Evaluation of ground stiffness using multiple accelerometers on the ground during compaction by vibratory rollers

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Abstract –

Soil compaction is one of the most important basic elements in construction work because it directly affects the quality of structures. Compaction work using vibratory rollers is generally applied to strengthen ground stiffness, and the method that focuses on the number of compaction cycles is widely used to manage the ground stiffness by vibratory rollers. In contrast to this method, the continuous compaction control (CCC) using accelerometers installed on the vibratory rollers has been proposed as a quantitative evaluation method more suited to actual ground conditions. This method quantifies the distortion rate of the acceleration waveform of the vibratory roller. However, this method based on acceleration response has problems in measurement discrimination accuracy and sensor durability because the accelerometer is installed on the vibration roller, which is the source of vibration. In this paper, we propose a new ground stiffness evaluation method using multiple accelerometers installed on the ground surface. The proposed method measures the acceleration response during compaction work by vibratory rollers using multiple accelerometers on the ground surface. Experiments show the proposed method has a higher discrimination than the conventional methods.

Keywords –

Vibratory rollers, Ground stiffness evaluation

1 Introduction

Vibratory rollers are used for compaction to strengthen the ground stiffness. To manage the ground stiffness using vibratory rollers, the number of compaction cycles is widely used as a compaction work management method.

In contrast, the continuous compaction control (CCC) method utilizing acceleration response during compaction has been proposed as a quantitative evaluation method that reflects actual ground conditions [1] [2] [3] [4] [5]. This method uses accelerometers installed on a vibratory roller to quantitatively evaluate changes in ground stiffness owing to compaction. Performance was compared between CCC measurements and location-specific in-situ test results. By including the effect of moisture content using multivariate regression, the consistency between the CCC and in situ test data sets was higher than without inclusion [6].

This method uses the phenomenon in which the acceleration waveform of a vibratory roller is disturbed as the stiffness of the compacted soil increases and quantifies the distortion rate of the waveform. This phenomenon is caused by the vibratory rollers bouncing up and impacting against the stiffened ground.

However, this method based on acceleration response has problems in terms of measurement discrimination accuracy and sensor durability because accelerometers are attached to the vibratory rollers that are the source of vibration.

This paper proposes a ground stiffness evaluation method with a higher discrimination than that in the conventional method using multiple accelerometers installed on the ground surface to measure the acceleration response during compaction by a vibratory roller.

In the experiment, the embankment was compacted using a vibratory roller, and the acceleration signals of the ground surface vibration were measured during compaction using accelerometers installed on the ground (proposed) and on the vibratory roller (conventional). The compaction control value (CCV) [7] was used as an index to evaluate the ground stiffness. The CCV obtained by the proposed method which utilizes the multiple accelerometers on the ground was compared with the conventional CCV obtained by the accelerometer on the vibratory roller. In addition, the coefficient of the ground reaction force was measured using a light falling weight deflectometer (LFWD) test and its relationship with the

CCV obtained using the proposed method was also verified.

2 Background

CCC (or the acceleration response method) uses an acceleration sensor fixed to the main body of a vibratory roller to estimate the degree of ground compaction from the acceleration waveform during the compaction process. The phenomenon used in this method is that when compaction by the vibratory roller progresses, a spectrum appears in the amplitude spectrum of the acceleration waveform at a frequency other than the fundamental frequency of the compaction by the vibratory roller.

This phenomenon is considered to be caused by a vibratory roller bouncing up against a rigid ground and impacting it [8]. CCC evaluates the ground stiffness by calculating the spectral turbulence using the compaction meter value (CMV) [1], the resonance meter value (RMV), CCV [5], etc., which calculates turbulence ratio based on the ratio of the spectra at multiple vibration frequencies. CCC can manage the compaction condition in 2-dimensions by combining the obtained spectral disturbance with the positional information obtained by the GNSS installed on the vibratory roller.

However, this conventional method has a problem with measurement discrimination accuracy, particularly in soils with a high water content. In such cases, the spectral turbulence becomes unclear, and evaluating the degree of compaction is often difficult. In addition, because the accelerometer is installed at the vibration source, the measured values contain a significant amount of noise. Furthermore, the proximity of the sensor to the vibration source can cause the sensor to malfunction.

The ground stiffness evaluation method proposed in this study is similar, in that it is based on the amplitude spectrum ratio of the acceleration waveforms. The difference is that the multiple accelerometers are installed on the ground. The installation of the accelerometers on the ground reduces sensor failures and the signal-to-noise ratio; this is expected to improve the measurement discrimination accuracy.

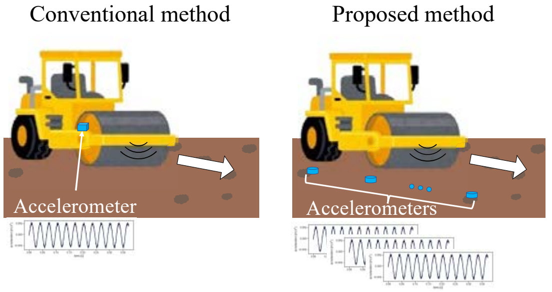


Figure 1. Comparison image of the conventional method and the proposed method

Figure 1 shows the comparison image of the conventional method and the proposed method.

3 Evaluation method

In this study, the ground stiffness during compaction by a vibratory roller is evaluated by integrating the vibration data obtained from several distributed accelerometers on the ground. The vibration data from each sensor are obtained as triaxial acceleration signals corresponding to the operation of the vibratory roller.

The Z-axis is vertical to the ground, and the X-Y axis is horizontal to the ground. This study uses only the X-Y-axis component that is stably obtained because the Z-axis signal is suppressed when the wheel of the vibratory roller passes over the ground.

First, the short-time Fourier transform (STFT) is applied to acceleration signals $a_{i,x}$, $a_{i,y}$ in the X-Y axis at the i-th sensor ($i = 1 \ldots N$) (N is the total number of sensors) to obtain spectrogram $S_{i,x}$, $S_{i,y}$. Next, composite spectrogram $\widetilde{S_i}$ is calculated as follows:

$$\widetilde{S_i} = \sqrt{S_{i,x}^2 + S_{i,y}^2} \tag{1}$$

As explained above, ground stiffness is estimated using the obtained composite spectrogram, $\widetilde{S_i}$. In the evaluation of ground stiffness based on the roller acceleration response, the acceleration waveform is known to be disturbed as the ground stiffness increases.

Unlike conventional methods that directly measure acceleration signals of the vibratory roller, which is a vibration source, this study measures the acceleration signals of vibrations propagating on the ground surface. This method is expected to reduce the signal-to-noise ratio. In this study, CCV [7], defined by the following equation, is used as the ground stiffness index.

$$\mathrm{CCV}(S) = \frac{s_0' + s_1' + s_1 + s_2' + s_2}{s_0' + s_0} \times 100 \tag{2}$$

s_0 denotes the fundamental component corresponding to oscillation frequency of spectrogram S (the vibratory roller frequency), s_n denotes the high-frequency component corresponding to $n + 1$ times the frequency, and s_n' is the $1/2$ fractional harmonic component corresponding to $n + 0.5$ times the frequency. As the ground stiffness increases, high-frequency and fractional harmonic components dominate, and the CCV increases owing to turbulence in the acceleration waveform. Finally, the CCVs obtained from N sensors are averaged.

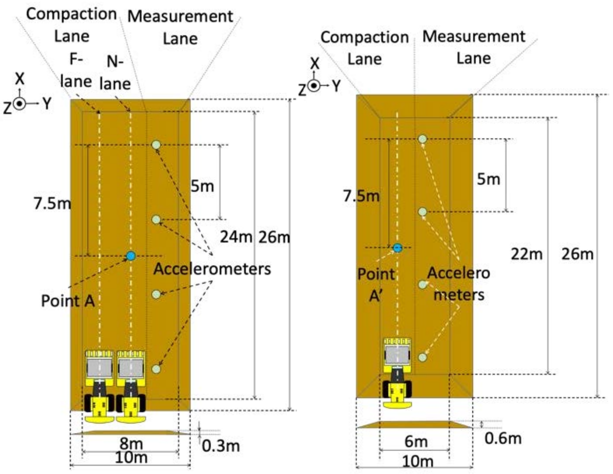
$$\mathrm{CCV} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{CCV}(\widetilde{S_i}) \tag{3}$$

4 Experiment

4.1 Experimental setup

In this study, an embankment was used as the experimental environment. The ground rolling experiment was conducted at an outdoor test site located on the Ito campus at Kyushu University. The experiment was conducted using a vibration roller (SAKAI, SV512D V) and high-sensitivity 3-axis accelerometers (Onosokki, NP-7310).

In the experiment, compaction and measurement lanes were prepared on the embankment. Accelerometers were placed at 5 m intervals at the top of the embankment, and a vibratory roller ran along the compaction lane. The compaction experiments were conducted on two layers (1st and 2nd layers). In the 1st layer, there were two compaction lanes: the F-lane far from the accelerometers and the N-lane close to them. Figure 2 shows the arrangement of the accelerometers and dimensions of the embankment on each layer, and Figure 3 shows the experimental conditions. The experiments were conducted as follows.



(a) 1st layer (b) 2nd layer

Figure 2. Arrangement of accelerometers

Figure 3. Experimental setup in the outdoor field

(1) A 0.3 m thick layer of soil was spread onto a well-compacted base. (1st layer)

(2) The soil was rolled 12 times back and forth (24 times in total) using a vibratory roller on the measurement lane. After rolling the measurement lane, four accelerometers were fixed to the ground surface of the measurement lane with stakes at intervals of 5 m along compaction lanes.

(3) Twelve round trips (24 times in total) of rolling by the vibratory rollers were repeated on the compaction lane, and the measured values of each accelerometer were recorded.

(4) After removing accelerometers, a 0.3 m thick 2nd layer of soil was spread on the former layer.

(5) The 2nd layer test was subjected to the same procedure (2) to (3) as the 1st layer to measure acceleration.

LFWD tests were conducted during compaction (2, 4, 6, 8, and 10 round trips) on each layer. In the LFWD test, an impact load was applied by free-falling a weight on the loading plate. The displacement caused by the impact was measured at the center of the load and at the radial position from the center of the load to obtain the coefficient of the subgrade reaction [9].

$$K_{\mathrm{P.FWD}} = \left(\frac{P_{\mathrm{X}}}{\delta_{\mathrm{X}}}\right) \cdot \left(\frac{D_{\mathrm{Y1}}}{D_{\mathrm{Y2}}}\right) \tag{4}$$

$K_{\mathrm{P.FWD}}$: Coefficient of subgrade reaction by LFWD (MN/m3)

P_{X}: Load stress at displacement X mm (MN/m3)

δ_{X}: Displacement X (mm)

$D_{\mathrm{Y1}}, D_{\mathrm{Y2}}$: Diameter of LFWD loading plate Y1 (cm), Diameter of FWD loading plate Y2 (cm)

4.2 Soil condition

Figure 4 shows the particle size distribution curve of the fill material used in this experiment. The gravel content was low, but the fine-grained (clay and silt) content was high (> 50%), making the soil difficult to compact. All uniformity coefficients were higher than 10, and the grain size distribution was good. Table 1 shows the result of particle component ratio.

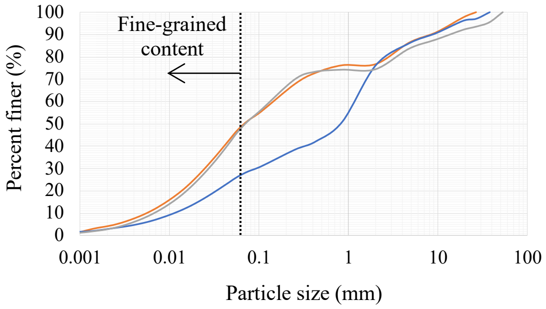


Figure 4. Particle size distribution curve

Table 1 Particle component ratio

	Sample		
Parameters used for classification	No.1	No.2	No.3
Coarse gravel %	2.4	3.9	8.0
Medium gravel %	11.3	10.1	8.4
Fine gravel %	9.6	9.9	9.2
Coarse sand %	0.5	25.2	0.2
Medium sand %	8.4	12.6	4.3
Fine sand %	16.4	9.8	18.7
Silt %	42.1	23.1	43.5
Clay %	9.3	5.6	7.7
Maximum grain size mm	26.5	37.5	53.0
Coefficient of uniformity	30.0	104.2	21.5
Coefficient of curvature	0.8	0.5	0.8

The dry density versus moisture content curve for the same fill material is shown in Figure 5. The samples used for the measurements were prepared using the dry method and were us ed in the repeat method. Table 2 presents the number of times the samples were rammed and the other test parameters.

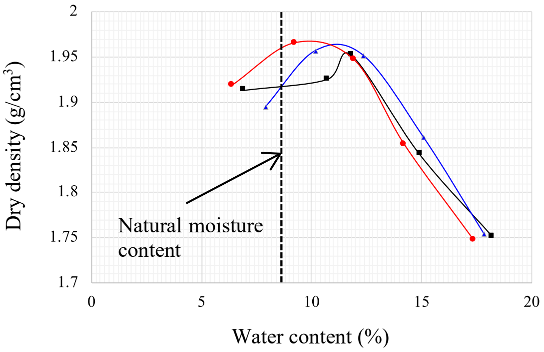


Figure 5. Moisture–density curve for fill materials

Table 2 Dry density versus moisture content test conditions

Type of soil	Decomposed granite
Mass of rammer (kg)	2.5
Falling height (m)	0.3
Number of times tampered per layer	25
Number of layers tampered	3
Inner diameter of mold (m)	0.1
Height of mold (m)	0.1273
Volume of mold (m^3)	0.001
Maximum grain size (m)	0.019

The results of the experiment on the samples from the three sites showed that the average optimum moisture content was approximately 10.9%, average maximum dry density was approximately 1.96 g/cm3, and natural moisture content at the time of the experiment was approximately 8.7%.

4.3 Experimental results

Figure 6 shows the CCV. In each figure, the CCV for each position on the forward journey (left), CCV for each position on the backward journey (center), and CCV rate of change averaged over the travel section (right) are also shown. Results of N-lane on the 1st layer are shown in Figure 6 (a), and 2nd layer are shown in Figure 6(b). In these figures, #1 ~ #4 indicate the positions of accelerometers.

The CCV rate of change is defined as relative rate of change r_n with respect to the CCV_n at the nth time of compaction. The r_n is calculated separately for each case of forward and backward journey, thus n is $3 \leq n \leq 24$ when determining the r_n.

$$r_n = \frac{\mathrm{CCV}_n - \mathrm{CCV}_{n-2}}{\mathrm{CCV}_{n-2}} \tag{5}$$

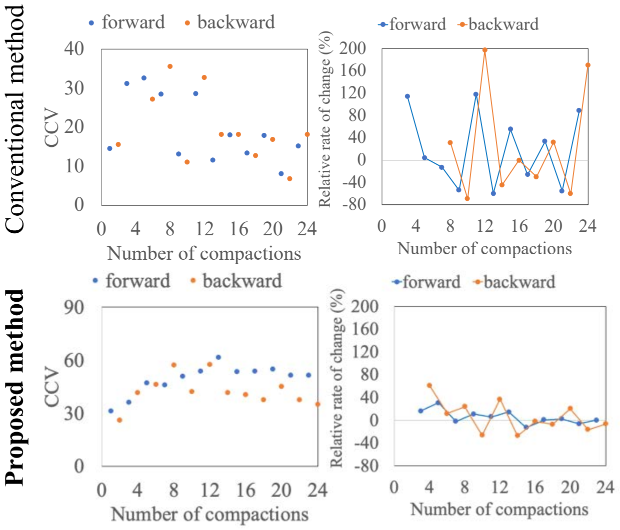
As shown in Figure 6, the CCV of the proposed method increased with the number of compaction cycles, showing a convergence trend on each layer. However, the CCV of the conventional method increased and decreased irregularly and did not converge. This is considered to be owing to the reduction in the signal-to-noise ratio by the separation of the vibration source and the measurement device that improves the convergence and discrimination of the proposed method.

In addition, Figure 7 shows the relationship between CCV and the number of compaction cycles when the vibratory roller passed at the position A on the N-lane and A′ (midway position, 7.5m) in Figure 2. The relationship between the rate of change of CCV and the number of compaction cycles with same condition is also shown in Figure 7.

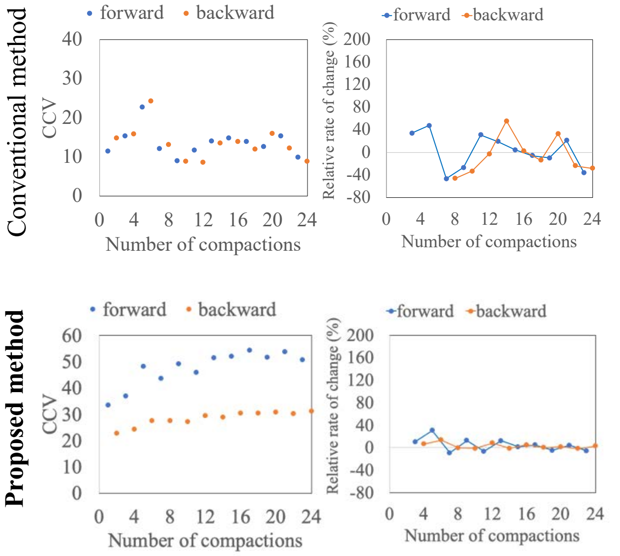
The conventional method has a large variation in CCV. The CCV increased when the number of compaction cycles was small, but decreased when the compaction had progressed on each layer.

On the other hand, the CCV measured by the proposed method tended to increase and converge as the number of compaction cycles increased. The CCV values measured in the forward directions were larger than those measured in the backward direction. It is possible that the rear wheels block the vibrations propagating through the ground when the rear wheels are ahead of the vibratory wheels, but this should be verified in the future.

The CCV rate of change varied widely with the conventional method and the trend was difficult to read, but with the proposed method, it decreased and showed a convergence trend on each layer.



(a) CCVs and r_n evaluated on N-lane of the 1st layer



(b) CCVs and r_n evaluated on the 2nd layer

Figure 7. CCVs and r_n when the vibratory roller passed at the positions A and A′ in Figure 2

Figure 8 shows the comparison of CCVs at three points (5m, 7.5m and 10m) on the N-lane of the 1st layer for the conventional and proposed methods. Compared to the conventional method, CCVs of the proposed method are stable and the convergence trend is clearly observed.

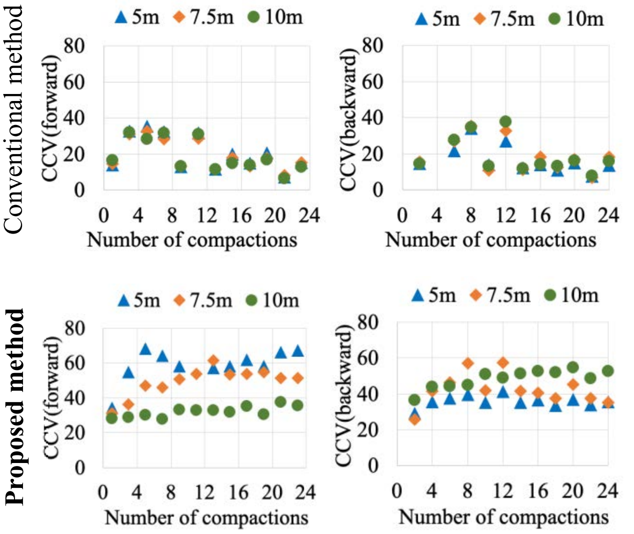
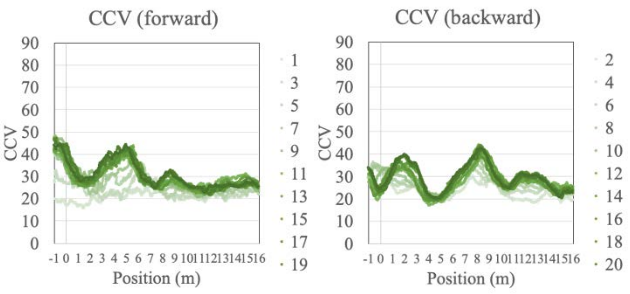


Figure 8. CCVs evaluated on N-lane of the 1st layer on each point

The results of this experiment were obtained under limited soil conditions. It is well known that the change of CCV tends to become unclear with increasing moisture content [10]. A similar trend may be obtained with the proposed method, and this will be discussed in the future.

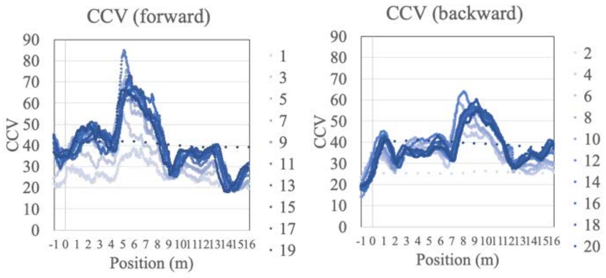
To investigate the effect of the distance from the accelerometers to the vibratory roller, an additional experiment was conducted in which the vibratory roller compacted the compaction lane on the far side (F-lane) and more than 4 m away from the accelerometer.

Figure 9 shows the CCVs of the F-lane and N-lane. Although the CCV is larger on N-lane than on F-lane, the CCVs of both lanes clearly converge. This indicates that the proposed method is effective even when the vibration roller is more than 4 m away from the accelerometer.



(a) F-lane on the 1st layer

Figure 9. CCVs for varying distance from vibration source to accelerometers



(b) N-lane on the 1st layer

Figure 9. CCVs on F-lane and N-lane.

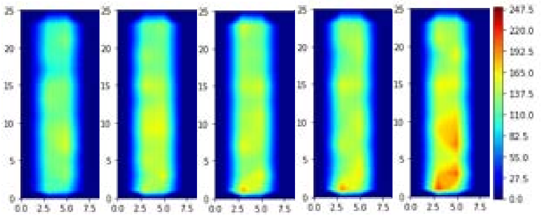
The resulting coefficients of the subgrade reaction (MN/m3) are listed in Table 3 and Table 4. The LFWD test was conducted at the fourth, eighth, 12th, 16th, and 20th of compaction on each layer. The heat map for the case where the embankment traveled in the longitudinal direction is shown in Figure 10.

Table 3 Coefficients of subgrade reaction on 1st layer with LFWD. (MN/m^3) (n = 24)

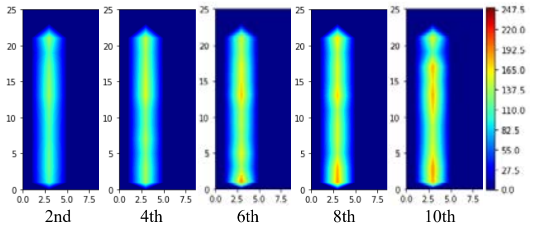
	4th	8th	12th	16th	20th
Ave.	118	137	139	139	155
Max.	155	160	180	189	210
Min.	88	112	118	110	112
SD	15.4	14.4	14.7	17.4	23.5

Table 4 Coefficients of subgrade reaction on 2nd layer with LFWD. (MN/m3) (n = 11)

	4th	8th	12th	16th	20th
Ave.	119	137	155	157	163
Max.	133	152	189	185	187
Min.	109	125	139	139	113
SD	8.7	8.9	15.9	15.5	21.5



(a) Coefficients of subgrade reaction on 1st layer



(b) Coefficients of subgrade reaction on 2nd layer

Figure 10. Coefficients of subgrade reaction with LFWD

The results confirmed that the coefficients of the subgrade reaction tended to increase as the number of compaction cycles increased.

The rate of change of the coefficients of the subgrade reaction obtained by the LFWD was also calculated. Because LFWD measurements were obtained at 4th, 8th, 12th, 16th, and 20th compaction, the unmeasured coefficients of the subgrade reaction were linearly complemented, and the average rate of change was obtained. Figure 11 shows the results and same convergence trend as the CCV rate of change shown in Figure 6.

Because the LFWD is measured over a long period of time at the surface of the compacted ground, it is difficult to measure at construction sites. The acceleration response method proposed in this study can be measured at a location off the compaction ground and is considered to be useful at construction sites.

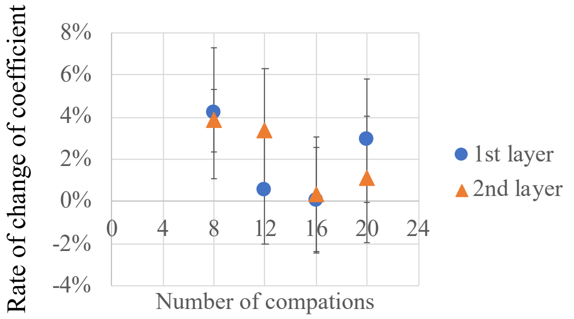


Figure 11. Rate of change of coefficient of subgrade reaction with LFWD

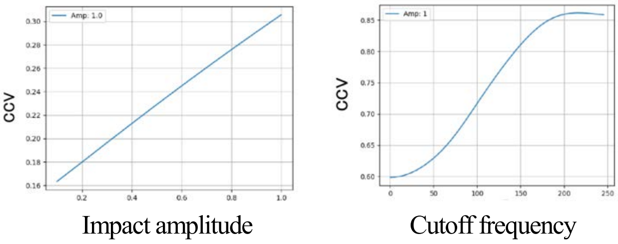
4.4 Simulation results

Simulations were conducted to find out the characteristics of the conventional and proposed methods.

The acceleration of the roller was varied so that the impact amplitude between the roller and the ground increased as the compaction cycles increased. In addition, a low-pass filter was applied to smooth the vibration as it passed through the ground in the proposed method. Since damping decreases as the stiffness of the ground increased, it was assumed that the cutoff frequency increased as the number of compaction cycles increased.

Figure 12 shows the CCVs when the impact amplitude and the cutoff frequency of the low-pass filter were increased in the conventional and proposed methods, respectively. In both cases, the CCVs increase when the impact amplitude or the cutoff frequency increases. In particular, the proposed method showed a nonlinear relationship between the cutoff frequency and the CCVs. From this non-linearity, it is expected that the

CCVs change gradually during initial compaction cycles. On the other hand, the CCVs increase uniformly for any compaction cycles for conventional method. This may cause the different characteristics and may be one of the reasons why the proposed method has higher discriminability than conventional method.



(a) Conventional method

(b) Proposed method

Figure 12. CCVs of conventional and proposed method obtained by the simulation

4.5 Advantages and limitations

The experimental results suggest that the proposed method is more discriminative than the conventional method. The proposed method also shows superiority in failure resistance and signal-to-noise ratio compared to the conventional method.

On the other hand, the proposed method has disadvantages compared to the conventional method in terms of labor and cost required to install sensors. It is also necessary to consider the effects of vibrations generated by surrounding machinery. Furthermore, since absolute values vary depending on the distance from the roller to the acceleration sensor, evaluation by absolute values are currently difficult and can only be compared relatively. Further discussion on this issue is needed in the future.

5 Conclusions

This paper proposes a method for evaluating ground stiffness using multiple synchronous acceleration sensors placed on the ground. The proposed method is superior to the conventional method in terms of discrimination and convergence with respect to the number of compaction cycles, as confirmed by ground rolling tests on embankments. The convergence tendency of the proposed method was similar to that of the coefficient of the subgrade reaction calculated using LFWD.

In a future study, experiments will be conducted on soils with various moisture contents to clarify the characteristics of the proposed method.

Acknowledgement

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References

[1] Thurner H. and Sandstrom A. A New Device for Instant Compaction Control. In International Conference on Compaction, Vol. II pages 611-614, France, 1980.

[2] Forssblad L. Compaction Meter on Vibrating Rollers for Improved Compaction Control. In *International Conference on Compaction*, pages 541– 546, Paris, France, 1980.

[3] Adam D. Continuous Compaction Control with vibratory rollers. In *Geo Environment 97*, pages 245-250, Rotterdam, Netherlands, 1997.

[4] Adam D. and Brandl H. Sophisticated roller integrated continuous compaction control. In *12th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, Vol. 1 pages 427-430, Singapore, 2003.

[5] R. Anderegg and K. Kaufmann. Intelligent Compaction with Vibratory Rollers: Feedback Control Systems in Automatic Compaction and Compaction Control. *Journal of the Transportation Research Board*, 1868(1):124-134, 2004.

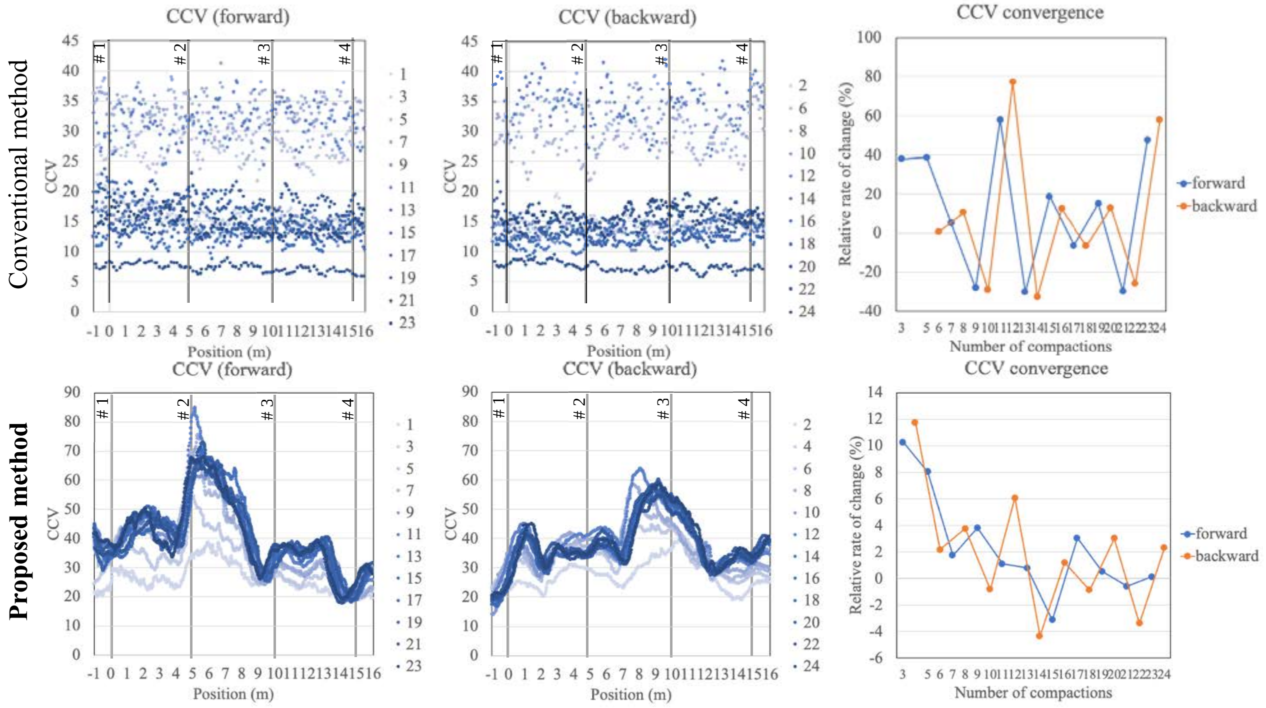
[6] Christopher M, Daniel C, Faraz T and William B. Assessing soil compaction using continuous compaction control and location-specific in situ tests. *Automation in Construction*, 73:31-44, 2017.

[7] Sakai Heavy Industries, Ltd. Vibrating roller type soil compaction quality controller CCV (compaction control value), Operating & Maintenance Instructions, pages 1-5, 2007.

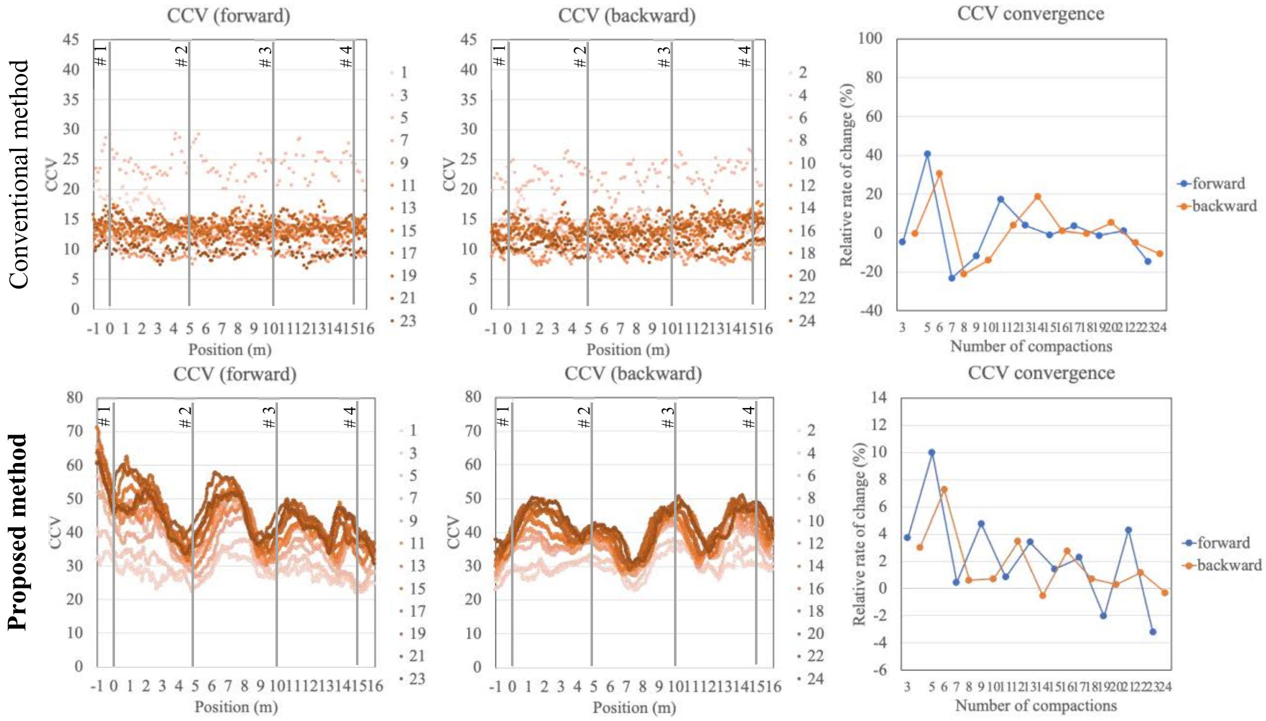
[8] Hashimoto T. Fujino K. and Tateyama K. Suggestion of the ground stiffness estimative method with the running speed of a plate compactor. In *International Symposium on Automation and Robotics in Construction*, pages 1-6, Alabama, USA, 2016.

[9] University of Maryland College Park. Standardizing lightweight deflectometer modulus measurements for compaction quality assurance, pages 5-8, Final report for Maryland Department of Transportation State Highway Administration Research Report, 2017.

[10] Wei H, Pawel P, Xiaoyang J, Hongren G and Baoshan Huange. Visualization and quantification of lab vibratory compacting process for T aggregate base materials using accelerometer. *Transportation Geotechnics*, 25:1-8, 2020.



(a) CCVs and r_n evaluated on N-lane of the 1st layer



(b) CCVs and r_n evaluated on the 2nd layer

Figure 6. CCVs and r_n evaluated results ("$\#n$" denotes the position of the n-th accelerometer)