Possibility of Induced Seismicity in Pancheshwar Dam Site on Kali River, Uttarakhand

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***Abstract*— The geomorphological and seismic evidence near NW of proposed Pancheshwar dam site on Kali River in Kumaun Lesser Himalaya suggests influence of neotectonics along imbricated zone of high-angle North Almora Thrust (NAT) dipping towards SW. The NAT zone represents the deformed northern margin of Almora nappe. It separates the granite gneisses of Almora crystallines from the quartzites and slates of Lesser Himalayan sequence. The region shows earthquakes swarm with strongest event of M=6-7.5 in the years of 1966 and 1974. The seismisity of M≥ 3.5 is being continuously recorded till very recently. The region has not experienced any major earthquake since 1974. A prominent seismically active linear segment is noticed near NW of study area. The mass of 315m high water column of the future dam-reservoir may transmit the stress into the subsurface rocks that are characerized by occurrence of duplex structures bounded by multiple discrete shears. The chlrorite-sericite schist developed within shear zones may accommodate the on-going convergence of Indian plate towards Himalaya in the form of shear strain in the subsurface region. This accumulated strain may cause gravity collapse along steeply dipping shear planes. Thus the reservoir-induced seismicity may be one of the consequences of active deformation prevailing in the region.**

Keywords—: Pancheshwar, Neotectonics, Earthquakes, Kumaun Himalaya.

INTRODUCTION

The inter-continental collision of the Indian and Eurasian plates, onset at ~ 55 Ma, gave rise to the still evolving Himalayan fold- and thrust-belt 1, 2 and 3. The northward convergence of Indian plate towards the Himalaya has resulted the crustal shortening of the northern margin of the Indian continent; the deformation is being accommodated by south verging thrusts [4], [5]. In the Himalayan foreland propagation thrust system, the Main Central Thrust (MCT), Main Boundary Thrust and Himalayan Frontal Thrust descending in their ages are continuously shallowing towards south (Fig. 1a). This suggests southward migration of the main Himalayan deformation front [6], [7]. In the Himalaya the seismicity could be resulted due to movement of a mega crustal-scale fault-bend fold towards southward at a rate of 15mm/yr above the mid-crustal ramp 8 that lies beneath the Higher Himalaya 9.

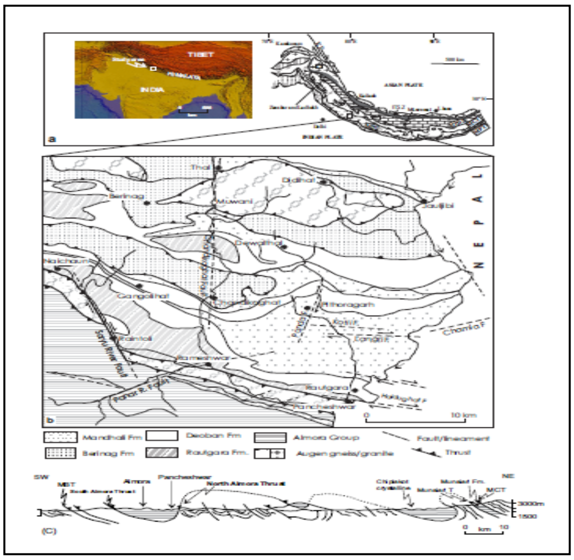

Fig.1. (a) Study area with structural features (b) geological map of the study area and (c) simplified geological cross section across the Lesser Himalaya.

The fault plane solution data suggest that the detachment-flat south of the Higher Himalaya dips 60±30N, whereas the mid-crustal ramp (dipping 15°N) coincides with a bend of high seismicity[10],[7].

The Almora Nappe represents a large thrust sheet now disconnected from its root zone, which lies in the north and is known as the Munsiari Formation, along with a number of klippen resting over the Lesser Himalayan sequence [11] [12], [13] .

The study area is dissected by the E-W trending North Almora Thrust (NAT), Haldughat Fault, NE-SW trending Panar Fault, E-W trending Kotli Fault, NW-SE trending Saryu River Fault (SRF), N-S trending Chandikaghat Fault, and NE-SW trending Panda Fault. The NAT and South Almora Thrust (SAT) are two major thrusts delimiting the northern and southern boundaries of the Almora nappe (Figs. 1b & 2b). The lithotectonic setting of the Kumaun Lesser Himalaya is characterized by occurrence of duplex structures [12], [13] [14], [15] [5], [7].

The proposed Pancheshwar Dam site is situated ($20^0$26'708" N Latitude and $80^0$14'517" E Longitude) on the Kali River in the eastern Kumaun Himalaya (Fig. 1a). The geoloical conditions of the Pancheshwar dam site are almost similar to that of the Tehri dam, which is build on the confluence of the Bhagirathi and Bhillangana rivers. The Srinagar Thrust (equivalent to NAT) and Tons Thrust are located in Tehri area (Fig. 2a). The regional scale NAT marks the boudary between the inner and outer Lesser Himalaya. Both dam sites are located on the steeply dipping northern limbs of major synclines (Fig. 1c). The area around the Tehri is characterized by occurrence of major and minor earthquakes in recent past [16]. Their fault plane solution data suggest that the strong events are related to thrust and few are associated with normal faults. The microseismicity occurring around Tehri area is associated with strike-slip tectonic environments [19], [18].

The Koyna dam in India and Hsinfengkiang dam in China have failed due to reservoir-induced seismic events [10]. The numbers of instances of reservoir-induced earthquakes are large enough to be potentially damaging, and only four induced events have exceeded magnitude 5.7. These are Hsinfengkiang, in China, (1962, M = 6.1); Kariba, Rhodesia-Zambia, (1963, M = 5.8); Kremasta, Greece, (1966, M = 6.3); and Koyna, India (M = 6.5) [19], [20]. These earthquakes were associated with reservoirs with water depths exceeding 80 m - 92 m.

Below the Himalaya the basal detachment surface is interpreted to have locked and this ~ 100 km wide zone, between the foothills and Higher Himalaya, is building up a slip deficit at a rate of 14 ± 1 mm/yr and will eventually fail in future great earthquakes [19]. Moreover, the spatial distribution and time sequence of the two moderate earthquake events of 1991, Uttarkashi earthquake and 1999, Chamoli earthquake suggest that the recent seismicity trend has shifted from west to east direction within short recurrence interval of eight years. The latter event falls towards northwest of the present study area. Therefore the present study is aimed to understand the present status of neotectonics near northwest of the proposed Pancheshwar dam site.

METHODOLOGY

The status of neotectonics near NW of dam site is studied by using geomorphic and seismic criteria. The paper highlights the geological reasons of active tectonics and its consequences. The Digital Elevation Model (DEM) data are used to understand landscape patterns and mapping of geomorphic features, delineation of lineaments and drainage pattern of the study area (Fig. 2a).

LINEAMENTS

The major linear tectonic lineament is the ESE-WNW trending NAT. Others lineaments are subparallel to oblique to the NAT. The eastern limit of the Kumaun Himalaya is dominated by two dominant sets of transverse faults; one is trending NE-SW and other one NNW-SSE (Fig. 2a).

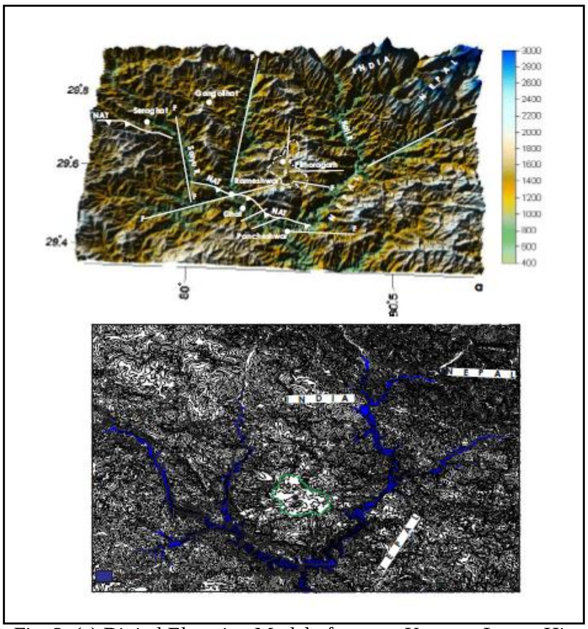

Fig. 2. (a) Digital Elevation Model of eastern Kumaun Lesser Himalaya showing development of geomorphic features and traces of North Almora Thrust, (b) contour map showing fault/lineament and reservoir area of Pancheshwar dam.

Near west of the Pancheshwar, the Saryu River follows the major NNW-SSE trending dextral SRF. The movement along this fault has given rise widening of Saryu river course [17]. In the Makaraun-Kakrighat-Rameshwar section the NE-SW trending Panar River River (PRF) passes across the NAT.

The movement along this fault tilted the Dabaula terraces towards SE. The principal lineaments show a NNW-SSE trend. The trends of lineaments around Pancheshwar are NW-SE and NNW–SSE, which control the NNW-SSE flowing Kheti Gad. The major lineament along the Pirnali gad shows a NNE-SSW trend. The lineaments trending NE-SW and NW-SE have controlled the river profile at Amer and Gherla gads (local name for canyon).

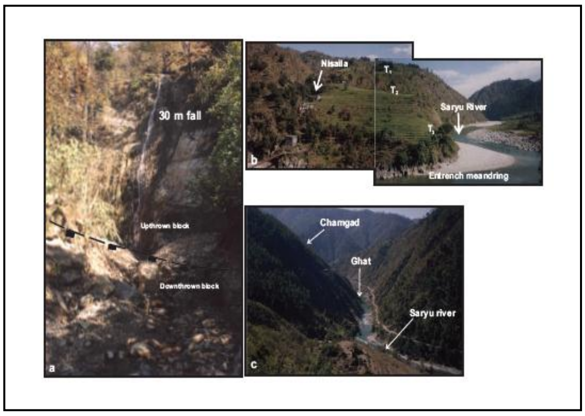

Fig. 3: Upthrown block side of NAT (a) normal fault, (b) three levels of strath terraces at Nisaila with incision and entrenchment of river valley, (c) Saryu river flow through gorge in thrust zone at Ghat.

The Amer gad is marked by a deep gorge and straight valley; so that the tectonic activity of the Amer Gad is controlled by NE-SW trending lineament. Near Pancheshwar the southward flow of Kali River turns toward west and deepening of the river valleyr near Haldughat area along the E-W trending dextrial strike-slip fault is observed. North of Pancheshwar 50^0S hading fault scarp has developed along the E-W trending Kotli Fault. The upliftment along the fault has blocked the south-flowing stream Thuli gad. The NNE-SSW trending fault passing from Panda area resulted ponding in Raie area and development of vertical scarp. Hence the dominance of NNW-SSE and NE-SW trends of faults and lineaments in the eastern Kumaun has been responsible for development of tectonic geomorphic landscapes in this region**.**

GEOMORPHOLOGY OF DAM SITE

The Pancheshwar-Seri section of the NATZ lies in the eastern most India territory of the Kumaun Lesser Himalaya. The area, bounded by the $29^0$18'40"- $29^0$26'708" N Latitude and $80^0$01'60"- $80^0$14'517" E Longitude, is drained by wide Saryu valley with development of gorge at Ghat; this suggests rapid river incision rate. The earlier course of Saryu river has shifted laterally from south facing hill slopes towards southward, and now flowing through Ghat. The geomorphological developments in this section have been studied with the help of DEM and later by field check (Fig. 2a). Five levels of fluvial terraces have developed at Pancheshwar area with elevation differences of 7, 5, 17, 28 and 15m from riverbed along the Kali River valley. It implies five pulses of uplift in the Quaternary period along the NATZ. The terraces are mainly composed of pebbles of 40% granite gneiss of the Saryu Formation, 40% quartzite of the Rautgara Formation, 10% slate of the Rautgara Formation, and 10% other rock fragments, with sandy matrix. The recent tectonic activity is marked by >5km displacement along E-W trending dextral strike-slip fault between Haldu and Pancheshwar. (Fig. 1b). The southward flowing Kali River has been shifted towards

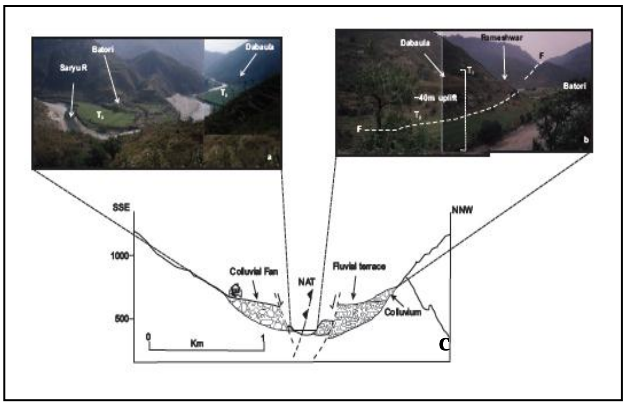

Fig. 4: (a) Truncation of the landslide debris cone at Batori, (b) Uplifted terrace profiles at Batori-Dabula near Rameshwar and (c) Cross section showing valley and terrace relationship.

west along the strike-slip Haldu Fault. Near the fault zone the river Kali become narrower and takes 90^0 turn with large entrenchment and then flows towards SW (Fig. 3c). The vertical uplift has resulted development of straight course and gullies in the upper part of Thalkedar range and entrenched deep canyon course with convex walls of the north flowing Gheria, Amer and Pundia streams south of the Saryu river. In NAT zone before confluence of Kali River with Thuligad the latter stream has developed deep gorge, which also indicate rapid rate of incision. Between Pancheshwar and Cham Gad the Saryu river has a wide and almost straight course as it follows along the NAT and takes almost 90^0 turn around Nisaila followed upward by entrenched-meandering till Ghat. The uplift along the NAT has also caused mass movement in the form of large landslides between Nisaila-Ghat. On the up thrown block, the ~30m fall of Simila Gad and ~15m fall 35 of Khati gad are noticed in the NAT zone.

SEISMICITY PATTERN

In the Himalayan region the seismicity is focused along the detachment surface 31 and the Kumaun Lesser Himalaya is seismically active [3], [4] [5]. In between the MCT and MBT more than 100 events have been located since 1999-2005. The fault plane solutions suggest the fault passing from northeastern limit of the Kumaun

Himalaya is releasing accumulated stressing the form of earthquake [13], [17] [18]. The present work has been concentrated only along the NATZ where ~30 micro earthquakes (M<3) have been recorded from 1999 to 2000 (Fig. 5a).

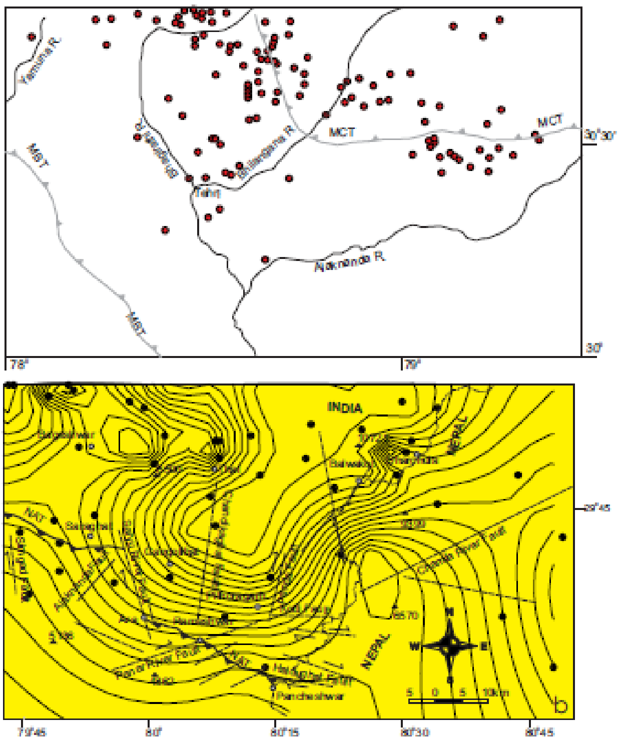

Fig. 5: (a) Tectonic map of Kumaun Himalaya showing hypothetical seismic contouring and epicentral location.(b) seismotectonic map shows transverse faults across the eastern limit is seismically more active.

The majority of seismic events generally of low magnitude with focal depth of 10-30 km are located in the area bounded by the MCT and NAT (Fig. 7a). This suggests that moderate to low intensity earthquakes dominate in the strain building process. These events are of magnitude ≥ 0.3, whereas few minor events were also recorded with M ≤ 1.5 and 1.5-0.3. The contour diagram of focal depth of earthquakes of M 1.5 to 3.0 across the NAT and Kali valley shows NE-SW trend, which is transverse to the trace of the NAT (Fig. 7b). However, towards Thal-Bageshwar area this trend becomes parallel to the NAT. Particularly across the NAT >30 events were recorded with M ≥ 0.3, and ~ 20 minor events with M ≤ 1.5 and the stress drop value of these events are very low. The strain building process is going beneath the Lesser Himalayan domain and it could be indicative of possible major earthquake in the future.

WATERSHED MORPHOMETRY

Drainage basin morphometry of the Kali and Saryu rivers were carried out by using SRTM 90m and 1:250,000-scaled maps. These rivers cover total drainage basin area 2,520.5324 km2. The watershed catchment area of the Kali River in India is 1338.33 km2 whereas it is 153.0975 km2 only in Nepal. The marked difference in areas suggests the basin asymmetry across the Kali River. This might reflect the neotectonic activity of the region. The total catchment area of the Saryu river is 1029.105 km2 with different environmental factors (Fig. 8). The proposed dam height is 315 m and the area likely to be submerged by the reservoir will be ~120 km2 in India (Fig. 4b) and ~14 km2 in Nepal (data source uswatrnews@aol.com).

DISCUSSION AND CONCLUSIONS

The GPS study reveals that much of the surface deformation is localized in the Lesser Himalayan region located south of the MCT. One prominent ESE-WNW trending linear seismically active segment has been demarcated south of the MCT. It suggests that the maximum epicenters of seismicity is localized in the region between the MCT and MBT where dam site likely to be located. The mass of 315m high future water column of reservoir may transmit the stress into the subsurface rocks characterized by multiple brittle shear zones and normal faults. The schistose rocks developed within shear zones may serve as the zones of accommodation of shear strain. The depth of basal detachment below the Almora nappe is ~15 km 28 (Fig. 1c). Thus the hinge zone of synclinal part of the folded NAT and SAT might be located ~12 km above the basal detachment. The sub-surface region below the plane connecting the NAT and SAT in the Lesser Himalaya is characterized by occurrence of duplex structures. Thus the tectonic planes bounding the horses of the Lesser Himalayan duplex system may witness reactivation due to converging Indian plate at a faster rate of 15-20 mm/year in the Himalayan region.

In the Pancheshwar area the maximum neotectonic activity is noticed due to the strike-slip and oblique-slip faulting along the NATZ and associated transverse and oblique fault system (Fig. 7b). The recent reactivation of these faults has been responsible for development of tectonically induced landforms. Within a short period of eight years the recent seismicity trend has shifted from west (1991, Uttarkashi earthquake) to east (1999, Chamoli earthquake). Latter event falls towards northwest of the NAT. The eight years (1991-1999) of recurrence interval of earthquake events implies that rate of accumulation of subsurface strain was fast in the region south of the Munsiari Thrust. Now eight years have spent after 1999 Chamoli event. If west to east shifting trend of earthquakes is assumed to be continued in the future also then the similar earthquake epicenter can hypothetically be expected towards NW of Pancheshwar, where a prominent E-W trending seismically active linear segment with cluster of >50 epicenters of micro earthquakes falls (Fig. 1).

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