Engineering Characteristics of Crushed Rockfill Material

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요 지

파쇄된 석괴댐 재료의 공학적 특성을 조사하기 위하여 대형 삼축시험을 실시하였다. 시험에 사용된 재료는 greywacke이고, 시료는 골재의 최대치수가 각각 38.1mm, 25.4mm 및 19.1mm이며 서로 평행한 3개의 입도분포곡선을 사용하였다. 시료의 크기는 ϕ300mm×600mm이고, 구속응력은 5t/m²에서 60t/m²까지 변화시켰다.

시험결과, 석괴재료의 응력-변형율 관계 및 내부마찰각에 미치는 골재의 최대치수의 영향은 무시할 수 있는 것으로 나타났다. 구속응력이 5t/m²에서 60t/m²으로 증가될 때, 내부마찰각은 51.6°에서부터 40.5°까지 감소 하였다. 석괴재료에 대한 삼축시험결과로부터 쌍곡선 모델의 매개변수를 산정하여, 이 값들을 Duncan등(1980)의 입상재료(GW및 GP재료)에 대한 추천치와 비교하였다. 매개변수 중, 석괴재료의 시험결과로부터 산정된 ϕ_0 및 K치가 특히 입상재료(GW및 GP재료)에 대한 추천치와 많은 차이를 보이는 것으로 판명되었다.

Abstract

To investigate the engineering characteristics of crushed rockfill material, the large-scaled triaxial tests have been carried out. The rockfill is made from the greywacke, and the 3 parallel gradations with different maximum particle size(d_{max}=38.1mm, 25.4mm and 19.1mm) were designed for the test.

The dimension of the specimen is 300mm in diameter and 600mm in height, and the applied confining stress varied from 5t/m² to 60t/m².

The test results show that the influence of the maximum particle size on the stress-strain relations and the angle of internal friction is negligible. The angle of internal friction decreases from 51.6°to 40.5° when the confining stress increases from 5t/m² to 60t/m². The hyperbolic parameter values estimated from the test result for rockfill are much different from the recommended values by Duncan et. al(1980) for GW and GP material, especially in the ϕ_0 ad K-values.

Keywords : Rockfill, Large-scaled triaxial tests, Stress-Strain relationslips, Strength characteristics, Hyperbolic model

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1. Introduction

The rockfill is being increasingly used as construction material of large dams in Korea. The first attempt of large rockfill dam is the Soyanggang dam which was completed in 1973. Since completion of this dam, a large number of rockfill dams have been constructed and also many dams are currently under construction as shown in Table 1.

Table 1. General Configuration of Major Large Rockfill Dams in Korea(Height>70m)

Name of Dam	Dam height(m)	Length of Dam(m)	Storage of Reservoir (10^3 m^3)	year of construction
Soyanggang	123	530	2,900,000	1973
Andong	83	624	1,248,000	1976
Deacheong	72	495	1,490,000	1980
Samrangin	78	529	4,766	1986
Kangnung Hydropower plant	72	310	40,000	1991
Juam Regulation	106	575	210,000	1991
Imha	73	515	497,000	1992
Yongdam	70	498	815,000	under construction
Miryang	89	535	73,600	under construction

Appropriate researches related to rockfill dam are mainly focused on the stress-deformation analysis during construction and operation. However, only a few research works towards a better understanding of the mechanical behaviour of rockfill materials have been carried out at design and construction stage. This anomaly has been largely due to a lack of the adequate laboratory facilities by their high capital cost. During design stages of the rockfill structure, estimation of load-deformation characteristics of the structure can only be accomplished by carrying out stress analysis which in turn uses the stress-strain relations established from laboratory tests on that particular material.

In this regard, the mechanical behaviour of rockfill material has been investigated in this paper by performing the experimental works with the large-scaled triaxial test appartus, of which dimension is 300mm in diameter and 600mm in height. In addition, the parameters involved in the nonlinear elastic hyperbolic model(Duncan & Chang, 1970) are evaluated on the basis of the results of triaxial test, and these parameter values are compared with those recommended by Duncan et al.(1980).

2. The Large -scaled Triaxial Test Apparatus

The large-scaled triaxial apparatus, a product of Seiken Inc., Japan(Model : DTC-300), can accommodate a sample size of 300mm diameter × 600mm height. The apparatus consists of five functional units, i.e., the vertical loading unit, the triaxial chamber, the hydraulic unit, the air pressure and water control units and the electrical measuring and control unit. A detailed schematic diagram of the test system can be referred to Lee(1986). The followings are the brief descriptions about the five functional units.

(1) Vertical Loading Unit

This system can apply a vertical load either at a constant rate of displacement or at a constant value of controlled load. The axial load can be applied through the top by means of an electro-hydraulic servo control system up to a maximum load of 50tons. The three principal parts of this system are the hydraulic actuator, the servo valve and the load cell. The load can be applied by a static servo controller in an electrical unit. The hydraulic pressure is supplied by a hydraulic unit to a maximum stress of 210kg/cm^2. Then the servo valve attached to the actuator controls either the load or the displacement according to the command voltage from the electrical control unit.

(2) Triaxial Chamber

The triaxial chamber enables a vertical cylindrical sample to be confined by a uniform radial fluid pressure while an independent axial stress is applied through a piston ram (diameter : 8cm) by a vertical loading unit. The triaxial chamber is made of stainless steel in a dome shape and it can sustain a maximum cell stress of 100t/m^2. The deformation dial gauge and the vertical displacement transducer are located in the upper part of the dome chamber. The transducers for the pore pressure and the cell fluid pressure are connected to the bottom of the chamber unit. The constant cell pressure is applied through the Belofram cylinder by the use of an air-water pressure system in which the air pressure is maintained by adjusting the pressure regulator. The volume change of the sample can be measured by either through the back pressure line connected to the burette or through the volumenometer (Belofram cylinder type) which is interconnected to the upper part of the triaxial chamber.

(3) Hydraulic Unit

The oil pump unit is designed as a console-type. It supplies a high oil pressure(maximum working pressure : 210kg/cm^2) to a hydraulic servo system unit at a discharge (pumping) rate of 5liter/min. This unit is connected to an electric power outlet with three-phase 380V AC, 50Hz. An oil cooler is equipped at the rear of the oil pump unit and this cooler is provided with two hose joints for supply and drainage of the cooling water. The oil used in this pump is ISO 56 and the required volume of the oil is 100liters.

(4) Air Pressure and Water Control Unit

This unit consists of two control panels, i.e., the air pressure control panel and the water control panel. An air pressure of approximately 10kg/cm^2 can be supplied from an air compressor to the pressure control unit. The pressure is then controlled by the pressure regulator to a desired level through an air filter. The cell stress is transmitted to the air-water pressure system through the Belofram cylinder which is interconnected to the cell chamber.

Also the cell fluid supplied from the confining stress water tank to the bottom of the cell chamber makes it possible to adjust the level of the Belofram cylinder when it is fully engaged.

The back pressure is applied through a back pressure tank to the sample. The deaired water in the back pressure tank is pressurized by applying the air pressure to the inside of the bladder(rubber baloon type) so that the air may be separated from the deaired water outside the bladder. This system is an improved version of the conventional air-water system, which prevents the dissolution of air into the deaired water.

(5) Electrical Measuring and Control unit

This unit is capable of controlling the vertical load by a servo controller and measuring the applied stress, or the strain(axial and volumetric deformations) and the pore pressure. The three principal parts of this unit are the static servo controller, the conditioner type strain amplifier with DV and the automatic digital data acquisition system.

3. Experimental Investigation

3.1. Test Material and Sample Gradation

The crushed rockfill of greywacke was separated into different sizes by dry sieving with vibration. A complete set of classification tests were performed to identify the rockfill from the other materials. The material properties measured in accordance with the standard testing procedure of ASTM are listed in Table 2, and it indicates that the material is relatively sound, homogeneous and angular.

Table 2. Index Properties of Rockfill

Material Index	Index values
Bulk specific gravity	2.65
L.A. abrasion resistance(%)	33.0
Grain shape factor	0.65
Uniaxial compressive strength(MPa)	102~172
Soundness(% loss by Sodium Sulfate)	3.20

Three gradation, J, K and F(see Fig. 1) were used in this work, which were approximately parallel, but smaller gradations when plotted in a semi-logarithmic particle size distribution. The maximum particle size for designed gradations are 38.1mm, 25.4mm and 19.1mm respectively.

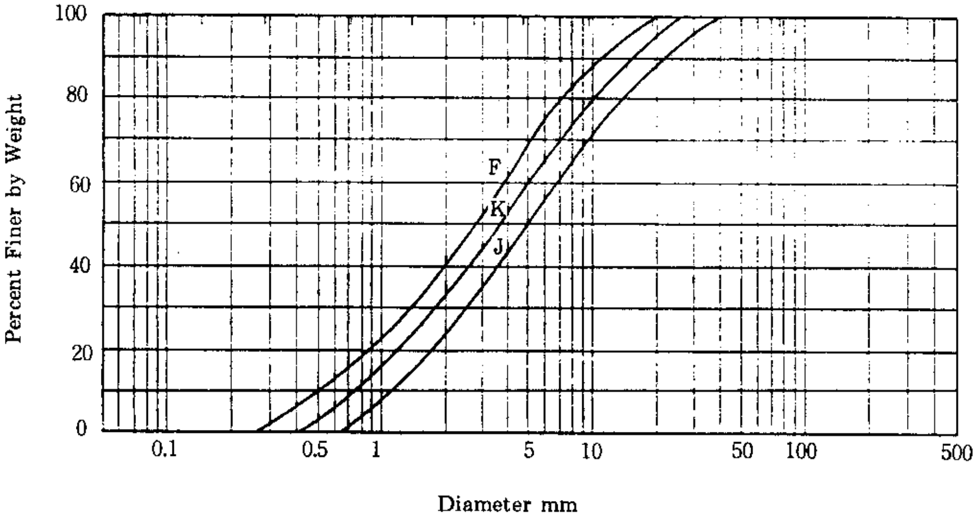

Fig. 1 Gradations of graywacke rockfill for large triaxial tests

3.2. Sample Preparation

The steps of preparing the test samples are as follows :

(1) From the designated gradation curve the percentage of each fraction size to be used was estimated.

(2) The quantity of the required materials was calculated from the dry unit weight based on the volume of the sample and the natural water content of the rockfill.

(3) The material weighed from each size fraction was blended thoroughly in a container.

(4) A compaction mould composed of two half-cylinders was placed on the base plate with the pedestal. Before placing the mould the rubber sheet(2mm thick) was fixed to the pedestal of the base plate and then extended over the inside of the mould.

(5) The rubber sheet was sealed to the collar of the mould so that it could be stretched out inside the mould by applying a suction of 30 to 40 cm Hg.

(6) The weighed material was divided into 6 batches and the material of each batch was poured into the mould and compacted by means of a vibrocompactor (weight : 5kg) to obtain the desired density.

(7) After all the material was poured into the mould the collar was removed and covered by the cap. The rubber sheet was then fixed to the cap by wrapping the rubber band to maintain the suction inside the sample when the mould was removed.

(8) The sample including the mould was moved to the base of the triaxial cell by using a hand-operating lift (Photo-1).

(9) Before removing the mould from the sample, a suction was applied inside the sample through lines connected to the cap, which extended to the outside of the cell chamber.

(10) The sample was covered by a latex membrane(1.5mm thick) outside of the rubber sheet by using the cylindrical membrane expander after removing the mould.

(11) The steel triaxial cell was fixed to the base and the cell chamber was filled with tapwater. Before releasing the suction inside the sample the cell fluid was pressurized by 0.5t/m^2 to prevent the sample from unwarranted deformation(Photo-2).

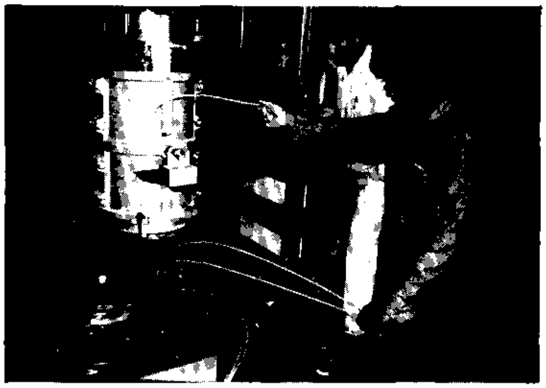

Photo 1. Sample(including the Mould) Set up to the Base of Triaxial Cell

Photo 2. Filling the Steel Triaxial Chamber with the Cell Fluid

3.3 Triaxial Test

A total of 11 cylindrical samples has been used in a conventional drained shear test with confining stresses varying from 5t/m^2 to 60t/m^2. The adopted 3 parallel gradations for this test have the maximum particle size ranging from 19.1mm to 38.1mm. The dry unit weight of the samples is 1.99~2.00t/m^3. The sample was first flushed with water. The back pressure was applied by incraesing the cell pressure first to 1.0t/m^2, and then both the cell presure and the back pressure were inccreased at the same rate to 10t/m^2. The sample was left under a back pressure of 10t/m^2 for 12 hours and the saturation was checked by measuring the pore pressure parameter, B. Generally B-values were about 0.85~0.90. The isotropic consolidation stress was applied through the Belofram cylinder to the sample by an air-water pressure system. This was made through an accurate pressure gague(least accuracy : 0.02kg/cm^2) and the pressure transducer gave the reading in the data acquisition system. The volume change of the sample can be measured both by the volume change transducer (capacity : 5000cc) and the volume change burette (capacity : 2500cc). When the conditioner type strain amplifier was adjusted, the hydraulic pressure in the oil pump unit was increased to 100kg/cm^2. The loading piston was lowered to contact the top of sample by controlling the dial of the test form placer section in the static servo controller. With the attachment of the displacement transducer to the loading piston, the DV indication spans for the axial load, the displacement and the volume change were set to the maximum capacity balances of the electrical transducers (i.e., 50 ton, 120 mm and 5000 cc respectively).

Then the initial values were set to zero. Thereafter by setting the strain rate and pushing the start button in the slope DC generator section of the static servo controller, the loading was started. The test results such as the axial load, the displacement, the confining stress, the back pressure and the volume change were recorded on the printer automatically by selecting the block time. The axial strain rate employed in this test is 0.08% per minuite, and this rate is based on the conclusion derived by Holtz and Gibbs (1956), that is, the conclusion that the variation of the axial strain rates from 0.086 to 1.81% per minute gives no significant effect on the stress-deformation relations for free draining sand-gravel samples. The corrections both for membrane strength and membrane penetration were made by the method suggested by Bishop and Henkel(1962).

4. Test Results and Discussions

4.1. Stress-Strain Relationships

The results of the isotropically consolidated-drained triaxial compression tests for the specimens are shown in Fig.2. The confining stress was varied from 5 to 60 t/m^2 and the maximum particle size is 38.1mm. The peak deviator stress increases as the confining

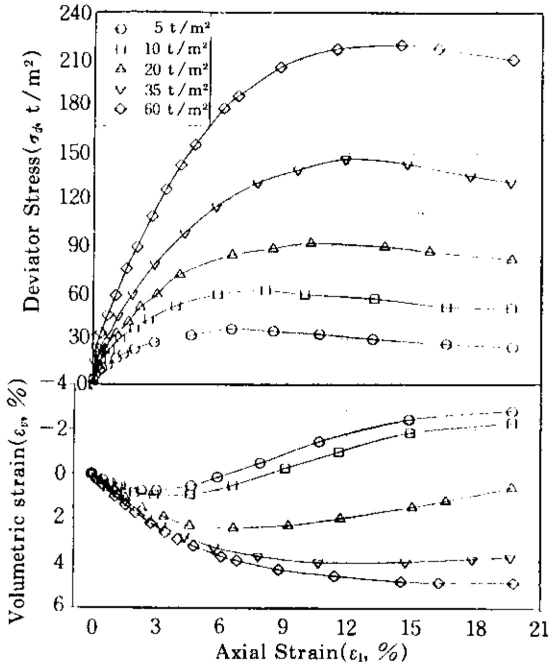

Fig.2 Deviator stress−strain and volumetric strain relationships of graywacke rockfill

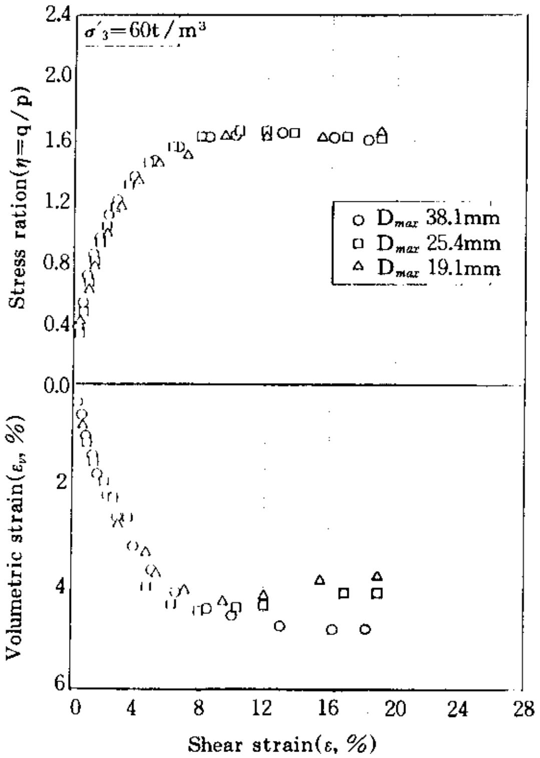

Fig.3 ($\eta-\varepsilon-v$)Relationships of rockfills with different particle sizes stress increases whereas a slight decrease in the deviator stress was noted after the peak value. The volumetric strain at low stress level is compressive in the initial range and then it becomes expansive when the shear strain increases up to 4%. But the trend of dilatancy decreases as the confining stress increases.

The influence of the maximum particle size on the stress-strain behaviour of rockfill is also presented in Fig.3, which shows the stress-strain curves for the specimens having parallel but different maximum particle sizes. Based on these results it can be seen that the effect of particle size is not significant on the stress-strain behaviours of rockfill under the test condition adopted in this research.

Figures 4 and 5 show the curves of volumetric strain and shear strain at peak deviator stress as a function of the confining stress respectively. The magnitude of volumetric strain at peak deviator stress increases rapidly with increase in confining stress at relatively low stress levels. Then the volumetric strains approach a asymptote value at particular level of confining stress of 50t/m². The magnitude of volumetric strains at peak deviator stress was generally the same irrespective of the maximum particle size. The influence of the maximum particle size on the shear strains at $(\sigma_1-\sigma_3)_{max}$ is also negligible and the variation of these strains with respect to the confining stresses is relatively small as represented in Fig.5.

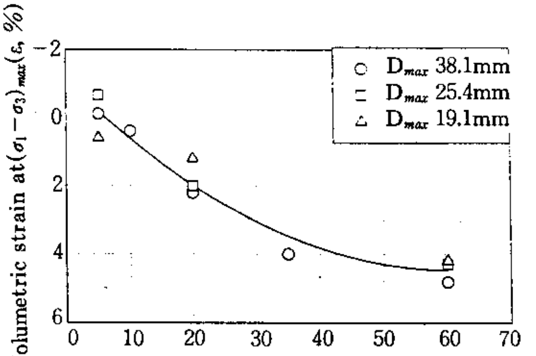

Fig.4 Volumetric strain at $(\sigma_1-\sigma_3)_{max}$ vs. confining stress from large triaxial tests

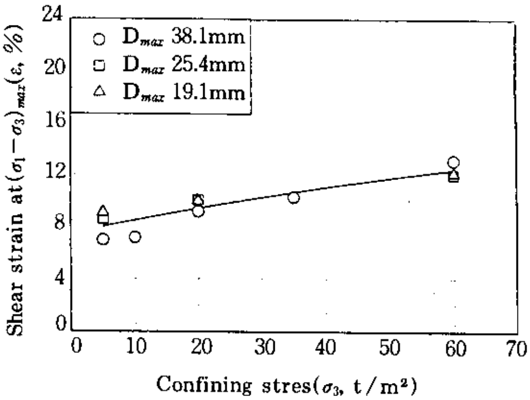

Fig.5 Shear strain at$(\sigma_1-\sigma_3)_{max}$ vs. confining stress from large triaxial tests

4.2 Angle of Internal Friction

It is customary to represent the shear strength of rockfill, measured from the drained test, by the Mohr-Coulomb criterion with assumption of zero cohesion intercept as represented in Eq. (1).

$$\sin\phi'=(\sigma'_1-\sigma'_3)/(\sigma'_1+\sigma'_3) \tag{1}$$

The Mohr failure envelope presented in Fig.6 shows a pronounced curvature. A curved failure envelope is noted particularly at low confining stress. The influence of the confining stress on the strength of rockfill may have a particular significance in certain slope stability when it is designed on the basis of a single ϕ'-value. Charles & Watts(1980) suggested that it may be highly desirable to measure the shear strength of rockfill at low confining stress and to use the shear strength parameters which closely approximate to the curvature of the failure envelope. This is to account for most stability problems that are principally concerned with the strength of rockfill at a low normal stress. When the single ϕ'-valueis used, the failure may occur mostly in the surficial depth of the dam. However, the higher strength observed at low normal stress implies that the surface stability is not critical even in a homogeneous rockfill dam.

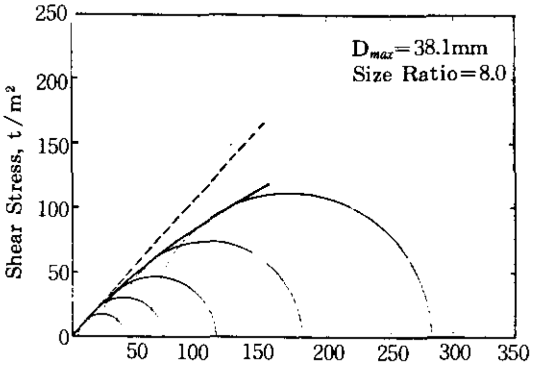

Fig.6 Mohr failure envelope of drained triaxial compression tests on graywacke rockfill

The calculated angles of internal friction are also plotted in Fig.7 as a function of confining stress. This figure shows that the angle of internal friction decreases as the confining stress increases and there is no significant effect of the maximum particle size. However, it is too premature to make definite conclusion about the effect of the maximum particle size on the stress-strain and strength characteristics because of limited test data available. Several researchers had investigated in the past about the effect of the maximum particle size on the ϕ'-value, and derived the split conclusions. Marachi et al.(1972) found, from the triaxial shear tests with maximum particle size(d_{max}) of 152 mm, that the ϕ'-value increases as the particle size decreases, whereas Charles(1973) concluded that the ϕ'-value slightly increases as the d_{max} increases. On the other hand, Valstad & Strom(1976) and Donaghe & Cohen(1978) have found that the ϕ'-value does not change significantly with increase in the d_{max}.

The remarkable increase in the measured values of the internal friction angle at low confining stress is probably caused by dilatancy(Lee & Seed, 1967). Bishop(1966) attributed the relative reduction of the strength at high confining stress to particle crushing. Initially local crushing at interparticle contacts occurs and ultimately shattering of the complete particles takes place. This in turn leads to a marked reduction in the angle of internal friction, which is associated with the reduced rate of volume change.

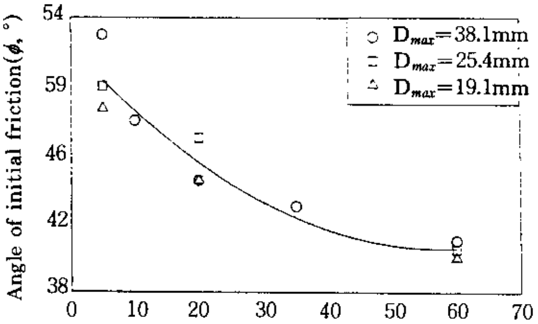

Fig.7 Angle of internal friction as function of confining stress

4.3 Parameter Values Involved in the Hyperbolic Model

The hyperbolic model is very effective for practical application in such a way that it incorporates three very important aspects of the stress-strain behavior of rockfill: nonlinearity, stress-dependency, and inelasticity. It provides simple techniques for interpreting the results of laboratory tests in a form which may be used very conveniently in finite element analysis of rockfill dam.

On the other hand, this model provides little theoretical background of the real soil (rockfill) behaviour. Christian(1980) argued that the hyperbolic model works best when the deviations from linear under the working loads are small, but it is difficult to apply effectively when a significant non-linear response is anticipated.

The load-deformation analysis of rockfill dam is done practically by finite element method(FEM) incorporating with the hyperbolic model due to its simplicity. However,

Table 3. Hyperbolic parameter values of rockfill estimated from the results of triaxial test values.

Classification		RC Stand. AASHTO	ϕ_0 (deg)	$\Delta\phi$ (deg)	K	n	R_f	K_b	m	Remarks
Rockfill (d_{max}, mm)	(38.1)	–	48.4	10.3	101	0.46	0.60~0.80	90	0.12	tested by the author
	(25.4)	–	48.0	8.6	85	0.41	0.54~0.74	80	0.12	
	(19.1)	–	46.4	8.0	90	0.43	0.58~0.80	60	0.23	
	Average	–	47.6	9.0	92	0.43	0.54~0.80	77	0.16	
GW, GP SW, SP		105 100 95 90	42 39 36 33	9 7 5 3	600 450 300 200	0.4 0.4 0.4 0.4	0.7 0.7 0.7 0.7	175 125 75 50	0.2 0.2 0.2 0.2	suggested by Duncan et.al.(1980)

evaluation of the hyperbolic parameters requires the large-scaled triaxial test apparatus, which is rather expensive and not available in most of the laboratories. This limitation leads to the use of parameter values which were suggested by Duncan et. al(1980) for various type of soils.

In this regard, the efforts have been made to determine the parameter values from the results of large triaxial tests for crushed rockfill. Figures 8 through 10 show the various plots to determine the parameter values for greywacke rockfill with the maximum partical size of 38.1mm. The parameter values obtained from the tests results for three gradations are shown in Table 3.

The parameter values of granular materials(GW,GP,SW,SP) recommended by Duncan et. al(1980) are also compared with the values estimated from the triaxial test results for rockfill in this table. It can be seen that the K-value of rockfill(average value : 92), which determines the tangent modulus(E_t) in certain stress level, is much smaller than the recommended values for GW and GP. The measured ϕ_0 values of rockfill(average value : 47.6deg.) are higher by 6 deg. than those for GW and GP. The values of the other parameters such as 'n', 'Rf', 'Kb', 'm' for rockfill are not much different from the recommended values for GW and GP.

However, when we consider the sensitivity of ϕ_0 and K values in the stress-strain relationship, it is suggested here that the load-deformation behavior of rockfill structure be analyzed by using the appropriate parameter values estimated form the results of triaxial test on that material.

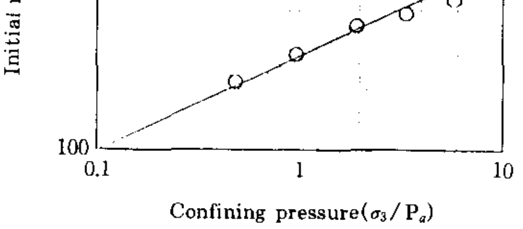

Fig.8 Variation of initial tangent modulus with confining stress

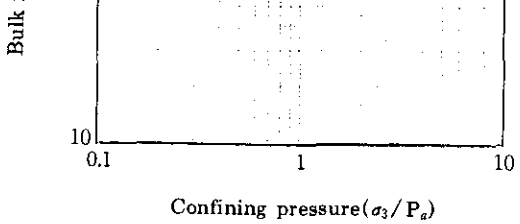

Fig.9 Variation of bulk modulus with confining stress

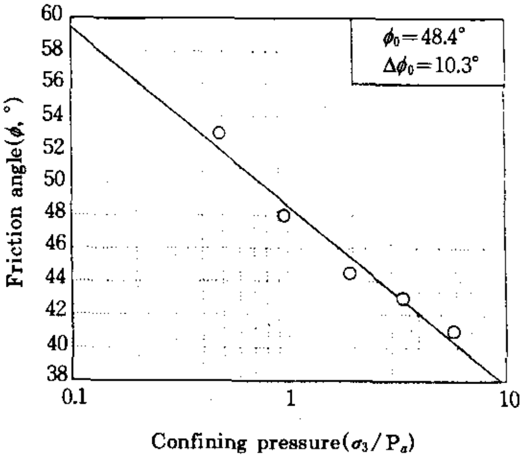

Fig.10 Variation of friction angle with confining stress

5. Conclusions

Based on the results of large triaxial test for rockfill material, the following conclusions are reached:

(1) The effect of the maximum particle size on the stress-strain behavior of rockfill during triaxial test is negligible under the test condition adopted in this research.

(2) The angle of internal friction decreases as the confining stress increases. The ϕ' value decreases form 51.6° to 40.5° when the confining stress increases from $5t/m^2$ to $60t/m^2$. The effect of particle size on the angle of internal friction is not nignificiant.

(3) The magnitude of volumetric strain at peak deviator stress increases rapidly with increase in confining stress at low stress level, and then it approaches to an asymptote value at higher confining stress.

(4) The hyperbolic parameter values estimated from the results of large triaxial tests for rockfill are much different from the recommended values by Duncan et. al(1980) for GW and GP material, especially in the ϕ_0 and K values.

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