4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1370

EARTHQUAKE DAMAGES TO EMBANKMENTS IN ANDAMAN ISLANDS IN INDIA

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ABSTRACT

This paper presents the damages suffered by highway embankments and dams in Andaman Islands during the recent Sumatra earthquake of December 2004. Though the major damage was witnessed due to the power of Tsunami, the focus of this paper is on damage caused during earth shaking. The discussion identified four damaged embankments that include a Rockfill dam across river Kalpong and a small rural highway in the northern Andaman Island and two earthen dams in Little Andaman Island, namely R. K. Pura dam and Vishnu Nalla dam. The typical damage included longitudinal crack along the crest, horizontal crack, dislocation of some pitching material and slope failure, settlement and loss of alignment. The earthen dams also suffered loss of water on their reservoir side. The rural highway embankment suffered severe damage over a length of around 1 km. It was inferred that weak subsoil was the major culprit for rural highway embankment based on the field test performed at the site.

Keywords: Field Investigation, Embankment failure, Earthquake damage, Subsoil Weakening

INTRODUCTION

Geotechnical facilities such as embankments, quay walls and dykes commonly suffer severe damage during earthquakes. Liquefaction being one of the main causes for such damage, its ill effects was very well exposed during the recent earthquakes of Northridge (1994) in USA, Hyogo Ken Nambu (1995) in Japan and Bhuj (2001) in India. Many earthen embankments worldwide are located in seismically active areas. Many of these embankments are founded on liquefiable soils. The damage of the embankments was often mainly due to the liquefaction of the embankment and/or foundation soil. In most cases, large deformations developed when the supporting loose cohesionless foundation soil liquefied, resulting in cracking, settlement, lateral spreading, and slumping.

During the 1995 Hyogo Ken Nambu earthquake in Japan, nearly 1200 small earth embankments (80% were 10 m in height or less) suffered some level of damage. In many of these earthen embankments, the damage was associated with liquefaction of foundation soil. At most of the damaged sites sand boils were observed on the ground surface near the dykes, further suggesting foundation subsoil liquefaction.

More than thirty medium and minor dams have suffered considerable damage during the Bhuj earthquake of 2001(Towhata et al., 2002, Prasad et al., 2002). More damage was observed on upstream slopes than on the downstream slopes though the water levels in January in the reservoirs were low. Because of this, the foundation material, which was fully saturated on upstream side developed high pore pressure during earthquake resulting in liquefaction to variable degree. This resulted in cracking, slumping and subsidence.

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SUMATRA EARTHQUAKE AND ITS EFFECT ON ANDAMAN ISLANDS

The recent earthquake in Sumatra on 26th December 2004 has already gone in to the history as the fourth largest earthquake ever recorded on the globe with the moment magnitude M_w of 9.0 on the Richter's Scale. It has also become famous for the generation of Tsunami that took away nearly three hundred thousand lives in Indonesia, India, Srilanka and Thailand. The epicenter was at around 250 km South – South East of Aceh in Sumatra, 600 km South of Port Blair, 1200 km South - South West of Bangkok and 1600 km North West of Jakarta. Seismological explanation suggests that the tectonic activity resulted in thrust faulting and Burma plate slipped perpendicular to Sunda trench causing a fault rupture over 100 km long from the epicenter. The average displacement of the fault plane was 20 m. The ground shaking was felt in many parts of main land India, Thailand and Srilanka. The intensity of damage in Sumatra and Port Blair were IX and VII respectively on Modified Mercalli's Scale. Many aftershocks of magnitude 5 and above were recorded on daily basis with magnitude 7.1 in Nicobar Islands being the biggest in magnitude.

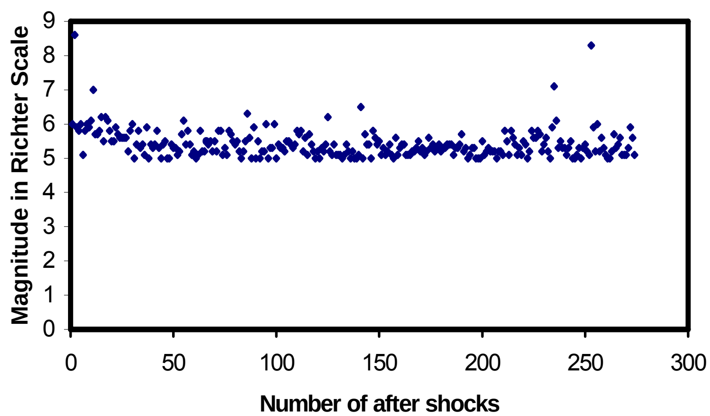

Figure 1: After shocks of magnitude more than 5 on Richter Scale in Andaman and Nicobar Islands recorded from January 2005 to March 2005

Figure 1 presents some of the after shocks greater than 5 in magnitude on Richter's Scale recorded in Port Blair of Andaman Islands for a period of 3 months after the major event. It is interesting to note that there were more than 270 such events. While majority of shakings had a magnitude of 6, some after shocks were close to 7 in magnitude on the Richter's Scale. According to United States Geological Survey (USGS), this boxing day earthquake of 26th December 2004 triggered swarms of minor earthquakes in Alaska 11000 km away. It had the longest fault rupture along 1300 km fault line deep below ocean with an average sudden shift of over 5 m. This earthquake produced a long duration of shaking and most energetic swarms of after shocks.

The important source parameters of Sumatra earthquake of 2004 as ascertained by the United States Geological Survey (USGS) are highlighted in Table 1.

Table 1: Summary of Sumatra Earthquake of 2004

S. No.	Parameters	Description
1	Date and Time	26th Dec, 2004, 07:58:53 Local time at Epicenter (0:58:53 UTC)
2	Epicenter	3.316^0 N, 95.854^0 E
3	Location	250 km SSE of Banda Ache, Sumatra, Indonesia
4	Focal depth	30 km
5	Magnitude	M_w 9.0
6	Fault Source	Subduction zone between the India plate and the Burma micro plate
7	Fault length	1200-1300 km
8	Energy Released	1.13×10^{23} N-m (Joules)

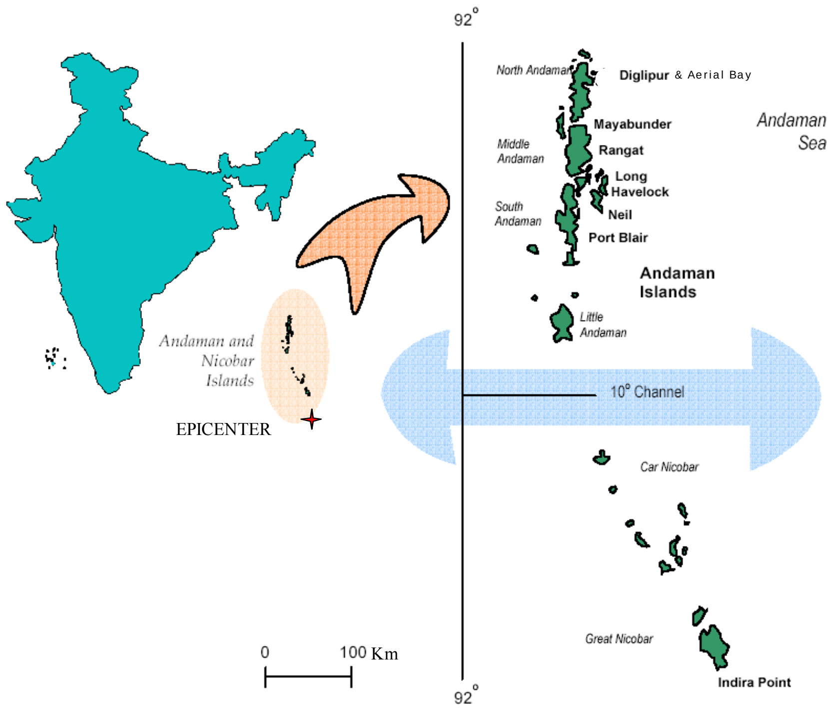

Figure 2: Index Map Of Andaman And Nicobar Islands With The Location Of Epicenter of Sumatra Earthquake of 2004 [Modified from Rai and Murthy (2003)]

Seismicity of Andaman Islands

Andaman Islands form a group of Islands on the eastern part of India about 1300 km from both Chennai and Kolkata. Together with Nicobar Islands, they form a union territory of Indian republic with Port Blair as their capital. The Andaman and Nicobar Islands consist of an archipelago of 572 Islands sprawling like an arch in the Bay of Bengal covering a distance of 700 km. The Islands are made up of tropical forest and rich natural vegetation. A low range of hills and valleys characterizes the topography of Andaman Islands. They possess the tropical wet, warm and humid climate with an average rainfall of 3000 mm per year. Four major habitant Islands along with many smaller and farther ones form Andaman Islands. The major Islands are North Andaman Island, Middle Andaman Island, South Andaman Island and Little Andaman Island. Port Blair is situated on the south east of South Andaman Island. The main trades of Andaman Islands are tourism and fisheries. The Islands maintain rich scenic beauty and a lot of greenery and forest. Figure 2 presents the map of Andaman Islands along with the Nicobar group to the south east of the main land India.

Seismicity in Andaman Islands is not uncommon. It is grouped in Zone V according to the seismic zonation of India by the bureau of Indian Standards based on the seismic activity. Zone V forms the seismically most active zone which may be subjected to a shaking of earthquake intensity VII and above on Modified Mercallis Scale. In fact, from plate tectonic considerations, these Islands are situated on a small tectonic plate called Burma plate which is sandwiched between the Eurasian plate in the north and east and Indo-Australian plate in the south and west. The Indo-Australian plate is moving at around 8 cm per year in North-East direction. It subducts below the Burma plate (at Sunda trench) causing regular seismic activity in the region. Many large magnitude earthquakes have stuck the region in the recent past. Table 2 provides some of the historic earthquakes that hit the Andaman and Nicobar Islands during the last 125 years.

Table 2: Seismic Activities in Andaman and Nicobar Islands since 1881

DATE	Magnitude	Location	Remarks
31 Dec 1881	M_w 7.9	9.5° N of Car Nicobar	Based on recent study
16 Nov 1914	M_s 7.2	12.00° N 94.00° E	SW of Barren Island
28 Jun 1925	-	10.20° N 92.80° E	SE of Little Andaman Island
19 May 1928	M_s 6.2	13.00° N 93.00° E	-
01 Aug 1929	M_s 6.5	12.00° N 95.50° E	Andaman Sea ESE of Barren Island
09 Dec 1929	M_s 6.7	04.50° N 94.50° E	SE of Great Nicobar Island
19 Mar 1936	M_s 6.5	10.50° N 92.50° E	Little Andaman Island
14 Sep 1939	M_s 6.0	11.50° N 95.00° E	SE of Barren Island
26 Jun 1941	M_w 7.7	12.50° N 92.50° E	W of middle Andaman Island
14 Jul 1941	M_s 6.0	12.40° N 92.50° E	-
09 Aug 1941	M_s 6.0	12.40° N 92.50° E	-
08 Aug 1945	M_s 6.7	11.00° N 92.50° E	N of Little Andaman Island
23 Jan 1949	M_s 7.2	09.50° N 94.50° E	E of Car Nicobar Island
17 May 1955	M_s 7.2	07.00° N 94.00° E	Off E coast of great Nicobar Islands
18 Jun 1957	M_s 6.5	14.00° N 96.00° E	ENE of Narcodam Island
16 Nov 1962	M_s 6.1	13.50° N 93.20° E	-
14 Feb 1967	M_s 6.8	13.70° N 96.50° E	Andaman Sea W of Mergui Archipliago
20 Jan 1982	M_w 6.2	06.95° N 94.00° E	Great Nicobar Islands E of Benanga
20 Jan 1982	M_w 6.1	07.12° N 93.90° E	Great Nicobar Islands SE of Leful
23 Jan 1983	M_w 6.1	12.91° N 93.59° E	-
14 Sep 2002	M_w 6.5	13.10° N 93.10° E	SSE of Diglipur, North Andaman
26 Dec 2004	M_w 9.4	03.30° N 96.00° E	Off W Coast of Northern Sumatra
28 Mar 2005	M_w 8.7	02.10° N 97.00° E	Nias Region in Northern Sumatra

Ground Motion Recordings

The Sumatra earthquake caused wide spread damage to various facilities in Andaman Islands. Though Port Blair is situated at least 600 km North of the epicenter, considerable damages to buildings, air strip and some parts of high way were reported. USGS has placed the seismicity in Andaman Islands at an intensity of VII on Modified Mercalli's Scale based on the assessment of damages suffered.

Table 3: Details Of Different Attenuation Relations And The Respective Contributors

S.No	Attenuation Relation	Contributor
1	$A_{max} = 0.125 X 10^{0.602*Ijma}$	Ishimoto, M (1932)
2	$A_{max} = 0.253 X 10^{0.5*Ijma}$	Kawasumi, H (1937)
3	$A_{max} = 0.91 X 10^{0.308*Imm}$	Neumann, F (1952)
4	$Vmax = 0.31 X 10^{0.18*Imm}$	Neumann, F (1952)
5	$Log D_{max} = M – 1.73 log \Delta + 0.83$	Tanaka, T (1974)
6	$Log A_{max} = 0.74 M – 0.89 log \Delta - 2.2$	Tanaka, T (1974)
7	$Log D_{max} = M – 1.73 log \Delta - 3.17$	Kanai. K
	$Log V_{max} = 0.61 M – 1.73 log \Delta - 0.67$	Kanai. K
8	$Log (0.001A_{max}) = 0.01*(\Delta + 50)(-4.93+0.89M-0.043M^2)$	Kinugawa (1979)
9	$Ln (0.001A_{max}) = -4.141+0.868 M -1.09 ln (\Delta + 0.0606e^{0.7M})$	Campbell (1981)
10	$Ln\ 0.001A_{max} = -3.512 + 0.904\ Mw – 1.328\ ln\ sqrt(\Delta^2+(0.149e^{0.647Mw})^2) + (1.125 – 0.112\ ln\ \Delta – 0.0957Mw)*F + (0.44-0.171\ ln\ \Delta) * S_{SR} + 0.405 – 0.222\ ln\ \Delta) S_{HR}$ In soft rock, $S_{SR} = 1$, $S_{HR} = 0$, In hard rock, $S_{SR} = 0$, $S_{HR} = 1$, In alluvium, $S_{SR} = 0$, $S_{HR} = 0$ F = 0 for strike slip normal fault,F = 1 for reverse fault	Campbell & Bozorgnia (1994)
11	$Log\ 0.001A_{max} = b_1 + b_2 (M – 6) + b_3 (M – 6)^2 + b_4\Delta + b_5 log \Delta + b_6G_B + b_7G_C$	Boore et al. (1993)
12	$Ln\ 0.001A_{max} = 2.20 + 0.81 (M – 6) – 1.27 ln \Delta_m$	Toro et al. (1994)
13	$Ln\ 0.001A_{max} = 19.16 + 1.045 M_w – 4.738ln(R+205.5e^{0.0968Mw}) + 0.54 Z$	Youngs et al. (1988)
14	$LogV_{max} =j_1 + j_2 (M – 6) + j_3 (M – 6)^2 + j_4 log \Delta + j_5\Delta + j_6$	Joyner & Boore (1988)

Unfortunately, strong motion accelerograph recordings of the ground motion during the Sumatra earthquake were not available to the authors. Hence the empirical relations are used to roughly assess the approximate ground motion suffered at different sites during the Sumatra earthquake. It is based on the evaluation of attenuation of ground motion with distance, magnitude of shaking, local geology and geotechnical aspects. Table 3 provides a list of empirical relationships available to estimate the ground motion parameters such as maximum acceleration, maximum velocity etc. based on the characteristics of the earthquake and geological aspects of the region. In the above table, care has been taken to compile all the data available in literature (Kanai, 1983, Okamaoto, 1984 and Kramer, 1993) and the variables are expressed in consistent units. However, some equations are applicable for near earthquakes ($\Delta < 50$ km) and some can cater to earthquakes with epicentral distance up to 500 km. Here, M stands for the magnitude of earthquake in Richter Scale. Wherever, moment magnitude is used specifically, it is represented as M_w. A_{max} stands for maximum acceleration in gals (cm/s^2), V_{max} stands of maximum velocity in cm/s and D_{max} stands for maximum displacement in cm. I_{mm} and I_{jma} stand for intensity of earthquake in modified mercalli's and JMA scales respectively. The relation between I_{mm} and I_{jma} is given by the empirical equation

$$I_{mm} = 0.5 + 1.5 * I_{jma}$$

Table 4: Estimated Ground motion parameters for sites in Andaman Islands during the Sumatra Earthquake of 2004

Sl No	Method	A_{max} (cm/s^2)	V_{max} (cm/s)	D_{max} (cm)
1	Ishimoto, M (1932)	128		
2	Kawasumi, H (1937)	80		
3	Neumann, F (1952)	130	5.64	
4	-	50 - 200		
5	Tanaka, T (1974)	192	-	26.6
6	Kanai. K	-	1.81	26.5
7	Kinugawa (1979)	43		
8	Campbell (1981)	48		
9	Campbell & Bozorgnia (1994)	30		
10	Boore et al. (1993)	33		
11	Toro et al. (1994)	15		
12	Youngs et al. (1988)	14.4		
13	Joyner & Boore (1988)		4.65	

The equations in Table 3 are used to establish the probable intensity of shaking that the sites in Andaman Islands were subjected to during the Sumatra earthquake of 2004. In the absence of available ground motion, these estimated parameters provide useful design details. Considering the fact that the Andaman Islands are situated at around 600 km from the epicenter of the earthquake, the following input data were used. $I_{mm} = 7$, $I_{jma} = 5$, $M = M_w = 9.4$ and $\Delta = 600$ km. As the analysis was made for the ground motion on alluvium, SSR = SHR = 0 were used. For strike slip normal fault F = 0 was considered. Table 4 provides the numerical values of ground motion parameters estimated from the magnitude, intensity and epicentral distance of earthquake.

Based on the response from the above table, a reasonable estimate of the ground motion parameters experienced in Andaman Islands during the Sumatra earthquake of 2004 was made as follows.

$A_{max} = 100\ cm/s^2$
$V_{max} = 5\ cm/s$
$D_{max} = 25\ cm$

Structural and Geotechnical Effects of Earthquake in Andaman Islands

Damages to buildings and other structures were primarily due to tsunami waves in Little Andaman and other Islands. In the present investigation, only damages caused due to ground shaking have been discussed. Many structural damages in Andaman Islands have been reported due to the Sumatra earthquake of 2004. Only few structures have been damaged due to ground shaking in north Andaman and Little Andaman. A few Reinforced Concrete buildings and concrete block masonry buildings in Port Blair have been damaged. Majority of buildings in Port Blair suffered moderate to low levels of damages. The airport building and the airstrip were affected. Port structures in various ports of these Islands also experienced some levels of damages (Prasad et al., 2005a). A number of jetties collapsed or were severely damaged in a number of Islands. Many embankments from Little Andaman Island to North Andaman Island experienced from minor to major levels of damages.

FIELD INVESTIGATION

Many embankments from Little Andaman Island to North Andaman Island experienced from minor to major levels of damages. A rockfill dam in north Andaman Island, a highway embankment for a rural road also in the same island and two earthen dams, Vishnu Nalla dam and R. K. Pura dam in Little Andaman Island suffered damages of different magnitudes and types during the Sumatra earthquake. The authors visited the above sites during April – May 2005 to assess the damages suffered by various geotechnical facilities. As mentioned earlier, the four embankment failures observed after the Sumatra earthquake are explained in the following section. The damages suffered by other structures and the detailed literature is presented elsewhere (Prasad, et. al., 2005a, 2005b and 2005c)

Kalpong Rockfill Dam

Kalpong project in North Andaman Island is the only hydro electric project in the whole of Andaman and Nicobar Islands. Otherwise the electricity in these Islands is generated by diesel power with diesel transported for 1200 km from the main land. The project was executed by National Hydro-electric power corporation along with Andaman and Nicobar administration. Available surface water resource from Kalpong river is used for the generation of power. The project possesses the live storage of 1527 Ha. M with a gross head of 161.8 m. The major components of the project include 35.4 m high concrete dam and 25 m high rockfill dam. The water from the river is transferred to the main reservoir through a link channel having a length of 248 m. An intake channel of 3 m base width will carry the design discharge to the tunnel intake structure. The depressions in the periphery of the reservoir are plugged by 90 to 100 m long rockfill saddle dykes. 1.2 m diameter, 650 m long penstock carries water to the power house situated on the right bank of Kalara Nalla. Three units of Francis turbines produce a power of 1750 kW each and the water is discharged to the tail race channel in Kalara Nalla. Figure 3 provides the schematic view of the Kalpong Hydel Project consisting of the reservoir, actual river course, the two main dams, a number of saddle dykes to maintain the capacity of reservoir, penstock layout and power house.

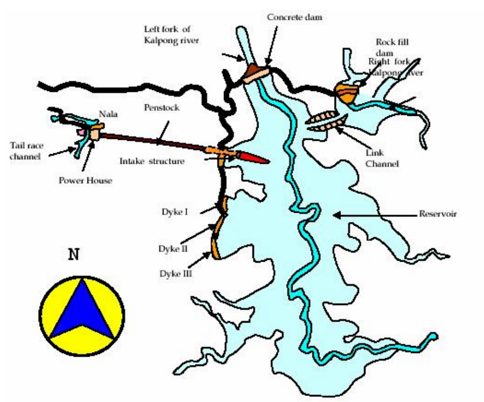

Figure 3 : Schematic view of Kalpong Hydro electric project [Reproduced from Rai and Murthy, 2002]

Figure 4 : Picturesque hill side slopes experienced slope failure

The project is recently completed and the Sumatra earthquake was the first major earthquake experienced by the structures after completion. The site is located at over 750 km from the epicenter of the earthquake. Further, considerable shaking was experienced by the people in the region. The concrete dam did not suffer any damage. However, the rockfill dams including saddle dykes suffered longitudinal cracks all along their length after the shaking. The reservoir was not full during the earthquake. Cracks were visible on the upstream slopes of the dam. Some of the natural slopes had experienced land slides and slope failure. It was difficult to establish whether the slope failures were the effect of earthquake. Figure 4 shows some of the slopes that experienced landslide and failure. It should be noted that most of these are not natural, but recently formed after the construction of the project.

Figure 5 presents the upstream slope that had a few of the revetments disturbed. Both upstream and downstream surfaces of the dam were supported by Reinforced Cement Concrete ribs around 0.6 m wide. The ribs extended in both the directions. These ribs did not suffer any damage during the earthquake. If the ribs were closely spaced and properly tied the pitching failure would have been prevented. Figure 6 shows the top view of the dam with cracks on the crest of the dam. It can be observed that the cracks continue all along the length of the dam. The power house building on the down stream experienced some structural damage. This indicates the impact of shaking even from such a far epicentral distance.

Figure 5 : Side slope of rockfill dam that experienced some disturbance

Figure 6: Longitudinal crack developed all along the length of rockfill dam

R. K. Pura Dam

Hutbay is a small town with a population of around thirteen thousand on the south eastern coast of Little Andaman Island. It has a small harbor with jetties and break waters to cater to small ships that travel to and from the port. It is perhaps the only connection to the entire Island from other places. It actually connects the Nicobar Islands from the rest of main land and Andaman Islands. Palm oil extraction and development of beetle nut industry are the main occupations of people from the Island. Though many beautiful beaches are available, tourism is not still the main occupation. Forest office, Andaman Public Works Department, Andaman and Lakshadweep Harbor Works, Hospitals are the major governmental offices in the land. The neighboring agricultural lands get irrigated by a few small dams constructed in the region. Drinking water is also supplied from the reservoirs of these dams.

A school building located on the interiors of Little Andamans about 10 km from Hutbay suffered complete collapse. The ground shaking was of such a magnitude that the building was completely brought down. As the school building is quite far from the coast and is at much higher elevations than the MSL, it was inferred that the building was not affected by the Tsunami waves. Hence, the failure of the building is solely due to earth shaking. This implies that the dynamic force of earthquake in the region was considerable.

R. K. Pura dam is situated about 15 km from Hutbay on the interiors. It is reasonably away from the sea beach, at least by around 6 km. The reservoir is always filled and over flows during the rainy season. After the earthquake, the reservoir became empty and the dam embankment was subjected to sufficient shaking. It should be noted that the region being at a higher elevation and sufficiently far from the coast, there was no effect of Tsunami and all the damages observed were due to earthquake shaking. Figure 7 presents the upstream reservoir portion of the dam after the quake. It can be seen that the reservoir is completely dry. The vertical scale in the reservoir with changes in color indicates the previous minimum level of water. The earthen embankment dam had experienced dislocation of alignment in addition to settlement, longitudinal cracks and side slope failure.

Figure 7 : Upstream of the reservoir of R. K. Pura Dam

Figure 8 : Side rails and side slope of embankment dam still in distress

Figure 8 shows some of the failures on the slope of the earthen embankment portion. The alignment and the longitudinal cracks had already been repaired by the time the authors visited the spot. It is interesting that the concrete portion of the dam consisting of the spill way was intact during the earthquake. Hence strong and stable constructions withstood the earthquake.

Some of the slopes in the neighborhood experienced slides and slope failures. It was observed that most slopes that failed were sufficiently steep. The worst effect of the earthquake had been the draining of upstream water. It is difficult to imagine whether the entire water escaped to the down stream due to the breaching of earthen embankment or the developed cracks on the floor of the reservoir absorbed the water.

Vishnu Nalla Dam

It is another small irrigation dam in the neighborhood of Hutbay. Similar to R. K. Pura dam, this dam is made of long earthen embankment and a small concrete spill way portion. It is interesting that the dam experienced similar failures as in R. K. Pura dam. Figure 9 and Figure 10 show the common distresses observed in this case. The distorted alignment of the dam, longitudinal crack at the crest of dam, settlement and uneven movement of the embankment crest, failures of side slope and horizontal cracks were the common failures observed.

Figure 9: Loss of alignment of Vishnu Nalla Dam

Figure 10: Longitudinal crack on the Vishnu Nalla earthen dam

Rural embankment road

A rural road leading to a jetty diverts from the main road between Maya Bander and Diglipur at 12 km from the Austin bridge in North Andaman Island. It is situated near Mohanpur village. About 900 m length of the road and about 150 m from the junction with the main road suffered considerable damage during the earthquake. Even four months after the earthquake, the road was not repaired and was unfit for use.

Figure 11 : Complete and close up View of Longitudinal crack along the rural embankment

Figure 11 shows the stretch of the road, which is about 3.5 m wide on an embankment that experienced a distress. The height of embankment varies from 1 to 3 m. The longitudinal crack at the middle of the road was as wide as 300 mm and extending to over 1 m depth. On either side of the embankment road, cultivable land is observed. There were horizontal cracks that developed across the road (Figure 12). The embankment was about 7 m wide and 2 m deep with a side slope of 1.5 horizontal to 1 vertical. Figure 13 provides the location and schematic view of the rural embankment. It can be seen that the rural road for a length of about 900 m has suffered severe damage. The damaged location is 150 m beyond the intersection point with the main road. The road leading to a local jetty has agricultural field on either side of the embankment. The approximate water table in the region at the time of testing was assessed to be 2.5 m below natural ground level from the observation open well available in the region. The longitudinal crack on the surface of embankment was sufficiently wide and extended to great depth.

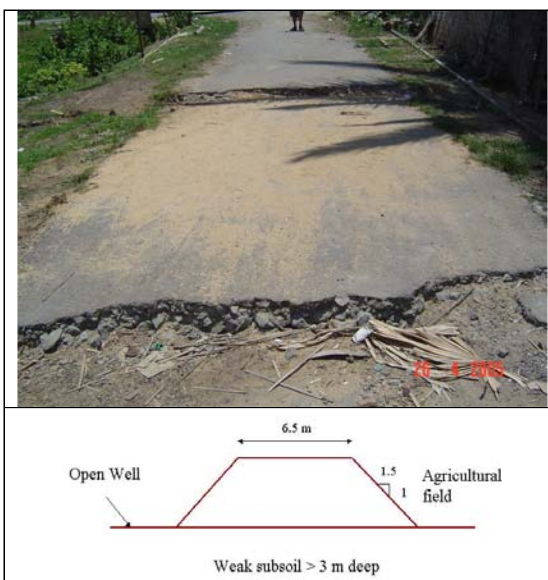

Figure 12: Horizontal cracks along the rural embankment and the Cross Section of the Embankment near Testing Site

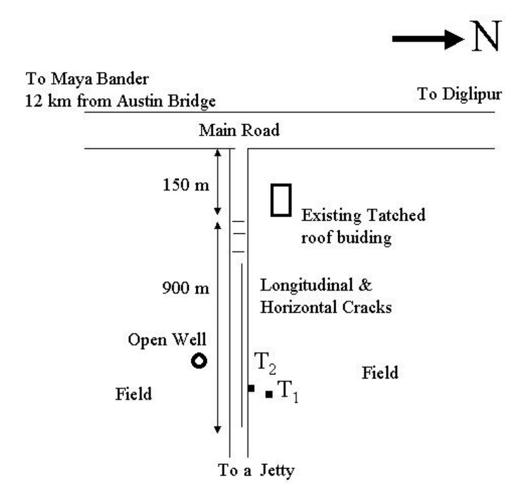

Figure 13 : Key plan showing the Road and Test locations

In order to find the probable reason for the failure, two tests were carried out to assess the strength and stiffness of the subsoil and the embankment portion using a newly developed weight sounding equipment (Prasad et al., 2005a and Prasad et al., 2005c). The tests were carried out at two locations, one away from the embankment to assess the properties of subsoil and the other on the side slope of embankment to assess the properties of embankment. An open well close to the site showed that the ground water table was at around 2.5 m below the natural ground level.

The weight sounding was carried out for a depth of 3 m in to the subsoil. As the ground was inferred to be fairly soft, the total weight placed was half of the standard weight (500 N). Figure 14 shows variation of N_{WS} (along horizontal axis) with depth below ground level (along vertical axis). N_{WS} refers to number of rotations required for 1 m penetration of the sounding rod. It can be seen that N_{WS} is sufficiently large at around 0.4 m below ground level. There after it decreases to a very low value. Even at a depth of 3 m below ground level, the number of rotations required for 200 mm penetration was less than 3 ($N_{WS} < 15$)with a weight of 500 N. The soil consisted of fine clayey silt, dark brown in colour. The approximate correlation obtained between SPT 'N' value and N_{WS} after initial calibration was $N = N_{WS}/10$, up to $N_{WS} = 100$. It is believed that the SPT N value in the subsoil at the site was therefore much lower than 5.

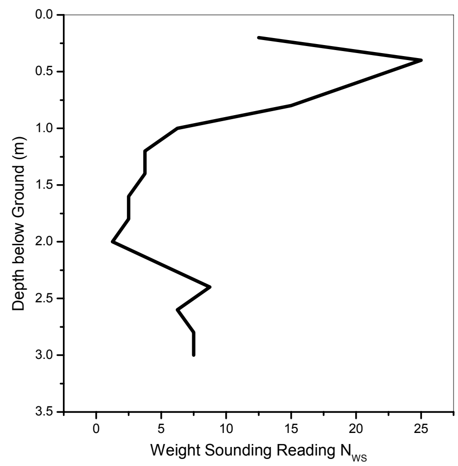

Figure 14 : Variation of Weight Sounding Number with depth for Diglipur rural road embankment

The test clearly revealed that the subsoil below the embankment was very soft and weak. It could not withstand the shaking and perhaps the ground motion was amplified causing a distress in the embankment.

SUMMARY AND CONCLUDING REMARKS

Embankments are vulnerable to earthquake loading. It is well established that the performance of embankments under any type of loading depends on the amount of compaction achieved and the type of soil used. It is also very important to ensure the quality of foundation soil. During earthquakes, strong shaking and inertial effects will reduce the strength and stiffness of both foundation soil and the embankment material. Increased strain level causes the loss of stiffness of soil. In addition, the development of excess pore water pressure in saturated loose soil will further decrease the strength and stiffness of ground due to liquefaction. Inertial effects due to the weight of material of embankment increases the dynamic stresses on the foundation soil and material of embankment. In addition, when the reservoir contains water, the hydro-static and hydro-dynamic force exerted by the reservoir water creates an additional pressure on the walls of the embankments. All these effects are responsible for the typical failures suffered by the embankments during earthquakes. The embankments studied ranged from a simple rural embankment to earthen and rockfill dams. It is important to note that the dynamic action of earthquake causes longitudinal tension along the embankment in addition to developing slope failures along the slopes. Whenever the magnitude of shaking was large, the disturbance to alignment was observed. Horizontal cracks and subsidence were the consequence of shaking. Weak and soft subsoil made the embankment very vulnerable to seismic action. It is therefore very important to construct dense and compact embankment on a good foundation soil to withstand the earthquake force. The side slopes should be stable against dynamic force. Studies on mitigation measures against the seismic failure are essential.

ACKNOWLEDGEMENTS

The authors thank Department of Science and Technology, Government of India, New Delhi for the financial assistance for carrying out a reconnaissance survey of damages to geotechnical facilities in Andaman Islands during the Sumatra earthquake of December 2004 through the project no. DST/23(518)/SU/2005. The authors are grateful for the assistance provided by the engineers from Andaman Public works Department. The authors also thank their colleagues Prof. Yadunandan C. N., Prof. Jagadeesh N. M. and Prof. Nanjundaswamy P. for being part of the research team.

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