Soils and Foundations 2015;55(1):127–142

HOSTED BY
ELSEVIER

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Dynamic behavior of slope models with various slope inclinations

Masahiro Shinoda[a,*], Kenji Watanabe[a,1], Taisuke Sanagawa[a,1], Keita Abe[a,1], Hidetaka Nakamura[b,2], Tadashi Kawai[c,3], Susumu Nakamura[d,4]

[a]Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji-shi, Tokyo 185-8540, Japan
[b]Japan Nuclear Energy Safety Organization, Toranomon Towers Office, 4-1-28, Toranomon, Minato-ku, Tokyo 105-0001, Japan
[c]Tohoku University, 6-6-6, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan
[d]Nihon University, Nakagawara 1, Tokusada, Tamura Koriyama, Fukushima 963-86420, Japan

Received 1 June 2013; received in revised form 28 June 2014; accepted 21 October 2014
Available online 12 January 2015

Abstract

The regulatory guide for the seismic design of nuclear power reactor facilities in Japan was revised in 2006. The guide requires the facilities to be designed to withstand earthquakes, taking into consideration slope collapses that can be expected to occur around such facilities. Although these requirements were included in the previous edition of the guide, definite specifications are given in the new edition. This has made the study of the stability of slopes subjected to earthquakes more important. This paper describes the dynamic behavior of slope models based on the findings of experimental and analytical investigations. In the experimental investigation, a series of shaking table tests was conducted using slope models with various inclinations. The feature of the present experimental investigation was to use an image processor to precisely measure the dynamic shear strain of the models when shaken. In the analytical investigation, Newmark's sliding block analysis was used to assess the validity of the test results. The sliding block analyses of the slope models were based on the results of stability and displacement analyses with the assumption of a circular slip surface. The results of the analyses are used to propose a method for evaluating the stability of rock slopes.

Keywords: Slope stability; Shaking table test; Stability analysis; Displacement analysis

1. Introduction

NSC, 2006-59 (2006), the regulatory guide for the seismic design of nuclear power reactor facilities was revised. The guide requires the facilities to be designed to withstand earthquakes, taking into consideration slope collapses that can be expected to occur around the facilities. Although these requirements were included in the previous edition of the guide, definite specifications are given in the new edition. In the current regulatory guide, any slope with its toe within 50 m of a nuclear power plant, or at a distance of less than 1.4 times its height from the plant, should be carefully considered. This is because the failure of such slopes may result in damage to the nuclear power plant. In Japan, there are 54 nuclear power

*Corresponding author at: Railway Technical Research Institute, Senior Researcher, 2-8-38, Hikari-cho, Kokubunji-shi,Tokyo 185-8540, Japan. Tel.: +81 42 573 7261.

E-mail addresses: shinoda.masahiro.97@rtri.or.jp (M. Shinoda), watanabe.kenji.71@rtri.or.jp (K. Watanabe), sanagawa.taisuke.39@rtri.or.jp (T. Sanagawa), abe.keita.06@rtri.or.jp (K. Abe), hidetaka-nakamura@jnes.go.jp (H. Nakamura), t-kawai@civil.tohoku.ac.jp (T. Kawai), s-nak@civil.ne.nihon-u.ac.jp (S. Nakamura).

[1]Tel.: +81 42 573 7261.
[2]Tel.: +81 3 4511 1561.
[3]Tel.: +81 22 795 7433.
[4]Tel.: +81 24 956 8712.
Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2014.12.010
0038-0806/

reactor plants spread over 18 areas. Their specific locations are shown in Fig. 1. The slopes around the plants in 13 of these areas, the heights of which range between 10 and 200 m, require careful consideration.

In studying modalities for reducing the risk of damage to a nuclear power reactor plant in the event of the failure or collapse of the surrounding slopes due to an earthquake, we assumed a critical scenario in which falling rocks of sliding slope masses strike the plant, as shown in Fig. 2. The findings of this study would facilitate active consideration of risks beyond those considered in the conventional design of nuclear power plants, thereby improving their safety. The first step of the study focused on evaluating the stability of a slope around a nuclear power plant. The evaluation of falling soil or rock masses after the collapse of the slope is beyond the scope of this study.

In the meantime, the 11 March 2011 off the Pacific Coast of Tohoku Earthquake, Japan, along with subsequent events, including a large tsunami, severely damaged many earth structures, including earth and rock slopes. Koseki et al. (2012), Hyodo et al. (2012) reported several case histories including cut and earth slope failures. In an actual rock slope, there are several types of geological structures, which may result in different types of failures. Duncan and Christopher (2004) identified four categories of failures, namely, plane failure, wedge failure, toppling failure, and circular failure (see Fig. 3). In this study, only plain failure and circular failure were investigated, and this was done empirically and numerically. Our study of wedge failure and toppling failure is in progress and will be reported in the future.

Fig. 1. Locations of nuclear power reactor facilities in Japan.

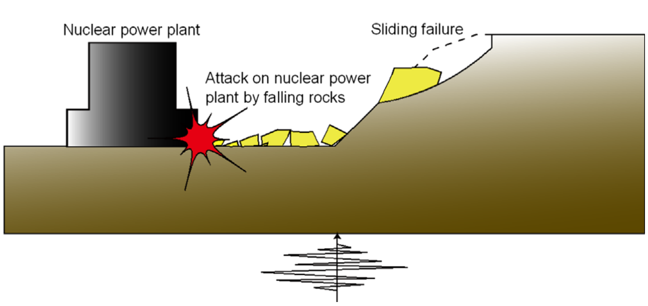

Fig. 2. Scenario of a serious threat to a nuclear power plant due to rock slope failure.

Plane failure occurs in rock slopes that have joints that protrude from the slope face and strike the face in a parallel direction, as shown in Fig. 3a. Ishimaru and Kawai (2011) conducted a centrifuge model test on a rock slope model exhibiting plane failure and used the results of an equivalent linear analysis to calculate the safety factor, which was confirmed to be conservative.

Circular failure occurs in rock fills, very weak rocks, and closely fractured rocks containing randomly oriented discontinuities. A large amount of literature on circular failure has accumulated over the last half-century. Sugawara et al. (1983) conducted a series of centrifuge model tests on a rock slope model with a circular slip surface and noted that the peak strength of the rock mass should be used to evaluate the stability. Many methods for analyzing the stability of circular and noncircular slip surfaces have been presented, such as the ordinary method of slices (Fellenius, 1927), Bishop's modified method (Bishop, 1955), Janbu's generalized procedure of slices (Janbu, 1968), Morgenstern and Price's method (Morgenstern and Price, 1965), and Spencer's method (Spencer, 1967).

However, as the stability of a slope in a plain failure mode or a circular failure mode is concerned, many previous studies have employed Newmark's sliding block analysis (Newmark, 1965). In addition, it is well know that Newmark's sliding block analysis can be extended to estimate slope displacements for engineering practice. Goodman and Seed (1966), Wartman et al. (2003, 2005) used it to verify laboratory model tests, and Wilson and Keefer (1983), Pradel et al. (2005) used it to validate their analyses of earthquake-induced landslides in natural slopes. Yan et al. (1996) proposed a modified Newmark analysis for a rigid block on an inclined plane that considers the vertical component of the seismic motion. Kramer (1996), Wasowsli et al. (2011), Jibson (2011) comprehensively reviewed the procedures for sliding block analysis.

Jibson (2011) classified the analytical procedures for estimating earthquake-induced slope displacement into three types, namely, rigid-block, decoupled, and coupled. In the rigid-block analysis, the sliding block is modeled by a rigid mass that slides on an inclined plane. This analysis assumes that there is no or negligible deformation of the soil mass. The decoupled analysis is more sophisticated and takes the deformation of the soil mass into consideration. The most commonly used version of the analysis was developed by Makdisi and Seed (1978). In their analysis, the dynamic analysis response and the plastic displacement are independently computed. In the coupled analysis, the dynamic response of the soil mass and the permanent displacement are modeled together, so that the effect of the plastic sliding displacement on the ground motions is considered. Bray and Travasarou (2007) developed a simplified approach that used a nonlinear and fully coupled sliding-block model to determine a semi-empirical relationship for estimating seismic displacement.