DEVELOPMENT OF SOIL COMPACTION ANALYSIS PROGRAM BASED ON VARIOUS GIS ANALYSIS METHODS

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ABSTRACT: Soil Compaction Analysis (SCAN) program has developed to assess compaction states by modeling trajectory of a roller and analyzing data from sensors attached on the roller. SCAN program is distinguished from previous software for intelligent compaction (IC) that it operates on using a low cost GPS receiver, and has an optimal structure for managing large data gathered from many rollers remotely. For this research, positioning results from the low cost GPS receiver were optimized through developing some spatial object models to model the roller trajectory and joining them with sensed data, and using many filters. Methods used to analyze the vibrating roller's trajectory and compaction states were the overlay analysis method and least square collocation. SCAN program was verified through some field compaction data tests, and was shown to be very effective in evaluating field compaction states.

1. INTRODUCTION

Soil compaction represents a significant portion of construction budgets, and is very important to the performance and stability of soil structures. However, the required compaction level is difficult to achieve due to heterogeneity of earth materials, variations in equipment and operators, and difficulty in maintaining uniform lift thickness and moisture content. Generally, static or vibrating rollers have been used for compaction work. This process often leaves unevenly compacted earthwork area that a certain part of the area is sufficiently compacted, and the rest is over-compacted or insufficiently compacted. The quality assurance process is also very time consuming and inefficient. However, these are still commonly used as the methods of quality control for the soil compaction.

This research focuses on the application program for the soil compaction analysis which takes a part in the IC process. These programs support functions for analyzing compaction information from sensors of a compaction roller by linking GPS positioning results and helping workers access to the sufficiency of compaction. SCAN is designed to be used as a part of the IC system, which works as a module for analyzing compaction data. Advanced features of SCAN is distinguished from other commercial programs for its functions for utilizing low cost GPS receiver and adequate structure for monitoring many rollers.

Existing IC systems uses high priced GPS equipment supporting RTK (real time kinematic) positioning, and its analysis software is largely depended upon the positioning results from the GPS equipment, so it uses the results from the GPS equipment without any processing. These limitations lead to raising the price of the positioning part of the entire IC system. SCAN supports not only RTK positioning, but also SBAS (satellite based augmentation system) positioning and SPP (single point positioning). This makes it possible to adopt low cost of the GPS equipment to the IC process. The KF (kalman filter) which uses velocity calculated from a GPS receiver as a control variable and other filters are adopted to utilize the low cost GPS receiver. In this paper, these major functions and features of SCAN and description of development methodology for the compaction analysis software of the IC are discussed as well.

2. MAIN PROCESS OF SCAN

SCAN is designed to be used as a software module for analyzing soil compaction data on the monitoring system and tablet PC on a roller. The process of primary data processing and algorithms configuring of each step are composed of 3 steps. The purpose of this process is to analyze data from multiple rollers quickly and to minimize error range of the low cost GPS receiver.

The main process includes three steps: 1) generating point-type spatial objects by converting and integrating data from GPS and Compactometer mounted on a roller; 2) converting point-type data to continuous quadrangle cell-type spatial objects and building a spatial index; and 3) producing compaction results through statistical and spatial analysis.

In Step 1), GPS coordinates are filtered by three filters, GVKF (GPS velocity based on kalman filter), smoother, and distance filter, to reduce errors on GPS coordinates and to make it easy to generate continuous quadrangle cell. Then, filtered GPS data and Compactometer data are integrated on the basis of time to be converted into point-type spatial objects. In Step 2), using properties of point objects, 2-D coordinates, grid azimuth and time, the movement of a roller is analyzed and continuous quadrangle cells are generated. These cells can model the roller's continuous path of movement very well and includes every datum gathered by the GPS and Compactomter to be adequate for soil compaction analysis. Finally, spatial indexes are generated for cells for fast data finding and analyzing. In Step 3), some spatial analysis is performed using cell objects to get analysis results for investigating compaction status of the ground. Then, final result with analysis result of the whole area is calculated by least square collocation.

3. METHODS FOR SOIL COMPACTION ANALYSIS

Many methods were used to realize SCAN process. They can be divided into three categories -filtering, spatial object modeling and spatial analysis - and a description of them are as follows.

3.1 Filtering

In this study, three types of filters were used to remove gross errors and to obtain correct GPS coordinates. First, GVKF was used to improve the GPS positioning results using the velocity and true azimuth calculated by the Doppler phenomena of the GPS carrier. Second, a least squares smoother with first-order to third-order polynomials was used to remove residual gross errors occurring whenever the positioning data deviated from a smoothed polynomial line generated from adjacent GPS positions. Third, a distance filter was employed to set the minimum distance and create spatial objects with quadrangle cells more effectively. Table 1 shows the filters used to manage GPS coordinates in SCAN and their related values.

Table 1. Filters used for improving GPS positioning results

Order	Applied filter	Used data	Function
1	GVKF (GPS velocity based kalman filter)	2-D coordinates, time, velocity, grid azimuth, HDOP	Accuracy improvement and gross error detection
2	Smoother	2-D coordinates	Residual gross error detection
3	Distance filter	2-D coordinates, time	Maintaining minimum distance between adjacent two points for effective spatial modeling of roller trajectory

3.2 Spatial object modeling

Two types of spatial object models were used for modeling vibrating roller's continuous trajectory and analyzing compaction states of ground. The filtered data converted to point objects include following properties that are: 3-D position, velocity obtained from GPS, and compaction properties such as degree of compaction, CMV, RMV, and vibration frequency of the roller. Next, the point objects were converted to continuous quadrangle cell objects having all properties of point objects. Fig. 4 shows the converting and creating processes of spatial object models.

Fig. 1 shows the algorithm of converting point objects to cell objects using two steps. First, the azimuth angles perpendicular to connect lines between the first and second point, and between the second and third point were calculated. Next, averaged two azimuths to determine the azimuth of the second point were configured. This process was iterated to calculate each azimuth for every point.
Lastly, two points that were located half-width of the roller drum away from the center point were calculated. Then, continuous quadrangle cell objects were created by connecting these points with adjacent points. The properties of each cell were calculated by averaging the properties of the adjacent two points.

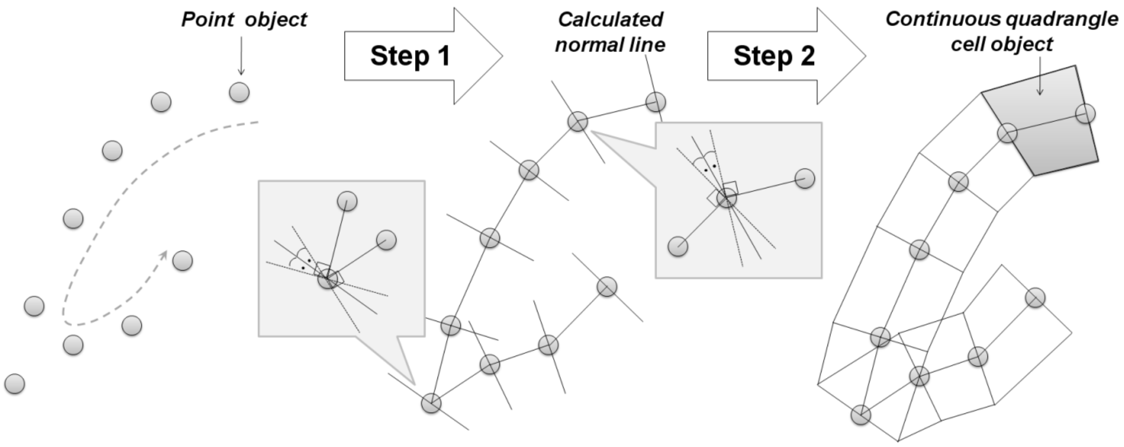

Fig. 1. Algorithm for converting point objects to continuous quadrangle cell objects

3.3 Spatial analysis

GPS and compaction sensors mounted on a vibrating roller can produce at least 3,600 positions and compaction relating data per hour. To treat this quantity of data quickly and effectively, an appropriate spatial index and processing method was required for an analysis.
In this study, a simple grid index, which is frequently used for spatial indexing of earth observation data, was employed to realize continuous cell objects widely distributed over a large area (Kevin et al, 2003). Overlay analysis, general method used in the GIS analysis, was also employed in SCAN.

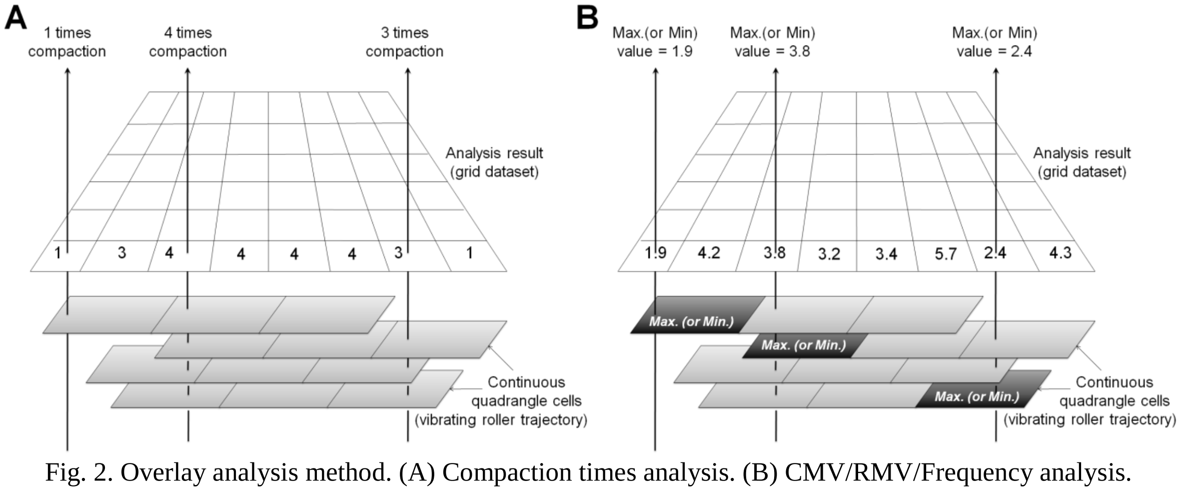

Fig. 2. Overlay analysis method. (A) Compaction times analysis. (B) CMV/RMV/Frequency analysis.

Fig. 2 shows the concept of the overlay analysis method developed in this study. The first step was to make a grid type data set covering the entire analyzing domain, and to search vertically-superposed cells on each grid position. A number of superposed cells represent a number of vibratory roller passes, and minimum or maximum values of the compaction properties in overlaid cells can be chosen for analyzing compaction states of the ground.
Least squares collocation was used to produce reasonable compaction results for the entire earthwork area by considering correlation among adjacent values to even data distribution, to interpolate data for areas of no data, and to prevent gross errors

4. FIELD TESTS AND RESULTS

SCAN was evaluated from the processing sample data and test operation of monitoring software in terms of accuracy of analysis, capability for processing low cost GPS data, and processing speed to manage multiple roller data in real time.

4.1 Analysis accuracy tests

Sample data gathered from 5 different sites (A, B, C, D, E) were processed to verify the accuracy of analysis from SCAN. The results show that the roller's continuous motions were modeled very accurately from the continuous quadrangle cells, and compaction times were analyzed accurately by overlay analysis methods.

Fig. 3 shows analysis results of the number of roller passes, compaction properties, CMV, RMV, and vibration frequency using data from a roller at site E. Especially, Fig. 11B shows the CMV and relative degree of compaction obtained from the Compactometer. The CMV of the area through which the roller had passed at least four times was generally greater than the CMV of the other areas. Thus, the number of passes, the vibration frequency, the CMV varying from 0 to 80, and the RMV varying from 0 to 4 were effectively displayed by SCAN in order to characterize the state of roller compaction at site E.

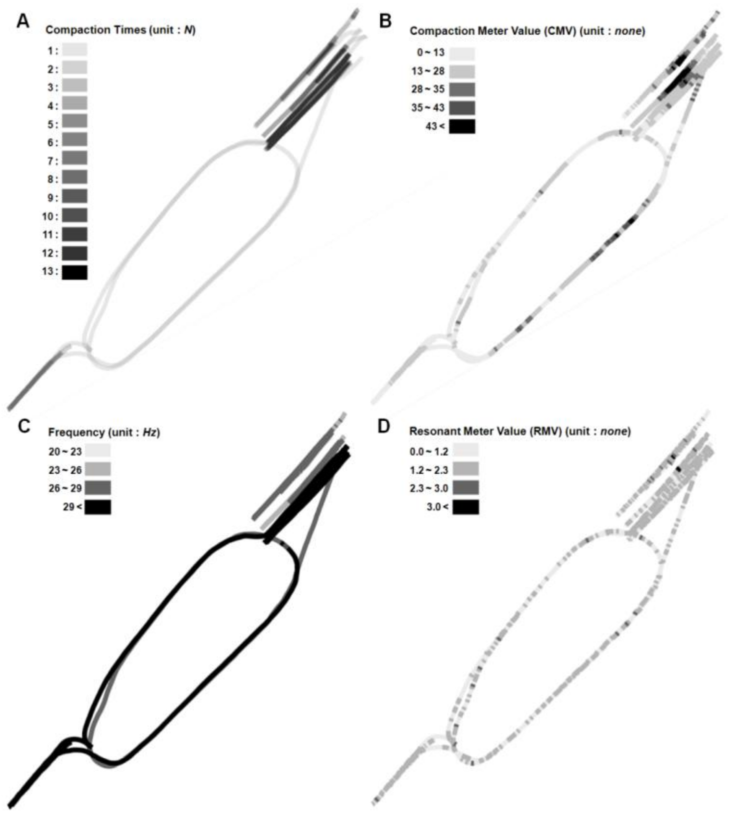

Fig. 3. Field data analysis results at site E. (A) Compaction times from GPS data only. (B) Compaction meter value (CMV). (C) Vibrating frequency (D) Resonant meter value (RMV). The values of (B), (C) and (D) were obtained from the combination of GPS and Compactometer data.

4.2 Low-cost GPS measurements utilization tests

GVKF and SCAN's capability was tested and evaluated for its improvement of positioning accuracy and analysis of compaction properties obtained by a roller trajectory modeling with a low cost GPS receiver. For this evaluation, two tests were performed: 1) a utilization test for GVKF capability to improve positioning accuracy of the result provided by the low cost GPS receiver used by the SPP and SBAS signal mounted on a moving vehicle, and 2) a utilization test for SCAN (with GVKF), analyzing the roller trajectory and compaction properties from the roller's low cost GPS results which result in precise compaction control work of the IC under similar compaction work environments.

Fig. 4A shows raw SPP and SPP with GVKF positioning results plotted in the form of points, and Fig. 4B shows the trajectory width of compaction roller modeled by each positioning result according to the roller's path. Also,

Fig. 5A and 5B presented the same content on each of raw SBAS and SBAS with GVKF positioning methods to those of Fig. 4A and 4B respectively.

It was found in Table 2, Fig. 4B and 5B that compaction analysis results generated from raw SPP data are inadequate for both simple IC work like compaction times monitoring and precise compaction control work of IC. However, it is shown that the compaction analysis results generated from GVKF-filtered SPP results could be used for compaction times monitoring.

Conversely, the compaction analysis results generated from all SBAS results (raw and GVKF-filtered) were very similar to those from RTK results. Therefore, it was possible to use the raw SBAS results (without GVKF) directly for both simple and precise compaction control work of IC. However, the accuracy of unfiltered SBAS positioning results can be degraded in bad GPS signal reception environment, and gross error in positioning results can seriously affect the compaction analysis. Therefore, it is more stable to use GVKF-filtered SBAS results for more precise compaction analysis.

Table 2. Statistics of positioning differences of various positioning methods with based on RTK results in test compaction site.

Positioning Methods	**raw SPP (unit : m)**	**SPP with GVKF (unit : m)**	**raw SBAS (unit : m)**	**SBAS with GVKF (unit : m)**
MIN	-1.611	-0.690	-0.346	-0.325
MAX	1.668	0.856	0.424	0.505
MEAN	-0.009	-0.009	-0.011	0.003
Std. dev.	0.487	0.255	0.127	0.117

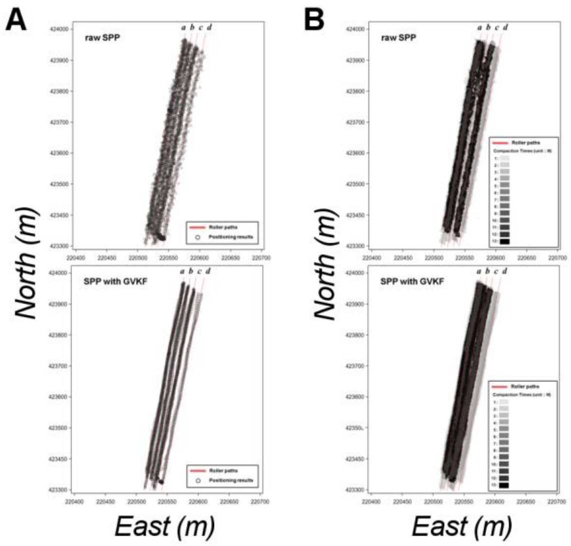

Fig. 15. Utilization test results of SCAN capability for precise compaction analysis using SPP. (A) Point positions from raw SPP (upper) and SPP with GVKF (lower) positioning method. (B) Compaction times analysis by SCAN on each of positioning methods.

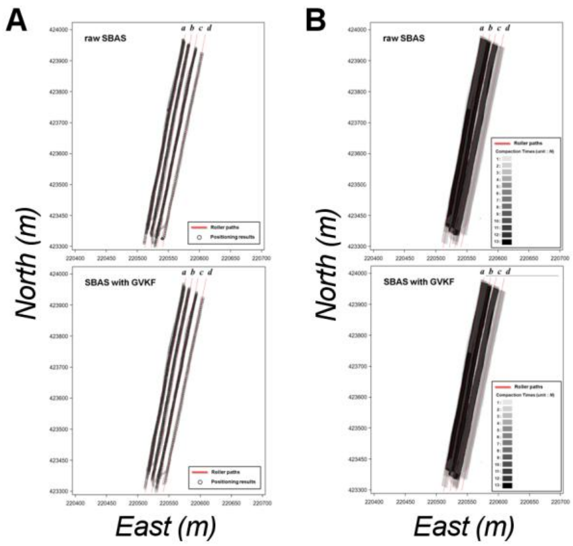

Fig. 16. Utilization test results of SCAN capability for precise compaction analysis using SBAS. (A) Point positions from raw SBAS (upper) and SBAS with GVKF (lower) method. (B) Compaction times analysis by SCAN on each of positioning methods.

5. CONCLUSIONS

In this study, a software module, SCAN, was developed as an effective analysis tool to evaluate the compaction state of the ground for the IC work. A process composed of many methods was developed for very accurate analysis and utilization of a low cost GPS and of SCAN with GVKF. From the results of this study, the following conclusions are drawn:

A spatial object based on a continuous quadrangle cell is very effective in modeling trajectory of rollers and compaction properties during compaction. Modeling spatial objects with appropriate filters and topology structures makes the adoption of various GIS analyzing methods more convenient.

It is possible to utilize low cost GPS for the IC work by applying filters to improve positional accuracy and to remove gross errors. Especially GVKF – a main filter - works well to improve the GPS positioning results without any external sensors. By using filters included in SCAN. The SPP results can be used for a simple IC work like compaction times analysis and SBAS results can be used for the IC work that requires higher level of precision.

Overlay analysis and spatial indexing based on GIS analyze more effectively since the data of continuous quadrangle cells are adequate to display the state of roller compaction in the field. These analysis method and structure are able to process data from multiple rollers in real time because their processing speed is fast enough to support the real time compaction state analysis work.

For further study, new spatial indexing method adequate for continuous cell object array needed to be developed to reduce processing time for soil compaction analysis.

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