論文の内容の要旨

論文題目

Case studies on the mechanism of earthquake-induced failure of dip slopes containing a weak layer
(弱層を含む流れ盤斜面の地震時崩壊メカニズムに関する事例研究)

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The purpose of this study is to investigate the mechanism of earthquake-induced failure of dip slopes containing a weak layer by site-specific analysis. Two sites were investigated in this study, including: investigating the properties of materials at the two sites, conducting stability analyses and slope displacement calculations of the two sites.

Background of this study and results from relevant field investigations are the followings:

1) Earthquake-induced landslides are a hazard in many countries in the world, causing billions of dollars of damage and many casualties. The 2004 Niigata-ken Chuetsu Earthquake, with a main shock of $M_j$=6.8, triggered extensive landslides in Mid Niigata Prefecture, Japan on October 23 in 2004. Two factors are likely to affect the extensive failure of slopes in this earthquake. One is that, before the earthquake, this area had a continuous strong rainfall which was more than 100 mm/day up to 20th October. The other is that, after the mainshock, many large aftershocks struck this area repeatedly. According to aerial photo interpretation, 3,791 slopes failed with total breakdown volume of about $100 \times 10^6$ $m^3$ over an area of about 1,310 $km^2$. Landslides severely damaged roads, rail lines, life lines, and houses, and dammed streams and rivers.

2) The investigated sites were Yokowatashi site and Higashi-Takezawa site. Yokowatashi site (about 40 m wide, 70 m long and 4 m deep with a slope displacement of over than 50 m) and Higashi-Takezawa site (about 295 m wide, 350 m long and 30 m deep with a slope displacement of about 100 m) both located near the epicenters of mainshock and aftershocks. Evidence proved that the sliding plane was saturated on both sites during the earthquake. Further more, a weak layer was found on the sliding surfaces of these two failed slopes.

3) Detailed investigation at Yokowatashi site shows that: a) Debris showed that the material on and below sliding plane was within tuff sandy layer which is 1~3 cm thick. Cavities were found in the sandy layer in the vicinity of the failed slope. b) Sliding plane was very planar with a dip angle of about 22°. c) Sandy layer on the sliding plane had been possibly saturated before the earthquake.

4) Detailed investigation at Higashi-Takezawa site shows that: a) Debris showed the material beneath sliding plane was slightly weathered siltrock. Soft sandy silt was found on a part of sliding surface and in the vicinity of the investigated previous sliding plane. Cavities were not found in the soft sandy silt layer. As most part of the current sliding plane is not exposed, the details of sliding plane need more investigation. b) Sliding plane had a dip angle of 18° at top region and 20° at toe region. c) Ground water level was high during the earthquake.

To investigate the properties of material from Yokowatashi, triaxial compression tests on six groups of undisturbed specimens were performed. Determining the strength of weak layer under saturated conditions is the main purpose of the tests. The details of the test results are described as follows:

1) The strength was likely to be affected by the soil type and degree of weathering. The softrock specimens, which did not contain the sandy layer, had a peak strength of over 3 MPa in unconfined compression tests and TC tests. The specimens with slightly weathered sandy layer had a peak strength of over 500 kPa in undrained triaxial compression tests under an initial effective confining stress of 20 kPa, and the corresponding shear stress ratio mobilized on the sandy layer was over 1.6. The specimens which had been deeply weathered while having a few cavities in the sandy layer, mobilized the peak stress ratio of 1.3 in undrained triaxial compression tests. The specimens which contained deeply weathered sandy layer with many visible cavities, were the weakest among the six groups tested in this present study.

2) Under saturated conditions, the strength parameters mobilized along the weak layer in terms of effective stress were $c$=0 and $\phi'$=39.0° . As the failed slope has a dip angle of 22°, the slope was stable under normal condition when there was no earthquake and the ground water level was not extremely high. In the cyclic loading tests, possibly affected by the system compliance, liquefaction was not observed. However build-up of excess pore water pressure was observed. The maximum value of excess pore water pressure ratio, which is the ratio of excess pore water pressure to the initial effective vertical stress, is 0.55.

3) The failure patterns were different among the six groups. The specimens without the sandy layer failed like an ordinary softrock. The shear band of specimens having the sandy layer was formed along the boundary between the sandy layer and the lower softrock. For the specimens which contained many visible cavities in the weak layer, the shear band was thicker than the others and crushing of intermediate sandy softrock blocks were observed. The average thickness of the weak layer has a range from about 3 mm to 13 mm.

4) The above failure pattern seems to contribute to the large residual displacement of the slope that was induced by the earthquake. It is reasonable to extrapolate that in the failed slope there were more cavities in the saturated sandy layer. So, when these cavities that were sandwiched between adjacent softrocks with low permeability were compressed during sliding, the pore water pressure could have increased more significantly than the behavior observed in the present laboratory tests.

To investigate the properties of material from Higashi-Takezawa, triaxial compression tests and simple shear tests on undisturbed specimens were performed. Determining the strength of weak layer under saturated conditions is the main purpose of the tests. The details of the test results are described as follows:

1) The specimens from Higashi-Takezawa site had a weak sandy silt layer which was 3 to 32 mm thick according to the measurement after failure. The shear band with an irregular interface formed within this sandy silt layer in all of the triaxial compression tests and in most of the simple shear tests.

2) In triaxial compression tests under saturated conditions, the peak strength mobilized along the weak layer in terms of effective stress was c=0, $\phi'$=36.2° according to triaxial compression test results. As the dip angle was 18°~20°, the slope was stable under normal condition when there was no earthquake and the ground water level was not extremely high. In undrained triaxial compression test, the increment of strain induced by cyclic loading was very limited, and full liquefaction did not occur under undrained cyclic loading conditions.

3) In simple shear tests under saturated conditions, significant strain softening at large deformation was observed in cyclic simple shear tests while keeping the specimen height constant. After accumulation of horizontal displacement $\Sigma|\delta|$ exceeded 60 cm, the value of stress ratio $\tau_{peak}/\sigma'_{v0}$ became nearly constant at 0.3, which corresponds to $\phi$=16.7°.

To investigate the occurrence of liquefaction within thin weak layer, liquefaction tests on artificial specimens which contain a Toyoura sand layer were performed. The details of the test results are described as follows:

1) For prismatic specimens with a 74 mm-thick sand layer (Dr=60%), during undrained cyclic loading after a drained preshear, liquefaction was observed. When the sand layer was thinner than 32 mm, under the test conditions without minimizing system compliance, no full liquefaction occurred.

2) For prismatic specimens with a 17 mm-thick sand layer (Dr=60%), during undrained cyclic loading without drained preshear, liquefaction was not observed either. Under the test conditions with minimizing system compliance, on the other hand, full liquefaction occurred.

3) For cylindrical specimens, with a 39 mm-thick sand layer (Dr=60%), during undrained cyclic loading after a drained preshear, full liquefaction was observed.

4) Tests results on artificial specimens showed that the occurrence of liquefaction in the thin sand layer was affected by system compliance significantly.

Using the strength parameters determined by triaxial compressions, stability analyses were performed with limit equilibrium methods.

Stability analysis at Yokowatashi site showed that:

1) Stability analysis results by three methods are consistent with each other. Stability analysis methods include Modeling as infinite slope, Modified Janbu Method and Modified Sweden Method.

2) Instability could not occur at normal time without large earthquake and without an extremely high ground water level.

3) After seismic coefficient exceeds 0.3, even if ground water level is on the sandy layer level, the slope will start to move.

4) Even if ground water level was on the sandy layer level, when excess pore water pressure ratio was 0.55 as observed in cyclic undrained triaxial compression tests, this slope can slide with a horizontal seismic coefficient $K$=0.

Stability analysis at Higashi-Takezawa site showed that:

1) Stability analysis results by three methods show that, safety factor has the same trends. The analysis results showed that ground water level, excess pore water pressure and earthquake force can affect the stability significantly. Possibly due to the over-simplification on curved sliding plane and non-uniform slice height, results yielded by modeling as infinite slope were largely different from the results yielded by the other two methods.

2) Instability does not occur at normal time without large earthquake and without an extremely high ground water level. Without earthquake and with a ground water level 10 m above the sliding plane, the safety factor is above 1.7.

3) After seismic coefficient exceeds 0.35, even if ground water level was on the sandy layer level, the slope will start to move.

4) Even if ground water level was on the previous sliding plane, when excess pore water pressure ratio was 0.6, this slope can slide with a horizontal seismic coefficient $K$=0. However, such a high value of excess pore water pressure ratio may not be realistic, since the weak layer consisted of sandy silt with a plasticity index of 19.

Using the strength parameters determined by triaxial compressions and/or simple shear tests, displacement calculation were performed with extended Newmark methods where the effects of 1) excess pore water pressure or decreasing of apparent friction angle and 2) the change of sliding plane on yield seismic coefficient $K_y$ were considered.

Results of displacement calculation of Yokowatashi site showed that:

1) Three methods result in similar displacements under the condition that excess pore water pressure ratio equals zero. The methods include Modeling as infinite slope, Newmark with Janbu Method and Newmark with Sweden Method.

2) Excess pore water pressure has extremely significant effect on displacement. The calculation result is similar to the measured value by using an excess pore water pressure ratio of 0.55. However, the displacement by numerical calculation is 0.9~2.1 m if excess pore water pressure ratio equals zero.

3) Ground water level has significant effect on displacement. If ground water level is 2 m above the sliding plane, the displacement is about 100 m with an excess pore water pressure ratio of 0.55 by Newmark with Janbu Method. However, it is about 70 m if ground water level is on the sliding plane.

Results of displacement calculation of Higashi-Takezawa site showed that:

1) Modified Newmark with Sweden Method and Modified Newmark with Janbu Method result in similar displacements when the calculated displacements are small. However the difference between the calculated displacements by these two methods is large when the calculated displacement is more than 25 m. A possible reason is the effects of shape of sliding plane.

2) Excess pore water pressure has extremely significant effect on displacement. By using the decreasing friction angle obtained from cyclic simple shear tests, the calculation results in a displacement of about 59 m by Modified Newmark with Janbu Method. However, if the friction angle is kept constant as its peak value, the displacement is about 0.5 m.

3) Ground water level has significant effect on displacement. If ground water level is 12 m above the sliding plane, the residual displacement can be about 59 m by Modified Newmark with Janbu Method. However, it will be only 4.6 m if ground water level is on the sliding plane.

According to the displacement calculation results and stability analysis results, with an excess pore water pressure ratio of 0.55 and an ground water level about 1 m above the sliding plane, the failure mechanism of Yokowatashi site can be inferred as follows:

At normal time without large earthquake and without an extremely high ground water level, since the silt layer on the previous sliding plane has a friction angle of 39.0 °, the slope is stable.

From three days before the 2004 Niigata-ken Chuetsu Earthquake, the excessive antecedent rainfalls saturated the sandy layer and raised the ground water level. The safety factor was decreased by this precipitation. During the earthquake the excess pore water pressure increased significantly, the slope started to slide along the sandy layer with a low yield seismic coefficient $K_y$. The maximum velocity by simulation was about 10 m/s. After the sliding mass reached the road location at the toe of the slope, $K_y$ began to increase rapidly. Almost simultaneously seismic motion ceased. After having horizontally slid about 60 m, the sliding stopped.

The key point for the long residual displacement of this slope is the build-up of excess pore water pressure.

According to the displacement calculation results and stability analysis results, the failure mechanism of Higashi-Takezawa site can be inferred as follows:

At normal time without large earthquake and without an extremely high ground water level, since the silt layer on the previous sliding plane has a friction angle of 36.2°, the slope is stable.

From three days before the 2004 Niigata-ken Chuetsu Earthquake, the excessive antecedent rainfalls saturated the weak silt layer and raised the ground water level. The safety factor was decreased by this precipitation. During the earthquake, the slope started to slide mainly along the saturated weak layer. Since the friction angle decreased with the slope displacement, the yield seismic coefficient $K_y$ decreased to a value below zero. This negative $K_y$ accelerated the sliding. The maximum velocity by simulation was about 7 m/s. After the sliding mass reached the riverbed at the toe of the slope, $K_y$ began to increase rapidly. Almost simultaneously seismic motion decreased from this time. After having horizontally slid about 110 m, the movement of slope was obstructed by the slope and embankment on the other side.

The key point for the long residual displacement of this slope is the decreasing friction angle.