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Seismic performance of hydropower plant and highway system during the 2015 Gorkha Earthquake in Nepal

Y. Huang[1], J. L. Liu[2]

[1] *Associate researcher, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, huangyong@iem.ac.cn*

[2] *Associate researcher, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, liuliu_jinlong@163.com*

Abstract

In 2015, the Gorkha earthquake in Nepal with the magnitude of 8.1, which is a typical mountainous earthquake, caused tremendous loss in infrastructure system. Particularly hydropower plant and highway system were damaged seriously. Geological hazards and strong ground motion are the main reasons for the damage of lifeline engineering. This paper is to discuss the damage of hydropower plant and highway system based on field investigations firstly. Then a comparison of the earthquake damage and geological disaster during Wenchuan earthquakes in China is given. Finally, some seismic countermeasures of hydropower plant and highway system in mountainous area are proposed.

Keywords: Gorkha Earthquake; damage characteristics; lifeline engineering; geological disaster; seismic countermeasures

1. Introduction

On April 25, 2015, a huge earthquake with M8.1 occurred at Gorkha in Nepal, which and its related aftershocks results numerous structures collapsed and nearly 9000 lives were lost, the economic losses estimated at several billion US dollars.

At the request of the Foreign Aid Department in Ministry of Commerce in China, Institute of Engineering Mechanics in China Earthquake Administration organized an earthquake disaster assessment team to investigate Nepal earthquake losses. The team had produced the seismic intensity map of the earthquake (Sun Baitao and Yan Peilei, 2015) according to the Chinese Seismic Intensity Scale (GB/T 17742-2008, 2008) shown in Fig. 1. As members of the team, authors conducted the seismic damage investigations on lifeline system, especially on the hydropower plant and highway system at Sindhupalchok and Rasuwa in Nepal.

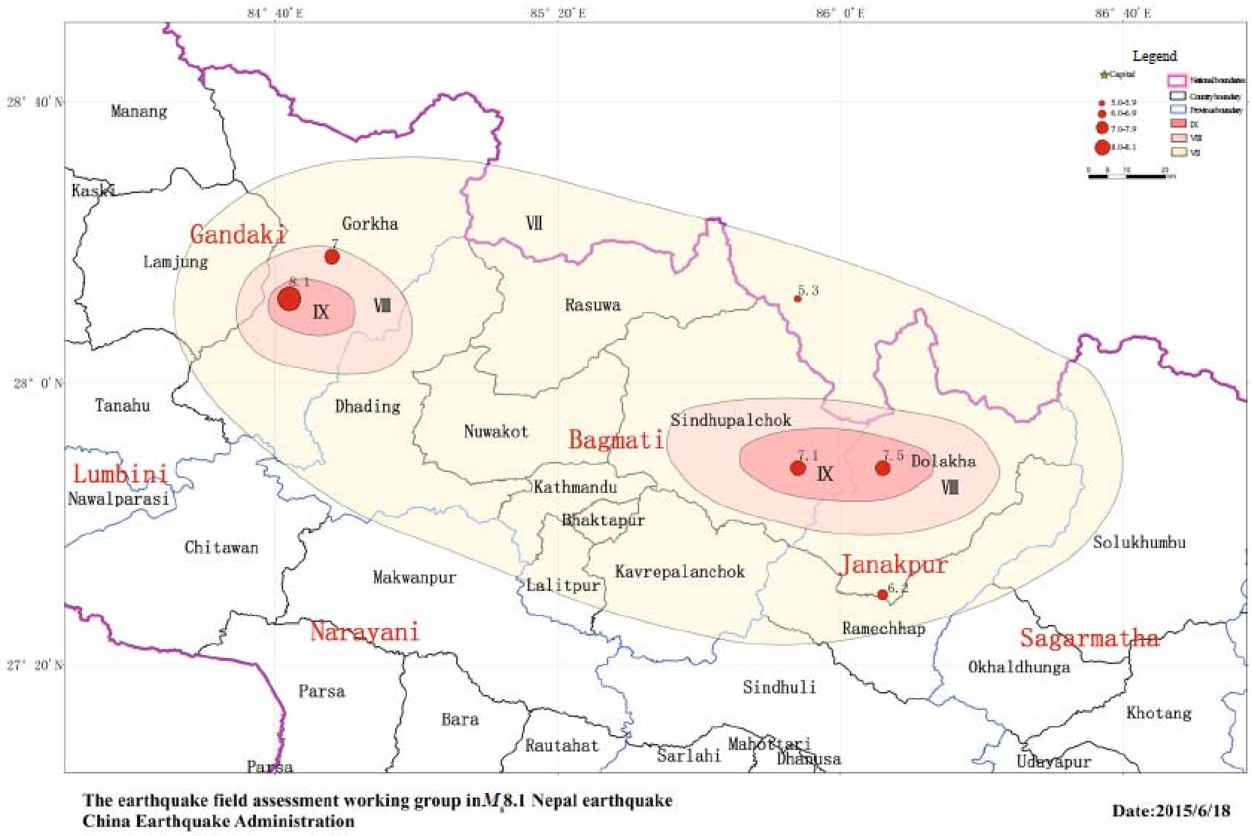

Fig. 1 – Seismic intensity map of Nepal M_s8.1 earthquake [1]

In this paper, the damage characteristics of hydropower plant and highway system during Gorkha Earthquake are discussed. With a comparison of the earthquake damage and geological disaster during Wenchuan earthquakes in China, some seismic countermeasures of hydropower plant and highway system in mountainous area are proposed.

2. Performance of hydropower plant

With its steep mountainous topography and around 6000 rivers, rivulets, and tributaries, Nepal has the world's second largest hydropower resources, with a potential to generate 42,000 MW of hydropower. Despite this huge potential, the country was producing only 800 MW through 20 major hydropower plants and a number of small micro hydropower plants before the earthquake.

The earthquake of April 25 and series of aftershocks have damaged several hydropower plants across the country, resulting to loss of 150 MW of electricity from country's power grid. There were six projects of the Nepal Hydroelectric Authority, totaling approximately 190 Megawatts (MW) of generating capacity, and 10 projects by independent power producers, totaling over 80 MW of capacity, which located in Sindhupalchok and Rasuwa, damaged. We visited projects along the Trishuli River and Pasang Lhamu Highway which mainly located in Rasuwa near the mainshock epicenter, including Chilime (22MW) and Upper Trishuli 3A (60MW). We also visited projects along the Sunkoshi River and Araniko Highway which mainly located in Sindhupalchok near the aftershock epicenter, including Upper Bhotekoshi (45MW), Sunkoshi (10.05MW), Sunkoshi Khola (2.5MW) and Jhyali Khola (2MW). Fig.2 shows the location of the visited hydropower plants.

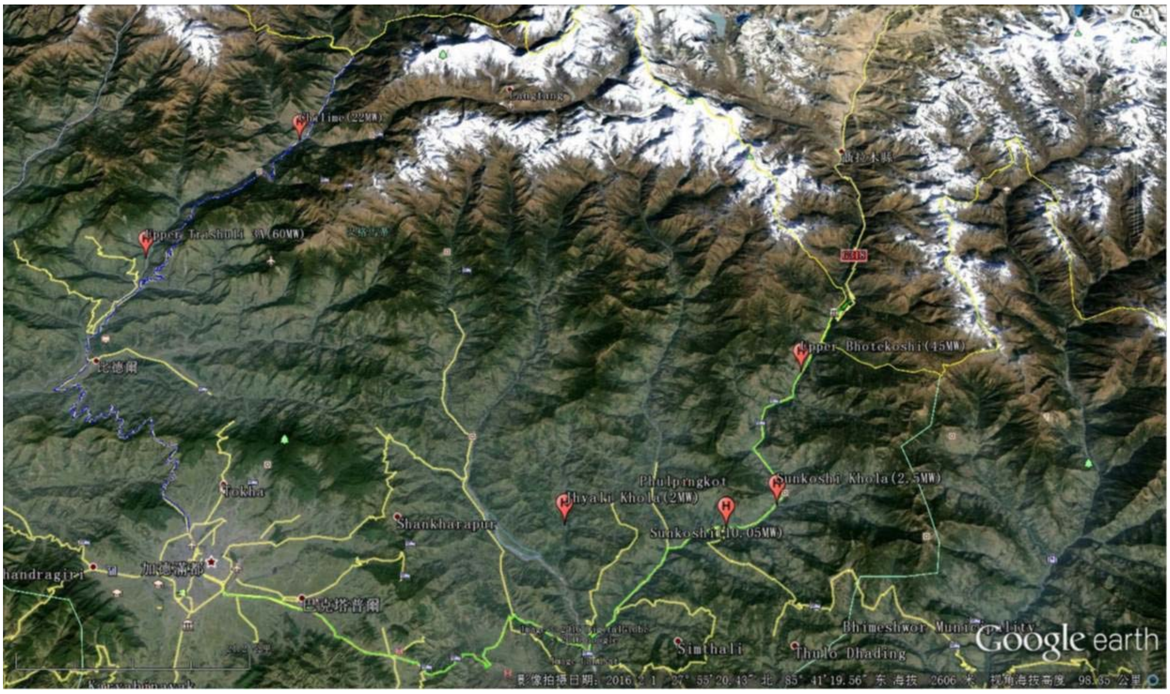

Fig. 2 – The location of the visited hydropower plants

Due to earthquake-induced landslide and strong ground motion, the hydropower plants were damaged severely. Table 1 shows the status of the visited hydropower plants. We also got some information about other hydropower projects in Sindhupalchok and Rasuwa from China Gezhouba Group Co., LTD.

Table 1 – Status of the visited hydropower plants

No.	Project	Status
1	Chilime	Damage in transmission line.
2	Upper Trishuli 3A	Severe damage in the construction works after landslide from both sides not only killed 4 employees but also buried heavy equipment; damage in the audit tunnels and a suspension bridge.
3	Upper Bhotekoshi	Penstock burst due to the landslide, power house submerged due to penstock.
4	Sunkoshi	Severe leakage in a stretch of 200 meter canal, maintenance in the headworks damaged by 2014 landslide remains incomplete; not in operation.
5	Sunkoshi Khola	Power house wall fall, equipment damaged, headwork and penstock damaged by landslide.
6	Jhyali Khola	Penstock burst, power house wall cracked.

In general, hydropower project includes structure and equipment, and the former can be classified three parts: headworks, water diversion system and powerhouse, the latter can be classified generator, transformation equipment, transmission equipment.

2.1 Damage to structure

2.1.1 Damage to headworks

During these earthquakes, the damage of headworks is mainly caused by falling rocks, and shaking from the earthquake produced some crack in the wall of structures. For Upper Trishuli 3A, infrastructure in the headworks area sustained minimal damage, with the diversion dam, sand catcher and canal structures mostly unaffected. However, two radial gates of the gate dam were damaged which cannot be opened and might lead to additional damage to the site on monsoon (Fig.3). The upstream cofferdam, stone pitching and inlet slope were damaged by falling rocks. There were obvious cracks between dam and the water inlet. Power transformer lines in the headworks area were damaged severely (Fig4). Continuous falling rocks blocked the main access road to the headworks, and damaged a 100 m suspension bridge completely.

Fig. 3 – Gate dam of Upper Trishuli 3A was damaged by falling rocks.

Fig. 4 – Cracks between dam and the water inlet, damaged power transformer lines in the headworks area.

2.1.2 Damage to water diversion system

In general, water diversion system includes diversion tunnel, surge chamber and penstock. During earthquakes, the falling rocks always damaged tunnel portal and penstock, and shaking produced some crack in the wall of surge chamber. For Upper Trishuli 3A, the diversion channel and the grit chamber were damaged by falling rocks, and their structural joint dislocated. For Upper Bhotekoshi, penstock punctured by rock fall. Mobilization of falling rock debris by water from the burst penstock created a debris flow that inundated the workers colony, scoured the penstock liner and inundated buildings and electrical equipment on the upstream side of the powerhouse (Fig.5). For Sunkoshi, severe leakage in a stretch of 200 meter canal. For Sunkoshi Khola, the canal was dry at the inspection due to penstock burst by rock fall (Fig.6).

Fig. 5 – Penstock burst blowing out powerhouse.

Fig. 6 – The canal of Sunkoshi Khola was dry.

2.1.3 Damage to powerhouse

The underground powerhouse sustained minimal damage. For example, the powerhouse of Chilime, which is underground powerhouse, was operating during the earthquake (Fig.7). On the other hand, ground power house had to face the falling rocks and shaking. As mentioned before, the powerhouse of Upper Bhotekoshi was submerged due to penstock burst, and the powerhouse of Sunkoshi Khola was damaged by strong ground motion (Fig.8).

Fig. 7 – Underground powerhouse in Chilime.

Fig. 8 – Ground powerhouse in Sunkoshi Khola.

2.2 Damage to equipment

During the earthquakes, the generator in Upper Bhotekoshi lost its function because powerhouse was submerged (Fig.9). Meanwhile, falling rocks also damaged transformation equipment and transmission equipment at switching station (Fig.10). For Chilime, transmission line were damage by shaking. For Upper Trishuli 3A, power transformer lines were damaged duo to falling rocks.

Fig. 9 – Submerged generator in Upper Bhotekoshi.

Fig. 10 – Switching station in Upper Bhotekoshi.

3. Performance of highway system

There are three types of roads across Nepal which are blacktop, gravel, and earthen roads. Nepal government classified these roads in four main categories: national highway, major and minor feeder roads, mid-hill roads, and postal roads. More than 40% of the road network is located in the central region of Nepal, where is affected by the earthquake of April 25 and series of aftershocks. The earthquakes have caused significant damage to road network of Nepal. Ministry of Physical Infrastructure and Transport has calculated the loss and damage of roads and other official infrastructures in current rates at around 23.5 million dollars based on the preliminary studies. The expected final cost for the repair and rehabilitation work for the strategic road network to be around 4.7 million dollars. Table 2 shows the earthquake damage of the highway system.

Table 2 – Earthquake damage of the highway system [6]

No.	District	Affected Highway/ Feeder Road (km)	Damage /Slide (km)	Embank ment Settleme nt(km)	Pavement damaged (km)	Retaining structures damaged (km)	Drainage Damaged (km)	Damage Value (1000NR)
1	Sindhupalc howk	105	18.95	24	22.6	22.2	23.65	1015000
2	Dolakha	101	3.15	4.8	4.7	2.35	4.3	152500
3	Nuwakot	95	0.675	0	2.95	1	0	41100
4	Rasuwa	71	0.61	0	2.25	1.21	0	47200
5	Gorkha	60.1	8.925	5.5	0.15	0.58	0	97500
6	Palpa	56.75	1.25	2	0.45	0.1	0	14000
7	Ramechhap	37.9	0.05	0.03	0.01	0.02	0.03	5000
8	Lalitpur	24	0.35	0	0	0.2	0	3700
9	Makawanp ur	22.7	0.36	0.45	0.37	0.355	0.13	13600
10	Chitawan	22	0.2	0.15	0.2	0.1	0.15	3000
11	Kathmandu	16	0.15	0.175	0.31	0.23	0	14900
12	Dhading	14	0.135	0.05	0.08	0.15	0	47000
13	Myagdi	7	4.5	1	0	0.15	0	30000
14	Kaski	4	0.03	0	0.5	0.55	0	18000

15	Lamjung	1	0	0.2	0.2	0	0	3500
16	Parbat	1	0.045	0	0.05	0.15	0	8000
17	Gulmi	0	0.5	1.2	0	0.03	0	4000
18	Shyanja	0	0.02	0	0.02	0.01	0	1500
19	Sindhuli	0	0.3	0.3	1	0.05	0	50000
20	Bhaktapur	0	0	0.41	1.1	0.37	0.35	56000
21	Kavre	0	0.03	0.1	0.03	0	0	1000
22	Tanahu	0	0	0	0.02	0.03	0	3500

We mainly visited highway system along the Pasang Lhamu Highway (F021) which was mainly located in Rasuwa, Kashmandu Ring Road (H16) which was located in Kathmandu and Araniko Highway (H03) which was mainly located in Sindhupalchok. Fig.11 shows the location of the visited roads and bridges.

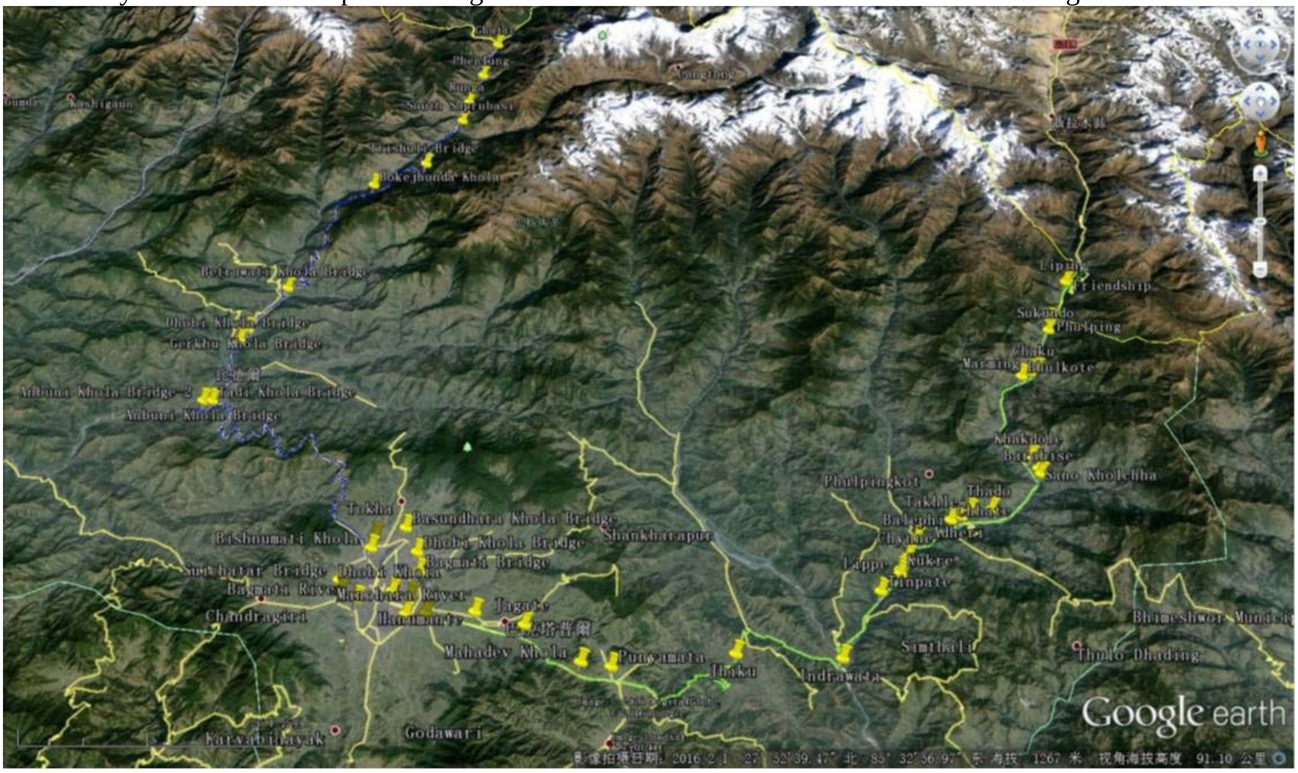

Fig.11 – The location of the visited road and bridge

3.1 Damage to highways or roads

Damage to roadways, bridges and retaining structures was also primarily related to landsliding. The greater concentration of infrastructure damage along steep hillsides, ridges and mountain peaks offers a proxy for the occurrence of topographic amplification. Falling rocks after the Gorkha earthquake and aftershocks caused interruption and damage in road network especially in Sindhupalchok and Rasuwa.

3.1.1 Damage to slope

Through visual interpretation work for high resolution satellite images, combined with field investigation, we found that the earthquake landslide damage directly 36 points on the Araniko Highway, and the total length is 1415m. The earthquake landslide damage directly 89 points on the Pasang Lhamu Highway, and the total length is 2842m. Interruptions and damage on roadways caused by the earthquake-induced landslides often can be found on the investigation road. Fig. 12 and Fig.13 shows the interruption caused by the earthquake-induced landslides on Pasang Lhamu Highway and Araniko Highway.

Fig.12 – The interruption caused by the earthquake-induced landslides on Pasang Lhamu Highway.

Fig.13 – The interruption caused by the earthquake-induced landslides on Araniko Highway.

3.1.2 Damage to subgrades

During the earthquakes, some road subgrades were subsided. For example, the Kathmandu–Bhaktapur Road of Araniko Highway was heavily damaged in the Lokanthali area (Fig.14). The subsidence of soft soil sand their lateral spreading in this area may have exacerbated the damage to this road.

Fig.14 – Slope failure and subsidence in the Lokanthali area.

3.1.3 Damage to retaining structures

There are two types of retaining walls, one is a reinforced retaining wall and the other is a gravity retaining wall. During the earthquakes, gravity retaining wall was damaged heavily by falling rocks (Fig.15) and shaking.

Fig.15 – Gravity retaining wall was damaged heavily by falling rocks.

3.2 Damage to bridges

Most of bridges performed well during the 2015 Gorkha earthquake and its aftershock sequences. We visited 7 bridges on the Pasang Lhamu Highway, 9 bridges on Kashmandu Ring Road and 22 bridges on Araniko Highway. There were three types bridge (RC girder, RC arch and steel truss) in these highways. Fig.16 shows the percent of investigation bridges and damage ratio.

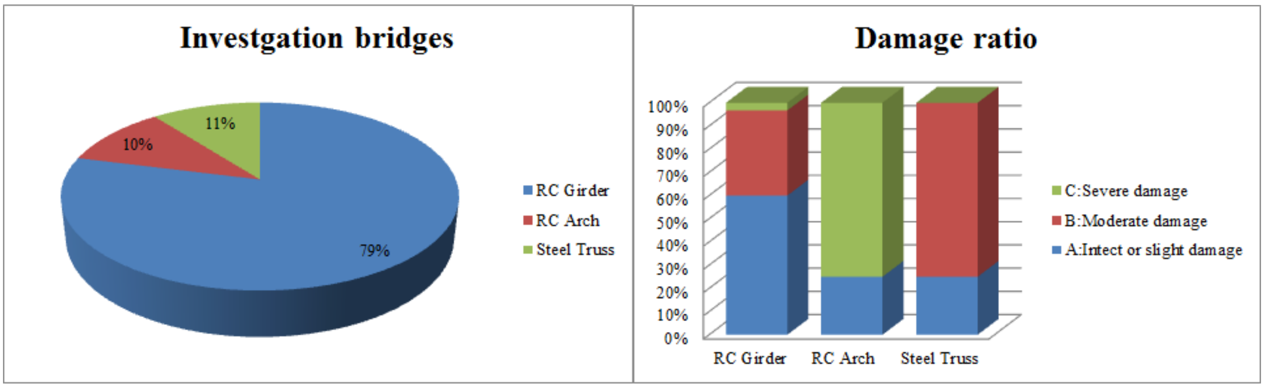

Fig.16 – Investigation bridges and damage ratio.

We can find RC Arch Bridge is one of the types which did not resist earthquakes this time. In the total four severe damaged bridges, there are three arch bridges, which built in 1960's, and located in the Arniko Highway near the Chinese Border. The damage patterns consist of inner-arch rig and sign pillar cracked due to strong shaking, bridge deck and guardrail damaged by fall rocks, taper revetment crushed. Both RC box arch bridge (Friendship Bridge and Phulping Bridge, 1*60m) and RC two-way curved arch bridge (Sukundo Bridge, 1*31.4m) was damaged severely, as shows in Fig.17 (a-c).

The other severe damaged bridge is Jilong Port Bridge which is 3*40m RC simple supported girder bridge, located in the Pasang Lhamu Highway close to the Jilong Port on the Chinese Border. The flange slab of main girder, bridge deck and guardrail were smashed by falling rocks, as show in Fig.17 (d).

Steel truss bridges performed relatively well in the earthquake affected areas, but because build in 1960's, some steel truss diagonal bracing deformed during earthquakes, steel beam and bearing corroded. Some outer wrapped concrete of piers was cracked. Show as Fig.18.

(a)Friendship Bridge (b) Phulping Bridge

(c) Sukundo Bridge (d) Jilong Port Bridge

Fig.17 – Severe damaged bridges in investigation.

Fig.18 – Moderate damaged steel truss bridges in investigation.

The RC simple supported girder bridge is the most in investigation. Although there are many multi span simple supported girder bridges in Kashmandu Ring Road, but in the Pasang Lhamu Highway and Araniko Highway, almost only are one span simple supported girder bridges except the Jilong Port Bridge and Chaku Bridge (2*22.5m). The damage patterns consist of guardrail damaged, taper revetment cracked, stopper and expansion joint damaged, drainage damaged result to water seepage.

4. Comparison with Wenchuan Earthquake

As a typical mountainous earthquake, the 2015 Gorkha earthquake and its aftershock sequences as same as the 2008 Wenchuan earthquake (M8.0), caused tremendous loss in hydropower plant and highway system. However, there are some differences in earthquake damage characteristics.

4.1 Hydropower plant

There were about 2360 hydropower plants in the Wenchuan earthquake disaster area, and about 800 hydropower plants were damaged, which include large, medium and small projects. There were dam type and diversion type two kinds development mode. But in Gorkha earthquake disaster area, there were only diversion type medium and small 25 projects affected. During the Wenchuan earthquake, for hydropower projects, we can find that the project which closed to fault or built many years ago or small scale, earthquake damage was serious, otherwise damage was slight. Main structure, underground structure and engineering slop were damaged more slightly than secondary structure, ground structure and natural slop. For equipment, geological disaster damaged more seriously than earthquake shaking. The Gorkha earthquake almost showed the similar characteristic. However, specifically in the steep, narrow upper reaches of the drainages, projects were impacted primarily by falling rocks. Roads, penstocks and secondary structures received the brunt of damage from these slope failures. In the lower reaches of the drainages, where river valleys open up and water is typically transmitted via open canals, shaking-related impacts such as settlement and structural damage to structures was more common. The geological disaster damaged more seriously than earthquake shaking.

4.2 Highways system

During the Wenchuan earthquake, for road subgrade, we can find that subgrade damage occurs mainly in digging and filling embankment and slope embankment, cutting is relatively small. Subgrade damage mainly concentrated in the mountainside line, the second is the slope toe line, minority in the ridge line. The damage of subgrade built on the soil foundation is more serious than on the rock foundation. The gravity retaining wall was damaged heavily than concrete flexibility retaining wall. Cutting retaining wall damaged more seriously than shoulder retaining wall. The Gorkha earthquake almost showed the similar characteristic. For bridges, the Wenchuan earthquake damage to the bridge is much more serious than the Gorkha earthquake. Not only strong ground motion but also falling rock damaged many bridges in Wenchuan earthquake, however during the Gorkha earthquake only a few bridges were damaged seriously by falling rocks mainly and no one was collapsed.

5. Conclusions and suggestions

The 2015 Gorkha earthquake caused widespread and catastrophic damage to hydropower projects and highways system. A 15-day field investigation was conducted by authors in the affected area. In general, most of the damage of hydropower and road observed in this survey were mainly caused by the earthquake-induced landslides. Of course, the strong ground motion also made some structures damaged. Compared with the Wenchuan Earthquake, hydropower plant performs obviously some difference damage mode between upper reaches and lower reaches, and highways damaged mainly by falling rocks.

For typical mountainous earthquake, suggestions are listed as follows:

(1) Project site should be carefully selected in order to avoid the active fault.

(2) Investigation of regional landslide, potential unstable rock mass or the mountain stability is necessary for the selection of project site.

(3) Hydropower engineering, the seismic performance of underground structure is good, while the ground buildings are vulnerable to be damaged by earthquake or geological disaster. So appropriate underground engineering should be chosen, the tunnel entrance should be construct to avoid the adverse effects of landslide, collapse, debris flow, etc.

(4) The structure which may be threatened by falling rocks, in addition to the slope surface protection should be strengthened, also should strengthen the structure of collision prevention measures to avoid the falling rocks.

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