Reduction of static and dynamic shear strength due to the weathering of mudstones

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SUMMARY:
An embankment of Tomei Expressway failed at Makinohara district during an earthquake in Japan. After the earthquake, detailed soil investigations and seismic analyses etc. were carried out to know the mechanism of the failure. One major reason was estimated as the weathering so called slaking of the mudstone filled about 40 years ago. In Japan there are many embankments constructed by mudstones. However weathering speed may be different in those embankments. So, the authors conducted several laboratory tests to study effect of slaking on static and dynamic strength of mudstones. Two types of test, cyclic torsional shear and triaxial tests were conducted for a fresh crushed-mudstone and a filled weathered-mudstone. Artificial weathering was applied to the crushed mudstone by heating and submerging. Test results showed static and dynamic strength decreased with the weathering. Five cycles of heating and submerging caused about 40% and 20% reductions of static strength and dynamic strength, respectively.

Keywords: Embankment, Expressway, Slaking, Mudstone, Earthquake

1. INTRODUCTION

A medium-size earthquake with Mj=6.5 occurred on August 11, 2009 in Japan. Epicenter was under Suruga Bay in Shizuoka Prefecture as shown in Figure 1. Several damages occurred in Shizuoka Prefecture such as collapse of walls, uplift of manholes and collapse of tiles. Of them, an embankment of Tomei Expressway failed at Makinohara district where is about 31 km from epicentre. Ground surface accelerations recorded at two sites near Makinohara were 295 Gals and 488 Gals. Failed slope was about 40 m in width, 28 m in height and 80 m in length as shown in Figure 2. Social impact by the slope failure was very severe because Tomei Expressway had to be closed for four days though the expressway is the most important and crowded expressway connecting major cities Tokyo and Nagoya. The authors conducted site survey immediately after the earthquake to investigate mechanism of the failure, and found weathered mudstones at the toe of the failed slope. The embankment was constructed about 40 years ago by filling fresh crushed mudstones and other soils. However the mudstones observed at the toe were quite weathered dark-blue coloured clayey ones as shown in Figure 3. Some terrace gravels were included in the weathered mudstones. So, it is estimated the fresh crushed mudstones changed to clay due to weathering so called slaking during the 40 years.

After temporary restoration work, detailed soil investigations and seismic analyses etc. were carried out to demonstrate the mechanism of the failure and study appropriate permanent restoration work by a technical committee chaired by Prof. H. Ohta (Takagi et al., 2010, Nakamura et al., 2010). Figure 4 shows the estimated soil cross section before the earthquake at the failed slope. The road was constructed by filling crushed mudstones and terrace gravels on a base mudstone and a clay layer. The bed mudstone named Sagara Mudstone is convex shape and very hard as SPT *N*-value is greater than 50. Red coloured curve marked on Figure 4 is the slip surface caused by the earthquake. As the curve is crossing over the top of a retaining wall which had been constructed to prevent slide failure, it is estimated that the strength of the clay layer did not affect the slide during the earthquake. The SPT

N-values of the fill is not high as about 5 though the degree of compaction is more than 90% which is, in general, enough for the stability of the slopes of road embankments. Water table during the earthquake was estimated to be raised up to in the fill. Then the following features were pointed out by the technical committee.

(1) Slide occurred in the fill.

(2) In geographical feature this site is catchment.

(3) Water level was high during the earthquake.

(4) Two kind of banking materials were filled at the damaged site. Crushed mudstone which is easy to weathering and terrace gravel were deposited in lower and upper zones, respectively.

(5) The banking materials were filled by enough degree of compaction.

Therefore the main reason to cause the failure was the decrease of shear strength and permeability of the crushed mudstone due to long-term weathering named slaking. One more effect of the convex shape of the base mudstone on the shaking during the earthquake was also pointed out.

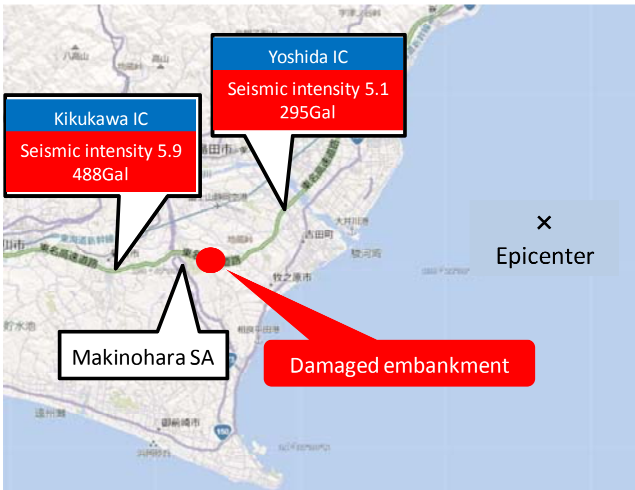

Figure 1. Locations of failed slope, epicenter of earthquake and recorded accelerations

Figure 2. Failed slope of Tomei Expressway at Makinohara

Figure 3. Weathered mudstones observed at the toe of the failed slope

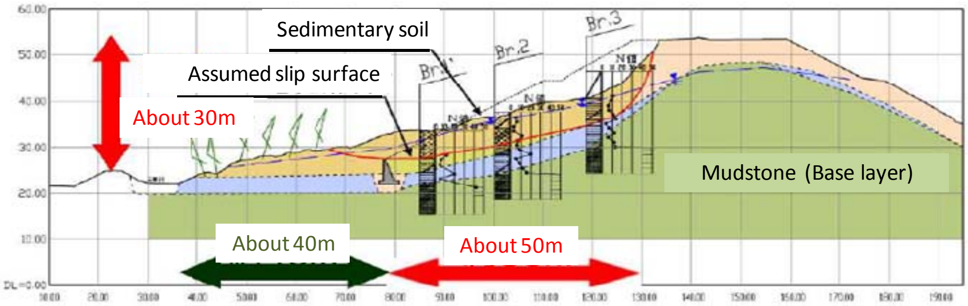

Figure 4. Estimated soil cress before failure section

2. BANKING MATERIAL FOR ROADS IN JAPAN

In Japan, about 1.2 million km of roads cover an area of 377,800 km^2. The roads are classified into 6 groups as shown in Table 1. National expressways are constructed and administrated by the Japan Highway Public Corporation (JH). In 2005, the JH was privatized and renamed Nexco. Nexco composes three companies, West Nippon Expressway Co., Ltd., Central Expressway Co., Ltd. and East Nippon Expressway Co., Ltd. The first and second national expressway, Meishin Expressway and Tomei Expressway were opened for traffic in 1963 and 1969, respectively. Since then many other national expressways have been constructed. Figure 5 shows the present national expressway network, 10,246 km of expressway are in operation, 1,427 km under construction, and about 2,327 km are being planned.

Table 1. Classification of roads in Japan

Classification of roads	Grade
(1) High-Standard Arterial Roads	High
a) National Expressways	⇕
b) Other Expressways	
(2) Urban Expressways	
(3) Ordinary Roads	
a) National Highways	
b) Prefectural Roads	
c) Municipal Roads	Low

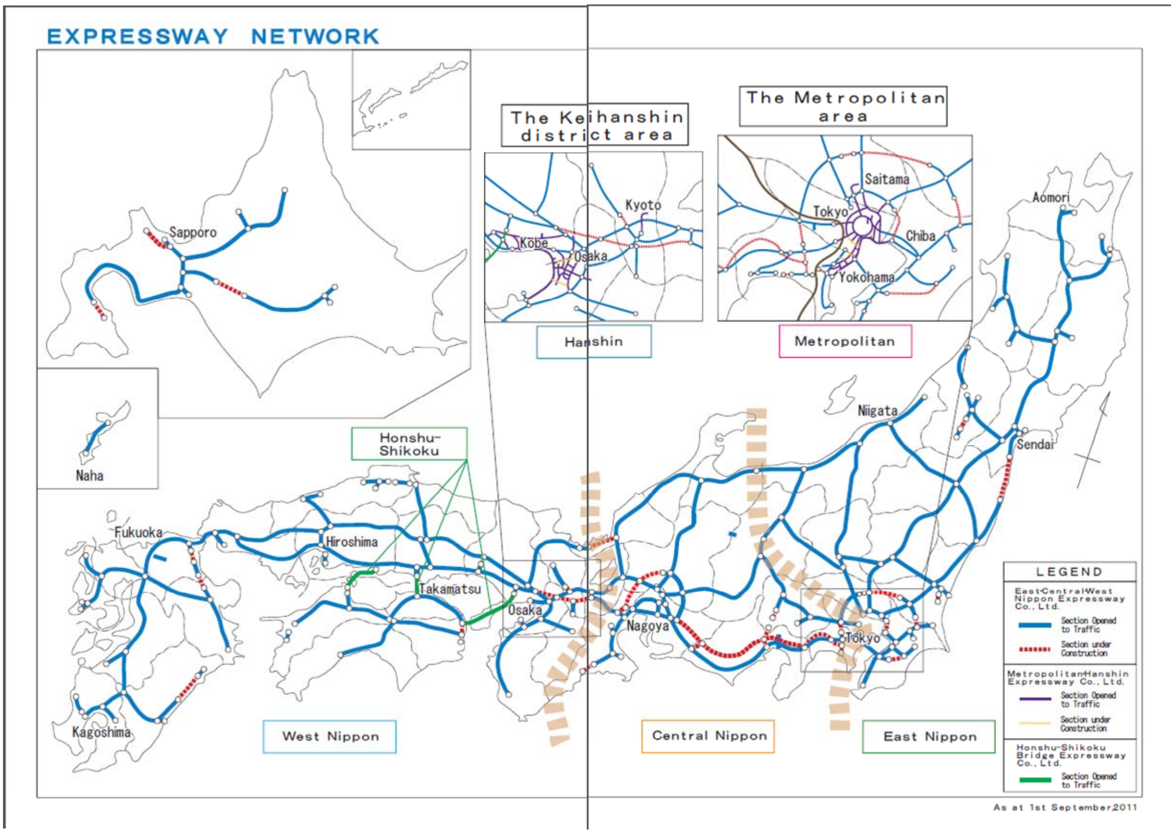

Figure 5. National expressway network by Nexco

In the design of a road embankment, the selection of appropriate banking material is important because bad material is inefficient to handle and leads to embankment settlement and instability. The inclination of slopes and the height of an embankment must be designed to prevent slope failure. Proper drainage must be designed to ensure during the construction of an embankment and to maintain embankment stability. In addition, banking materials must be appropriately placed, spread and compacted. In Japan, recently, general recommendations and requirements are summarized briefly in Table 2. However, design details differ by road type and the embankments of national expressways are well designed and are not easily damaged during earthquakes. In the table, one restriction for banking material embankment is mentioned as "Some sedimentation soft rocks, such as mudstone, shale and tuff. These rocks cause slaking after filling". Therefore, nowadays, mudstone is not used for banking material. However, about 40 years ago when Tomei Expressway was constructed, such restriction had not been recognized, and mudstone was used as the banking material at Makinohara because mudstone is widely distributed at and around there.

Table 2. General recommendations for the design of road embankments in Japan

Item	Recommendations	Restrictions
Banking material	In general, materials with the following properties are appropriate for embankment (1) Easy to place, spread and compaction. (2) Shear strength and bearing capacity are high, and compressibility is low. (3) Water absorption swelling is low. (4) Stable against erosion and shear strength does not decrease due to saturation. Well-graded gravelly or sandy soils satisfy these conditions and are recommended to use as banking materials.	Bentonite, solfataric soil, acidic clay and highly organic soil can not be used to construct the embankment. The following soils should not be used: a) Volcanic cohesive soil: Trafficability of the soil is low. The soil is unstable against slope failure, and causes long-term settlement of embankment. b) Some sedimentary soft rocks, such as mudstone, shale and tuff: These rocks cause slaking after filling.
Density of embankments	Bunking materials must be appropriately placed, spread, and compacted. In general, compaction control standard is decided before banking. Several compaction control methods are available as follows: i) Soil density measurement. ii) Degree of saturation. iii) Compaction method.	Compaction cannot be controlled by density measurement if the natural moisture content of banking material is greater than the optimum moisture content. Compaction cannot be controlled by strength if the strength of embankment material decreases due to saturation by rainfall or water seepage after compaction.
Gradient and height of slope	In general, inclinations of slopes are designed empirically without conducting slope stability analyses, because embankments are very long. In the empirical approach, appropriate inclination of a slope is decided based on the height and the material of the embankment. If the embankment is high and/or material is soft, low inclination is selected.	Slope stability analysis is necessary if conditions of the foundation ground and/or the embankment are bad as follows: a) Foundation ground is soft. b) Embankment is constructed in landslide area. c) Embankment is too high. d) Banking material is bad such as high moisture clay or volcanic ash. e) Houses exist near the embankment and the houses may be damaged if the embankment is deformed.
Drainage facilities	During the construction of embankments, seepage water and surface water must not be contained in the construction site temporarily. In the design of permanent drainage, two kinds of liners must be considered. The first ones are liners against surface water. Subsurface drainage, slope surface drainage are these facilities. The second ones are facilities against seepage water into embankments. Horizontal drains, horizontal blankets, drainage pipes, gabions are these lines.	Special care for drainage is necessary in the following locations: (1) Small river crossings or boundaries between cuts and embankments where flows of surface water concentrate. (2) Valleys, boundaries between cuts and embankments where much spring water spews out.

3. LABORATORY TESTS FOR THE EFFECT OF SLAKING OF MUDSTONE ON SHEAR STRENGTH AND OTHER CHARACTERS

In Japan many embankments have been filled by mudstones because the restriction mentioned above was recognizes around 1973. For expressway test method for slaking was first introduced in design manual in 1985. However weathering speed of the mudstones may be different at each site. So, the authors conducted several laboratory tests to study effect of slaking on static and dynamic strengths of mudstones. Freshly crushed and not weathered mudstones shown in Figure 6 were taken at Fujieda where is near Makinohara, and properties of the mudstones are judged as similar with that at Makinohara. Artificial weathering was applied to the crushed mudstones by heating and submerging. Figure 7 shows the artificial weathering method which is similar as the testing method introduced in the design manual for expressway. The crushed fresh mudstones smaller than 19 mm in diameter were selected and filled in a mold with 10 cm inner diameter and 12.73 cm height. Then the mudstones were compacted to be 99.5% of the degree of compaction under 15% of air content. Then five cycles of heating with 110 degree by oven-dry method and wetting by submerging in a pond were repeated to cause slaking as described in Figure 7. Time of one cycle was decided as 96 hours which is twice compare with normal testing method for expressways because the mold used in this test was bigger than the mold used for normal tests. Figure 8 compares grain-size distribution curves of different degree of slaking. As shown in the figure, size of the particles of crushed mudstones decreased gradually with weathering. Figure 9 shows a sample after 5 cycles of slaking.

Figure 6. Crushed mudstones used for laboratory tests

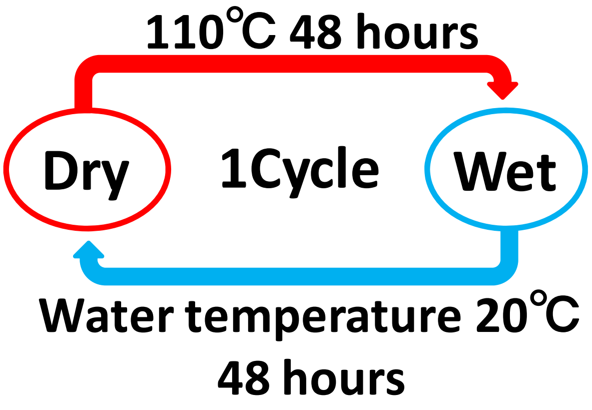

Figure 7. Artificial weathering method

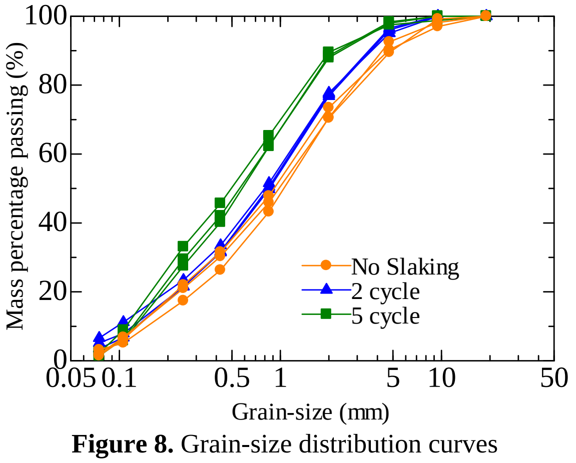

Figure 8. Grain-size distribution curves

Figure 9. A specimen after 5 cycles of slaking

Two types of test, cyclic torsional shear and triaxial tests were conducted to obtain several kinds of static and dynamic behaviours. Of them, static stress-strain and pore pressure-strain relationships obtained by torsional shear tests for the 5 cycle weathered crushed mudstone under different confining pressures are shown in Figure 10. Shear stress increased gradually with the increase of shear strain. On the contrary, pore water pressure increased slightly in small strain then deceased with the increase of shear strain. These behaviours are similar as those of medium sands. Figure 11 shows stress paths together with failure lines for different degree of slaking and different confining pressure. Increasing rate of pore water pressure in small strain is different with confining pressure. The rate is small in low confining pressure because of the effect of overconsolidation during compaction. The failure line of fresh sample is the highest and the lines decrease with the number of slaking cycles. This means static shear resistance decreases with slaking. Reduction rate is different with confining pressure, but about 30% to 50% in the range of 50 to 200 kPa of confining pressure. Relationships between angle of shear resistance ϕ, ϕ' and cohesion c and c' obtained from triaxial tests and torsional shear tests are summarized in Figure 12. Arrows show the decrease of ϕ, ϕ' and cohesion c and c' with the number of slaking cycles. In the indication by effective stress, ϕ' and c', cohesion mainly decreased with slaking because the directions of arrows are almost horizontal.

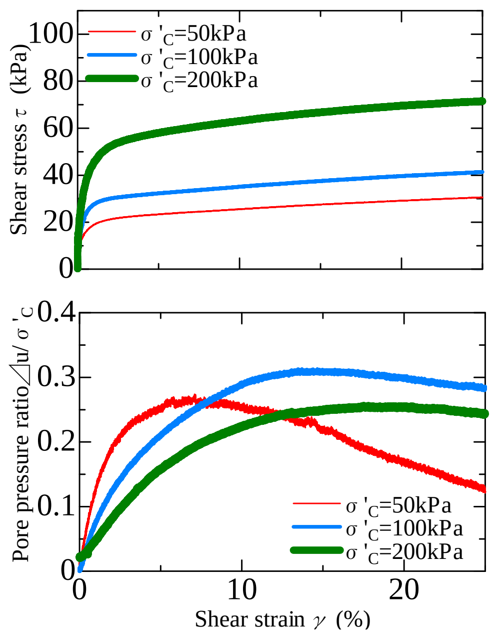

Figure 10. Static stress-strain and pore pressure-strain relationships (5 cycle weathered crushed mudstone, torsional shear test)

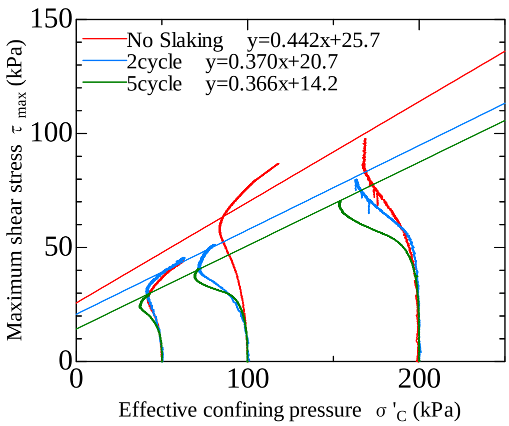

Figure 11. stress paths and failure lines for different degree of slaking and different confining pressure (crushed mudstone, torsional test)

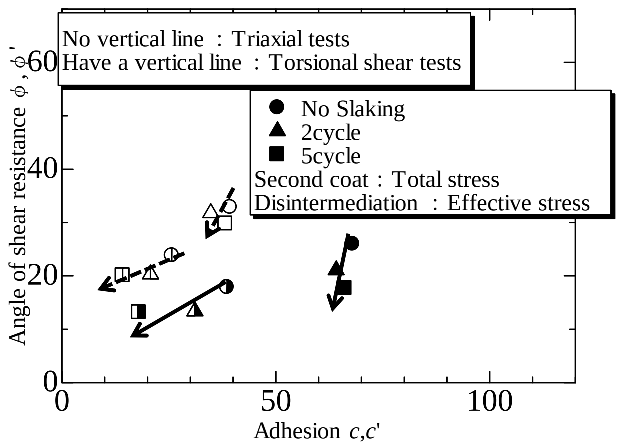

Figure 12. Relationships between angle of shear resistance and cohesion

For dynamic shear tests, 20 cycles of cyclic loading with 0.1 cycles/sec. were applied to specimens as shown in Figure 13, under undrained condition and 100 kPa of confining pressure. Monotonic loading was applied under undrained condition at a speed of 10 % of shear strain/min. Time histories of shear stress, shear strain and pore water pressure during the cyclic and monotonic loading were measured. About 4 to 8 specimens were used for each test condition, and different amplitudes of cyclic loading were applied to each specimen to control the safety factor against liquefaction, F_L, which implies the severity of failure. The relationships between the cyclic stress ratio, $R= \tau_d / \sigma_c'$ and the double amplitude of shear strain at the 20th cycle, γ_{DA} *(N=20)* are plotted on Figures 14. The stress ratio to cause 7.5% of shear strain by 20 cycles, $R_L(\gamma_{DA}=7.5\%, N_L=20)$ was estimated. As shown in the figure, $R_L(\gamma_{DA}=7.5\%, N_L=20)$ decreases with slaking. Reduction rate to five cycles of slaking is about 30%.

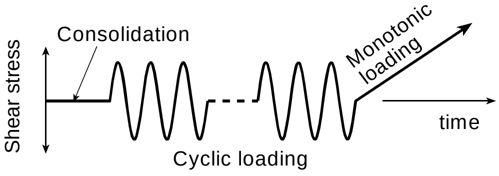

Figure 13. Procedure of cyclic and monotonic loading

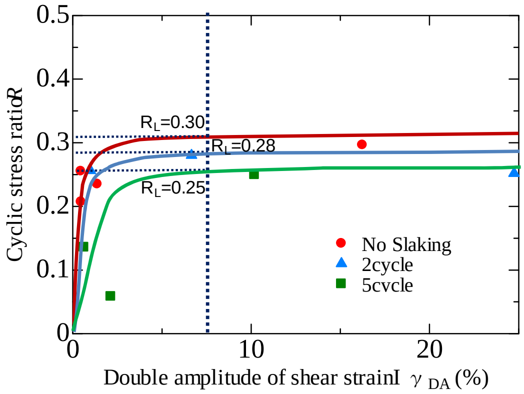

Figure 14. Relationships between the cyclic stress ratio and the double amplitude of shear strain at the 20th cycle

Another dynamic test was also conducted to demonstrate the effect of slaking on dynamic shear modulus and damping ratio. In the test 11 cycles of cyclic loading were applied to specimen with very small amplitude under undrained condition and 50 kPa of confining pressure. The amplitude of the cyclic loading was increased step by step up to failure. Shear stress – shear strain curves at 10 cycles in each step of loading were drawn to obtain dynamic shear modulus and damping ratios. Figure 15 shows relationships between shear strain and shear modulus, and shear strain and damping ratio in different slaking conditions. Shear modulus decreases drastically with slaking though damping ratio is not affected by slaking.

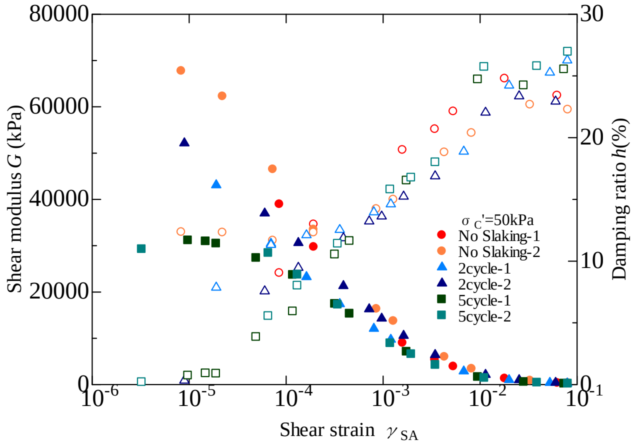

Figure 15. Relationships between shear strain and shear modulus, and shear strain and damping ratio

5. CONCLUSIONS

Several laboratory tests were conducted to study effect of slaking of mudstones on static and dynamic strength. The following conclusions were derived from the tests:
(1) Artificial slaking by heating and submerging caused 30% to 50% of reduction of static shear strength in five cycles.
(2) The slaking caused also about 30% of reduction of dynamic strength and drastic decrease of shear modulus.
(3) Through these tests, it was confirmed that one of the main reason to cause slope failure of Tomei Expressway at Makinohara during the 2009 earthquake was the slaking of filled mudstone during long term after construction.

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