hours was not performed. However, since the operation time per excavation-to-release cycle was approximately 90 s and the bucket capacity was 0.7 m<sup>3</sup>, the theoretical excavation capacity can be calculated as follows:

$$\frac{1 \text{ cycle}}{90 \text{ s}} \times 3600 \text{ s/h} \times 0.7 \text{ m}^3/\text{cycle} \approx 28 \text{ m}^3/\text{h} \quad (1)$$

As a reference, the target excavation volume for a manually operated excavator is approximately 500 m<sup>3</sup>/day. Considering that automation enables 24 hours continuous operation, it was demonstrated that the proposed system could

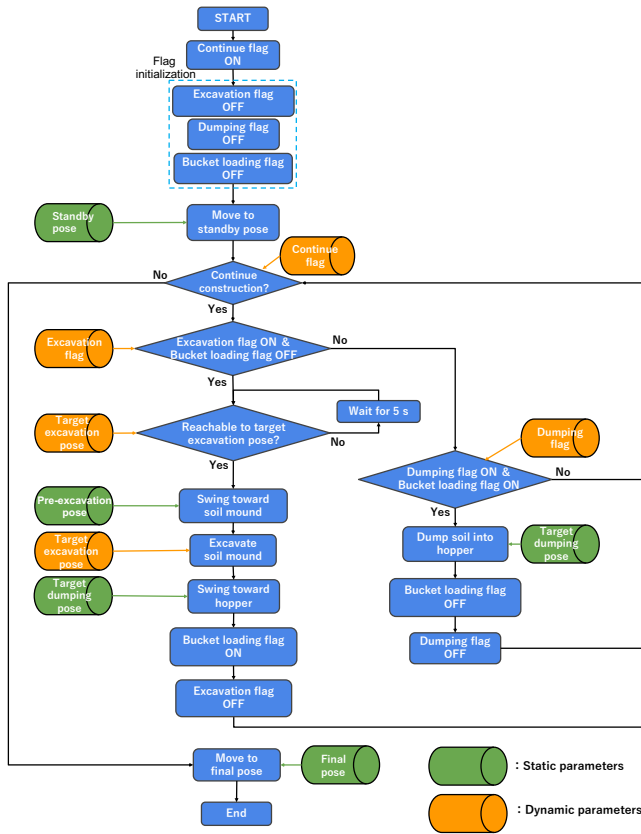


Fig. 10: Task sequence based on construction plan

achieve about 1.3 times the daily excavation volume of a human operator, as shown below:

$$\frac{28 \text{ m}^3/\text{h} \times 24 \text{ h}}{500 \text{ m}^3/\text{day}} \approx 1.3 \quad (2)$$

Furthermore, the subtasks described in Sec. V were successfully realized as planned.

6) *Discussion*: In this implementation, the joint angular speed was limited to an average of 0.2 rad/s, resulting in a longer cycle time of approximately 90 s, but the system still demonstrated the potential to exceed human productivity. In manual operation, the excavation-to-release cycle is completed in approximately 30 s. Considering this, if the same speed were applied to the automated system, the theoretical excavation performance would be about four times higher than that of human operation. To realize such high efficiency in practice, future experiments with higher-speed operation will be necessary. Moreover, since each motion within the subtasks introduced in Sec. V-C and V-D performs goal checking independently, short delays occur between successive motions. By seamlessly connecting these motions, further improvements in efficiency can be expected. In addition, for safety reasons, the task used in this experiment included redundant turning motions between the excavation subtask and the release subtask. In the future, it will be necessary to improve the control strategy so that safety is maintained without compromising efficiency.



Fig. 11: View of the experiment

## B. Slope excavation experiment

1) *Experimental overview*: We conducted slope excavation experiments to verify the performance of the excavation process shown in Sec. VI-B. In the experimental environment of Fig. 12, the ZX200 remained stationary while repeatedly performing a sequence of operations: excavating a slope and release soil at a fixed release point. The task sequence was similar to that of Fig. 10, but no flags were introduced for managing excavation and release.

2) *Experimental results*: The experimental results are shown in Fig. 13, demonstrating that the system was able to automatically determine whether excavation had been completed, assign the next excavation point, and perform excavation adaptively. When the area indicated as the next excavation area (green) is excavated, it is updated to the excavated area (red), and a new next excavation area (green) is assigned. In this way, the system can proceed with excavation sequentially.

3) *Discussion*: In this experiment, it was confirmed that the proposed system can be applied to slope excavation simply by modifying the sensing process, demonstrating



Fig. 12: View of the experiment environment

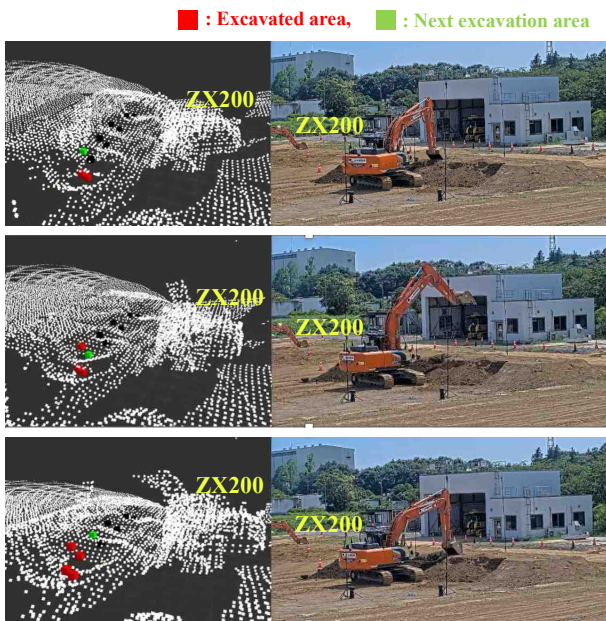


Fig. 13: Experimental results. It can be observed that as the excavation progresses, the region is successively regarded as the excavated area and the operation moves on to the next excavation area.

its versatility. However, with the current set of subtasks, the system cannot fully address situations specific to slope excavation, such as gathering collapsed soil generated during the excavation process. By introducing additional subtasks to handle such situations, the system can be extended to flexibly adapt to a wider range of earthwork scenarios, including slope excavation.

## VIII. CONCLUSION

In this study, as the first field implementation integrating ROS2-TMS for Construction with OPERA, we automated the task of loading cohesive soil into a hopper using the ZX200 during soil improvement work. By utilizing 3D LiDAR installed at the site, excavation positions were dynamically determined, and continuous operation for 1 (hour) was successfully demonstrated. Furthermore, by adapting the 3D LiDAR-based sensing for excavation position and pose determination according to the shape of the excavation area,

we demonstrated that the system can autonomously perform excavation in a generalized manner.

In the future, we aim to achieve fully automated field implementation by introducing additional subtasks for gathering and leveling soil, which were not automated in the present experiment. Furthermore, by conducting detailed analysis of excavator operations under manned control and incorporating feedback from operators, we plan to realize more efficient excavation and release motions.

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