AN INVESTIGATION INTO THE EFFECT OF DRAINAGE ON LARGE SLOPE FAILURE DURING EARTHQUAKES

(MECHANISM OF A LARGE LANDSLIDE COMPOSED OF MUDSTONE DEBRIS INDUCED BY THE 2004 MID NIIGATA PREFECTURE EARTHQUAKE)

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ABSTRACT :

A lot of large, long-distance landslides occurred due to a big earthquake in Japan, called the 2004 Mid Niigata Prefecture Earthquake. One of these landslides occurred when a slope composed of mudstone debris failed. Slopes composed of mudstone debris have been thought to be seriously damaged by rainfall but not so seriously by earthquakes. Sampling of several intact soil blocks was done at the landslide site and the cyclic tri-axial tests on the specimens were performed under undrained conditions in a laboratory. These experimental results suggested that the cause of the failure was possibly a rapid increase of the pore water pressure inside the mudstone due to the cyclic shear during the earthquake. That is, this rapid increase of the pore water pressure made the safety factor of the slope drop considerably below 1.0, which triggered the large, long-distance landslide.

We assumed the groundwater level at the time of the earthquake from the field investigation and calculated the safety factor of the large slope failure by limit equilibrium method. The groundwater level was calculated by seepage analysis (finite element method) after the drains were installed and their effect on the stability evaluated by limit equilibrium method.

KEYWORDS: Excess pore water pressure, Mid Niigata Prefecture earthquake, Limit equilibrium method

1. INTRODUCTION

A lot of large, long-distance landslides occurred due to a big earthquake in Japan, called the 2004 Mid Niigata Prefecture Earthquake. One of these landslides occurred when a slope composed of mudstone debris failed. Slopes composed of mudstone debris have been thought to be seriously damaged by rainfall but not so seriously by earthquakes. Sampling of several intact soil blocks was done at the landslide site and the cyclic tri-axial tests on the specimens were performed under undrained conditions in a laboratory. The size of the landslide was 250m long and 150m wide with a depth of 25m, which traveled a distance of 30-40m downhill due to the earthquake.

These experimental results suggested that the cause of the failure was possibly a rapid increase of the pore water pressure inside the mudstone due to the cyclic shear during the earthquake. That is, this rapid increase of the pore water pressure made the safety factor of the slope drop considerably below 1.0, which triggered the large, long-distance landslide.

The topography before the landslide was assumed to be a model case. The groundwater level at the time of the earthquake was assumed following the field investigation and the safety factor of the large slope failure was calculated by limit equilibrium method. The groundwater level was calculated by three-dimensional seepage analysis (finite element method) after the drains were installed and their effect on the stability evaluated by limit equilibrium method. Regarding the earthquake case, inertia was ignored and the ΔU method was used, which considered only the influence of excess pore water pressure.

2. THE INFLUENCE OF EXCESS PORE WATER PRESSURE

2.1. Undrained cycle triaxial tests on the undisturbed soil samples

In order to investigate the effect of the strong earthquake motion on the landslide, undrained cyclic triaxial tests have been done on the undisturbed samples. The initial consolidation pressures were 200 and 375kN/m2. As a result, excess pore water pressure was suddenly generated and is understood to have remained behind in large amounts in unloading. The residual pore water pressure in the sample after the cyclic triaxiality tests can be seen in Table 2.1. Regardless of how much greater the effective overburden pressure was than this, it can be supposed that about 60% excess pore water pressure was generated.

Table 2.1 The residual pore water pressure of the soils after cyclic loading

Initial consolidation pressure(A) 200 kN/m^2		Initial consolidation pressure(A) 375 kN/m^2	
Principal stress difference	Residual excess pore water pressure after the cyclic loading(B)	Principal stress difference	Residual excess pore water pressure after the cyclic loading(B)
155	109	299	215
140	155	277	166
127	118	254	241
115	151	231	264
B/A(Average)	0.67	B/A(Average)	0.59

2.2. Drainage effect and its relationship with excess pore water pressure

It can be understood from the results of the cyclic triaxiality tests that the big excess pore water pressure occurs as a result of the repetitive vibrations of the earthquake and it is thought that the shear strength of the soil may have fallen. This is thought to have contributed to the increased length of the landslide.

Therefore, in this report, the influence of excess pore water pressure (ΔU) at the time of the earthquake has been examined by using the ΔU method. The ΔU method is illustrated in the diagram below. Figure 1(a) shows a slice division piece before the drainage, And Figure 1(b) shows after the drainage.

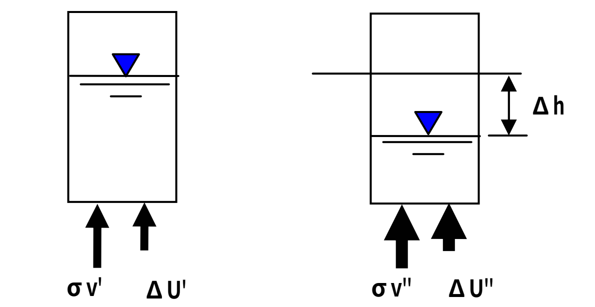

Figure 1 Effective overburden and excess pore water pressure in cross-sectional view

2.2.1 Effective overburden pressure before the drainage $\Sigma\sigma v'$

If the effective overburden pressure is $\sigma v'$ and the excess pore water pressure ratio is α, the excess pore water pressure is $\Delta U' = \alpha / \sigma v'$ at the time of the earthquake before drainage. Therefore, effective overburden pressure $\Sigma\ \sigma v'$ before the drainage becomes Eqn.2.1.

$$\Sigma\ \sigma v' = \sigma v' - \Delta U' = (1-\alpha)\sigma v' \quad (2.1)$$

2.2.2 Effective overburden pressure after the drainage $\Sigma\sigma v''$

Stress increases (Δv) as water level falls (Δh) as shown in Eqn.2.2.

$$\Delta v = \Delta h(\gamma t - \gamma') = \Delta h \cdot \gamma w \quad (2.2)$$

The increase in excess pore water pressure as a result of the earthquake can be calculated by Eqn.2.3.

$$\Delta u'' = \alpha \cdot \Delta v = \alpha \cdot \Delta h \cdot \gamma w \quad (2.3)$$

Therefore, incremental effective overburden pressure becomes Eqn.2.4.

$$\Delta v - \Delta u'' = \Delta h \cdot \gamma w - \alpha \cdot \Delta h \cdot \gamma w = (1-\alpha)\Delta h \cdot \gamma w = (1-\alpha)\Delta v \quad (2.4)$$

Thus, effective overburden pressure $\Sigma\sigma v''$ after the drainage becomes Eqn.2.5.

$$\Sigma\ \sigma v'' = \Sigma\ \sigma v' + (1-\alpha)\Delta v = (1-\alpha)(\sigma v' + \Delta v) \quad (2.5)$$

2.2.3 Drainage effect and its relationship with excess pore water pressure

It is found that the substantial effective earth artesian increment which occurs at the time of earthquake, considers the excessive pore water pressure excluding hydraulic ratio of $(1-\alpha)\Delta v$. Therefore, it is possible that the maximum effect of drainage decreases by$(1-\alpha)$times.

The factor of safety in this area is under 1.0 due to this effect. When water pressure rises, drainage occurs. Therefore, due to the dispersion effect, αbecomes smaller. However, the interval between drainage works is relatively huge and the dispersal effect is not taken into consideration.

3. A METHOD OF ANALYSIS

3.1. The estimate of the groundwater level

Groundwater level before and after the drainage was calculated using three-dimensional FEM seepage analysis. Figure 2 shows the analysis mesh. Figures 3(a) & (b) show the results of the analysis before drainage. Figures 4(a) & (b) show the results after drainage. Section B was taken where it is thought that the landslide was the deepest. As can be seen, water levels fell by around 3.0m after drainage.

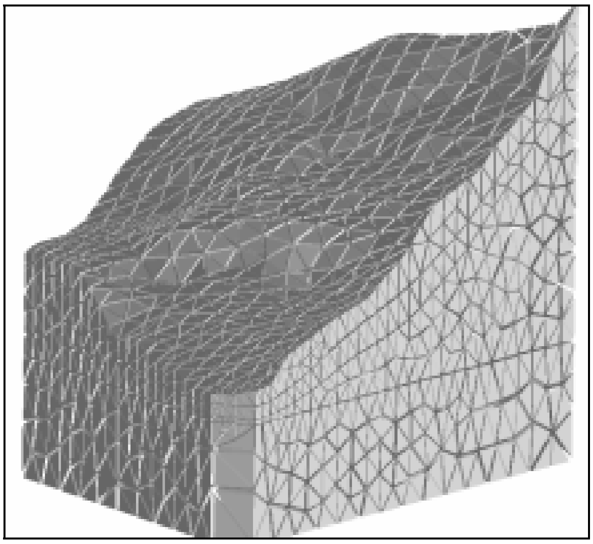

Figure 2 Three-dimensional seepage analysis mesh

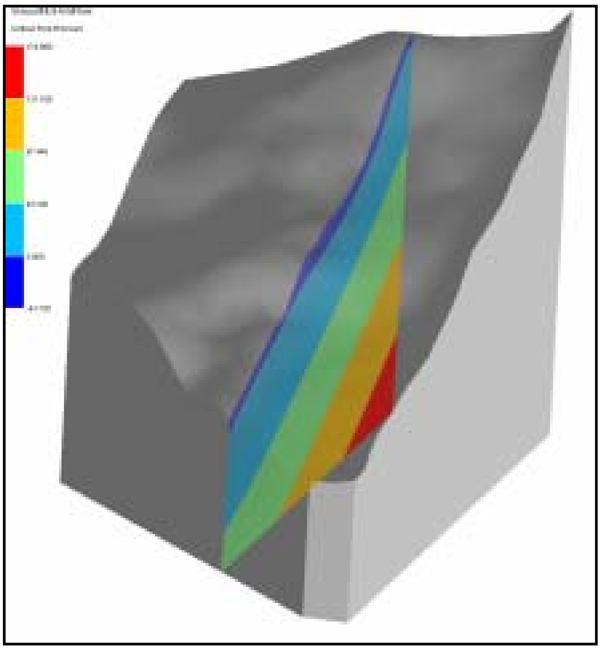

Figure 3(a) Seepage analysis result before drainage (3D)

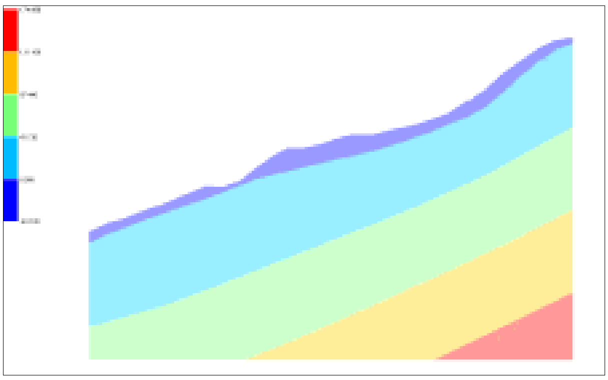

Figure 3(b) Seepage analysis result before drainage (Section B)

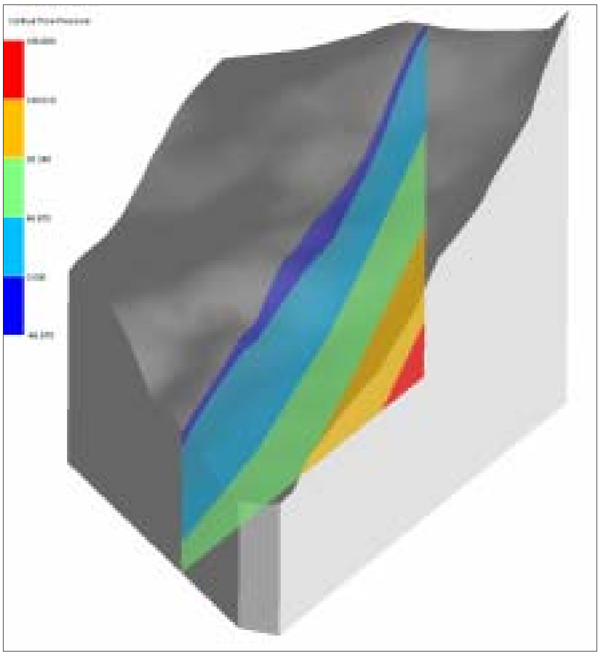

Figure 4(a) Seepage analysis result after drainage (3D)

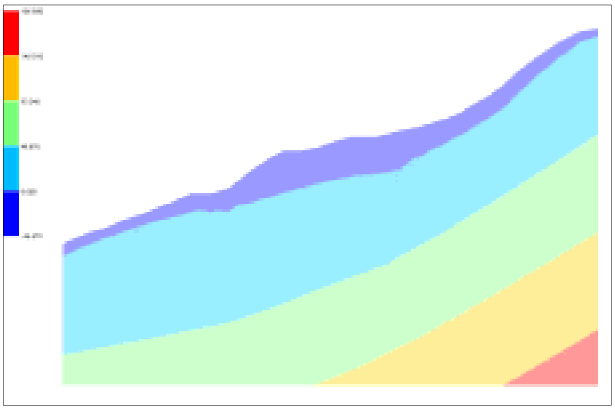

Figure 4(b) Seepage analysis result after drainage (Section B)

3.2. Slope stability by limit equilibrium method

3.2.1 Soil properties

In section B, the first layer is a cohesive silt layer of colluvial soil, and the second layer is strongly weathered mudstone. These two layers become moving stratum. The angle of shear resistance for the strongly weathered mudstone is 39°. The maximum depth of the landslide is about 25m and average depth is thought to be about 20m. Therefore the adhesive strength of the moving stratum was adjusted to 20kN/m2. The wet unit weight of the soil was assumed to be 18kN/m3. An analytical model was created by two-dimensional limit equilibrium method and is shown in Figure-5. The slide surface was made of the two layers.

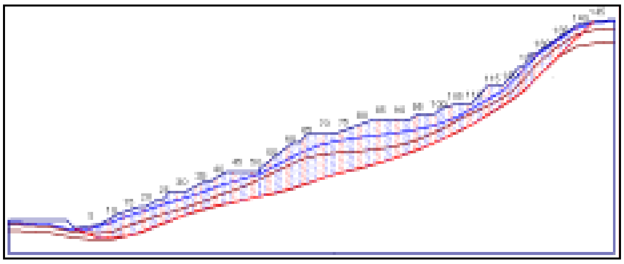

Figure 5 Landslide slope stability analytical model

3.2.2 Slice method

The safety factor can be calculated by Eqn.3.1

$$Fs = \frac{\sum (N - U) \times \tan \phi + c \times \sum L}{\sum S} \quad (3.1)$$

Fs: Safety factor
ΣN: Levee normal power (kN/m) applied by the weight of the slice (including buoyancy)
ΣU: Excess pore water pressure (kN/m) in the slice during the earthquake
ΣS: Sliding power (kN/m) applied by the weight of the slice (disregarding buoyancy)
ΣL: The extension of the slide surface of the slice. (m)
c: Adhesive strength of the slide surface(kN/m2)
ф:The angle of shear resistance for the slide surface(°)

4. Slope stability analysis result

4.1. Before drainage

The resistance power against earthquake and safety factors that occurs before drainage are shown in Tables 4.1 (a) and (b) respectively.

Table 4.1(a) Resistance before drainage

Case	ΣN'	ΣU'	c ΣL	Σ τ (kN/m)
Normal	36103.9	0.0	5966.9	42070.8
Earthquake	36103.9	21662.3	5966.9	20408.5

$$\sum \tau = \sum (N \times \tan \phi - \alpha \times N \times \tan \phi) + c \times \sum L \quad (4.1)$$

$$\sum \tau = \sum N' - \sum U' + c \times \sum L \quad (4.2)$$

Table 4.1(b) Safety factor before drainage

Case	Σ τ	Σ S	Fs=Σ τ / Σ S
Normal	42070.8	25892.1	1.62
Earthquake	20408.5	25892.1	0.79

4.2. After drainage

The resistance power against earthquake and safety factors that occurs after drainage are shown in Tables 4.2 (a) and (b) respectively.

Table 4.2(a) Resistance after drainage

Case	ΣN'	ΣU'	cΣL	Στ(kN/m)
Normal	40693.6	0.0	5966.9	46660.5
Earthquake	40693.6	24416.2	5966.9	22244.3

Table 4.2(b) Safety factor after drainage

Case	Στ	ΣS	Fs=Στ/ΣS
Normal	46660.5	25355.5	1.84
Earthquake	22244.3	25355.5	0.88

4.3. The comparison of the safety factor

How the safety factor changed before and after drainage for both normal and earthquake cases is shown in Table 4.3.

Table 4.3 The improvement rate of the safety factor

Case	Before	After	Fs
Normal	1.62	1.84	↑ 1.135(Δ0.22)
Earthquake	0.79	0.88	↑ 1.114(Δ0.09)

In the normal case, there was an improvement of about 14% (1.135 times) because of drain. In the earthquake case, there was an improvement of about 11% (1.114 times). That is, it appears that the effect of the drain diminishes as a result of the generation of excess pore water pressure.

5. CONCLUSION

The safety factor was calculated by the limit equilibrium method, as is presently considered to be the best design method, whilst considering excess pore water pressure caused by the earthquake. It was found that the safety factor becomes 0.88 after drainage and it is understood that it is considerably smaller than 1.0. Thus, the safety factor of the slope was able to be confirmed when assuming that significant excess pore water pressure was generated by the repetitive motion of the earthquake. It has been found that the effect of drain decreased by about 3% as a result of the excess pore water pressure caused by the earthquake.
This calculation is a trial calculation using a two-dimensional section (B section) where it is thought that the landslide side was the deepest. Therefore, it is thought that the safety factor is a little small compared with the three-dimensional landslide. It is not suggested to evaluate drain works solely from the safety factor in this report.
In the future, calculation of a three-dimensional model to analyse slope stability by the limit equilibrium method considering the excess pore water pressure of the entire landslide will provide more accurate calculation of the safety factor. The relationship between the effectiveness of the drain and the excess pore water pressure can then be reexamined.

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