ABSTRACT

Earth embankments are the most important and common infrastructural facilities used for dams, highways, railways, river training works, canals, tanks etc. The proper performance of these geotechnical structures during earthquake is extremely necessary as they form a part of life line. It is not only important that they survive moderate level earthquake, but it is necessary that they are restored back immediately after the major earthquakes. However, available literature suggests that the performance of earth embankments during earthquake is far from satisfaction. The major earthquakes of recent times, namely Northridge of 1994 in USA, Hyogo-ken Nanbu of 1995 in Japan, Chi-Chi of 1999 in Taiwan, Izmit of 1999 in Turkey, Bhuj of 2001 in India, Bam of 2003 in Iran, Sumatra of 2004 in Indonesia, Kashmir of 2005 in Pakistan have all witnessed the damage to earth embankments. Some embankments suffered minor to moderate levels of damage, while the others experienced total collapse. Historically, the failure of lower San Fernando dam during the 1971 San Fernando earthquake stands among the first to draw the attention of researchers for studies on seismic performance of earth dams. Liquefaction of subsoil beneath the earth dam was responsible for the breach of the dam. The fact that upper San Fernando dam remained intact made researchers enhance studies in this direction. It is very difficult to explain the cause for survival of a particular structure, whereas it is possible to identify the mistakes from failures.

The studies related to earth embankments are very complex because of varying material properties, complex boundary and loading conditions and irregular geometry. In addition, the force during earthquake is uncertain, complex and random. A study by USCOLD suggested that earthquake is the second largest cause for the failure of earth dams. In India, Bhuj earthquake of January 26th, 2001 was responsible for all the 185 earth dams in Kutch region to experience damage from minor to major levels. Even Sumatra earthquake December 26th, 2004 caused widespread embankment failures in Andaman Islands. Considering the number and magnitude of failure of earth embankments during earthquakes, importance of these structures in the present day context and complex nature of analysis of earth embankments subjected to earthquake
loading because of uncertainties and randomness, the present work of evaluating seismic response of earth embankment was taken up.

The main contribution of the present work can be summarized as

1. Ascertaining that the subsoil weakening during earthquake is the major cause for embankment failure.
2. Suggesting the provision of dense wall on the inside of the toe of embankment in subsoil portion to reduce the damaging effects of shaking.
3. Developing a few design methodologies for the analysis and design of embankments subjected to earthquake loading, and
4. The development of manual shaking table to carry out model testing for the purpose of understanding the mechanism of failure and the concept of mitigation.

To achieve these goals, the present work was carried out in three phases. The first phase comprised of field investigation at the sites of embankment immediately after the earthquake. The second phase included extensive model studies using 1-G shaking table embankment – subsoil system. The last phase was the analytical approach using Finite Element tool at various stages to understand the findings from field investigation and model studies and to propose recommendations for future modifications.

The field visit to Gujarat, three months after the Bhuj earthquake of 2001 helped in damage assessment of four earth dams, namely, Rudramata, Ratiya, Adoi 2 and Chang dams. For this purpose, extensive field tests and data collection were carried out at the sites. It was inferred from the studies that the subsoil weakening was the major cause for failure of Ratiya and Chang dams. While subsoil at the site of Ratiya dam was made of soft clay, the subsoil at the site of Chang dam consisted of loose cohesionless soil that liquefied. The effects of subsoil weakening resulted in longitudinal cracks along the length of the dam, lateral slope failure, subsidence and failure at the junction with rigid masonry or concrete structures etc., wherever subsoil was weak. It is interesting that the damage was less pronounced in the regions with relatively stable foundation soil. Similar visit to Andaman Islands four months after the Sumatra earthquake of December 2004 also revealed the failures suffered by
embankment dams. While a Rockfill dam in Kalpong of North Andaman Islands suffered longitudinal cracks at the surface and small localized slides on the slope, two earth dams catering to irrigation requirements in Little Andaman Island, namely, Vishnu Nalla dam and R. K. Pura dam suffered considerable amount of damage. Loss of alignment of dam and development of horizontal cracks were the additional damages. A rural highway in North Andaman Island that was considerably damaged was found to rest on soft subsoil. Based on field investigation, it was inferred that the soft subsoil was the major culprit.

In earthquake engineering, it is impossible to base the understandings through field results only. To develop the mechanism of failure and concepts a simulation of field behavior in laboratory is equally essential. In this regard, a manual shaking table to carry 750 kN payload and develop an acceleration of 0.5 g at 2 Hz was designed, fabricated and successfully used. The accessories for model tests consisted of manual shaking table, transparent model container of 1650 mm length 500 mm wide and 600 mm deep, accelerometers and pore water pressure transducers along with data logger, video camera etc.. The sophisticated program was carried out at a relatively low cost. After the initial calibration tests two series of tests were performed, namely, understanding the mode of failure of embankment subsoil system and proposing possible mitigation measure against seismic failure. Tests to understand the influence of subsoil strength and stiffness revealed that weak subsoil was mainly responsible for more damaging effects. Among the mitigation measures, provision of dense wall in the subsoil was found to be more practical and appropriate. Dense wall inside of the toe of embankment performed better. Such a comparison was made from acceleration records, pore pressure records in the body of embankment subsoil system and understanding the entire motion.

Analytical studies using Finite element approach were performed to mainly understand the findings from field investigations and laboratory model studies. The finite element solutions substantiated the facts that weak subsoil makes embankment subsoil system vulnerable and the provision of dense wall on the inside of the toe of embankment showed better performance under horizontal dynamic loading.
The above study indicated the importance of improving the design methodologies for embankments. Hence, attempts were made to understand the performance of embankment system using finite element tool. It was inferred that there is a need to consider the influence of subsoil on the overall performance. Natural frequency of embankment system will be very different from the available empirical equation prepared in the Indian standard code which holds good for embankment resting on hard strata only. A series of coefficients have been proposed in the present study for varying thicknesses of subsoil. Further, response spectrum charts were prepared for embankment subsoil system considering variation in the earthquake motions and damping coefficients. These charts will help in rational design of embankment subsoil system under earthquake loading.

In summary, the present study helps in understanding the behavior of embankment subsoil system during earthquake loading, proposing a suitable mitigation measure to improve its performance and developing schemes for rational design of embankment subsoil system during earthquake.