DEVELOPMENT OF SOIL STIFFNESS EVALUATION EQUIPMENT "ALFA-SYSTEM" USING ACCELERATION RESPONSE OF VIBRATORY ROLLER

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ABSTRACT: Recent years, new construction systems as AMG (automatic Machine Guidance) and AMC (Automatic Machine Control) have been developed with the Global Positioning System (GPS) and made fit for practical use. Added to this, an indirect measuring theory to control the compaction extent and elasticity, which uses the acceleration data of compaction drum, has been researched and developed since 1998 in Japan, and has recently come to be applied to the real construction sites. From such a background, the authors developed new equipment which is named "Alfa-system" for quality control of soil compaction. The advantage of the system is as follows. Fill compaction levels can be real-timely judged. Acceleration data of wheel vibration are consecutively measured, and these data are transmitted to the control room for data processing. Then, the data are compared with the standard control values that are established beforehand by the test executions. Examined data can be used for countermeasures, such as eliminating the under-compacted or inferior parts. And this system provides more benefit, once using system in construction, both supervisor in the sight office and driver of the compaction rollers can see 2-dimentional pictures of the compacted levels on the computer screens. And the data from Alfa-system can be used for QC/QA. Moreover, in the future, the system can be improved to feed back to the quality control immediately. This will improve the effectiveness and efficiency of compaction control.

Keywords: *Construction Machinery, Construction Method, Compaction, QC/QA, Real-time Measurement, Intelligent Compaction*

1. INTRODUCTION

The reliability design method has long been adopted in civil engineering work, for structures in particular. Placing orders for structures specifying the performance has been a common practice. Earth structures involve high design and construction uncertainty attributable mainly to soils that are used as material. Such structures have been designed using a simplified model and their construction has been controlled by specifying the method and through quality control based on the testing of soil samples. For construction control during embankment work, field density measurement using radioactive gauges or by sand replacement tests, or soil stiffness measurement through plate loading tests is generally employed at present to control the compaction of the fill in the field. Measurements are, however, taken only discretely, so effectively evaluating quality throughout the construction surface is difficult. Studies have been made on a method of determining the level of soil compaction by measuring the acceleration of vibrating wheel of a vibratory roller during construction using the tendency of acceleration response of a vibratory roller to vary according to the level of soil compaction. The method enables real-time evaluation of compaction quality along the surface during construction, so it will be much more effective than conventional compaction control methods.

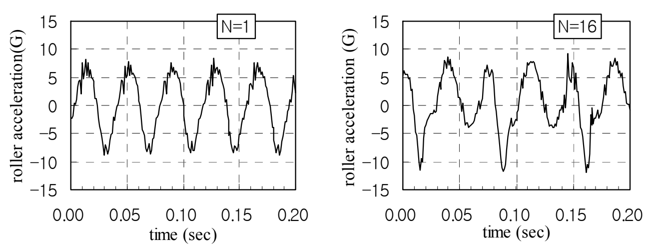
The method is also expected to provide sufficient data for reliability design. North European countries have been leading studies on the method[1)]. Studies were started in Japan around 1980[2)]. Various Roller Measured Value (RMV) have been invented by different roller manufacturers since the Compaction Meter Value (CMV) was developed (Thurner, 1980[1)]). Those systems with various formulae are listed in Table 1. There are dimensionless RMVs values such as CMV and Compaction Control Value [2)] (CCV Sakai, 2005) while other RMVs that measure stiffness in units of MN/m such as ks (Andergg et al., 2004), or with the dimension of a modulus in units of MN/m^2 (Scherocman et al.[3)], 2006) such as Alfa-System (advanced vibrating roller frequent analyze system) of this paper, and Evib[4)] (Kloubert, 2006). Applicable geological conditions have not yet been identified and the accuracy of construction control has yet to be fully verified. The method has therefore not been put to practical use. The authors have been conducting a series of researches for practical application of the method with such a respect as the effects of conditions of geology and vibratory roller[5)-9)]. This paper outlines soil compaction control equipment that the authors developed based on the researches to effectively control the compaction of fill materials. This document also makes a report on the results of evaluation of the applicability of the equipment.

Table 1: Intelligent compaction systems with various formulae

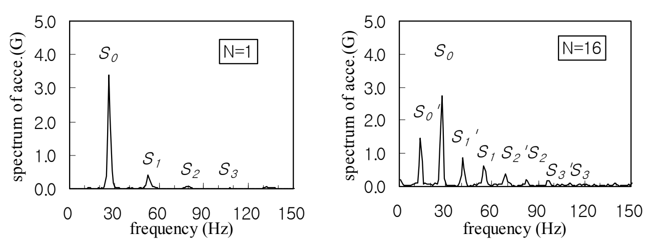
Vendors	IC system	Accel ero meter	Unit	Measurement and Analyzing method	CAD Compatibility
Caterpillar	CMV	Yes	None	$GeodynamikCMV = C\left(\frac{A_{2\Omega}}{A_\Omega}\right)$ $MDP - P_g - WV\left(\sin\alpha + \frac{a}{g}\right) - (mV + b)$	None
Dynapac	CMV	Yes	None	$GeodynamikCMV = C\left(\frac{A_{2\Omega}}{A_\Omega}\right)$ $BouncingValue = \frac{A_{0.5\Omega}}{A_\Omega}$	None
Sakai	CCV	Yes	None	$CCV - \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_\Omega}\right] \times 100$	Yes(2&3D)
Ammann	ks	Yes	MN/m	$ks = 4\pi^2 f^2\left(md + \frac{m_r\gamma_t\cos(\varphi)}{A}\right)$	Yes
Obayashi-Maeda	Alfa	Yes	MN/m²	$Ft = \frac{\frac{\sum_{i=1}^{3} S_i + \sum_{i=1}^{3} S_i'}{S_0 + S_0'}}{F/(m_1 + m_2)g}$ $E = \frac{2\cdot(1-\nu^2)}{B\cdot\pi}\cdot\frac{\left(\frac{4}{3}\cdot Ft + 1\right)\cdot(2\pi f_0)^2\cdot m_2}{1 - 0.32\alpha + \sqrt{0.1024\alpha^2 - 1.64\alpha + 1}}$ $\alpha = 1 - \left(\frac{F}{(m_1 + m_2)g}\right)^2$	Yes(2&3D)
Bomag	Evib	Yes	MN/m²	$Z_a = \frac{(1-\nu^2)}{E_{VIB}}\cdot\frac{F_t}{L}\cdot\frac{2}{\pi}\cdot\left(1.8864 + \ln\frac{L}{B}\right)$ $where, B = \sqrt{\frac{16}{\pi}\cdot\frac{R(1-\nu^2)}{E_{VIB}}\cdot\frac{F_s}{L}}$	None

2. OUTLINE OF SOIL STIFFNESS EVALUATION METHOD BASED ON THE ACCELERATION RESPONSE OF VIBRATORY ROLLER

This chapter outlines a soil stiffness evaluation method using the acceleration response of vibratory roller that the authors have been proposing[5)]. Figure 1 shows the acceleration waves obtained in the test where the subgrade was compacted by a roller, and the results of wave frequency analysis. With the increase of soil stiffness with the progress of roller compaction, the reaction from the soil caused the wave of acceleration of vibratory roller to be disturbed. Frequency analysis revealed that in addition to the spectrum of vibrating frequency S_0, higher harmonic wave spectra S_1, S_2, S_3, S_4... or half sub harmonic wave spectra S_1', S_2', S_3', S_4'... became predominant. Using the characteristics, turbulence factor (Ft) was defined as a quantitative indicator of acceleration wave (Equation (1)). A higher turbulence factor represents better soil compaction.



(a) Vertical roller acceleration



(b) Fourier spectrum of roller acceleration

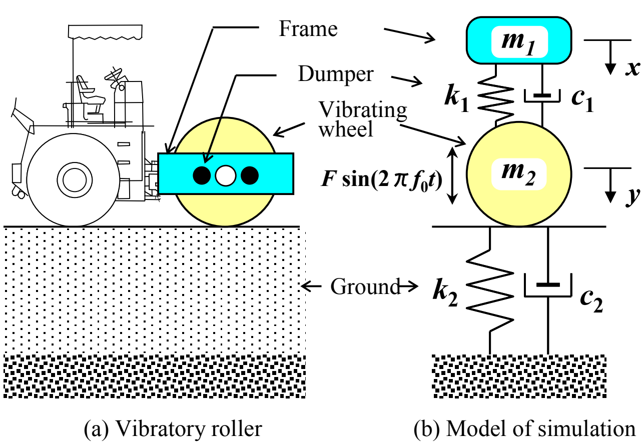
Figure 1. An example of measured roller acceleration during road construction

$$Ft = \frac{\dfrac{\sum_{i=1}^{3} S_i + \sum_{i=1}^{3} S_i'}{S_0 + S_0'}}{F/(m_1 + m_2)g} \quad \cdot\cdot\cdot \quad \text{Eq (1)}$$

Fujiyama and Tateyama[5] made a study through numerical computations by replacing the vibratory roller-soil system with a two-degree-of-freedom model (Figure 2). An equation was formulated to express the relationship among turbulence factor, specifications of vibratory roller (weight of the frame m_1, weight of vibrating wheel m_2, frequency f_0, vibrating force F and breadth of vibrating wheel B) and soil modulus of deformation E where ν is Poisson's ratio (equation (2)). A method of evaluating soil stiffness direct from the acceleration response (turbulence factor) of vibratory roller was proposed. The acceleration response of vibratory roller generally varies according not only to soil conditions but also to mechanical conditions of vibratory roller. Identifying the relation of turbulence factor to soil stiffness for each type of vibratory roller is therefore necessary. The proposed method has solved the problem and enables instantaneous computation of modulus of deformation by substituting mechanical specifications for any given type of vibratory roller.

$$E = \frac{2\cdot(1-\nu^2)}{B\cdot\pi}\cdot\frac{\left(\frac{4}{3}\cdot Ft+1\right)\cdot(2\pi f_0)^2\cdot m_2}{1-0.32\alpha+\sqrt{0.1024\alpha^2-1.64\alpha+1}} \quad \cdot\cdot\cdot \quad \text{Eq (2)}$$

$$\alpha = 1-\left(\frac{F}{(m_1+m_2)g}\right)^2$$



(a) Vibratory roller (b) Model of simulation

Figure 2. Simulation model for the roller-ground system

3. APPLICABILITY OF VIBRATORY ROLLER ACCELERATION METHOD TO COMPACTION CONTROL

The authors earlier noted that the range of application of the vibratory roller acceleration method was determined according to whether soil density or stiffness was evaluated as an indicator of soil compaction level[6]. A detailed explanation is given below.

Field compaction tests were conducted on two types of roadbed materials. The relation of dry density measured by nuclear gauge to turbulence factor *Ft* was investigated (Figure 3). Turbulence factor *Ft* was obtained by recording acceleration data on a data logger mounted on the vibratory roller, reproducing and extracting the wave right above the point of measurement by nuclear gauge and subjecting the wave to FFT (Fast Fourier Transform) using commercial software for post processing. Material A was soft rock and material B was tunnel muck. Tunnel muck was supplied with much belt conveyor cleaning water when the much was removed, and then was used for embankment. Figure 3 shows that the correlation between turbulence factor *Ft* and dry density varied greatly according to the type of material. A positive correlation was exhibited for material A. For material B, turbulence factor *Ft* remained nearly constant while density varied. Evaluating density based on turbulence factor *Ft* was therefore difficult. Weaving of material B was observed during the roller compaction test.

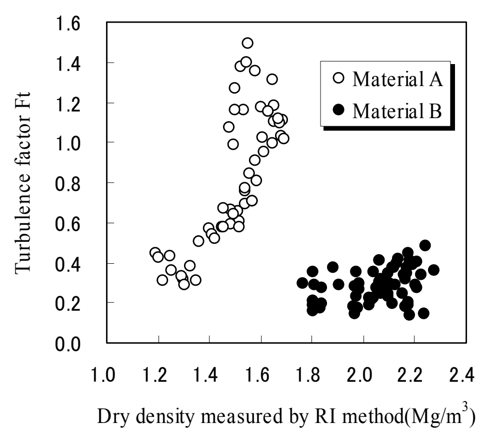


Figure 3. Relationship between Ft and dry density

It was assumed that the soil was highly saturated, that compaction could not increase soil reaction and that the acceleration response of the roller (turbulence factor : *Ft*) remained constant. Similar phenomena are generally observed in cohesive soil of high water content such as the soil in fill dam core. The proposed method can hardly be applied as an alternative to density control for such highly saturated materials. It should be noted that the method is actually applicable only to low saturated coarse grained soil fills with little fluctuation in material property.

The relationship between the soil modulus of deformation obtained from turbulence factor *Ft* using equation (2) and that identified in a separate plate loading test (JIS A1215) is shown in Figure 4. Also plotted in the figure are the results of roller compaction test for several materials such as subgrade materials and rockfill-dam materials as well as the roadbed materials. Figure 4 shows that the proposed method can evaluate the stiffness equivalent to in plate loading tests, for numerous materials including highly saturated materials. Multiple types of vibratory rollers were used in the plate loading test. Soil stiffness was adequately evaluated regardless of the type.

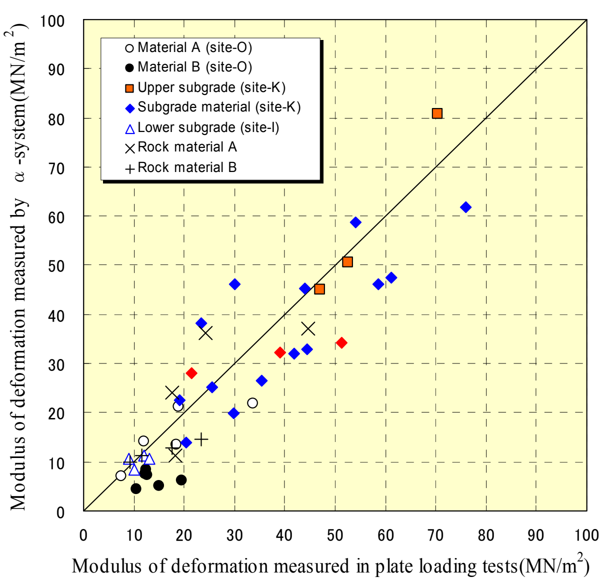


Figure 4. Comparison between measured E in plate loading tests and estimated E by roller acceleration at various conditions of materials and rollers

The validity of equation (2), which was derived theoretically, was thus verified. The proposed method can evaluate soil stiffness adequately for a given material and type of vibratory roller. It is considered highly applicable to soils that require stiffness of rolled surface such as road or airport subgrade and soils at housing sites. For subgrade in particular, uniform control is important because locally weak points lead to functional deterioration of pavement.

4. OUTLINE OF SOIL STIFFNESS EVALUATION EQUIPMENT "ALFA-SYSTEM"

Based on the test results, equipment was developed that automatically and centrally controls a series of steps from the measurement of acceleration to the determination of soil modulus of deformation. The authors developed new equipment which is named "Alfa-system" for quality control of soil compaction. The system is composed of the acceleration sensor, analyze system with connection port for GPS antenna and mobile PC (Alfa-system main body). The outline is shown in Photograph 1. Alfa-system was designed to consecutively calculate the turbulence factor *Ft* and soil modulus of deformation *E* every two seconds from the acceleration data collected and Alfa-system specifications that are input as parameters, using the method described earlier.

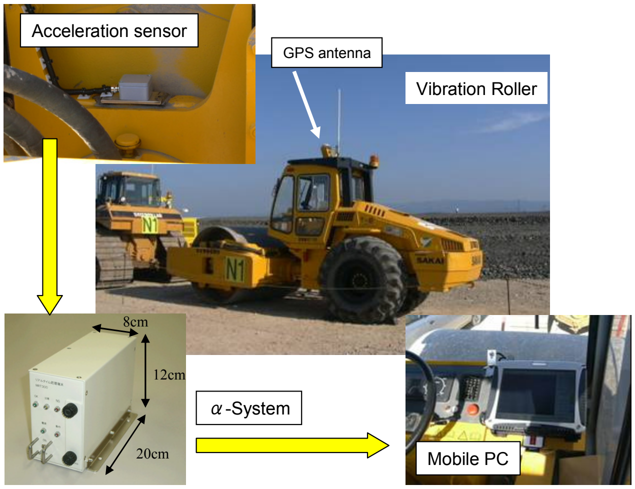
If the relationship between the turbulence factor *Ft* and dry density has been obtained in field compaction tests, it can be input as a parameter to evaluate density. Alfa-system has several other characteristics.

(i) It is so light and compact (12 cm wide, 20 cm long and 12 cm high, and weighs 3.0 kg) that it occupies only a small space in operator's seat in the vibratory roller.

(ii) Storage of large volumes of data in a built-in compact flash card can be ensured.

(iii) Vibratory roller coordinates are taken from GPS via RS232C port and synchronized with compaction indicators identified (*Ft*, soil modulus of deformation E_{roller} and soil density) for storage.

(iv) The results can be displayed real-time on outdoor personal digital assistants (PDA's) or personal computer screens.



Photograph 1.　An outline of the system

Photograph 2.　Field supervisors checking with PDA

Field supervisors can instantaneously access soil quality distribution in plan on PDA screen (Photograph 2 and Figure 5) and take remedial measures promptly for weak points. Installing a personal computer in the vibratory roller enables the operator to carry out compaction while confirming the level of soil compaction.

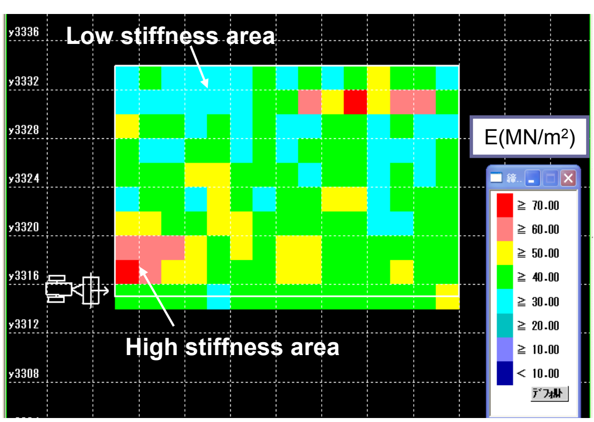


Figure 5.　An example of real-time monitor

5. SYSTEM VERIFICATION THROUGH FIELD TESTS

To verify the applicability of the developed system, a field roller compaction test was conducted. The test yard is outlined in Figure 6. Decomposed granite soils with a maximum grain size of 9.5 mm were used in the test. To verify the accuracy of detecting the points of low stiffness by the system, a high-water-content zone was built in the yard where water was added artificially. Initial density and water content measured by radioactive gauges are also provided in Figure 6. The soil modulus of deformation measured in plate loading tests and using handy falling weight deflectometers was compared with that output by the control equipment. The result (distribution of soil stiffness after 16 passes of roller) is shown in Figure 7. The figure shows that soil modulus of deformation E output by the control equipment was in good agreement with that measured in plate loading tests and by falling weight deflectometers and that E adequately represented low stiffness in low water content zone in particular. The control system can also be operated remotely from places a dozen meters away via wireless LAN (local area network). Field applicability as a practical field control system was thus verified.

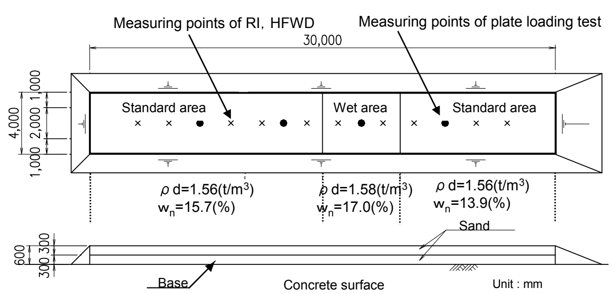


Figure 6.　Outline of the field compaction test

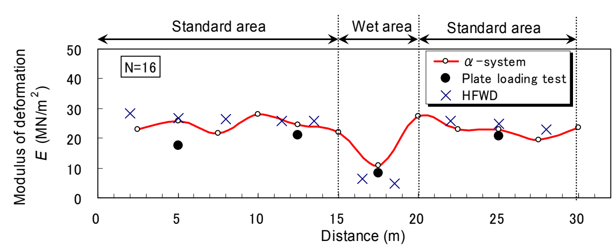


Figure 7.Measured and estimated distribution of modulus of deformation E

6. CONCLUSIONS

Soil stiffness evaluation equipment "Alfa-system" using the response acceleration of vibratory roller was developed and its applicability was verified. This paper described the verification results. Alfa-system has been in operation in the construction of the second-phase airport island of the Kansai International Airport and the development of roadbed and subgrade at Kobe Port. The objective is to control wide rolled surfaces effectively and highly accurately, supplementing radioactive measurement. At both construction sites, the number of roller passes is controlled using GPS in addition to quality control based on the acceleration of vibratory roller, for using uniformity and high quality of land improvement (QC/QA). And the execution management system of the similar idea for road construction which is called "IC (Intelligent Compaction) project" has started in the United States[10) 11)]. Centrally controlling quality and construction data and data on work progress obtained through surveying could enable information sharing among the organizations concerned via the website and system enhancement for construction of higher quality. Various three-dimensional data stored in a database may be used for future maintenance. The advent of means of obtaining three-dimensional quality information and recent advance of information technology are likely not only to make field control more effective but also to provide for future introduction of performance-specified control, so they are expected to make great contributions to more effective implementation of large-scale construction projects, response of vibratory roller.

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