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Effective evaluation method for quality control in the rock zone of a rockfill dam

La méthode d'évaluation effective pour le contrôle de qualité dans la zone rocheuse du barrage en enrochement

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ABSTRACT
To practically grasp two- and three-dimensional distributions of internal friction angle and the mechanical stability of rock zone in rockfill dams, a quality control method using the water content of embankment material and a post-embankment multi-point quality control method using vibratory roller acceleration measurements were established. Quality control using the combination of the two methods was found to help make effective use of embankment materials that were unusable for safety reasons when dams were required to meet the minimum quality requirements, and reduce excessive excavation or disposal of materials.

RÉSUMÉ
Pour saisir de façon pratique des répartitions bidimensionnelles et tridimensionnelles de l'angle de frottement interne et la stabilité mécanique de la zone rocheuse des barrages en enrochement, une méthode de contrôle de qualité utilisant la teneur en eau du matériau de l'endiguement et une méthode de contrôle de qualité multi-points après endiguement faisant intervenir la mesure des accélérations du rouleau vibratoire ont été établies. On s'est aperçu que le contrôle de qualité utilisant une combinaison des deux méthodes contribuait à faire un usage efficace des matériaux de l'endiguement qui n'étaient pas utilisables pour des raisons de sécurité lorsque les barrages devaient satisfaire aux normes de qualité standard, et à réduire un creusement ou une évacuation excessifs des matériaux.

1 INTRODUCTION

The rock zone of a rockfill dam occupies the majority of the volume of dam body and needs to be mechanically stable against slippage. The rock zone is therefore required to have the designated shear strength (angle of internal friction). At present, the quality of the rock zone is generally controlled indirectly at the site focusing on the density of compaction as a typical index. For measuring the density, the water displacement method is generally used that requires much energy and cost, so measurement can be made only for a limited number of samples. In order to establish high quality standards and satisfy the quality requirements on the safe side, therefore, specifications for dams need to be defined so as to satisfy the minimum quality requirements. Identifying the two- and three-dimensional distributions of internal friction angle and the mechanical stability of rock zone in actual dams is also extremely difficult.

To solve such problems in present site management of the rock zone as indirect control of density and difficulty in multi-point control, Matsuoka and others proposed a method for directly obtaining in-situ strength in in-situ shear tests. The RI (radioisotope) method for coarse grained materials of Toyota and others is capable of performing multi-point control of the density of compaction. Neither method, however, can measure the density of compaction throughout the compacted surface in detail in view of the construction speed at the site, so they are not suitable for area-wide real-time control. Tateyama, Fujiyama and others proposed a method for obtaining the density of compaction of the soil based on the turbulence factor. The factor is obtained by quantifying the acceleration due to varying vibrations caused by roller compaction that is measured using the accelerometer attached to the vibratory wheel of the roller. The method uses vibratory rollers also for quality control while they are rolling the surface, so it provides for unmanned, multi-point, planar and real-time monitoring of the density of compaction. Obtaining the correlation between the acceleration response of vibratory roller (turbulence factor) and the angle of internal friction in advance could enable in-situ area-wide real-time control of internal friction angle.

In this study, attention is focused on water content. Water content has good correlation with the angle of internal friction of rockfill material and serves as a parameter that enables easy identification of variations and changes of in-situ strength. A relationship between the turbulence factor and the angle of internal friction is deducted via water content, and a method is proposed for estimating the distribution of strength in the dam body, and the applicability of the method in actual construction is verified. The results are reported in this paper.

2 PROPOSAL OF A SIMPLE PARAMETER FOR IN-SITU STRENGTH EVALUATION IN ROCK ZONE

Existing methods for calculating the angle of internal friction involve obtaining the density of compaction in the rock zone and calculating the angle of internal friction based on the relationship between the density and the angle of internal friction identified in laboratory tests. These methods are effective where a certain type of material is used on a roller-compacted surface in tests. In actual construction, however, the type and class of rock material vary with time according to the quarry. The grain size of rock material is limited to a certain degree, but variations in rock type or class lead to different relationships between the density of compaction and internal friction angle. Density control is not necessarily practicable where multiple types of rock exist. A simple parameter correlated to the variations of rock material on actual roller compacted surface and related variations of internal friction angle would be practically very effective.

The engineering properties of rock material and influencing factors are listed in Table 1 based on the records collected at existing damsites and the results of evaluation of properties of

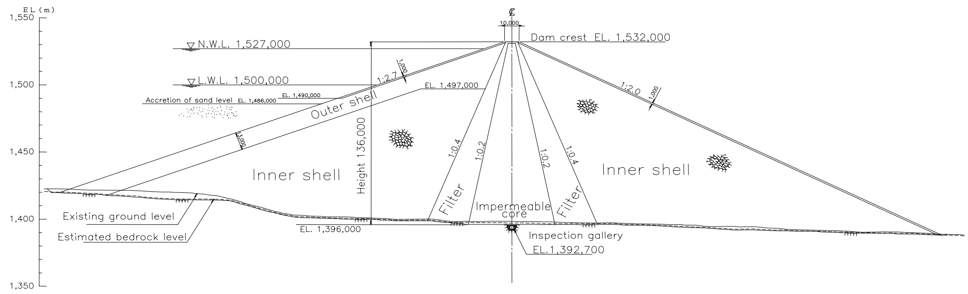


Figure 1. Typical cross section of the Minamiaiki dam

Table 1:Factors affecting the strength of rockfil material

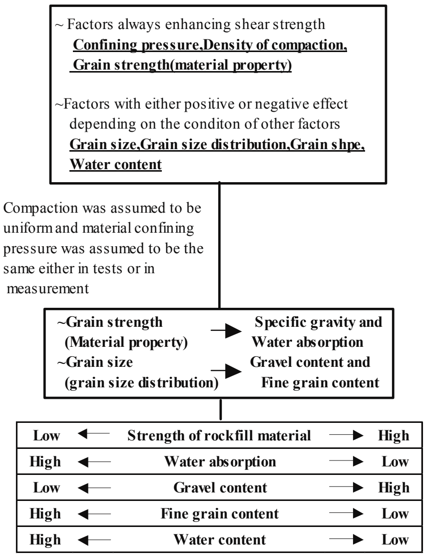


Table 2:Simple regression between strength characteristics and physical factor (n=40)

Physical factor	Explanatory variable	Coefficient of correlation with strength
Grain size distribution	Percentage passing by mass for sieve size 0.075mm	0.767
	Percentage passing by mass for sieve size 0.106mm	0.757
	Percentage passing by mass for sieve size 2.00mm	0.563
	Percentage passing by mass for sieve size 4.75mm	0.505
Rock properties	Specific gravity in absolutely dry condition	0.694
	Water absorption	0.753
	Rock type	-
	Unconfined compressive strength	-
Water content	Water content	0.861

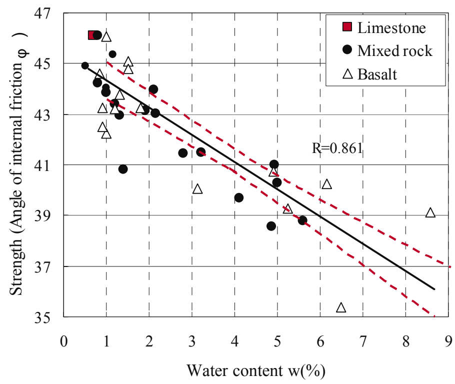


Figure 2. Water content and angle of internal friction

coarse grained material made by the Japanese Geotechnical Society. As long as the density and confining pressure remain constant, it is assumed that the lower the water content of rockfill material; or the harder the rock (the lower the absorption), the higher the gravel content and the lower the fine grain content; the greater the shear strength of rockfill material.

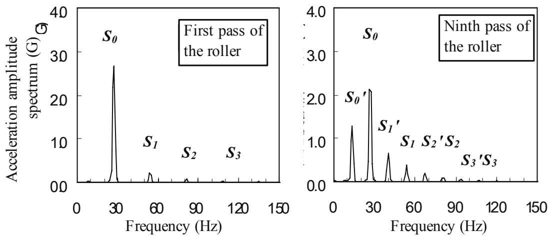
This study was made on the Minamiaiki Dam of the Kannagwa Power Plant, which is a central earth core rockfill dam with a height of 136 m, a dam crest length of 444 m and a dam body volume of 7.3 million m^3 (Figure 1). For rockfill materials, rock mixtures of olistoliths of sandstone, mudstone, chert, basalt and limestone in late paleozoic era through early mesozoic era in a pelite matrix were used. The materials were of grain sizes in a certain range, and the densities of compaction after in-situ roller compaction verified in trial construction were also in a certain range. so rockfill materials used in this site can be applicable to evaluation of Table 1. In this study, specimens were compacted using energy equivalent to that applied to compact the embankment material (1 Ec) according to the construction regulations, and subjected to consolidated drained triaxial compression tests. The angle of internal friction was defined under a confining pressure of 0 to 784 kN/m^2.

The results of simple regression analysis on the strengths obtained in laboratory tests are presented in Table 2 and Figure 2. Figure 2 represents the regression line and confidence intervals of 95% using a solid and dotted lines, respectively. Results are also presented by rock type. As a result of a simple regression analysis, it was found that the percentage passing by mass for sieve size 0.075 mm (the fine grain content), a grain-size-related factor, and the water absorption, a grain strength factor, were highly correlated to the angle of internal friction. Water content was also found to have higher correlation with the angle of internal friction than any other material property factors regardless of rock type. Water content had the highest correlation with the material strengththat is determined by the material properties and texture probably because water content was highly correlated with the fine grain content and water absorption. Correlation between the water content and the angle of internal friction was used as an indicator for controlling strength also at the Inamura Dam and other locations. In the strength control based on the water content at the Minamiaiki Dam, the effect of grain size characteristics was also considered. And water content could also be identified quickly at the site. Thus, water content was considered an effective quality control parameter.

3 PROPOSAL OF MULTI-POINT PLANAR CONTROL OF ROCK ZONE USING VIBRATORY ROLLER ACCELERATION MEASUREMENT SYSTEM

In this section, an embankment quality control method for properly grasping post-embankment variations of quality is assessed.

Figure 3 shows variations of acceleration amplitude spectrum according to the effect of roller compaction. In the initial stage of roller compaction, the acceleration amplitude spectrum was predominant at a basic frequency. As roller compaction progressed, the compacted surface and vibratory wheel reacted to



$$\text{Turbulence Factor} = \frac{\sum_{i=1}^{3} S_i + \sum_{i=1}^{3} S_i'}{S_0 + S_0'} \cdot F/(m_1+m_2)g \qquad \ldots(1)$$

m_1:Weight of the frame, m_2:Weight of vibratory wheel, F:Vibrating force

Figure 3.Fourier transform analysis of acceleration and definition of turbulence factor

each other, so acceleration amplitude spectrum occurred at other frequencies than the basic frequency. Grasping the relationship of soil density or stiffness to acceleration response in advance enables the determination of the degree of compaction of the soil during roller compaction based on the acceleration response of vibratory wheel. Turbulence factor was used in this study as a parameter for quantifying the vibratory roller acceleration measurement. Turbulence factor is shown in equation (1) using the frequency characteristics of acceleration waveform.

Rockfill materials obtained from quarries were subjected to roller compaction tests to investigate the relationship between the turbulence factor and the dry density on the roller compacted surface measured using RI density measurement equipment. As a result, it was found that the turbulence factor and dry density increased with the number of roller passes , and that different regression equations were applicable to different rock types (Figure 4). Estimating the soil density from the turbulence factor requires establishing the relationship between the two parameters in advance for all types of materials expected to be encountered. In the case where the rock type varies according to the quarry face, investigating the relationship between turbulence factor and dry density for respective rock types requires much cost and is considered impracticable.

Turbulence factor (acceleration was measured after four passes of a vibratory roller) was found to have a relatively close correlation with the water content on the compacted surface (measured using RI-based density measurement equipment) regardless of the rock type (Figure 5). This may be because materials with lower water content were coarser grained and contained harder rocks, so the vibrator wheel easily rebounded, increasing the turbulence factor.

It was therefore determined possible to estimate the angle of internal friction on the compacted surface from the turbulence factor via the water content using the relationship between water content and the angle of internal friction (Figure 2).

4 ESTIMATION OF POPULATION MEAN BY MULTI-POINT QUALITY CONTROL

In this section, the benefits of multi-point quality control are discussed.

The confidence interval of population mean estimated using the sampling data varies according to the frequency of quality control. In this study, the accuracy of estimation of population mean was verified when data were sampled from the water content measurements for rockfill materials obtained from a quarry.

Figure 6 shows the confidence interval of 95% of population mean that was calculated on the assumption that the mean water content of the population was 3.3% and that the population variance was unknown. Collecting three different data in one round of measurement, as in water content measurement, results

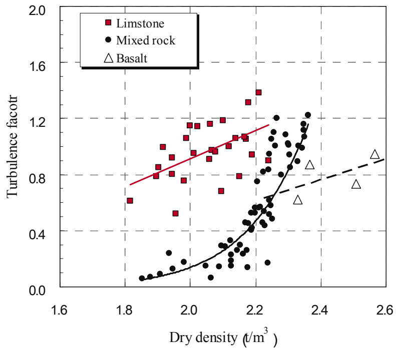


Figure 4.Dry density and turbulence factor of each material

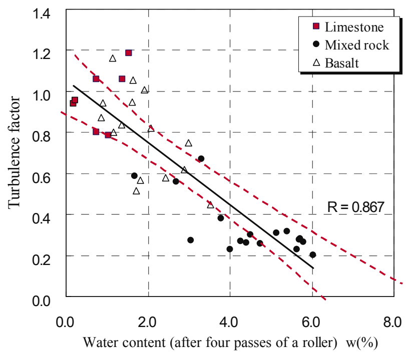


Figure 5.Water content and turbulence factor on roller compacted surface

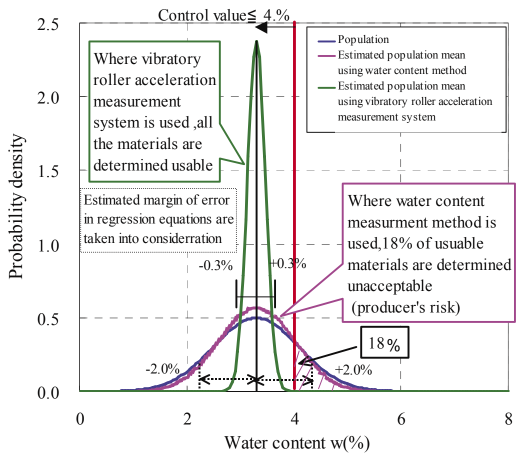


Figure 6. Estimation of population mean

in a margin of error of plus or minus 2.0% occurring in the calculation of the confidence interval of 95% of population mean. Suppose the control level of water content of the material is 4.0%, 18% of the population will be determined unacceptable. In the case where water content was obtained using the vibratory roller acceleration measurement system, turbulence factor data were collected in every 0.25 m^2, so 1600 data would be collected if construction took place in a yard of 400 m^2 in each round. Even where the margins of error of turbulence and water content estimated based on the regression lines were taken into consideration, the estimated margin of error in the confidence interval of 95% of population mean was held to plus or minus 0.3%. Then, no materials were determined unacceptable.

In conclusion, the method for calculating the angle of internal friction from the turbulence factor via water content, although an indirect method, helps make effective use of embankment materials through multi-point quality control that used to be unusable for safety reasons, and reduce excessive excavation or disposal of materials. This is because multi-point quality control greatly reduces the estimated margin of error of population mean.

5 DEVELOPMENT OF COMPACTION CONTROL SYSTEM

A compaction control system is composed of an accelerometer, GPS (geographical positioning system) and a wireless LAN (local area network). The accelerometer attached to the non-damping section of the vibratory roller detects vertical vibration of the roller.

The acceleration waveform data collected by the accelerometer are subjected to Fourier transform using the arithmetic unit carried on the vibratory roller to calculate the turbulence factor. The unit is also used for calculating the angle of internal friction from the relationship between turbulence factor and water content, and that between water content and the angle of internal friction. The data on time and the position of the vibratory roller received from GPS are interlocked with lever operation of the vibratory roller to identify the number of roller passes.

The data incorporated into the unit on the roller are accessible from the construction office a dozen or so kilometers away through a wireless LAN to confirm compaction conditions real-time. The operator of the roller can confirm the traces and the number of roller passes at the operator's seat, so construction can be carried out efficiently. Data collected through measurement are processed to obtain the distributions of internal friction angle in plan and in cross section, histogram etc. Thus, the quality of embankment finish can be verified.

Two- and three-dimensional distributions of internal friction angles on the compacted surface of the actual dam body were obtained using the proposed compaction control system. Figure 7 shows a two-dimensional distribution of internal friction angles at a certain elevation in different colors. The dam has inner shell and outer shell (Figure 1). Outer shell is designed to be made of high-strength materials. Figure 7 explicitly indicates the variations of internal friction angle on the roller compacted surface and difference in strength between zones. Figure 8 gives a histogram of internal friction angle on a construction day. The figure shows both the mean and design angles of internal friction. It is evident that the angle of internal friction varies nearly in the form of normal distribution and that the mean has an allowance of approximately three degrees above the design level. The water displacement method conventionally used at the dam provides much fewer samples of observation data, so statistical analysis of data is difficult. If 100% inspection is possible as shown in Figure 8, studies can be made by dealing with problems of means and the use of low-quality materials may be allowed.

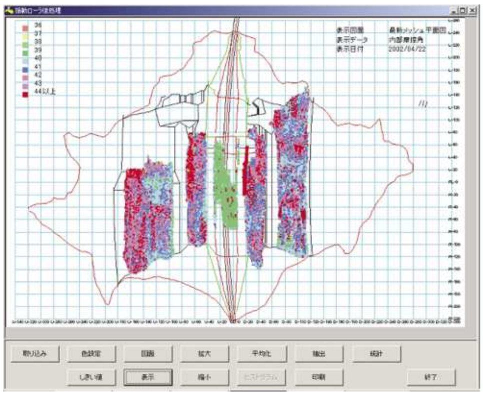


Figure 7. A two-dimensional distribution of internal friction angles at a certain elevation

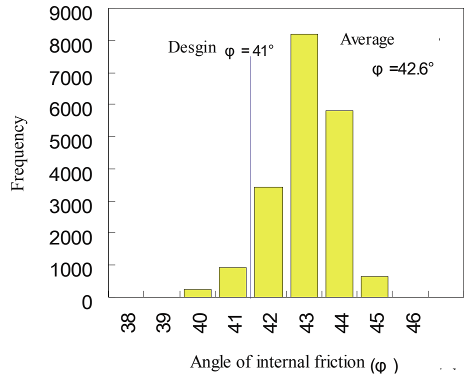


Figure 8. Histogram of the angle of internal friction

6 CONCLUSIONS

Attention was focused on water content of rockfill material as a major factor affecting the material strength. An embankment material quality control method and a post-embankment quality control method were proposed. The following conclusions were obtained from this study.

(1) It was found that the angle of internal friction of rockfill material was greatly affected by water content regardless of rock type where the degree of compaction was constant. This is because water content was related either to grain strength or grain size.

(2) Measuring the turbulence factor from the acceleration response of vibratory roller in the embankment area and evaluating the angle of internal friction in the embankment area through the water content proved possible.

(3) Multi-point quality control considerably increases the accuracy of estimation of population mean, so the range of materials of acceptable quality expands and excessive excavation and material disposal are reduced.

This study focused on coarse grained materials. For materials with varying density according to the water content such as high-water-content fine grained soils, the proposed methods are unlikely to be suitable for construction control. Identifying the range of materials to which these methods are applicable will be a future challenge.

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