A Study of Tensile Strain in Upper Surface of Rock Slope using Barodynamics Experiment

By Shoji OGINO*, Osamu SANO* and Yoshihiko SHIOZAKI**

(Received July 14, 1980)

Abstract

In order to investigate on the tension crack occurring in the upper surface of rock slopes, barodynamics experiment using models representing rock slope was performed, and tensile strain on upper surface was measured. Results obtained by this experiment were examined by elasto-plastic analysis using FEM.

By both barodynamics experiment and theoretical analysis following conclusions were obtained:

(1) In case of vertical slope, horizontal strain near upper surface is always tensile strain, and its magnitude increases as slope height increases.

(2) In case $\theta \leqq 80°$, horizontal strain near the upper surface is compressive strain when slope height is small. As slope height increases, compression failure near the toe of slope causes increase in compressive strain near the upper surface. When slope failure occurs the horizontal strain near the upper surface suddenly turns into tensile strain.

By these facts, it can be seen that slope failure occurs progressively from the toe of slope.

Introduction

Tension crack which occurs on the upper surface of a slope has a great influence on the extent of slope failure. Since such tension crack is caused by elongation of the upper surface, it seems to be significant for the estimation of slope stability to investigate mechanism of the elongation on the upper surface.

As the deformation of slope is caused by stress due to gravity, deformation analysis should be performed on a body which is subjected to gravity. In order to study this deformation by model experiment, models should be loaded by body force. Barodynamics experiment in which models are mounted in a rotation frame of a centrifuge and are subjected to centrifugal acceleration seems to be only available mean for this purpose.

From such point of view, tensile strain which occurs on the upper surface of the model was investigated by the barodynamics experiments, and was examined by the results of FEM analysis.

Few barodynamics experiments have been performed up to this time for the purpose of studying slope stability[1)2)3)]. One of the authors studied this problem using a centrifuge, rotating frame diameter of which is 440 mm. A new barodynamics appa-

* Department of Mining and Mineral Engineering
** Niihama Municipal Office

ratus, rotating frame diameter of which is 960 mm, was designed recently by the authors and model experiment was performed using models representing slopes excavated in a homogeneous ground.

Model Experiment

Slope Model

An example of slope model for the barodynamics experiment is shown in Fig. 1. Models were made mixing plaster of Paris, calcium carbonate, standard sand and water in weight ratio of 1: 1: 10: 4. Experiments were performed with models having five kinds of slope angle, $\theta=90°$, 80°, 76°, 70° and 60°.

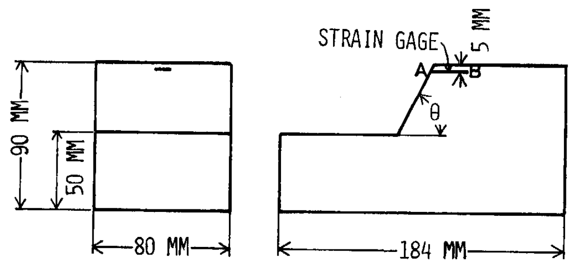

Fig. 1 Model of slope.

Uniaxial compressive strength of the material was measured for each model. Mean compressive strength obtained was 322 kPa and standard deviation was 87 kPa.

Model was molded in a vessel made of steel plates 8 mm thick, and was mounted on both ends of the rotating frame keeping the model in the vessel in order to prevent lateral deformation.

A strain gage having gage length of 20 mm was layed 5 mm under the upper surface near the upper end of the slope as shown in Fig. 1 by AB.

Barodynamics Apparatus

Fig. 2 shows the barodynamics apparatus used in this study. Two slope models were mounted on both ends of rotating frame which is driven by 15 kW variable speed motor having electro-magnetic coupling. Revolution rate was controlled smoothly by a controller up to 2000 rpm. Centrifugal acceleration on bottom of the model at this revolution rate was 20,967 m/s^2.

The revolution rate of rotating frame was measured using photo-tachometer, eliminating noise by low pass filter. Horizontal strain near the upper end of the slope and revolution rate were recorded by X–YY recorder, connecting the strain gage to the recorder through slip-ring fixed on rotating axis, strain amplifier and low pass filter. Since the centrifugal acceleration λg is in proportion to square of revolution rate, λg was modified using multiplier, output of which is equal to square of input.

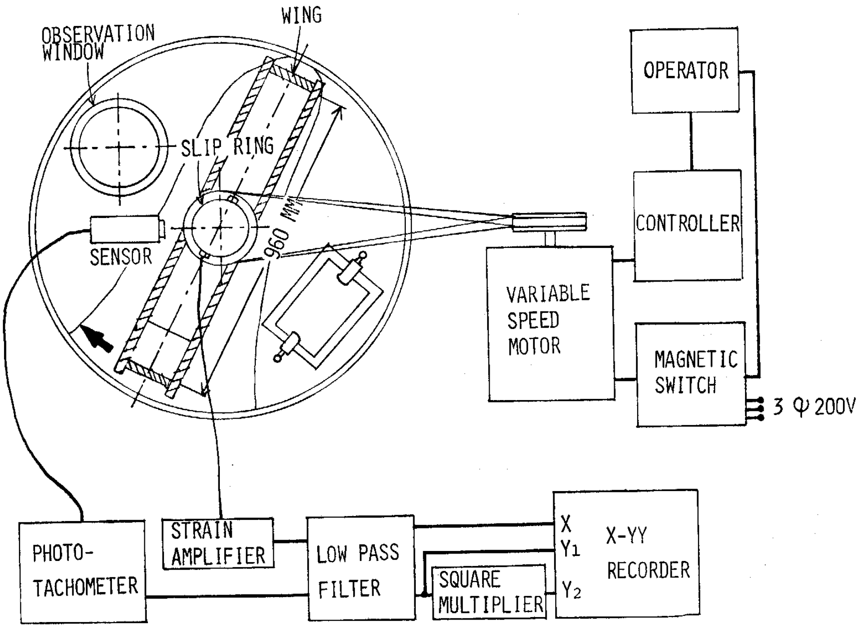

Fig. 2 Schematic configuration of barodynamics apparatus and experimental installation.

Theoretical Investigation on Behavior of Slope Model

Stress and deformation which take place in slope model were analyzed by FEM, in which post failure deformation characteristics of the material was taken into account[4]. Fig. 3 shows an example of the relation between differential stress and strain used in this elasto-plastic analysis, in which broken lines indicate stress-strain relation determined by triaxial test on the material for the slope model, and solid lines indicate stress-strain curves mathematically represented.

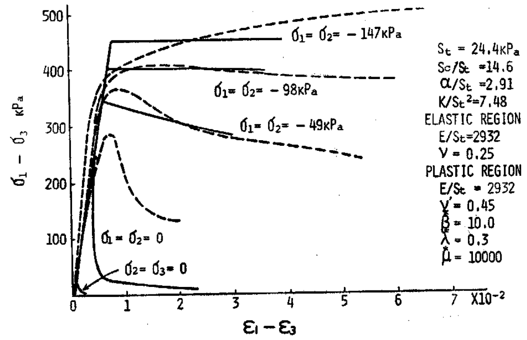

Fig. 3 Stress-strain curves of model material obtained by triaxial test (dotted lines) and their mathematical representation (solid lines).

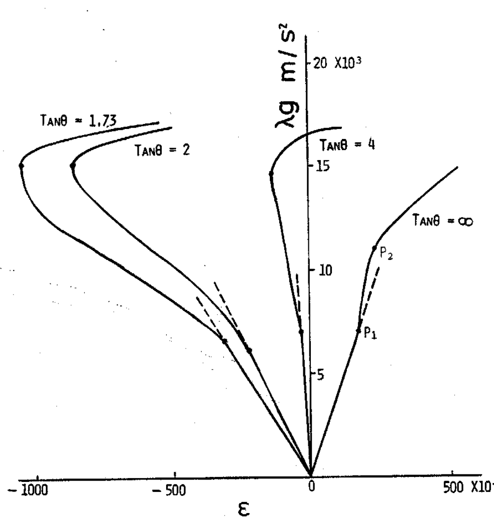

Fig. 4 Relation between centrifugal acceleration λg and strain ε of line AB shown in Fig. 1 determined theoretically.

Relation between horizontal strain ε which occurs at AB in Fig. 1 and centrifugal acceleration λg, determined by the elasto-plastic analysis is shown in Fig. 4 for four kinds of slope angle. λ corresponds to dimension ratio of prototype and model. As shown in this figure, in case of $\tan\theta=\infty$, only tensile strain occurs. In elastic region ε has linear relation with λg.

At a point indicated by P_1 this relation begins to deviate from straight line, and then at point indicated by P_2 this curve turns to right. According to the stress analysis compressive failure initiates near the toe of the slope when centrifugal acceleration approaches P_1, and failure of the slope occurs at P_2. In case of $\tan\theta\leqq 4$, compressive strain occurs for low λg value. Turning points P_1 and P_2 can be seen on those curves.

Experimental Results

Relation between centrifugal acceleration λg which is proportional to square of the revolution rate, and strain ε measured by the strain gage layed as depicted in Fig. 1 is shown in Fig. 5. It is shown in this figure that in case of $\theta=90°$ tensile strain occurs regardless of λg, and that in case of $\theta\leqq 80°$, compressive strain occurs for low value of λg, and then gradually turn to tensile strain. It can be seen from these curves that failure of slope occurs progressively.

In like manner as relation between λg and ε theoretically determined, failure initiation point P_1 and break-down point P_2 were determined from these $\lambda g-\varepsilon$ curves.

Relation between slope angle θ and $\lambda_f g$, centrifugal acceleration at P_1 obtained by the experiment, is shown in Fig. 6. Since compressive strength on the model material determined for each model showed fluctuation as mentioned above, points representing

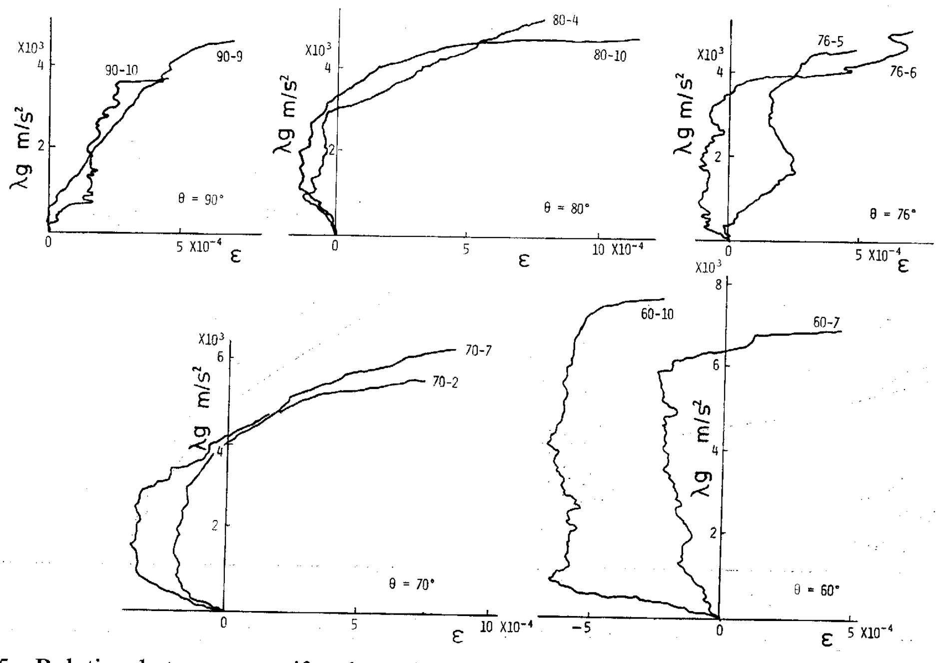

Fig. 5 Relation between centrifugal acceleration λg and strain ε of line AB shown in Fig. 1 obtained by the barodynamics experiments.

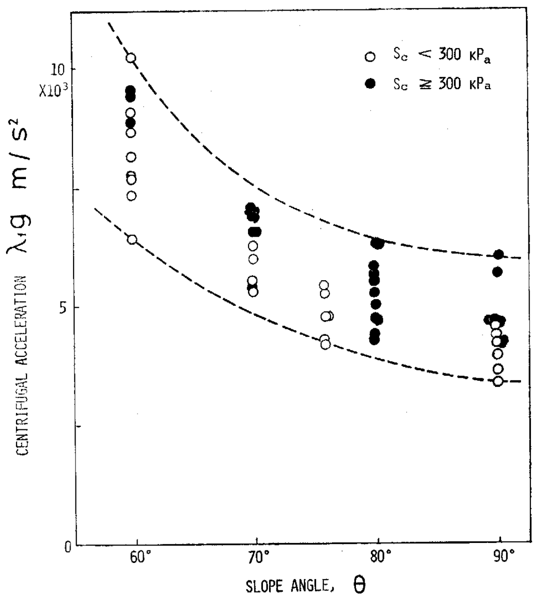

Fig. 6 Relation between slope angle θ and centrifugal acceleration $\lambda_f g$ causing slope failure.

relation between θ and $\lambda_f g$ was plotted in this figure separating models by compressive strength of the material.

By the pattern of failed surface, it was observed that in case of $\theta=90°$ and 80° slope failure occurred by joining of tension crack advanced from the upper surface with failure plane advanced from the toe of the slope.

In case of $\theta=76°$, 70° and 60°, two types of failure were observed. One was failure of wedge shaped zone caused by sliding surface advanced from the toe of the slope, and the other was failure caused by joining of tension crack with sliding surface through the toe of the slope.

Conclusion

Barodynamics experiment using models representing rock slope in homogeneous ground was performed and tensile strain on the upper surface was measured. Results obtained by this experiment were examined by elasto-plastic analysis using FEM.

By both barodynamics experiment and theoretical analysis following conclusions were obtained.

(1) In case of vertical slope, horizontal strain near the upper surface is always tensile and its magnitude increases as slope height increases.

(2) In case of $\theta \leq 80°$, horizontal strain near the upper surface is compressive strain when slope height is small. As the slope height increases compressive failure near the toe of the slope causes increase in compressive strain near the upper surface. When slope failure occurs the horizontal strain near the upper surface suddenly turns into tensile strain.

By the results mentioned above, it can be seen that slope failure occurs progressively from the toe of the slope. Results of experiment as well as theoretical analysis coincide with results of investigation by Okamura et al. fairly well, though method of experiment and precondition for the analysis considerably differ each other.

Acknowledgements

The authors wish to thank Dr. Yoshiaki Mizuta for his many important contribution throughout this investigation.

Barodynamics experiments was carried out by Jiro Hiramatsu and Mikio Futo and this is acknowledged.

Financial support for this study was offered by the Grant-in-aid for Scientific Research of the Education Ministry, 1977/78.

References

1) Goldstein, M., Berman, M., Goosev, B., Timofeyeva, T. and Turovskaya, A., "Stability investigation on fissured rock slopes", Proc. 1st Congress of ISRM, Lisbon, **2**, 175–178 (1966).
2) Ogino, S., Mizuta, Y. and Kunimatsu, S., "A study of stability analysis for slopes",. Tech. Rep. Yamaguchi Univ., **2**, 21–32 (1977).
3) Okamura, H., Sugahara, K., Akimoto, M., Kubota, S. and Kaneshige, O., "Experimental study on rock slope stability by the use of a centrifuge, — A study of the stability of rock slopes (1st Report))", Jour. Mining & Metal. Inst. Japan, **95**, 7–14 (1979) (in Japanese).
4) Mizuta, Y., Li, K., Oka, Y., Hiramatsu, Y. and Ogino, S., "The method of elasto-plastic analysis for underground excavations in consideration of the post-failure properties of rocks", Jour. Mining & Metal. Inst. Japan, **94**, 151–156 (1978) (in Japanese).