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Water-induced granular decomposition and its effects on geotechnical properties of crushed soft rocks

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Abstract. The widespread availability of soft rocks and their increasing use as cheap rockfill material is adding more to geotechnical hazards because time-dependent granular decomposition causes significant damage to their mechanical properties. An experimental study was conducted through monotonic torsional shear tests on crushed soft rocks under fully saturated and dry conditions and compared with analogous tests on standard Toyoura sand. Due to the sensitivity of material to disintegration upon submergence, saturated conditions accelerated granular decomposition and, hence, simulated loss of strength with time, whereas, dry test condition represented the response of the soil with intact grains. A degradation index, in relation to gradation analyses after each test, was defined to quantify the degree of granular decomposition. Possible correlations of this index, with strength and deformation characteristics of granular soils, were explored. Enormous volumetric compression during consolidation and monotonic loading of saturated specimens and drastic loss of strength parameters upon submergence were revealed. It is revealed that the observed soil behaviour can be critical for embankments constructed with such rockfill materials. Moreover, the enhanced ability of existing soil mechanics models to predict time-dependent behaviour by incorporating water-induced granular decomposition can simplify several in situ geotechnical problems.

1 Introduction

While dealing with a variety of non-conventional complex geomaterials, engineering structures are exposed to increased geohazards with intensive developments in hilly areas. Moreover, the economic constraints sometimes compel engineers to use cheap materials for the construction of various geotechnical structures, e.g. using mudstone as a rockfill material for embankments and placing foundations on such soils. A typical example of geotechnical hazards, caused directly by the phenomenon of negative ageing mainly due to water-induced granular decomposition of crushed rocks, is reported by Asada (2005). He compared SPT-N values in residential fills which were affected by earthquake and found a drastic decrease in the mean value with years after the completion of filling. The fill materials were later found to be affected by the phenomenon of water-induced disintegration of grains.

The conditions under which soft rocks are degraded due to physical or chemical decomposition are well established (Hawkins et al., 1988) and efforts are also made towards constitutive modelling of degradable geomaterials by Pinyol et al. (2007), Yuan and Harrison (2008), and Castellanza and Nova (2004). They concluded that granular decomposition affects the mechanical behaviour due to progressive degradation of bonding and loss of soil structure. It is important to note that the term weathering implies mechanical, physical and/or chemical changes, whereas granular decomposition is a byproduct of weathering causing the loss of strength and stiffness with time. The capabilities for a prediction of time-dependent response of geomaterials to both engineering and geological time scales are still very poor (Simpson and Tatsuoka, 2008). Hence, the gap between geology and geotechnical engineering needs to be bridged for successful realization of engineering problems faced in complex geology, as well as for efficient use of cheap rockfill materials.

2 Focus of this study

The geological changes in soil composition and its engineering properties may require thousands of years, whereas, it has been realised in the last few decades that there are also

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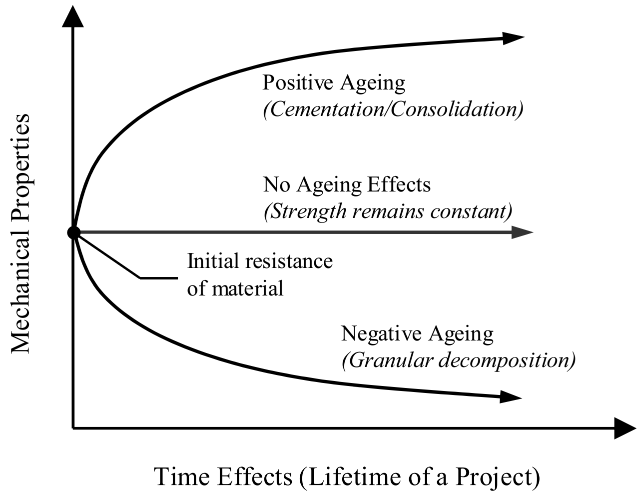

Fig. 1. Time-dependent behaviour of granular soils.

changes in soil properties over a shorter period of time which are more relevant to engineers. These changes are described as ageing effects and are schematically explained in Fig. 1. Conventionally, the ageing effects are believed to be positive, that is, the increase in strength and stiffness of soils over time under constant effective stresses after deposition. It is essentially due to the lithification of conventional granular materials consisting of durable soil grains under working conditions. However, naturally occurring sedimentary and residual deposits, generally treated as granular soils in geotechnical engineering, experience time-dependent granular decomposition due to the weathering process. Such a phenomena is associated with the loss of strength and stiffness parameters with time, hereafter referred to as "negative ageing". The description of such effects needs to be included in conventional concepts of soil mechanics.

Extensive research work is published on the effects of the particle breakage on mechanical behaviour of granular soils. However, the main focus is always made more or less on the effects of extremely high, overburdened stresses and extensive shear strains. Only a few studies are known to exist like, Neves and Pinto (1988) and Nakano et al. (1998), concerning the effects of slaking-induced degradation of soil grains on its engineering properties. Many researchers reported negligible influence by the presence of water on mechanical behaviour of standard sands like, Fioravante and Capoferri (1997), Wichtmann et al. (2005), and Youn et al. (2008). Such an approach is essentially true for most of the standard laboratory sands consisting of durable grains. On the contrary, Mizuhashi et al. (2006) showed significant effects of saturation on shear strength of weathered soils. Therefore, stability of natural slopes and the design of foundations and embankments in such soils will be strongly influenced due to such phenomenon. Keeping this in view, the investigation of water-induced granular decomposition with respect

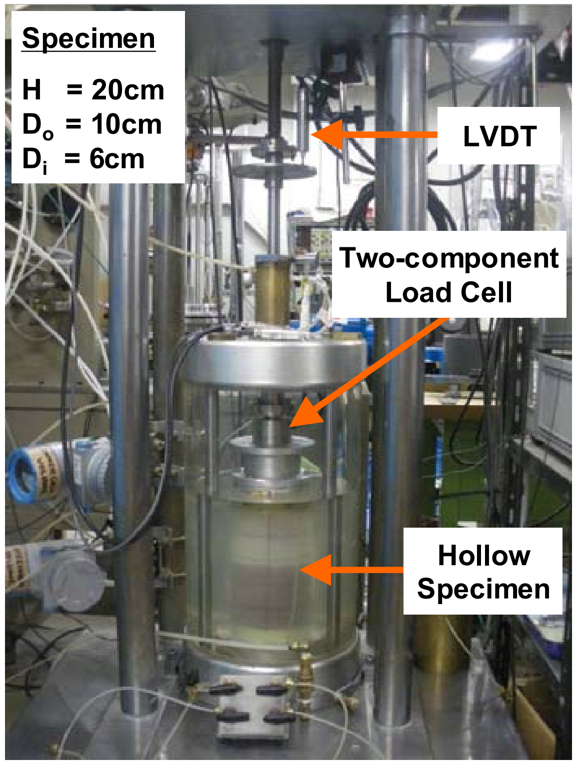

Fig. 2. General layout of specimen in torsional shear apparatus.

to its influence on strength and deformation characteristics of crushed soft rocks was carried out in this study. Deterioration of soil grains upon submergence is focused on because irrespective of the bonding nature of soft rocks, presence of water is always a key source of initiation of the weakening processes (Neves and Pinto, 1988).

3 Methodology

An experimental study was conducted through consolidated drained monotonic torsional shear tests on hollow cylindrical reconstituted specimens of crushed soft rocks under fully saturated and dry conditions. The results were compared with analogous tests on standard Toyoura sand. The tests were performed in accordance with Japanese Geotechnical Society standards for laboratory shear tests (JGS 0551-1998, 2000). A megatorque torsional shear device was used in this study. This device had the capabilities of monotonically shearing isotropically and anisotropically consolidated specimens to relatively large shear strain level. The effects of water-induced granular decomposition of material on its geotechnical properties were explored by shearing the specimens at a constant mean effective principal stress under drained conditions. The general layout of the specimen in torsional shear apparatus is shown in Fig. 2.

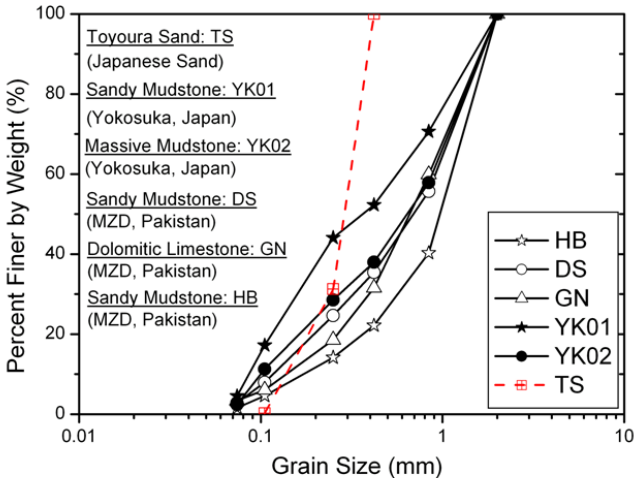

Fig. 3. Initial grain size distribution of all crushed rocks and Toyoura sand.

The use of crushed soft rocks was intended to accelerate the process of water-induced granular decomposition in a laboratory which takes months or years to complete under in situ conditions. Accordingly, saturated tests simulated the loss of strength and the increase in deformation characteristics with time, whereas, dry test represented the response of soil with intact grains. A degradation index, in relation to gradation analyses before, after saturation, and after shearing was defined to quantify the degree of water-induced granular decomposition. The effects of confining stress and shear strain level on particle breakage were investigated and possible correlations of the degradation index with geotechnical properties of soils were then explored.

3.1 Sampling sites and material preparation

Naturally weathered soft rocks were obtained from different parts of Japan and Pakistan. After air-drying the collected material, it was crushed to a specific grain size of 2.0–0.075 mm for preparation of 20 mm thick hollow cylindrical specimens of 200 mm height, 100 mm outer diameter and 60 mm inner diameter. According to JGS 0550-1998 (2000), maximum grain size, D_{max} should be limited to 0.1 times the wall thickness of the hollow specimen, therefore, D_{max} of all test materials was limited to 2 mm.

The grain size distribution (GSD) curves and physical properties of the crushed rocks and Toyoura sand are presented in Fig. 3 and Table 1, respectively. Where, G_s is the specific gravity of soil solids, e_{max} and e_{min} refer to the maximum and minimum void ratios, D_{max} and D_{50} corresponds to the maximum particle size and particle diameter at 50% passing, respectively, U_c is the coefficient of uniformity defined as D_{60}/D_{10} and F_C represents the fines content passing sieve size 0.075 mm. Microscopic photographs of test materials (2.0–0.84 mm) are shown in Fig. 4 to provide a general picture of particle shape and structure.

Table 1. Physical properties of the test materials.

Soil type	G_s	D_{max} (mm)	D_{50} (mm)	U_c	e_{max}	e_{min}
HB	2.75	2.00	1.00	6.9	1.132	0.708
DS	2.73	2.00	0.69	7.7	1.114	0.586
GN	2.81	2.00	0.69	5.7	0.906	0.443
YK01	2.52	2.00	0.37	6.6	1.724	1.174
YK02	2.40	2.00	0.64	8.8	1.669	1.029
TS	2.65	0.42	0.22	1.3	0.980	0.610

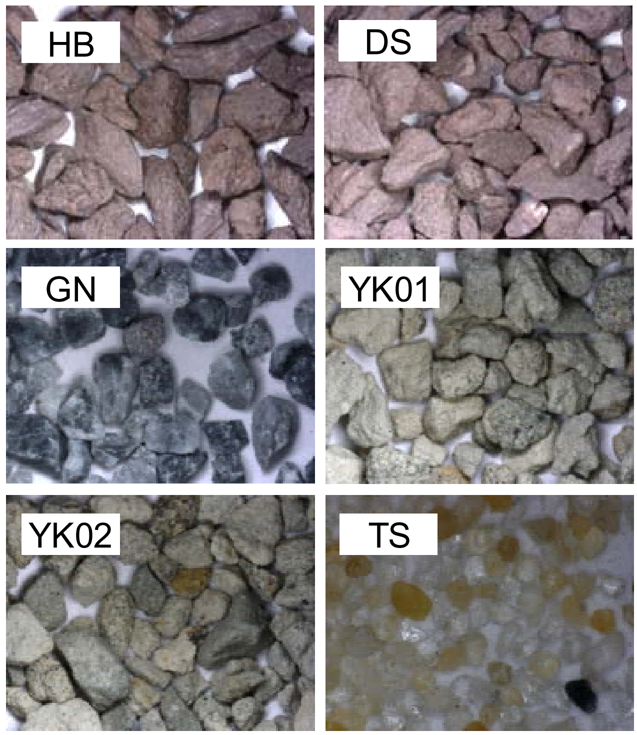

Fig. 4. Microscopic view of all crushed rocks (2.0–0.84 mm) and Toyoura sand grains.

3.2 General experimental procedure and stress paths

Air-dried, crushed material was thoroughly mixed before sample preparation for uniformity in the soil specimen. The use of air-dried samples can successfully minimize the complex suction problems for preliminary estimates of the shear strength parameters of unsaturated/dry soils (Vilar, 2006). Initially, dry specimens were prepared at desired initial relative densities (D_R) of about 70%. D_R was kept higher to simulate the field conditions of the construction of embankments and to reduce the large volume changes as expected in case of saturated rockfill materials.

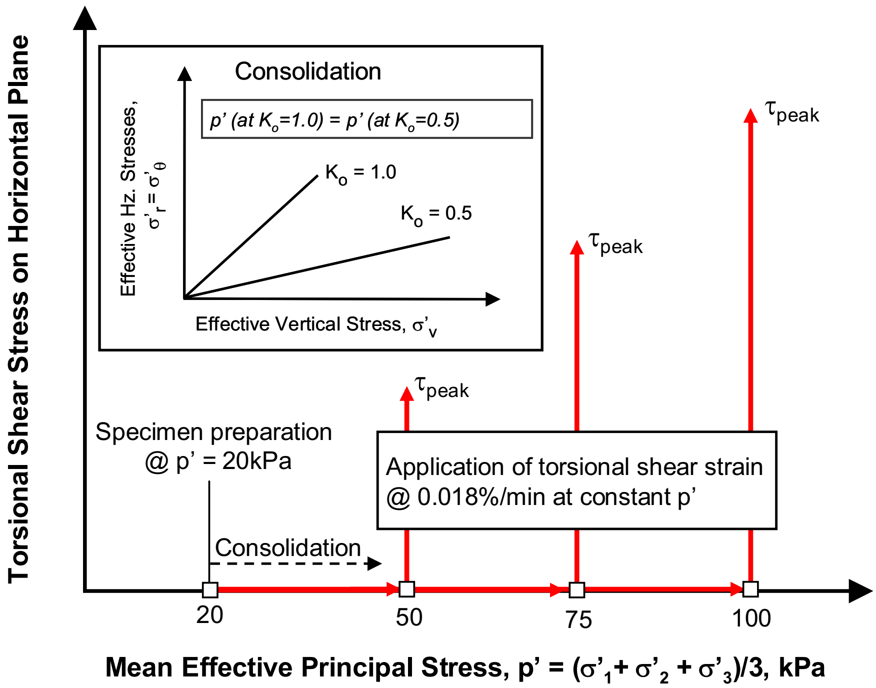

Fig. 5. Stress paths during consolidation and monotonic torsional shear.

Table 2. Consolidation conditions for each test material prior to shearing.

p' (kPa)	σ'_z (kPa)	$\sigma'_r=\sigma'_\theta$ (kPa)	K_o	Drainage conditions
50	50	50	1.0	i) Saturated test ii) Dry test
75	75	75	1.0	i) Saturated test ii) Dry test
100	100	100	1.0	i) Saturated test ii) Dry test
50	75	37.5	0.5	i) Saturated test ii) Dry test
75	112.5	56.25	0.5	i) Saturated test ii) Dry test
100	150	75	0.5	i) Saturated test ii) Dry test

The consolidation and shearing stress paths are shown in Fig. 5. Keeping all the initial conditions similar for two comparative tests, one specimen was consolidated and sheared under dry conditions, whereas, the other was saturated prior to consolidation and then sheared under drained conditions. In addition, to study the possible effects of the coefficient of lateral earth pressure at rest, K_o, and mean effective confining stress, p', on the deformation and strength response, specimens were consolidated at σ'_h/σ'_v=1.0 and 0.5 and p'=50, 75, and 100 kPa as described in Table 2. Drained tests at a relatively slow shear strain rate of 0.018%/min were performed to focus on long-term material response as well as to avoid the errors of partial saturation and membrane penetration. It was not possible to measure volumetric strain (ε_{vol}) of dry specimens using a double cell due to limited space between specimen and acrylic outer cell or using internal devices like clip gauge or LDTs due to the large shear strain levels. Therefore, only vertical strains (ε_z) were measured during dry tests and compared with ε_z of analogous saturated tests.

4 Experimental results and data analysis

To investigate the effects of water-induced granular decomposition on deformation and strength characteristics of crushed rocks, tests were performed on six different materials (TS, HB, DS, GN, YK01, and YK02). Data analysis and interpretation were carried out keeping in view the importance of soil-structure interaction, performance of foundations on weak granular soils, and response of embankments constructed by cheap rockfill. The effects of granular decomposition on geotechnical properties of the materials were then explored by comparing the experimental results between the crushed soft rocks and Toyoura sand.

It is important to mention that all the comparisons between deformation and strength characteristics of Toyoura sand and crushed rocks have been made at the same effective stress during consolidation and same shear strain during monotonic torsional shear.

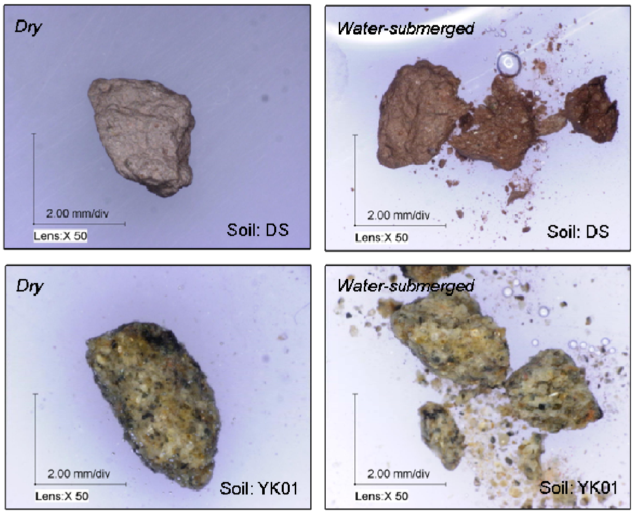

Fig. 6. Water-induced granular decomposition of crushed rocks.

4.1 Quantification of water-induced granular decomposition

The crushed rocks used in this study were highly susceptible to disintegrate upon wetting as shown in Fig. 6. The engineering properties (e.g. stress-strain behaviour and volume-change response, etc.) of granular materials are strongly dependent on GSD under in situ conditions. Therefore, it was necessary to identify and quantify the time-dependent, water-induced granular decomposition of all test materials. Although, the amount of fines (ΔF_C) at the end of each test indicated the extent of disintegration, but it did not exclusively describe the change in overall grain sizes. On the basis of maximum evolution potential of the initial GSD of a material, a degradation index, I_D, was defined, as shown in Fig. 7, to quantify the accelerated negative ageing of crushed rocks mainly due to water-induced granular decomposition. Such an index was perceived from grading index (I_G), defined by Wood and Maeda (2008), and relative breakage index (B_r) by Hardin (1985). They used such indices for quantifying particle crushing due to very high confining pressures and/or large shear strain levels.

Figure 8 presents I_D values summarized from all the experiments. Material YK01 showed the highest water-induced disintegration with an average I_D of 0.49 after saturated tests, whereas, material GN consisting of relatively durable grains, showed the least effects of saturation with an average degradation index of 0.04. The small amount of particle crushing of relatively weak grains was also observed in dry tests. It can be observed in this figure that water-induced disintegration completes during full saturation and is essentially independent of maximum confining stress of 100 kPa and a shear strain level of 40% employed in this study.

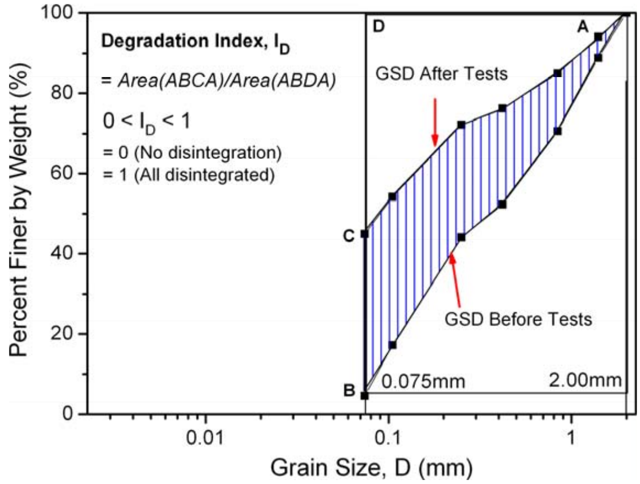

Fig. 7. Definition of degradation index, I_D (after Hardin, 1985).

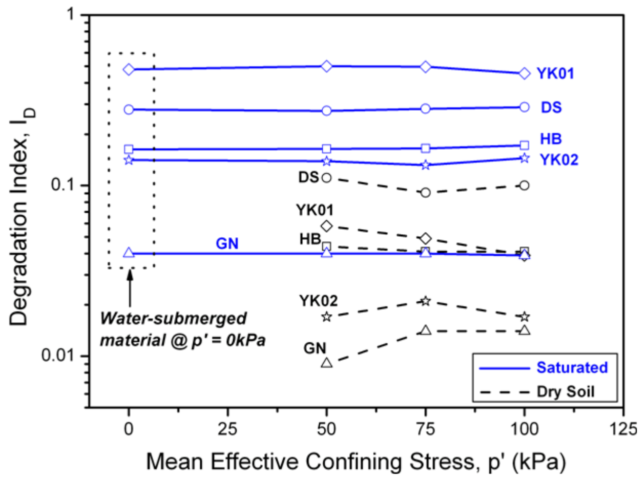

Fig. 8. Effects of confining stress on water-induced granular decomposition.

4.2 Effects on consolidation characteristics

Typical p'-ε_z relationships of crushed rocks and Toyoura sand at K_o=0.5 and 1.0 and p'=100k Pa under saturated and dry conditions are presented in Fig. 9. Here, the positive values of ε_z are denoted for vertical compression. The rate of increase in the cell pressure during consolidation was kept similar for all the test specimens at 3.0 kPa/min. It can be observed that there is an increase in vertical compression of TS and GN specimens with an increase in p', while the difference between the saturated and dry conditions being insignificant. On the contrary, crushed mudstones show enormous effects of saturation on the accumulation of vertical compression. Moreover, the volume-change in TS and GN specimens comes to an end after completion of primary compression. It is certainly due to a durable nature of grains unaffected by the presence of water. On the contrary, volume-change

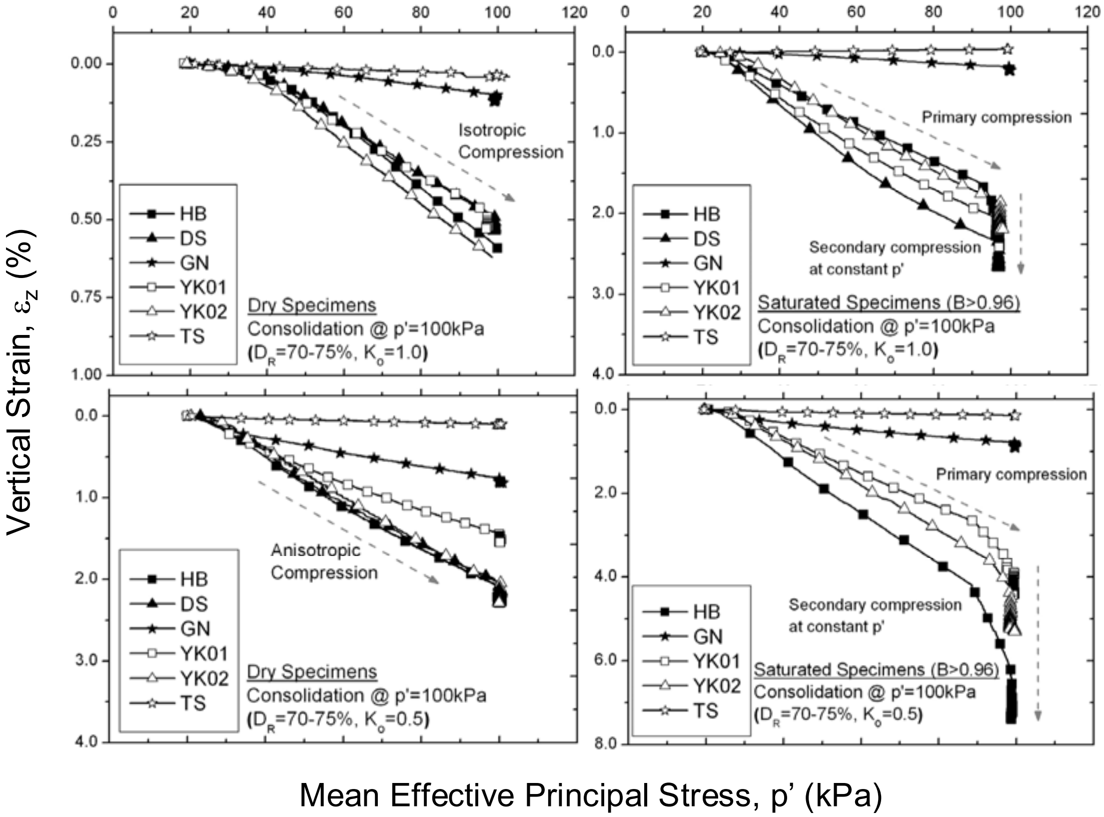

Fig. 9. Typical dry and saturated consolidation response of all materials at p'=100 kPa.

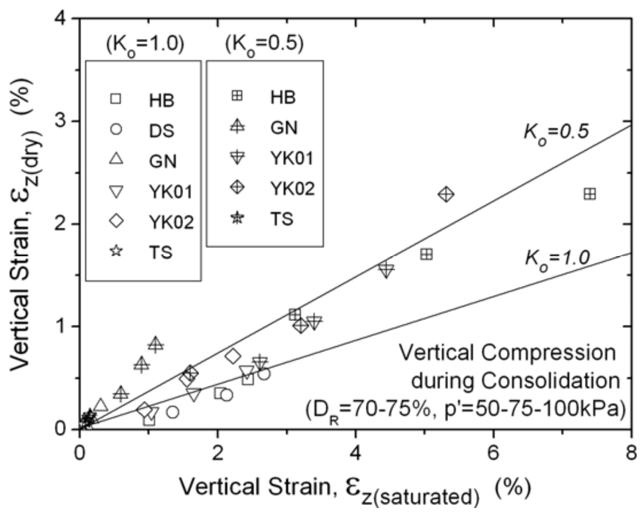

Fig. 10. Comparison of the total vertical compression during consolidation under dry and saturated conditions.

in saturated crushed mudstones does not cease at maximum confining stress. Such progressive compression under constant stress is referred to as secondary compression and is also reported by Nakano et al. (1998) and Mesri and Vardhanabhuti (2009). Such a phenomena is certainly due to water-induced disintegration and relatively loose intrinsic soil structure of the material. The effects of K_o on accumulation of vertical strains are also quite large as the specimens show a drastic increase in primary and secondary compression under anisotropic conditions at K_o=0.5.

$\varepsilon_{z(\mathrm{dry})}$-$\varepsilon_{z(\mathrm{saturated})}$ relationships derived from consolidation data of all materials are given in Fig. 10. A remarkable difference between deformation characteristics of TS and crushed rock specimens can be observed. Moreover, entire volume change, $\varepsilon_{\mathrm{vol}}$, during anisotropic consolidation at K_o=0.5 is caused by the vertical compression of the specimens with insignificant radial, ε_r and circumference strains, ε_θ. Such a behaviour is similar to 1-D compression response of soils. Therefore, it is inferred that for saturated, crushed rocks under anisotropic conditions at K_o=0.5, change in ε_z can represent the overall volume change of the material.

The relationships between degradation index and vertical strains of all test materials are given in Fig. 11. It is observed that I_D has a clear relationship with deformation characteristics of crushed rocks. It can also be seen that with increase in I_D value beyond some threshold (about 0.5), there is a little increase in volume change. It is essentially due to the reason that relatively denser packing is achieved in specimens after undergoing enormous water-induced granular decomposition.

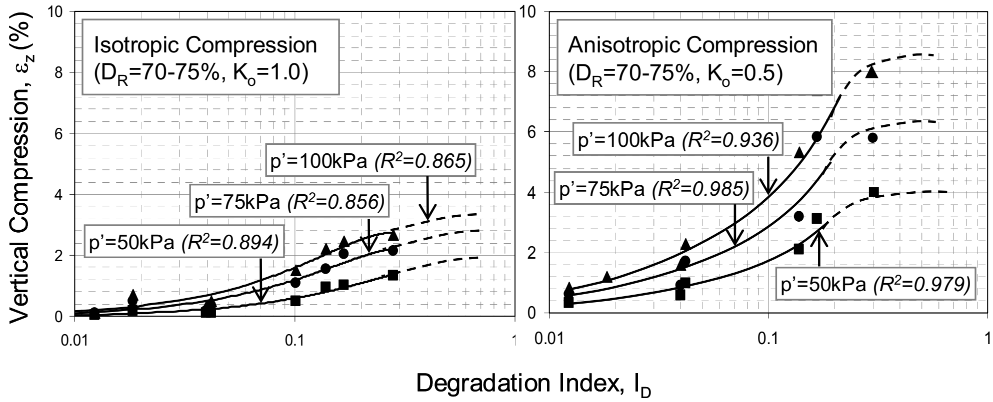

Fig. 11. I_D-ε_z relationships for K_o=1.0 and 0.5 from consolidation data.

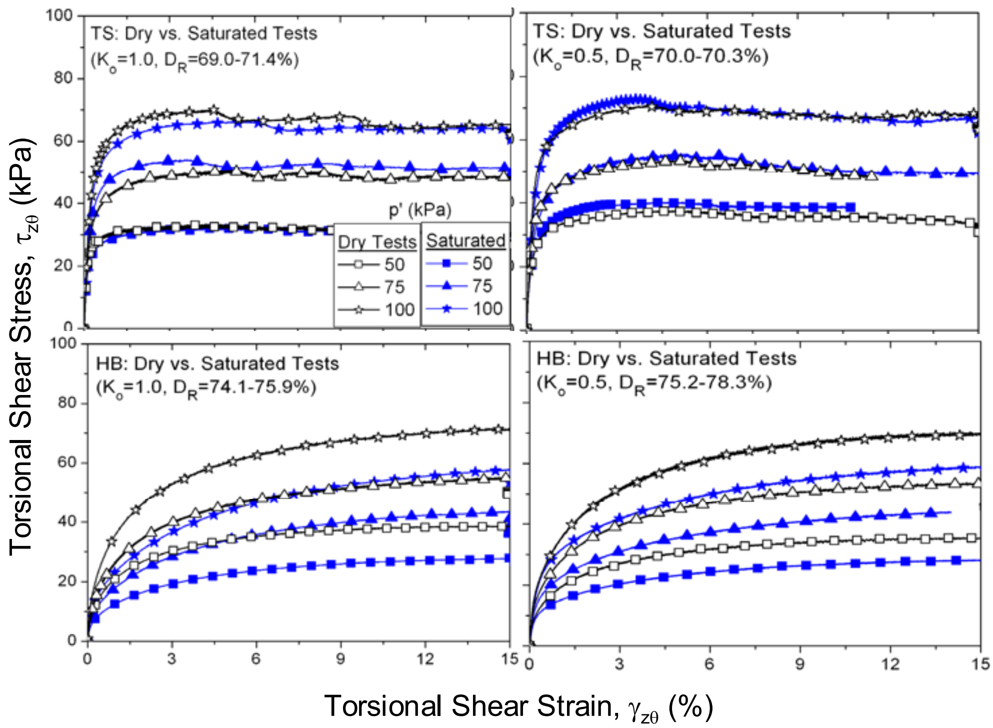

Fig. 12. CD monotonic torsional shear response of Toyoura sand and a typical crushed rock under saturated and dry conditions.

4.3 Effects on stress-strain behaviour and strength parameters

Consolidated drained monotonic torsional shear response of TS and a typical crushed rock (HB) under saturated and dry conditions is presented in Fig. 12. It is found that the stress-strain response of TS (soil with durable grains) becomes stiffer under both saturated and dry conditions with an increase in mean effective principal stress without showing any considerable difference between saturated and dry conditions. Clear peak and residual stress states are also observed at relatively higher p'. Although, shearing behaviour of dry and saturated crushed rocks demonstrate stiffer stress-strain response with an increase in mean effective principal stress, but at the same time showing a substantial difference between saturated and dry conditions. In spite of the fact that all specimens were prepared at high relative densities, saturated tests showed very weak stress-strain response like loose soils. Such phenomena is again attributed to water-induced granular decomposition of the material. On the contrary, GN specimens were unaffected by dry/saturated conditions mainly due to the durable nature of soil grains.

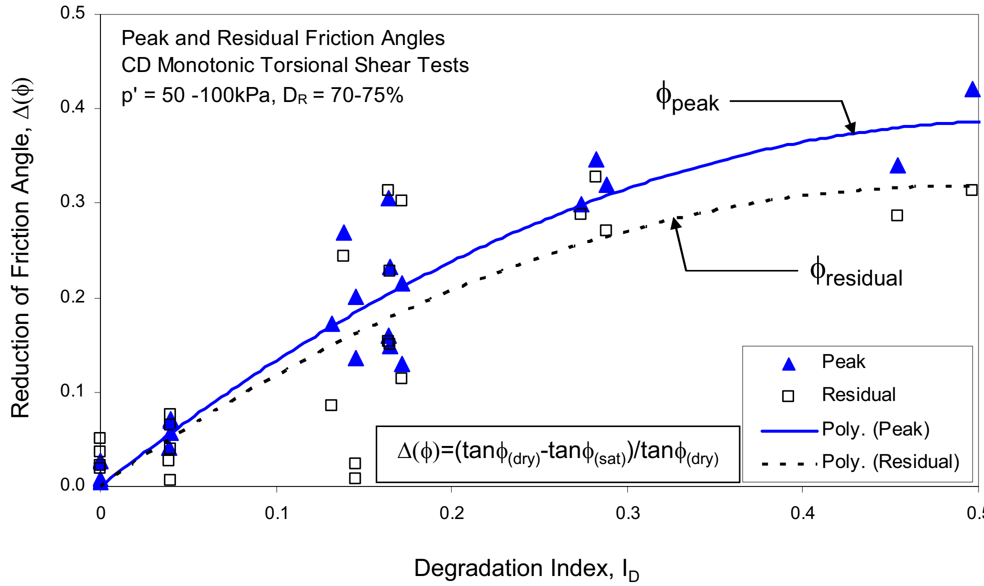

Fig. 13. Proposed relationship for assessment of time-dependent strength reduction of crushed rocks due to water-induced granular decomposition.

Figure 13 presents the effects of water-submergence on shear strength parameter (ϕ) of crushed rocks and Toyoura sand. The reduction of the friction angle between saturated and dry conditions is defined as follows:

$$\Delta(\phi) = \left\{\tan\phi_{\mathrm{dry}} - \tan\phi_{\mathrm{saturated}}\right\} / \tan\phi_{\mathrm{dry}} \tag{1}$$

where, $\phi = \mathrm{asin}\left[\left(\sigma_1' - \sigma_3'\right) / \left(\sigma_1' + \sigma_3'\right)\right]$.

Such a definition of the loss of strength parameter is adopted from a study by Mizuhashi et al. (2006) on drained triaxial compression tests on residual soils. From $I_\mathrm{D} - \Delta\phi'$ correlations presented in Fig. 13, it is quite clear that with the increase in I_D, there is a tremendous reduction in geotechnical properties of crushed rocks. Such a phenomenon can be quite crucial for various geotechnical hazards like; excessive settlements and failure of embankments, bearing capacity of foundations placed on such soils and slope stability problems. It can also be seen that peak strength parameters are relatively more vulnerable to reduce under saturated conditions as compared with residual strengths. The effects of I_D on reduction of mechanical properties of crushed rocks appear to be decreasing/stabilizing with the increase in I_D beyond some threshold. It is due to the fact that at $I_\mathrm{D} \geq 0.5$, a granular soil is essentially transformed into a relatively fine-grained soil. Therefore, with the introduction of apparent cohesion, governing strength parameters exclusively defined for coarse grained soils are no longer valid. It is important to mention here that the reduction of strength parameters due to water-induced granular decomposition seems to be independent of p' because, as discussed earlier, I_D is unaffected by p' of 50, 75, and 100 kPa employed in this study.

4.4 Effects on deformation response during monotonic torsional shear

The deformation response of typical test materials during monotonic torsional shear is presented in Figs. 14 and 15. For the comparison between saturated and dry tests, volume-change response ($\gamma_{z\theta} - \varepsilon_\mathrm{z}$ and $\gamma_{z\theta} - \varepsilon_\mathrm{vol} - \varepsilon_\mathrm{z}$ relationships) are mainly characterised by the change in specimen height (vertical strains, ε_z) before the formation of shear band. $+\varepsilon_\mathrm{vol}$ denotes volumetric compression (negative dilatancy) and $-\varepsilon_\mathrm{vol}$ refers to volumetric expansion (positive dilatancy), whereas, $\pm\varepsilon_\mathrm{z}$ represents the decrease/increase in the specimen height during shearing.

The specimens were prepared at high D_Ri, therefore, volumetric expansion (positive dilatancy) during shearing for TS specimens is observed. It can be seen that before the formation of shear band, ε_vol of saturated specimens remains negative under K_o=1.0 and 0.5. On the other hand, irrespective of drainage conditions, ε_z is always negative under K_o=1.0 and positive under K_o=0.5 before the formation of shear band. $\gamma_{z\theta} - \varepsilon_\mathrm{vol} - \varepsilon_\mathrm{z}$ relationships of TS specimens show that ε_z is approximately equal to ε_vol of the specimen before shear banding under K_o=1.0 condition. It is concluded that apart from effects of D_R, p' and K_o, deformation characteristic of durable granular soils are unaffected by the presence of water.

On the contrary, for saturated tests on crushed rocks (except GN, a crushed rock with relatively durable grains), ε_vol is always positive (volumetric contraction) during shearing under K_o=1.0 and 0.5. Moreover, ε_z is negative (vertical expansion) under K_o=1.0 and positive (vertical compression) under K_o=0.5 for dry tests, whereas, it always remains

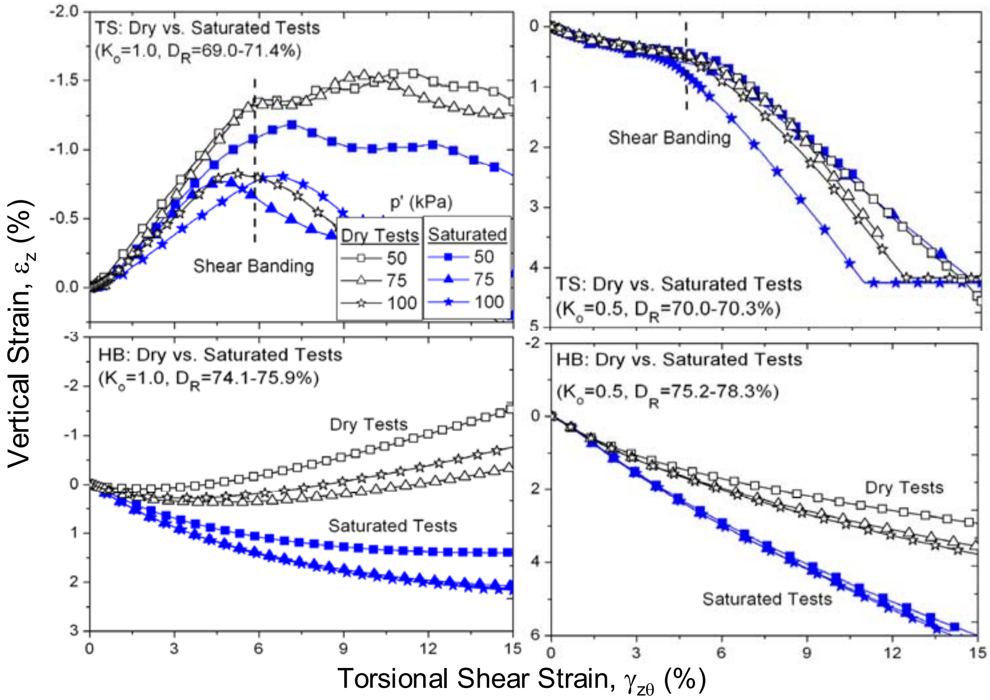

Fig. 14. Shear strain and vertical strain relationships during torsional shear.

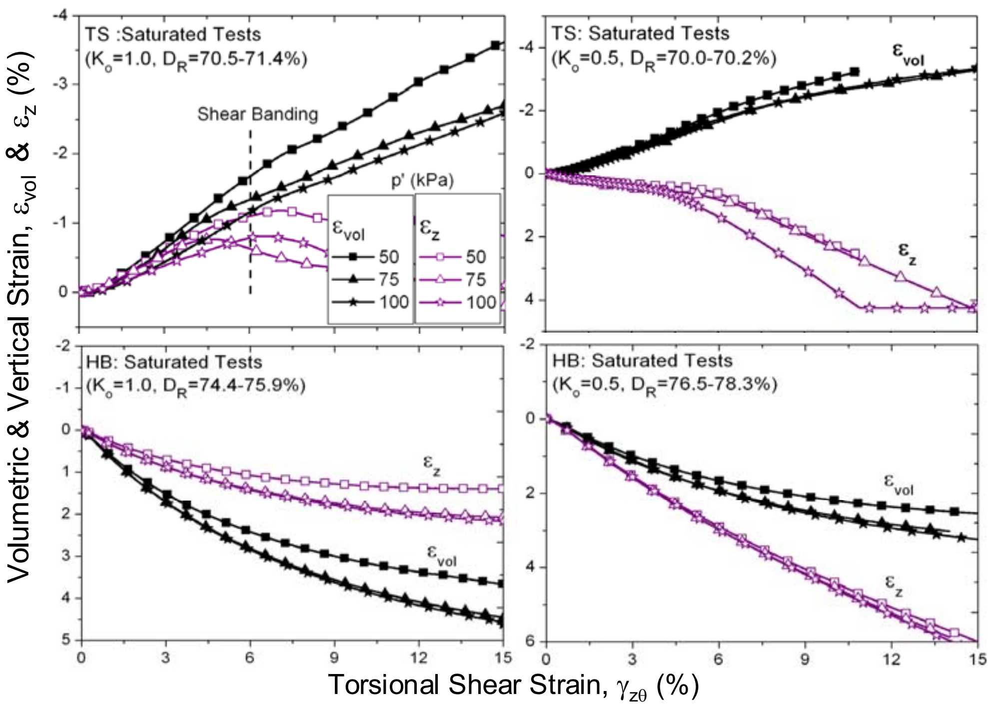

Fig. 15. Comparison between volumetric and vertical strains during torsional shear.

positive for saturated specimens, irrespective of K_o. Although in some cases, soil with a higher I_D showed relatively less compressive behaviour during shearing, nevertheless, the difference between the volume change characteristics under saturated and dry conditions seems to be highly dependent on the amount of water-induced granular decomposition, i.e. I_D value. Quite similar to consolidation behaviour, it is observed again that the overall volume change of rockfill material under K_o=0.5 conditions can be fairly assessed by vertical strains. These results are in good agreement with the findings of Yoshida and Hosokawa (2004) on compression and shear behaviour of mudstone aggregates.

5 Conclusions

As hypothesized, the strength and deformation characteristics of crushed rocks under saturated and dry conditions are not in agreement with our conventional geotechnical approach towards various standard granular soils. A degradation index, I_D, is defined, for a quantitative approach, to signify the degree of granular decomposition and its effects on engineering properties of crushed rocks. Apart from the evident effects of saturation and material type, it is found that I_D for saturated tests is more or less unaffected by the range of mean effective confining stress of 50–100 kPa and max. shear strain of 40% employed in this study.

For a given effective stress level, K_o value, and relative density, the degradation index shows clear relationships with maximum vertical and volumetric strains during consolidation. It is inferred that in situ collapse settlement of embankments can be reasonably assessed from these relationships by knowing I_D of material.

The analyses of monotonic torsional shear tests reveal that crushed rocks, under dry conditions, exhibit stiffer stress-strain behaviour, higher peak stress ratios and strain softening response. On the contrary, saturated crushed rocks experience an enormous loss of strength due to water-induced granular decomposition. Large effects of such a degradation on effective angle of internal friction are observed, whereas, effects of K_o on the strength parameters seem to be insignificant. With the increase in I_D beyond some threshold, reduction in mechanical properties appears to be decreasing/stabilizing. Likewise, deformation characteristics are also highly dependent on the degree of granular decomposition of crushed rocks.

Enormous volumetric compression during saturation, consolidation and loading of rockfill materials are observed in this study. It is concluded that the observed soil behaviour can be critical for embankments constructed with similar materials and the bearing capacity of foundations placed on such soils. The ability of existing soil mechanics models for risk assessment of geotechnical hazards can be improved by incorporating water-induced granular decomposition of rockfill materials.

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