Slope Failures due to rainfalls after the 1995 Hyogo-ken Nanbu (Kobe), Japan earthquake

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On January 17th, 1995, the Kobe earthquake (Mj=7.3) fatally damaged this city. In Rokko Mountains located behind the urbanized area of Kobe city, the earthquake triggered 747 slope failures. Furthermore 938 slopes failed additionally by post-quake rainfalls till the end of Oct. 1995. These post-quake rainfalls were little amount of rainfall and intensity as compared to the warning rainfall level obtained empirically before the Kobe earthquake in the Rokko Mountains.

In this study, the following analyses were performed. Firstly, the topographic analysis was carried out to investigate the topographic features of the slope failures due to post-quake rainfalls statistically by using topographic map and Digital Elevation Model (50m cell spacing). Concretely, the topographic features of slope failures due to post-quake rainfalls were compared with another trigger (earthquake and purely rainfall in the past in the Rokko Mountains). Secondly, the seismic response analysis was applied to failed slopes at Gosukebashi area in the Rokko Mountains to look into the dynamic response property. The results of above analyses are as follows: 1) A lot of slope failures induced by post-quake rainfalls occurred as not progressive failure type but new failure type. To prevent and mitigate post-quake secondary disasters, it is necessary to be concerned about the occurrence of new failures at the slope where slope failures not occurred during earthquake. 2) The topographic features of slope failures induced by post-quake rainfalls were similar to those of slope failures induced by the earthquake rather than by rainfalls in the past. This result means that some slopes where slope failure did not occur during the earthquake, although they were affected by seismic motion, failed by little amount of rainfall and intensity. 3) At failed slope caused by earthquake, larger value of maximum response acceleration and peak of maximum shear strain appeared as compared to other slopes. At failed sites caused by post-quake rainfalls, peak of maximum shear strain appeared 10-4 level. Although this level of strain does not lead failure, it begins to generate some deformation. Therefore, the seismic motion plays an important role for the occurrence of not only earthquake-induced failure but also post-quake rainfall-induced failure.

Next, the experiments using the triaxial test apparatus were carried out to experimentally clarify the effect of seismic motion and post-quake rainfalls on the soil shear strength. Concretely, in order to examine the effect of the cyclic load and the submergence on the shear strength of the soil, consolidated drained shear test (CD triaxial test) performed under four kinds of different conditions. The decomposed granite soil with the gypsum mixing was used as a specimen of the experiment. The results of experiment are as follows: 1) The soil shear strength was reduced by 35% because of saturation. 2) The soil shear strength was reduced by 18% because of cyclic loading. 3) The soil shear strength was reduced by 44% because of saturation after the cyclic load was given. These mean that the soil shear strength was decreased because the skeletal structure of the soil was destroyed by the seismic motion and decreasing of the shear strength was generated additionally by increasing of the degree of saturation due to the rainfall after the earthquake. This is one of mechanism that many slope failures occurred by rainfalls after the Kobe earthquake.

Keywords: Slope failure, Kobe earthquake, post-quake rainfalls, topographic feature, dynamic response property and soil shear strength

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Introduction

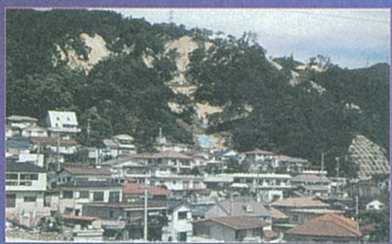
Rokko mountains

- W_{max} : 8Km, H_{max} : 931 m
- Bedrock:
  Granite
- Surface soil layer:
  Decomposed granite soil

The Rokko Mountains have a long history of slope disasters due to heavy rainfall.

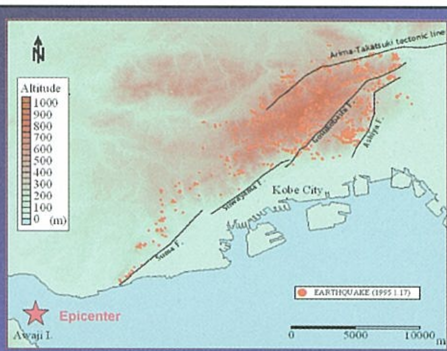
In more recent years, fatal disasters occurred in 1938, 1961 and 1967.

1995
JAN. — Kobe Earthquake (Mj=7.3) JAN. 17, 1995
Many slope failures occurred.



OCT.
1996

Slope failures induced by the Kobe earthquake

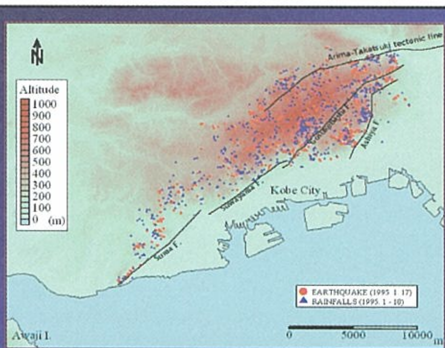


Distribution map of slope failures induced by the Kobe earthquake

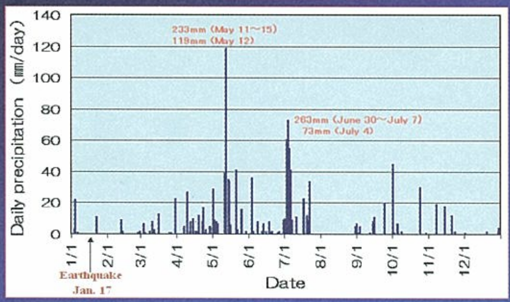
1995
JAN. — Kobe Earthquake (Mj=7.3) JAN. 17, 1995
Many slope failures appeared.

Rainfalls after the earthquake
Many slope failures occurred.

OCT.
1996



Distribution map of slope failures induced by the Kobe earthquake and post-quake rainfalls



Daily precipitation in 1995 at Kobe area

Max. hourly, daily and annual precipitation in decade (1986～1995) at Kobe Area

Year	Max. Hourly Precipitation (mm/hr)	Max. Daily Precipitation (mm/day)	Annual Precipitation (mm/year)
1986	44	128	1,144
1987	27	70	1,048
1988	25	150	1,321
1989	33	122	1,609
1990	28	72	1,513
1991	14	57	1,209
1992	39	80	1,226
1993	33	86	1,724
1994	20	40	597
1995*	20	119	1,131
Ave.	28.3	92.4	1,252

The data in 1995 is till the end October.

The number of slope failures induced by both triggers

1995 Kobe Earthquake	747
Post-quake rainfalls till the end of Oct. 1995	938

According to the Rokko Sabo Work Office, Ministry of Construction

Q. Why did over 900 slope failures occur by little amount of rainfall and intensity ?

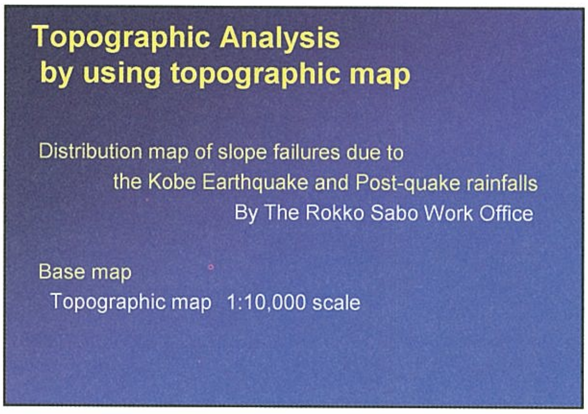
In this presentation...

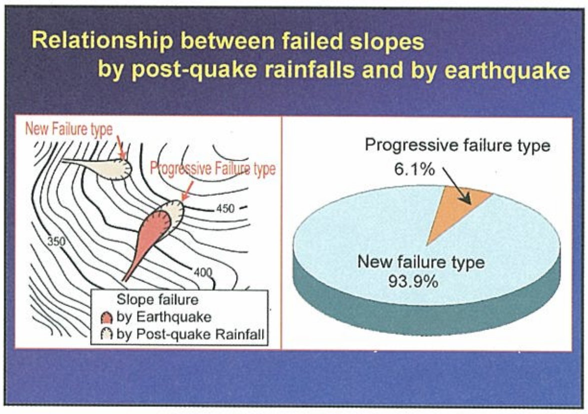
- Topographic Analysis
  the topographic features of the slope failures due to post-quake rainfalls
- Seismic Response Analysis
  the dynamic response property on failed slopes
- Experiment using the cyclic triaxial test apparatus
  the effect of seismic motion and post-quake rainfalls on the soil shear strength

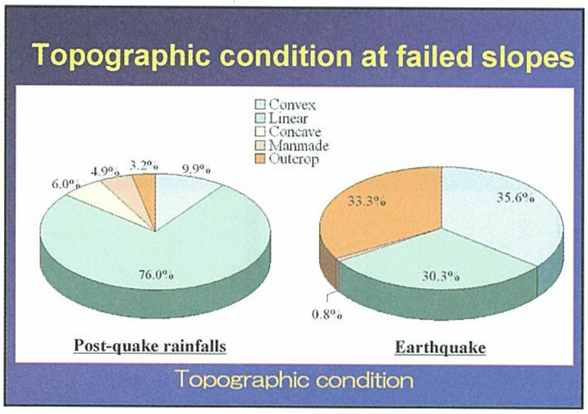
Topographic Analysis

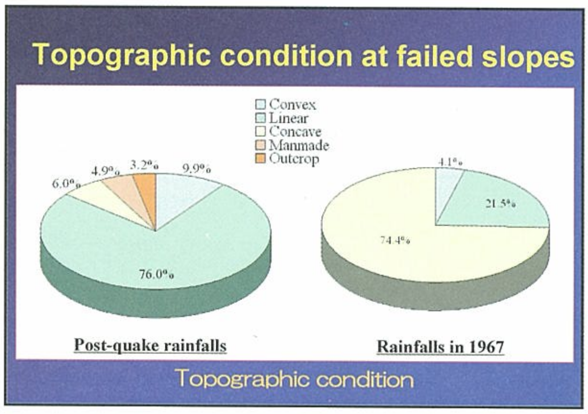
Topographic features of the failed slopes due to post-quake rainfalls

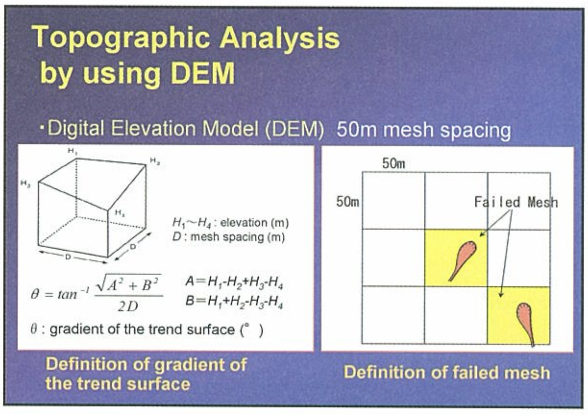
- Topographic map
- Digital elevation model (DEM)

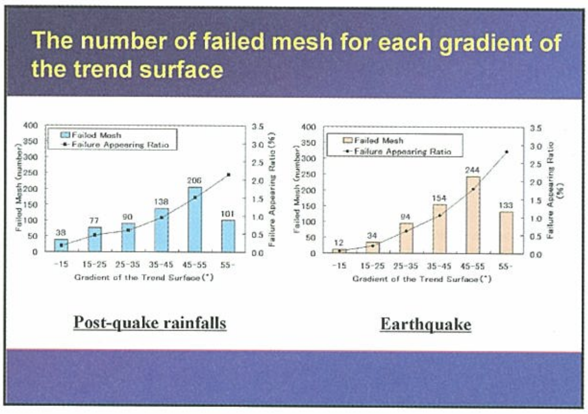

Topographic Analysis
by using topographic map
Distribution map of slope failures due to
the Kobe Earthquake and Post-quake rainfalls
By The Rokko Sabo Work Office
Base map
Topographic map 1:10,000 scale


Relationship between failed slopes
by post-quake rainfalls and by earthquake
New Failure type
Progressive Failure type
450
350
400
Slope failure
by Earthquake
by Post-quake Rainfall
Progressive failure type
6.1%
New failure type
93.9%


Topographic condition at failed slopes
Convex
Linear
Concave
Manmade
Outcrop
6.0%
4.9%
3.2%
9.9%
76.0%
33.3%
35.6%
30.3%
0.8%
Post-quake rainfalls
Earthquake
Topographic condition


Topographic condition at failed slopes
Convex
Linear
Concave
Manmade
Outcrop
6.0%
4.9%
3.2%
9.9%
76.0%
4.1%
21.5%
74.4%
Post-quake rainfalls
Rainfalls in 1967
Topographic condition


Topographic Analysis
by using DEM
・Digital Elevation Model (DEM) 50m mesh spacing
H_1~H_4: elevation (m)
D: mesh spacing (m)
$\theta = tan^{-1}\frac{\sqrt{A^2+B^2}}{2D}$
$A=H_1-H_2+H_3-H_4$
$B=H_1+H_2-H_3-H_4$
θ : gradient of the trend surface (°)
50m
50m
Failed Mesh
Definition of gradient of
the trend surface
Definition of failed mesh


The number of failed mesh for each gradient of
the trend surface
Failed Mesh
Failure Appearing Ratio
Failed Mesh (number)
Failure Appearing Ratio (%)
38
77
90
138
206
101
12
34
94
154
244
133
-15
15-25
25-35
35-45
45-55
55-
Gradient of the Trend Surface (°)
Post-quake rainfalls
Earthquake

From topographic analysis

- A lot of slope failures induced by post-quake rainfalls occurred as not progressive failure type but new failure type.
- The topographic features of slope failures induced by post-quake rainfalls were similar to those of slope failures induced by the earthquake rather than by rainfalls in the past.

Seismic response analysis

The dynamic response property on failed slopes

- Failed slopes by the earthquake
- Failed slopes by the post-quake rainfalls

Analysis code

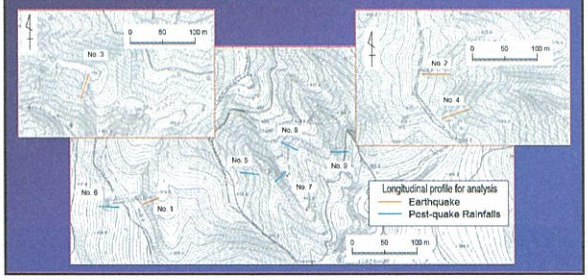
Super FLUSH/2D

2D-Equivalent Linearization Analysis

Analysis sites

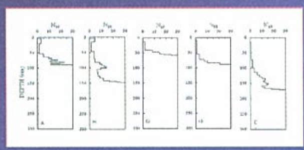
Failed slopes by the earthquake (No.1 - 4)

Failed slopes by post-quake rainfalls (No. 5 - 9)

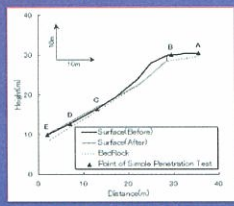


Field investigation

- Depth of surface soil layer by portable penetration test
- Longitudinal profile by longitudinal survey

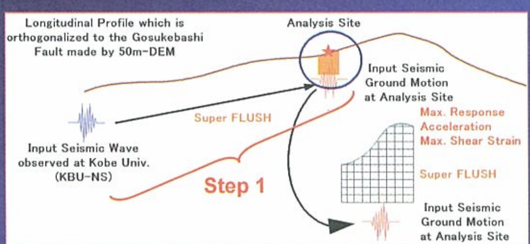


Results from portable penetration test

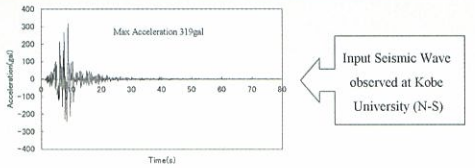


Longitudinal profile

Analysis process



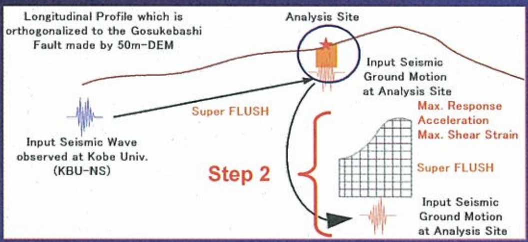
Parameters used for the analysis (Step 1)



Parameters used for the analysis (Step 1)

Shear wave velocity V_s(m/s)	Unit weight γ_t(kN/m^3)	Poisson's ratio	Initial shear modulus G_0(kPa)	Initial Damping Ratio
1,500	25.48	0.19	5,880,000	0.01

Analysis process

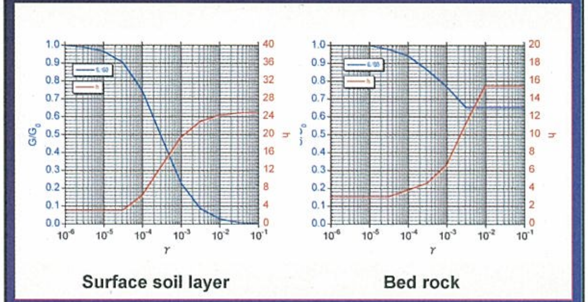


Parameters used for the analysis (Step 2)

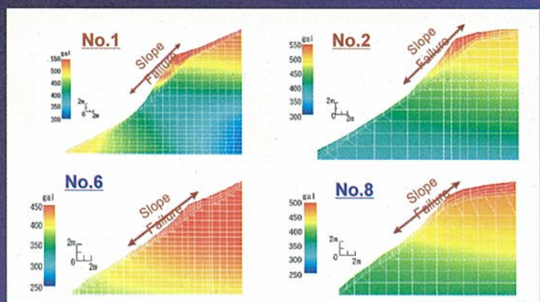
	Shear wave velocity V_s(m/s)	Unit weight γ_t(kN/m^3)	Poisson's ratio	Initial shear modulus G_0(kPa)	Initial damping ratio h_0
Surface soil layer	Refer to under table	14.41	0.39	Refer to under table	0.03
Bedrock	500	22.54	0.19	575300	0.03

Site No.	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9
Shear wave V_s(m/s)	114	113	124	124	108	112	116	122	118
Initial shear G_0(kPa)	19100	18800	23500	23500	17200	18400	19800	21900	20500

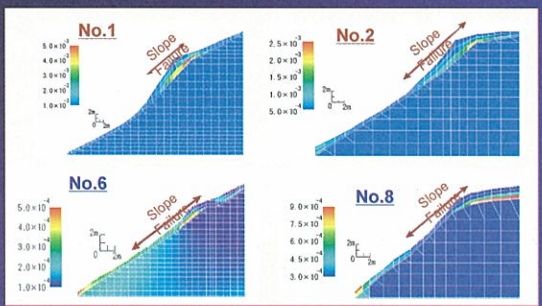
Parameters used for the analysis (Step 2)



Strain-dependent shear modulus ratio and damping ratio



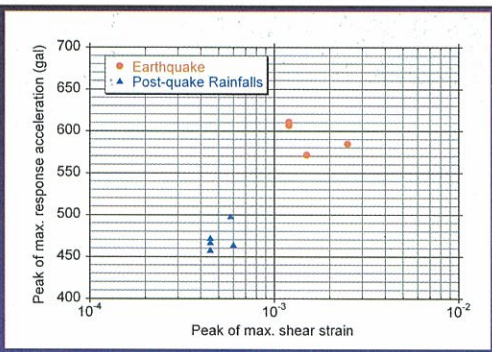
Distribution of max. response acceleration



Distribution of peak of max. shear strain

Distribution of max. response acceleration and peak of max. shear strain at failed part

Failed by		Distribution of max. response acceleration at failed part (gal)	Distribution of peak of max. shear strain at failed part
Earthquake	No.1	421~585	$2.0 \sim 2.5 \times 10^{-3}$
	No.2	438~572	$1.0 \sim 1.5 \times 10^{-3}$
	No.3	420~611	$0.9 \sim 1.2 \times 10^{-3}$
	No.4	430~607	$0.9 \sim 1.2 \times 10^{-3}$
Post-quake Rainfalls	No.5	368~464	$2.4 \sim 6.0 \times 10^{-4}$
	No.6	408~472	$1.4 \sim 4.5 \times 10^{-4}$
	No.7	372~467	$2.0 \sim 4.5 \times 10^{-4}$
	No.8	428~498	$1.3 \sim 5.8 \times 10^{-4}$
	No.9	395~458	$1.7 \sim 4.5 \times 10^{-4}$



Relationship between peak of max. response acceleration and max. shear strain at failed part

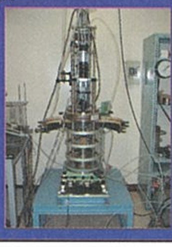
From seismic response analysis

- The seismic motion affected on failed slopes by post-quake rainfall, although the effect was smaller than the failed slopes by the earthquake.
- The seismic motion plays an important role for the occurrence of not only earthquake-induced failure but also post-quake rainfall-induced failure.

Experiment using the cyclic triaxial test apparatus

The effect of seismic motion and post-quake rainfalls on the soil shear strength

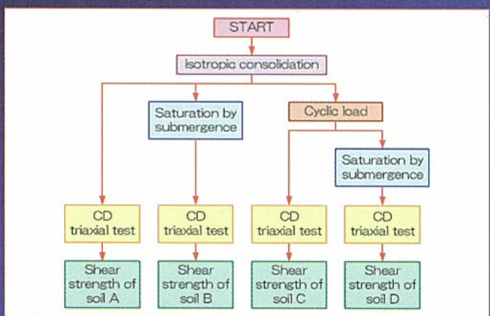
Consolidated drained shear test (CD triaxial test) performed under four kinds of different conditions



Specimen of the experiment

The decomposed granite soil with the gypsum mixing
Φ=50mm H=100mm

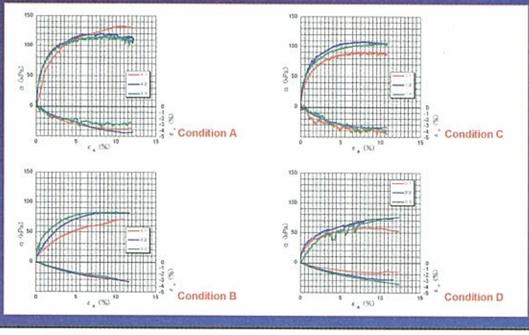
Flowchart of experiment



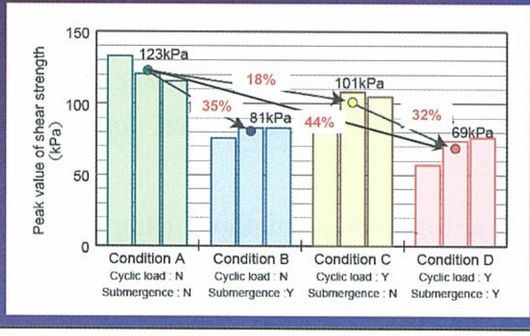
Experiment conditions

- Isotropic consolidation process
  Isotropic consolidation pressure: 20 kPa
- Cyclic loading process
  Cyclic load: strain control ±0.2%
  sine wave (period 1sec) 20 cycle
- Submergence process
  Saturation by deaeration water
- CD triaxial test
  Strain rate : 0.1%/min

q vs e_a and e_v vs e_a



Comparison of soil shear strength



From experiment

- The shear strength was reduced by cyclic loading and saturation by submergence.
- If the cyclic load is assumed seismic motion and submergence is assumed rainfall, the soil shear strength dropped by the seismic motion and decreasing of the shear strength was generated additionally by increasing of the degree of saturation due to the rainfall after the earthquake.

Conclusion

- In the Rokko mountains, many slope failures occurred by rainfalls after the Kobe earthquake, although they were little amount of rainfall and intensity.
- The topographic features of slope failures induced by post-quake rainfalls were similar to those of slope failures induced by the earthquake rather than by rainfalls in the past.

Conclusion

- The seismic motion affected on failed slopes by post-quake rainfall, although the effect was smaller than the failed slopes by the earthquake.
- The skeletal structure was destroyed by the effect of seismic motion, and as a result the soil shear strength dropped. And, decreasing of the shear strength was generated additionally by the effect of the rainfall after the earthquake.