Prediction of Stress-Strain Behaviour of Undisturbed "Masado"

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Abstract

In order to evaluate the stress-strain behaviours of undisturbed "Masado" which is one of unusual soils in Japan because of its collapsibility, the mechanical properties are investigated on the basis of the triaxial test results and the isotropic elastoplastic constitutive model for "Masado" is presented. The proposed model contains eight parameters which are easily determined from a few conventional triaxial tests. It is proved that the proposed model can reasonably evaluate the depedency of the stress-dilatancy and strength properties of undisturbed "Masado" on the confining pressure and the degrees of weathering.

Introduction

The residual soils "Masado" produced by the weathering of granitic rocks are mainly distributed in the western part of Japan, and it is very similar to those in China and southest Asian countries where natural and cut-off slopes have been suffered from failures due to heavy rain. Recently, the mechanical properties of undisturbed "Masado" have been discussed actively in relation to the earthwork for natural disaster in this area[1)~6)]. These studies have pointed out that their stress-strain behaviors are greatly changed from the strain hardening-softening behaviors to the strain hardening behaviours by the difference of the degrees of weathering and the variation of the moisture contents and confining pressure. Therefore, it is essential to use the constitutive equation which can take account of the above mentioned properties as much as possible, in order to analyze and precisely predict their stress-strain behaviours of "Masado" as boundary value problems.

In this paper, on the basis of the results of the drained triaxial compression tests, the mechanical behaviour of undisturbed "Masado" are presented and discussed from the standpoints of elasto-plastisity, paying attention to the degrees of weathering and the confining pressure. Thus based on the exprimental evidence and theoretical consideration, an elasto-plastic constitutive equation is presented to describe the overall stress-strain behaviours of undisturbed "Masado".

Residual Soils "Masado" Used

The typical index properties of eleven kinds of "Masado" used in this study are summarized in Table 1. These indices are often used as those of the degrees of

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Table 1 Index Properties of "Masado" Uted.

Sample No.		Specific gravity Gs	Ignition Loss* Li(%)	Void ratio e	Dry density ρ_d(g/cm³)	Natural water content ω_n(%)	Degree of saturation Sr_{nat}(%)	Water content at saturation ω_{sat}(%)	Color
Slightly weathered samples	1	2.617	1.37	0.464	1.789	8.7	49.07	17.73	Light gray
	2	2.664	1.44	0.480	1.800	8.5	47.18	18.02	
	3	2.611	2.19	0.474	1.773	7.9	43.52	18.15	
Moderately weathered samples	4	2.619	2.90	0.667	1.560	10.8	42.41	25.47	
	5	2.610	3.16	0.778	1.561	16.9	56.70	29.81	
	6	2.616	3.81	0.780	1.464	19.1	64.06	29.82	
	7	2.630	3.91	0.781	1.477	18.1	60.95	29.70	
	8	2.623	4.04	0.834	1.428	13.6	42.77	31.80	
	9	2.629	4.50	0.768	1.487	16.3	55.80	29.21	
Highly weathered samples	10	2.630	4.99	0.983	1.326	24.2	64.75	37.38	
	11	2.629	5.41	0.860	1.420	28.0	85.60	32.71	Indian red

Note : *defined by the contents of water of crystallization and absorbed water according to the standard of JSSMFE.

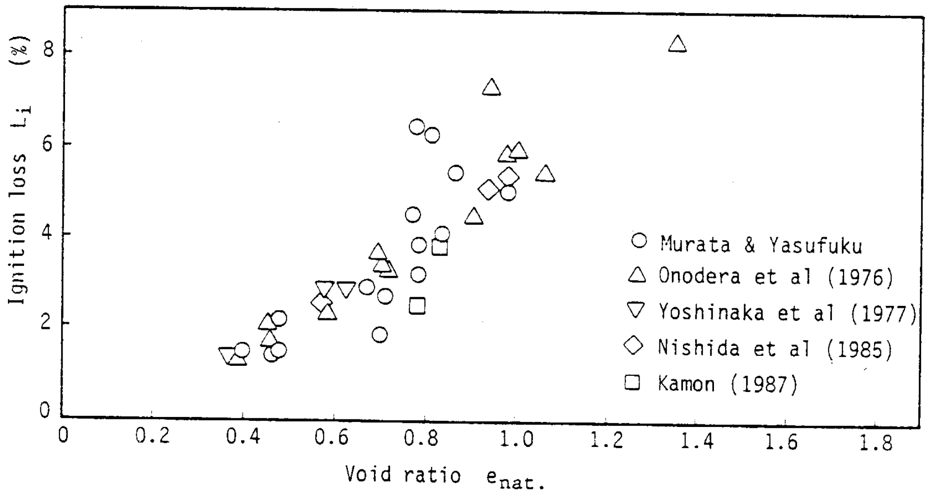

Fig. 1 Relation between Ingnition Loss and Void Ratio of Undisturbed "Masado".

weathering. As shown in this table, these soils were classified into three types on the basis of the index properties, so that, 1) Slightly weathered "Masado"; the void ratio is less than 0.5 and the natural water content is less than 10%, 2) Moderately weathered "Masado"; the void ratio is from 0.5 to 0.8 or the natural water content is from 10% to 20%, 3) Highly weathered "Masado"; the void ratio is more than 0.8 and the natural water content is more than 20%.

Fig. 1 shows the relation between the void ratio and ignition loss of these soils, together with the results indicated by other researchers. It is clear from this figure that there is a good correlation between these two weathering indices. In this study, the void ratio is used for convenience as the index of the degrees of weathering to evaluate the mechanical properties of undisturbed "Masado".

Mechanical Outline of "Masado"

The experimental procedure for making up the cylindrical undisturbed specimen and carrying out the triaxial compression tests were described in detail in a previous study[7]. The isotropic compression tests were conducted on the undisturbed samples with natural water contents. The volume change was measured by reading the change of de-aired water in the triaxial cell using a double buret. The typical test results for slightly weathered sample No.3, moderately weathered No.6 and highly weathered No.10 are shown in Fig. 2. It is recognized from this figure that 1) Δe-ln p curves of these undisturbed samples become bi-linear, where Δe means the change of void ratio, 2) the gradients of Δe-ln p curves for each samples under the virgin loading tend to gradually increase with the increases of p and converge the constant value and 3) the compressibility tends to increase with the increase of the degrees of weathering.

The standard triaxial compression tests on the specimens with natural water content were done under a consolidated-drained condition in a range of confining pressure up to 400kPa. The axial loading was imposed by means of strain control with the rate of 0.15%/min. The stress-strain curves are dependent on not only the degrees of weathering but also the confining pressure (see Fig. 8). The stress-dilatancy properties are gradually changed from the strain hardning-softening types to the strain hardening types with increase of the degrees of weathering and confining pressure. The secant friction angle ϕ_s depends on the confining pressure for each samples with natural water content and saturated samples. These properties indicate that (1) the values of ϕ_s for each samples decrease almost exponentially with increases of σ_r, and then converge to a constant value, namely, the failure envelopes of each weathered samples are not straight but curved, (2) the values of ϕ_s decrease with increases of the degrees of weathering under the same confining condition and (3) the most remarkable decrese of strength is seen for the moderately weathered samples in this stress region (see Fig. 9). In the following sections, these experimental results will be discussed from the standpoints of elasto-plastisity. Then, the following stress and strain increment parameters are used,

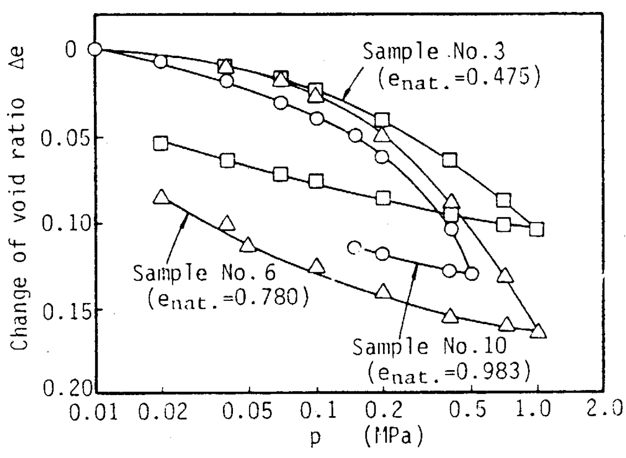

Fig. 2 $\Delta e-ln$p Curves Obtained from Isotropic Compression Tests.

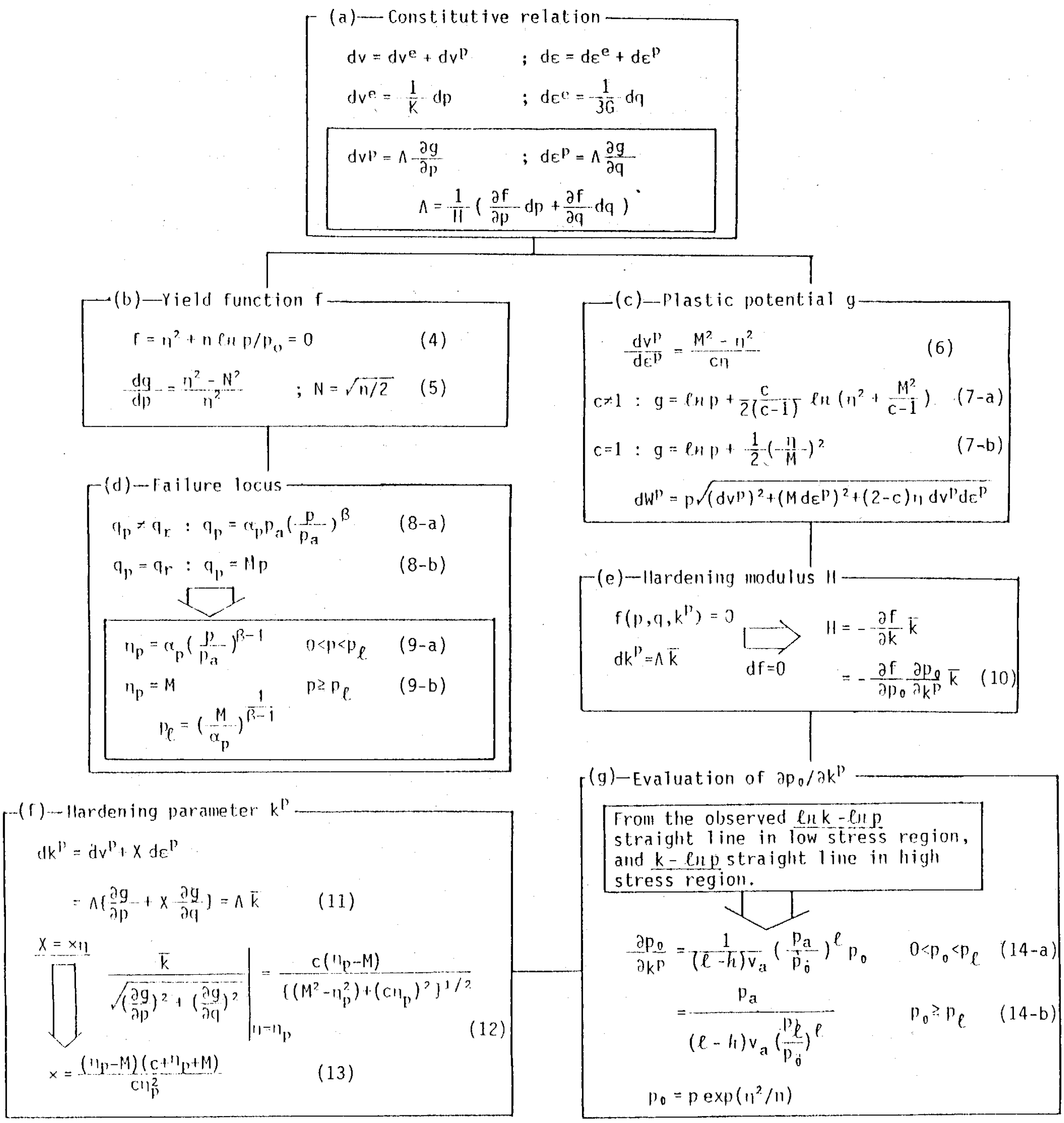

Fig. 3 Outline of Proposed Model.

$$p = (\sigma_a + 2\sigma_r)/3 \; ; \; dv = d\varepsilon_a + 2d\varepsilon_r \tag{1}$$

$$q = \sigma_a - \sigma_r \; ; \; d\varepsilon = 2(d\varepsilon_a - d\varepsilon_r)/3 \tag{2}$$

$$\eta = q/p \; ; \; \psi = dv^p/d\varepsilon^p \tag{3}$$

where p and q are the effective mean principal stress and deviator stress, η is the stress ratio, σ_a and σ_r are the effective axial and radial stresses, dv and $d\varepsilon$ are the volumetric and shear strain increments, ψ is the dilatancy index, $d\varepsilon_a$ and $d\varepsilon_r$ are the axial and radial strain increments, superscripts e and p denote "elastic" and "plastic", respectively. The compressive stresses and strains are taken as positive.

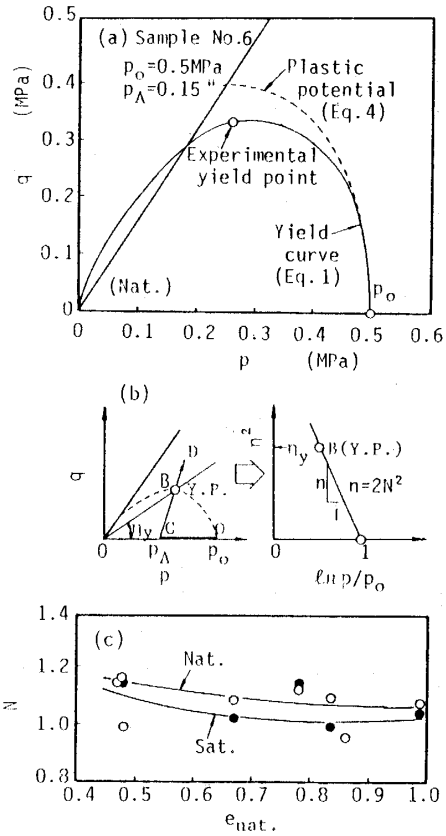

Fig. 4 Comparison of Proposed Yield Curves and Plastic Potential.

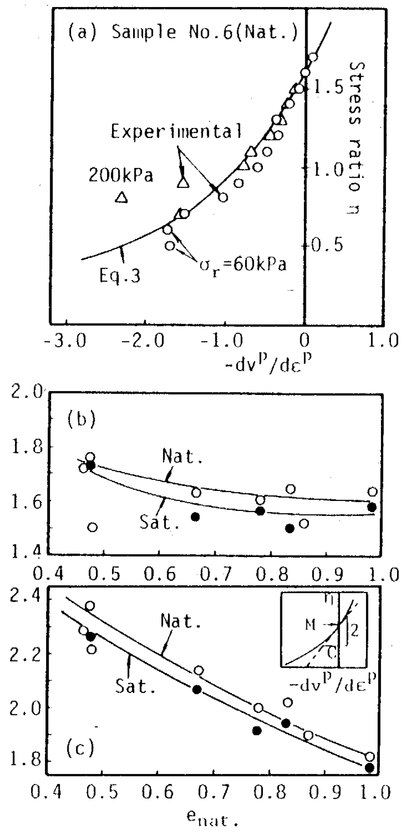

Fig. 5 Comparison of Predicted and Experimental Stress-Dilatancy Relation.

Elasto-Plastic Model Used

The model used to predict the stress-strain behaviours of "Masado" in this study is formulated on the basis of the fundamental concept that soil is changed from an isotropic hardenig-softening material to an isotropic hardening one with increase of the confining pressure. This model is derived by mainly modifying only the hardening parameter of isotropic hardening model which was proposed by the authors[8]. The outline of this model is shown in Fig. 3. The formulated model is assumed to be non associated as shown in Fig. 3(a).

The yield function is given by Eq. (4), which is derived based on the η^2-lnp/p_0 linear relation of the experimental yield curves as shown in Fig. 4(b), where p_0 is the value of p at which the yield surface intersect the p axies. Eq. (7) is the plastic potential which is derived based on the assumption that the η-$dv^p/d\varepsilon^p$ relation of "Masado" can be expressed by a hyperbola in Eq. (6). The applicability of Eq. (6) to the experimental stress-dilatancy relation is presented in Fig. 5(a). The comparison of the predicted yield curve and plastic potential curve of the moderately weathered sample No.6 is shown in Fig. 4(a). The failure locus, which is defined by the locus of the peak strength, is assumed by Eq. (9) based on the lnq-lnp linear relation at the peak and residual state as shown in Fig. 6(a). Using Eq. (9), we can evaluate the dependency of the peak

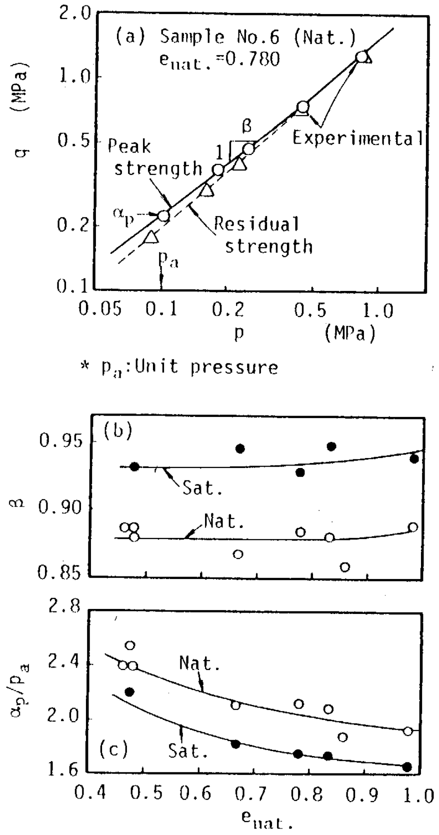

Fig. 6 Relation between q and p in peak and Residual Strength.

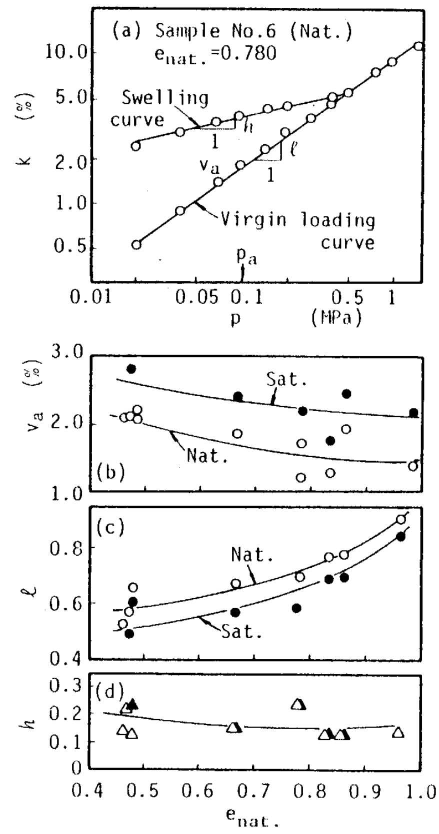

Fig. 7 lnk$-ln$p Relation in Isotropic Compression Test.

strength on the confining pressure (see Fig. 9). In order to evaluate the strain hardening-softening behaviour of "Masado", the new evolution form of the hardening parameter k^p is assumed as shown in Fig. 3(f). This hardening parameter can evaluate that (1) the development of the hardening behavior depends on not only dv^p but also $d\varepsilon^p$, (2) the contributing rate of both strain increments to the development of the hardening behaviour changes gradually with the increase of the values of p and η and (3) the softening process, modelled by setting X in Eq. (11) to zero, begins when η reaches the peak stress ratio η_p in Eq. (9). Then, in order to determine the hardening modulus in Eq. (10) concretely, the experimental evaluation of partial derivation, $\partial p_0/\partial k^p$ is given by Eq. (14) on the basis of the observed lnk-lnp straight line at $p_0 < p_l$, see Fig. 7(a), and k-lnp straight line at $p_0 \geq p_l$, where p_l is value of p at $q_p = q_r$ in Eq. (9). Thus, the concrete expression for the plastic strain increment in Fig. 3(a) is accurately determined from Eqs. (4), (7), (10), (11), (12), (13) and (14). The total volumetric and shear strain increment written in matrix form is given by Eq. (15). Here, using this model, we can evaluate the K_0 values of "Masado". The predicted K_0 values are given by Eq. (16), substituting the K_0 condition into Eq. (15).

$$\begin{vmatrix} dv \\ d\varepsilon \end{vmatrix} = \frac{1}{H} \begin{vmatrix} \frac{H}{K} + \frac{\partial f}{\partial p}\frac{\partial g}{\partial p} & \frac{\partial f}{\partial q}\frac{\partial g}{\partial p} \\ \frac{\partial f}{\partial p}\frac{\partial g}{\partial q} & \frac{\partial f}{\partial q}\frac{\partial g}{\partial q} \end{vmatrix} \begin{vmatrix} dp \\ dq \end{vmatrix} \tag{15-a}$$

$$\frac{1}{K} = h v_a \left(\frac{p}{p_a}\right)^{l} \frac{1}{p} \qquad 0 < p < p_l \tag{15-c}$$

$$\eta_{K_0}^2 + \{3(1-h/l)/2-(h/l)X\}\eta_{K_0} - M^2 = 0 \tag{16-a}$$

$$K_0 = \frac{3-\eta_{K_0}}{2\eta_{K_0}+3} \tag{16-b}$$

Prediction of Elasto-Plastic Behaviour

Experimental Parameters for "Masado"

The values of eight experimental parameters for the undisturbed "Masado" are summarized in Table 2. Here, the consolidation parameters l, h and v_a are determined from an isotropic consolidation test (see Fig. 7), and the dilatancy parameter M and c are evaluated by a stress-dilatancy relation obtained from a drained triaxial compression test as shown in Fig. 5, and then the strength parameters α and β are determined from the peak strength property obtained from a few triaxial compression tests as shown in Fig. 6. The parameter N, which is concerned with the yield property, is determined from the gradient of $\eta^2 - ln\,p/p_o$ straight line as shown in Fig. 4. As shown in Fig. 4(b), this straight line is easily described by getting the yield point B corresponding to the stress point O, which is determined from the drained triaxial compression test with stress path 0-O-C as shown in Fig. 4(b).

The relation between the above mentioned experimental parameters and the void ratio on both saturated and natural water content samples are shown in Figs. 4 to 7. From these figures, we can understand that the experimental parameters are closely connected with the degrees of weathering and the water content condition of undisturbed "Masado"

Table 2 Experimental Parameters of "Masado".

Sample No.		$e_{nat.}$	$L_i(\%)$	Consolidation parameters			Strength parameters		Dilatancy & yield parameters		
				l	h	v_a	α_P	β	C	M	N
1	Nat.	0.464	1.37	0.527	0.169	0.0210	2.40	0.887	2.29	1.72	1.14
2	Nat.	0.480	1.44	0.657	0.126	0.0222	2.40	0.880	2.21	1.50	0.99
3	Nat.	0.474	2.19	0.570	0.220	0.0212	2.55	0.884	2.38	1.82	1.16
	Sat.	—	—	0.533	0.220	0.0280	2.22	0.932	2.26	1.73	1.14
4	Nat.	0.667	2.90	0.675	0.150	0.0186	2.11	0.868	2.14	1.63	1.08
	Sat.	—	—	0.565	0.150	0.0242	1.82	0.946	2.00	1.61	1.12
	Sat.	—	—	0.589	0.238	0.0220	1.75	0.929	1.91	1.57	1.14
8	Nat.	0.834	4.04	0.774	0.129	0.0130	2.09	0.881	2.02	1.65	1.09
	Sat.			0.689	0.129	0.0176	1.74	0.948	1.94	1.50	0.99
10	Nat.	0.983	4.99	0.914	0.132	0.0140	1.94	0.889	1.82	1.64	1.08
	Sat.			0.847	0.132	0.0220	1.65	0.940	1.78	1.58	1.04
11	Nat.	0.860	5.41	0.781	0.127	0.0195	1.88	0.875	1.90	1.52	0.96

Prediction of stress-strain behaviour

Fig. 8(a) to (c) show the observed q-ε_a-v relations of the three kinds of weathered samples No.3, No.6 and No.10 with natural water content for the drained triaxial compression tests and also Fig. 8(d) to (f) show these predicted results, respectively. It can be seen that these predicted results reasonably describe the fundamental properties that the observed stress-strain curves are changed from the strain hardening-softening types to the strain hardening types with increase of the degrees of weathering and the confining pressure.

Fig. 9(a) to (c) show the comparison of the experimental and predicted results of the relation between the secant friction angle ϕ_s and confining pressure σ_r for each samples. It can be seen from these figure that the predicted strength properties evaluate the experimental ones which the values of ϕ_s for each samples decrease almost exponentially with increases of σ_r and then converge to the constant value.

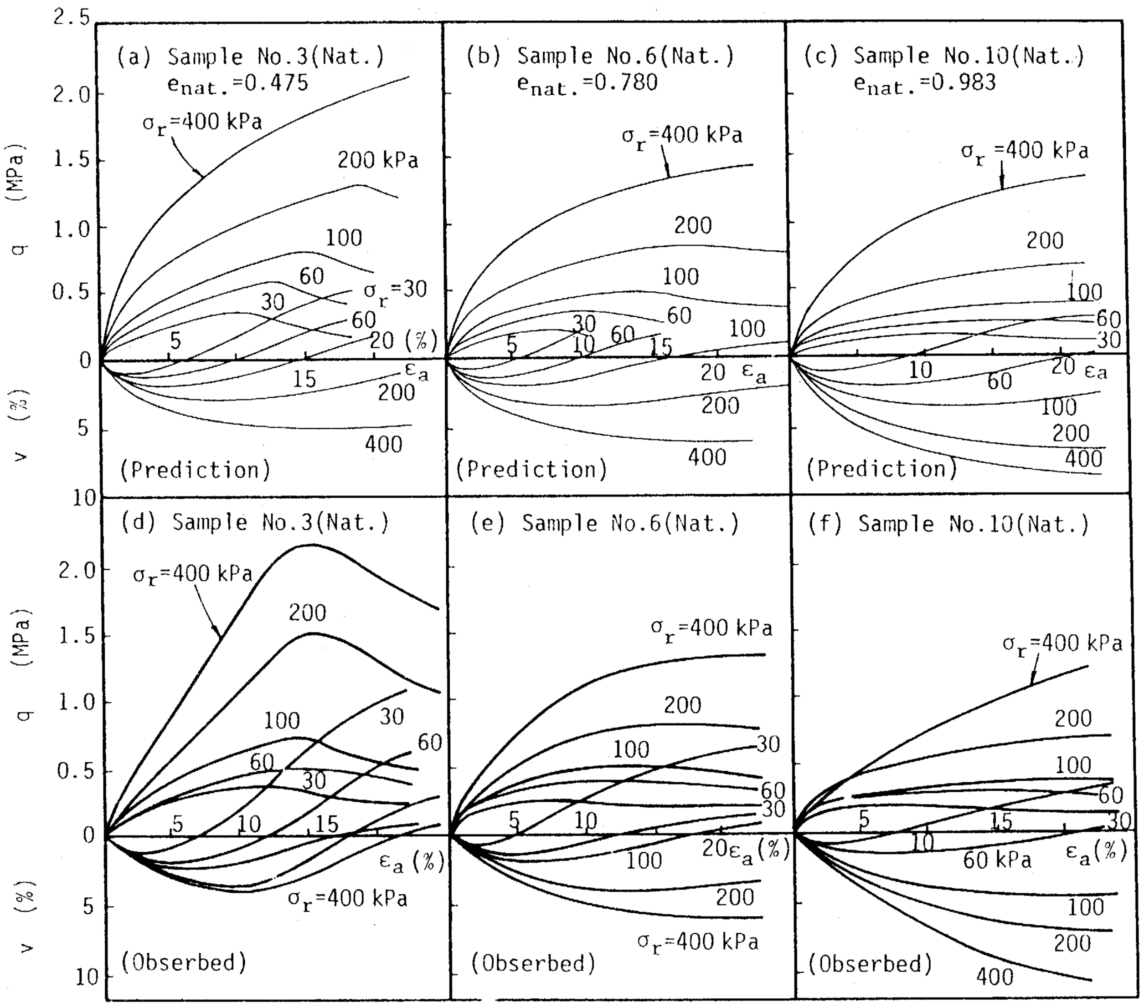

Fig. 8 Predicted and Experimental Stress–strain Curves in Drained Triaxial Compression Test.

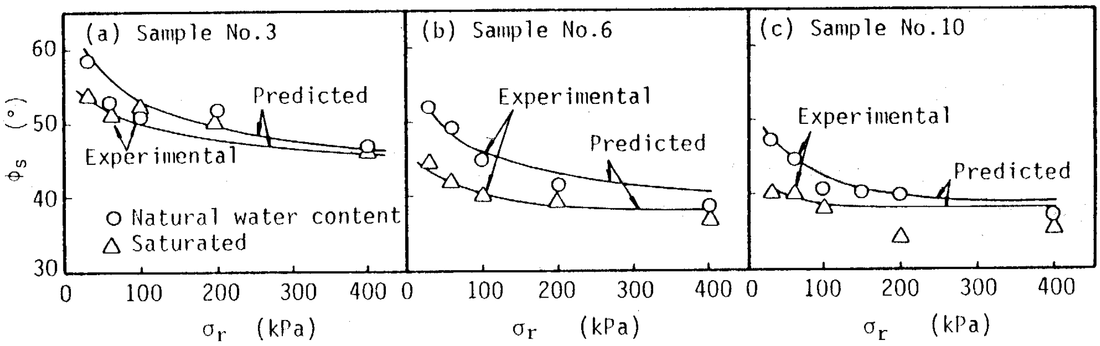

Fig. 9 Predicted and Experimental Relation between ϕ_s and σ_r.

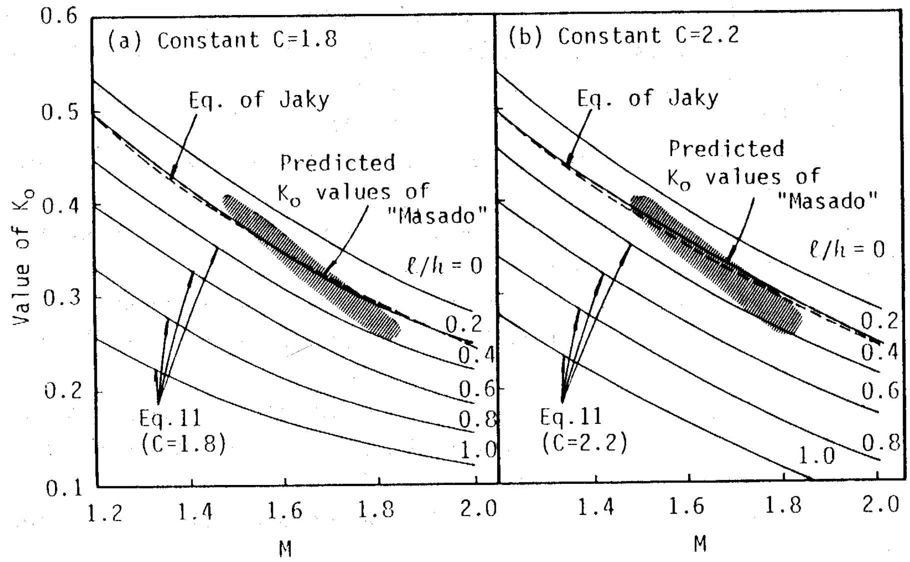

Fig. 10 Predicted Values of K_0 for Undisturbed "Masado".

Fig. 10(a) and (b) show the expected band of the K_0 values of undisturbed "Masado" predicted by Eq. (16) together with the predicted values from the empirical expression suggested by Jaky[9]. It can be seen that two predicted K_0 values show the good agreements. From these results, the satisfactory agreements in the stress-strain behaviours can be noted for undisturbed "Masado" by using the proposed model.

Conclusions

A simplified isotropic hardening model was presented in order to describe the mechanical behaviours of undisturbed "Masado" having the various degrees of weathering. The proposed model was expressed based on the theoretical considerations and experimental evidences through the drained triaxial compression tests of undisturbed "Masado". It was proved that the present model could reasonably evaluate the fundamental properties that the stress-strain behavior was changed from the strain hardening-softening types to the strain hardening ones with the increase of the degrees of weathering and the confining pressure.

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