Dam concrete compaction management system

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ABSTRACT

Compaction of concrete is of vital importance in dam construction when trying to attain the required water-tightness, durability and strength of the dam body. Viback concrete vibrator systems are usually used to compact conventional slumpable mixes. Decision as to when to stop compacting, however, is largely dependent on compaction time and empirical judgment based on visual observation, and there are no established quantitative criteria. There is concern, therefore, about problems such as segregation resulting from inadvertent failure to perform compaction, incomplete compaction and excessive compaction.

To solve these problems, a new dam concrete compaction management system has been developed. The new system directly measures changing concrete vibration with acceleration sensors and analyzes vibration waveforms so that an objective judgment can be made as to when to stop compacting and numerical data can be recorded. The system makes it possible to make the best decision as to when to stop compacting, regardless of the operator's experience or expertise.

1. INTRODUCTION

Compacting concrete is extremely important in concrete dam construction if the required watertightness, durability and strength of the dam body are to be ensured. Viback vibratory systems with three to four internal vibrators built into the backhoe are used to compact stiff dam concrete with a slump of 2 to 4 cm. At present, the decision as to when to stop compacting is based on the empirical judgment of the Viback operator and visual observation of the supervisor. In order to compensate for the recent shortage of experienced operators in Japan, new technologies are required to prevent excessive or incomplete compaction and ensure efficient work and high concrete quality.

There are no established quantitative criteria in Japan for the decision as to when to stop compacting. The decision is basically made when: (i) the concrete settles no more, (ii) no more large air voids are created, or (iii) the surface appears watery and lustrous (Japan Society of Civil Engineers, 2013).

There is, therefore, concern regarding concrete compaction about such problems as the insertion of heterogeneous vibrators, poor compaction due to insufficient vibration time, and segregation because of an excessively long operation time.

The authors thought that concrete vibration during vibratory compaction would vary according to the increase in density with compaction, and examined methods for evaluating when to stop compacting by measuring the changes in concrete vibration waveform near the internal vibrator. Then, the authors developed a new compaction management system for dam concrete that makes it possible to determine how compaction is being undertaken and record the condition based on objective numerical data.

2. STANDARD PROCESS FOR POURING DAM CONCRETE

The specifications for dam concrete and Viback at the test site are listed in Tables 1 and 2, respectively. Figure 1 shows how the concrete was compacted. Changes in the compaction process are shown in Figure 2.

Concrete, which is a mixture of aggregate, cement, water and air, piles up immediately after it is unloaded from the bucket. This mixture is compacted using Viback and the concrete is consolidated by integrating the aggregate and cement and removing any surplus air. Eventually, the required quality for dam concrete is achieved.

Figure 1. Compaction of dam concrete (using Viback with four vibrators)

Table 1. Specifications of the dam concrete (example)

Location	Unit quantity(kg/m^3)				Design strength (N/mm^2)	Maximum aggregate size(mm)	Slump (cm)
	Cement	Water	Fine aggregate	Coarse aggregate			
Outside	200	102	644	1467	4.0	80	3.0±1.0
Inside	150	107	696	1448			

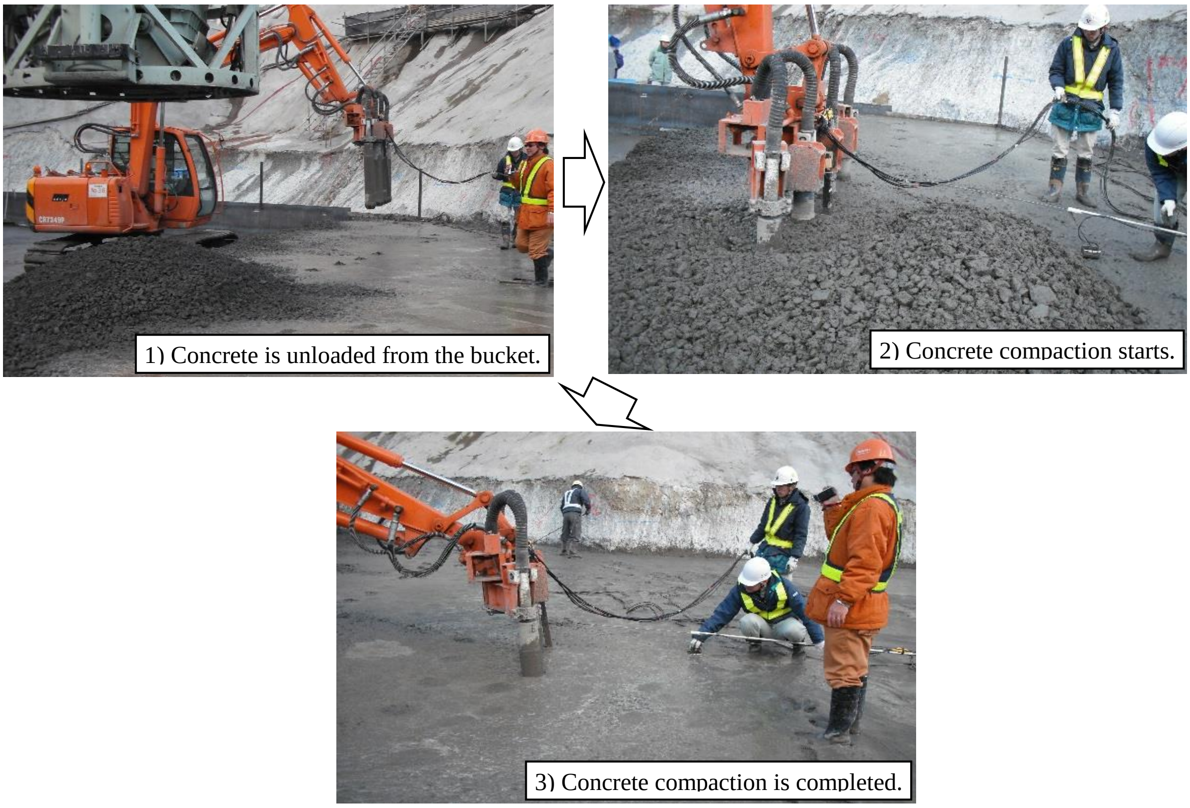
Table 2. Specifications of the base machine and vibrator

Base machime(VBH74EHL)

Total length × width × height (mm)	Weight (kg)	Contact pressure (kPa)	Number of vibrators
7,950 × 2,350 × 3,000	7,570	27	HIB150HL ×4

Vibrator capacity(HIB150HL)

Frequency (Hz)	Centrifugal force (kN)	Pressure used (MPa)	Vibrating section (Diameter × length) (mm)	Effective area (m)	Mass (kg/vibrator)
177-133	13.6-17.8	15.7	150 × 850	1	67



1) Concrete is unloaded from the bucket.

2) Concrete compaction starts.

3) Concrete compaction is completed.

Figure 2. The compaction situation of the dam concrete

Normal concrete can be compacted in roughly 5 to 15 seconds. Compacting dam concrete takes approximately 40 seconds including the time for compacting in several rounds per pile of concrete tipped from the bucket.

When the above compaction procedure is used for dam concrete, it is difficult to decide when to stop compacting based solely on the Viback operation time in terms of simple management using a task meter.

So far, decisions have been made based on the judgment of an experienced operator or supervisor in the field. As a result, the authors have developed a method for objectively determining whether concrete has been fully compacted or not as shown in the bottom photograph in Figure 2.

3. PROPOSAL FOR A CONCRETE COMPACTION MANAGEMENT SYSTEM

Concrete in the initial stage of compaction immediately after it is unloaded from the bucket has a lower density because of internal air voids. With the progress of compaction using vibrators, the concrete density gradually increases. Some of the existing studies (Kaneko et al. 2009; Liang et al. 2013) have tried to identify the changes in concrete property due to the increase in density based on the physical quantity concerning the vibration of vibrators. In this study, the following hypothesis was formed concerning the changes in concrete property.

A mass point (M) is located a certain distance from the vibrator used for compacting concrete, and the decision is made as to when to stop compacting based on the amplification of the vibrations. Simple oscillation harmony trembler is used (Figure 3). The reduction of the decay constant due to increased density upon concrete compaction is estimated.

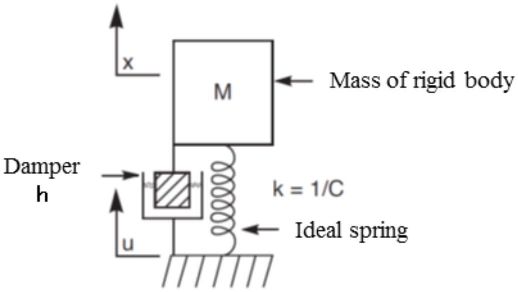


Figure 3. Simple oscillation harmony trembler

The model shown in Figure 3 can generally be expressed by the following equation of motion.

$$M\ddot{x} + h\dot{x} + k(x - u) = 0 \tag{1}$$

where, $\boldsymbol{M}$: mass, $\boldsymbol{h}$: damping coefficient, $\boldsymbol{k}$: spring constant, $\boldsymbol{u}$: displacement amplitude

The external force that generates displacement amplitude |u| at the end of the spring is damped by concrete in the fresh state. Transmissibility T to energy mass point M is given by equation (2). If ζ is 0.5, 0.3 or 0.1, equation (2) is expressed as shown in Figure 4.

$$T = \frac{|x|}{|u|} = \sqrt{\frac{1 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2}{\left(1 - \frac{\omega^2}{\omega_0{}^2}\right)^2 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2}} \tag{2}$$

where, ζ : the decay constant, ω/ω_0 : the frequency ratio.

In the field test described later, the vibration frequency of the Viback used was 125 Hz (median value), and the natural frequency of the measurement rod was 90 Hz (calculated value). Figure 5 shows ω/ω_0 = 90/125 = 0.72 extracted from Figure 4. This shows that transmissibility T increases as concrete is compacted, while the decay constant ζ decreases. Thus, it suggests the possibility that we can evaluate how the concrete is being compacted based on the changes in the external force measured at a point a certain distance from the vibrator. In this study, measurements were made using an acceleration sensor attached between vibrators, and verification was conducted in field tests.

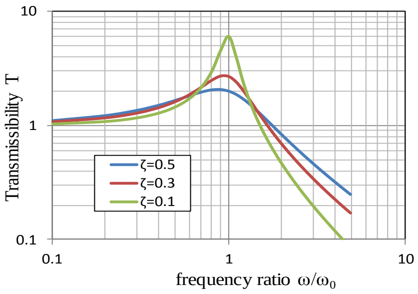


Figure 4. Transmissibility pro-vibration for the various decay constant level

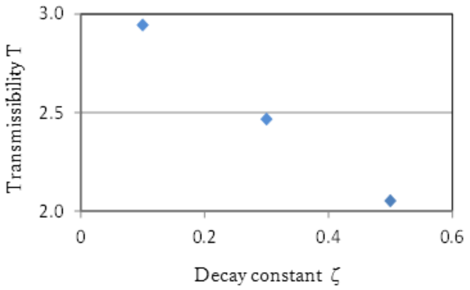


Figure 5. Relations of decay constant and the transmissibility T

4. VERIFICATION OF METHODS TO DECIDE WHEN TO STOP COMPACTING IN FIELD TESTS

Decision were made in the field based on the measurements of acceleration during actual concrete compaction using a Viback. Acceleration sensors capable of tri-axial measurement were installed in the direction of the x-axis in which the vibrators were arranged, in the longitudinal direction (y-axis) and in the vertical direction (z-axis). Acceleration sensors were installed internally at the tip of the square pipe placed between vibrators (Figure 6).

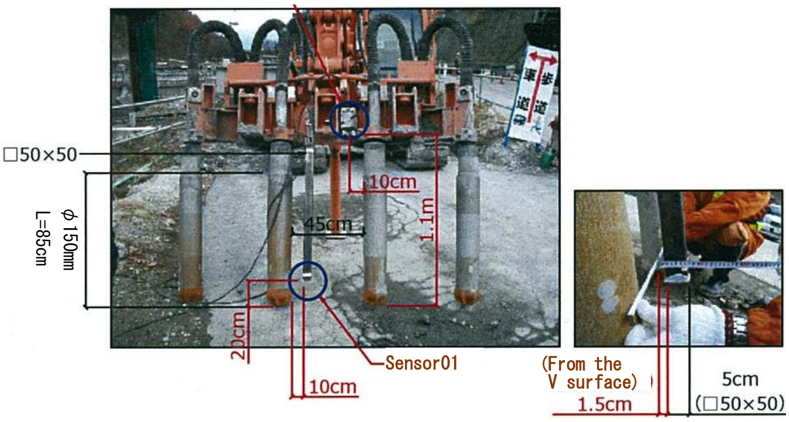


Figure 6. Mounting structure of acceleration sensors

4.1 Measurement of the vibrator’s energy transmission range

The vibrators attached to the Viback were operated as a row of four. Acceleration was measured to identify the scale of vibration and the range of transmission. Acceleration sensors were installed at 0.5, 1.0 and 1.5-m points transverse to the row of Viback vibrators to measure acceleration in concrete. The measurement results are shown in Figure 7. Approximated curves are also presented in the figure. Acceleration was nearly double at distances of 0.5 m and 1.0 m.

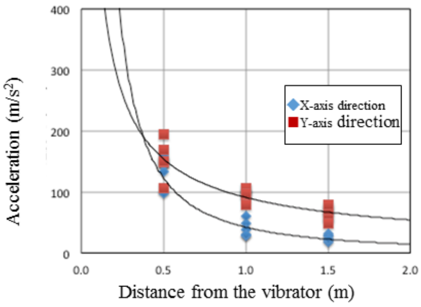


Figure 7. Acceleration distribution of the vibrator

4.2 Measurement of acceleration

Of the acceleration data measured during compaction in field tests, 198 waves (22 data points x three locations x three elements) were extracted for analysis. Examples of the acceleration waveforms measured using an acceleration sensor (sensor 01) are shown in Figure 8.

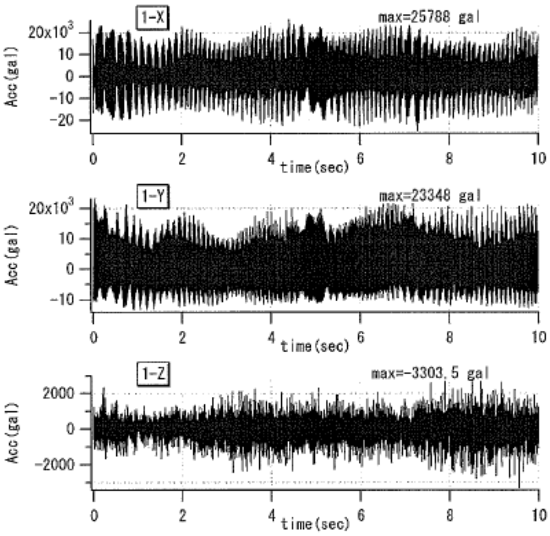


Figure 8. The acceleration wave pattern
(Time history (i): Data between 14:09:17 and 14:09:27)

The data characteristics are described below.

- The maximum acceleration during compaction was 20 to 40 x 10^3 gal (x10^{-2} m/s^2) in the x- and y-axes, and 2 to 10 x 10^3 gal (x10^{-2} m/s^2) in the z-axis.

- Changes in amplitude were large in the x- and y-axes, and small in the z-axis.

- Fourier spectra of the data in the x- and y-axes varied owing to compaction (Figure 11 below). It is highly likely that thise element can be used for judgment.

4.3 Analysis of acceleration data

Data was extracted and an evaluation and an evaluation was made based on the acceleration waveforms measured.

- The energy that was transmitted to the mass point (where the sensor was attached) was expected to increase due to reduction in the decay constant during compaction. Acceleration was, therefore, integrated to calculate velocity and the sum of squares of the velocity {V^2 (t)} was calculated (Figure 9).

- The ten-second period during which acceleration waveforms were measured was split into 0-to-3-, 3-to-6- and 6-to-9-second sections. The fourier spectrum was calculated for each section to evaluate the changes in characteristics of vibration frequency with time.

4.4 Evaluation of the sum of squares of the velocity

Figure 9 shows the sum of squares of the velocity for waveforms shown in Figure 8. Concrete was compacted by vibrators and the energy that was transmitted to the acceleration sensor increased as the decay constant decreased. Focus was placed on the y element perpendicular to the row of vibrators, and the result of division of the calculated sum of squares of the velocity at time t {V^2 (t)} by the calculated sum of squares of the velocity at t = 10 seconds {V^2 (10)} was represented by S (t). The results of hyperbolic approximation are shown in Figure 10. If the section along the y-axis and the gradient of the approximated line are represented by α and β , respectively, the equation below is obtained.

$$S(t) = S(0) + \frac{t}{\alpha + \beta t} \tag{3}$$

The results show that the calculated sum of squares of the velocity converges to a certain value. This lines have different gradients in Figure 10. This means that, no calculated sum converges to a specific value. For evaluation, therefore, no numbers were used as absolute values, but the way in which the sum of squares of the velocity converged was used.

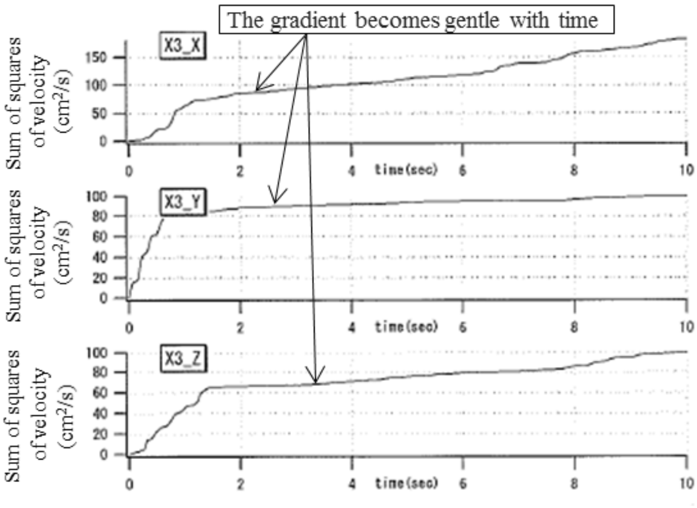


Figure 9. Square speed calculated from acceleration (Time history (i): Data between 14:09:17 and 14:09:27)

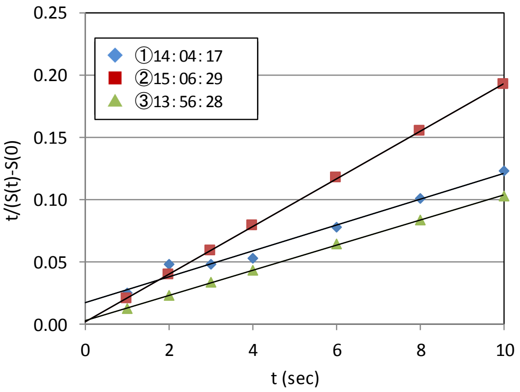


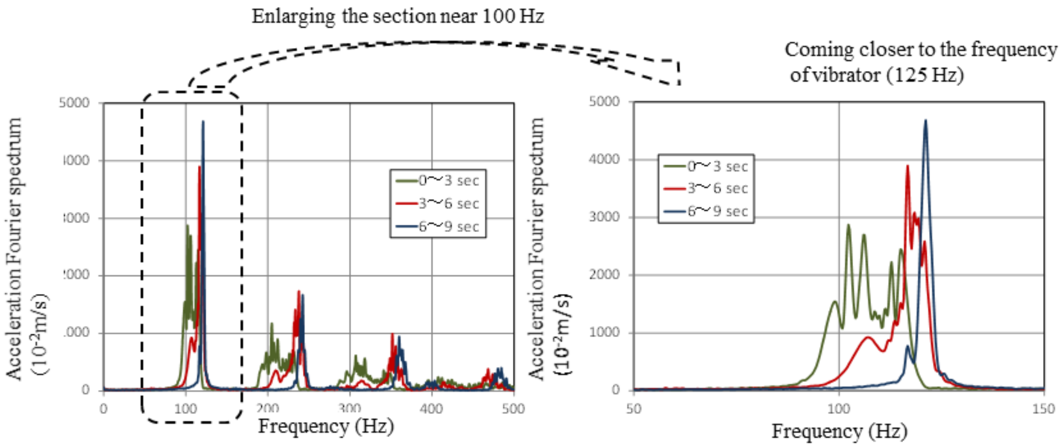
Figure 10. Hyperbola approximation of the square speed

4.5 Evaluation of the Fourier spectra

The ten-second period in which measurements were made using sensors was split into 0-to-3-, 3-to-6- and 6-to-9-second sections, and the Fourier spectrum was calculated in each section. Some of the results are shown in Figure 11. It was found that in the initial period between 0 and 3 seconds, peak vibrations occurred near the specific vibration, but vibration came closer to the vibration frequency of the vibrator (125 Hz) with the excitation of vibrators. This suggests the possibility that the process of concrete compaction is expressed by vibration frequency.

4.6 Method for deciding when to stop compacting

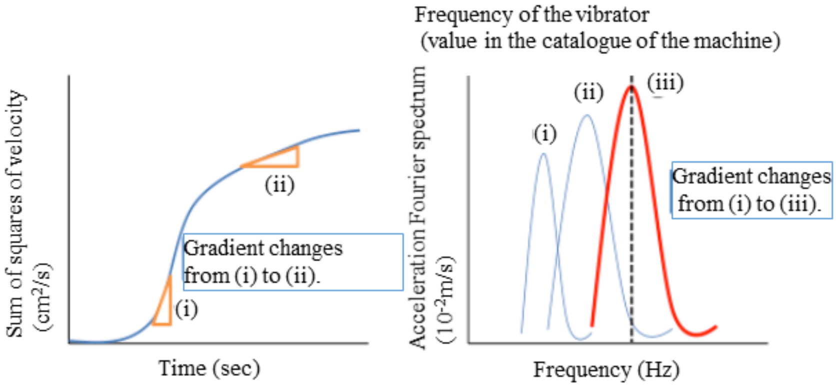
Based on the above results, it was decided to make a decision as to when to stop compacting using Viback based on: A. convergence of the sum of the squares of velocity, or B. transition of frequency (toward the vibration frequency of the vibrator). A conceptual view of the method of decision-making is shown in Figure 12. In the logic of judgment, however, the vibrator operating (insertion) time was also taken into consideration because a standard concrete compaction time has been established (Figure 13).



Time history (i): Data between 14:09:17 and 14:09:27

Enlargement of section near 100 Hz

Figure 11. Fourier spectrum (Y-axis direction)



Changes in the sum of squares

Changes in compaction frequency

Figure 12. Conception diagram of the compaction judgment technique

5. DEVELOPMENT OF COMPACTION MANAGEMENT SYSTEM

5.1 Outline of compaction management system

A configuration and a general view of the dam concrete compaction management system are shown in Figures 14 and 15, respectively. The judgment results are analyzed by a compaction judgment system and indicated to the operator via three different phases of revolving light (Figure 16). Confirming the location of the vibrator is a very important management factor to avoid inadequate concrete compaction and guarantee quality. In the proposed system, the coordinates of the location of the vibration insertion probe upon completion of compaction are displayed in real-time on a monitor on the in-vehicle personal computer via a global navigation satellite system (GNSS) and recorded (Figure 17).

After the system was built, tests were conducted at two dam construction sites in Japan to measure the acceleration of concrete that was being compacted and to judge when to stop compacting. Judgment was made as to when to stop compacting using the system, and condition of the concrete surface (air voids in particular) was observed in order to verify the effectiveness of the judgment.

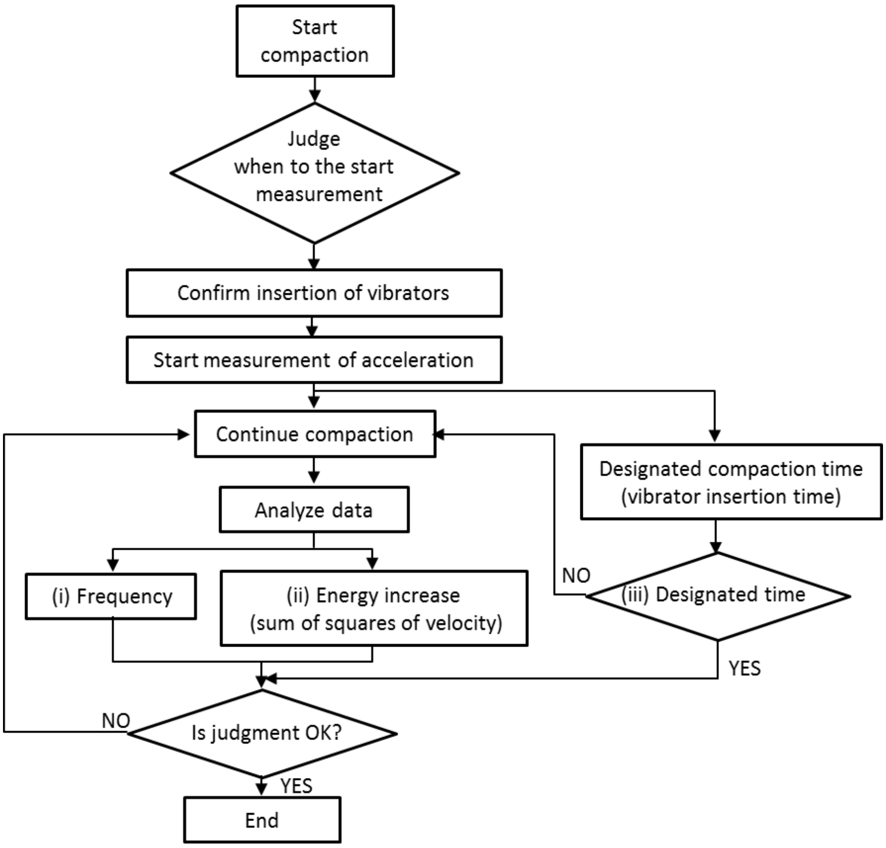


Figure 13. Figure of Compaction Judgment Flow

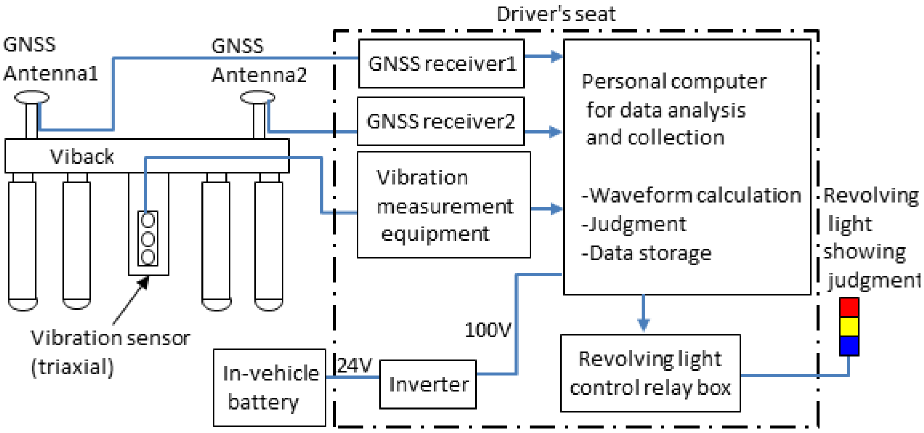


Figure 14. Configuration of Compaction Management System

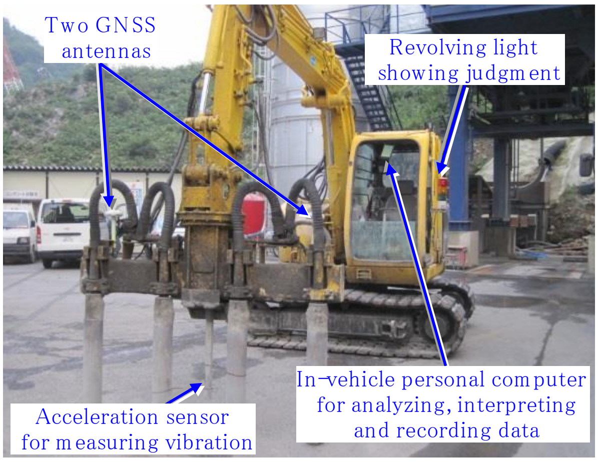


Figure 15. Administration Whole View of the System

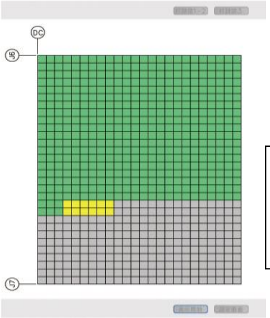
5.2 Results of system operation

The state of compaction is indicated by the system using three different phases of revolving lights. The light turns red while the Viback vibrator is in the air. When the vibrator is inserted into the concrete and compaction starts, the light turns yellow. When all the judgment criteria are satisfied, the light turns green. Threshold values can be set arbitrarily. Four successive increments of the sum of squares of the velocity at Δt= 0.5 sec were 3% or less. The frequency was set to 115 Hz or higher, and the designated time at 6 seconds.

Table 3. Main Judgement Factor of Trial Measurement System Operation

	Sum of squares of velocity (Increment is 4 consecutive less than 3%)	Frequency (>115Hz)	Insertion time (≧6sec)	Total
Number of measurement points	16	13	6	35
Percentage (%)	45.7	37.1	17.1	100

Phases of revolving light
"Red" :Standby
"Yellow" :Under way
"Green" :Completed



Legend
Gray ☐ : Not yet completed
Yellow 🟨 : Under way
Green 🟩 : Completed

Figure 16. Indication of the state of compaction using revolving light

Figure 17. Real-time indication of the state of compaction

Whether the vibrator was inserted into the concrete or not was determined by whether the sensor detected vibrations when the vibrator and measurement sensor entered the concrete.

Judgment as to when to stop compacting made using the system in the test agreed with the judgment based on visual observation by the supervisor, placement manager and operator. Thus, the effectiveness of the system was verified. The sum of squares of the velocity was the main judgment factor among the factors shown in Table 3. In judgment, it took 6.2 seconds on average for the light to turn green. The criteria were met within the designated time (six seconds) for 17% of the measurement points (insertion time). For other factors (sum of squares of the velocity, and frequency), the criteria were met in less than the designated time. This result suggests that excellent compaction is possible in less time than currently designated under favorable conditions.

5.3 Problems with the system

In the placement of dam concrete, Viback is inserted into a pile of concrete to a shallow depth and actions like spreading piles are frequently repeated at short intervals. The vibrators are then pulled out before completion of compaction. The proposed system, therefore, does not ensure proper judgment. The system should only be used in the parameters within which it acts effectively, based on an understanding of the above characteristics.

In order to judge where compaction should be stopped, the location at which compaction was completed is measured and recorded using GNSS and displayed in real-time on a computer screen. In order to enable the concrete placement manager to control the location of compaction in real-time, a system needs to be developed that can display the location of compaction on mobile equipment as well.

6. CONCLUSION

It was found that changes in acceleration of concrete that was being compacted were closely related to the state of concrete compaction and that analyzing accelerations could enable real-time judgment as to when to stop compacting. Using the system for judgment through acceleration analysis makes it possible to perform quantitative and objective compaction management, whereas conventional management was dependent on construction experience and could only be made based on visual inspection and checking the total construction time. This system is also likely to contribute to improved productivity.

With the reduction and aging of the construction workforce, and a shortage of young workers, rationalization of construction based on information and communications technology is expected to continue advancing. The method proposed in this study is an approach to quality control using observational construction technology (Furuya, 2010; Furuya, 2012). Information and communication technology(ICT) is also applicable to construction management for quality enhancement. Improvements will continue be made to the system.

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