Earthquakes in Nanga Parbat area, North Pakistan: Causes and concerns with particular reference to Basha Dam

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ABSTRACT: *In November 2002, two powerful earthquakes (magnitude 5.5 & 6.4 on Richter scale) and subsequent aftershocks rocked the Nanga Parbat area of north Pakistan. Even though the tremors were felt as far south as Peshawar and Islamabad the intensity of damage to the life and property remained within 10-15 km radius of the epicenters. The damage included: 34 people dead, 140 seriously injured, ~1200 houses flattened, many bridges and tens of kilometers of road lost to the ensuing landslides.*

The epicenters of these quakes were located within the Raikot fault zone. This is an active fault with dominantly northwestward-directed thrust and minor right-lateral strike slip motion. These earthquakes did not open any new fissures or cracks with substantial slip on them. However, few boulders within the fault zone did develop cracks but it was not possible to ascertain whether these were developed by motion on the fault or by landsliding. The other geological features clearly associated with these quakes included landsliding, rock fall, liquefaction and soil creep. No evidence of any volcanic activity, as feared by the local people, was found.

The tectonic setting of the area is such that the earthquake hazard will remain in future. It is imperative that planners fully evaluate the risk potentials of this area before embarking on any mega engineering project e.g. Basha Dam. The same 'threat' has already caused extensive damage to the life and the Karakorum Highway, not to mention the monetary bill, which runs into millions.

INTRODUCTION

On November 02, 2002 at 3:09 am, a powerful earthquake that measured 5.5 on Richter scale rocked the Nanga Parbat area in Diamer District, north Pakistan. The epicenter was located at 35° 20′ 53″ N, 74° 35′ 35″ E, which corresponds to an unnamed site on the right lateral moraine of the Raikot Glacier at an altitude of 4000 meters above sea level (Fig. 1). In just 19 days an even stronger earthquake that measured 6.4 on Richter scale (USGS web site) jolted the area again. This time the epicenter was located at 35° 31′ 48″ N, 74° 37′ 35″ E which falls just north of the Lichar village (Fig. 1). As the relief work entered its 12th week and the memory of horror started to wane the area was once again struck by an earthquake of magnitude 5.2 compounding the miseries and fear of the local people.

All of these earthquakes originated within the Nanga Parbat Massif (NPM) and the ensuing destruction were localized. Since the area in question (i.e.

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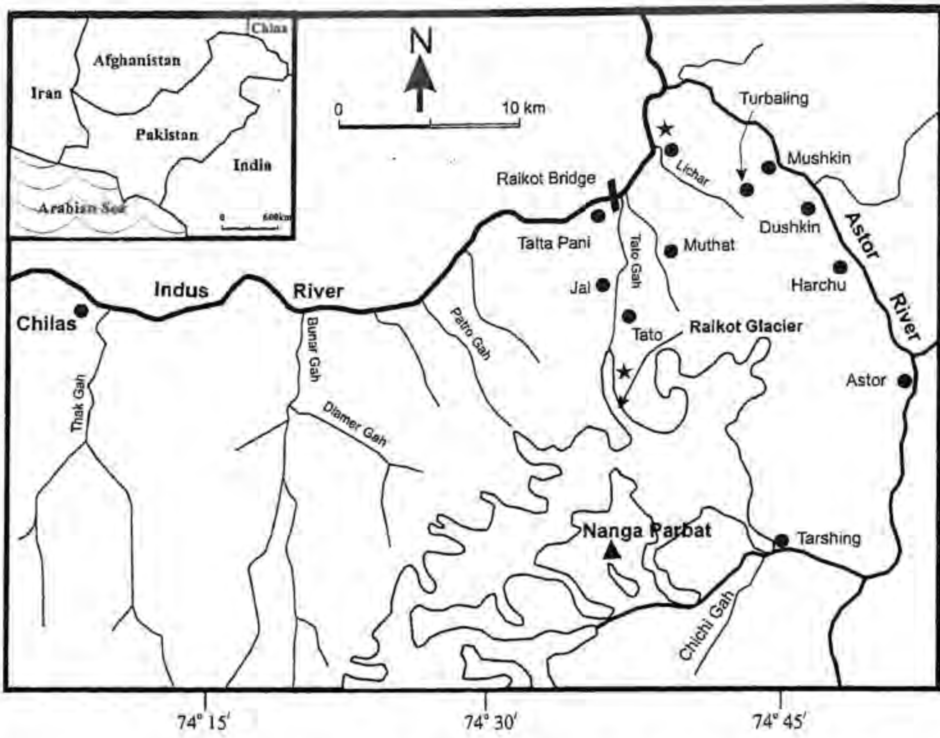


Fig. 1. Location map of Nanga Parbat area. Star identifies the location of epicenter.

Diamer district) is economically and strategically very important, it is imperative that we understand the causes of these earthquakes and be fully aware of the associated devastative potentials.

In the midst of the tremors, the authors visited the area to assess damages and study the geological manifestations of these earthquakes. This paper describes our observations and discusses the causes and concerns associated with these earthquakes. In particular we address the effects of these earthquakes on mega projects e.g. Basha Dam and Karakorum Highway.

DAMAGES

Even though these earthquakes were felt as far as Peshawar, Islamabad and Srinagar, the damage to the life and property was restricted to the immediate vicinity of the epicentral tract in the Nanga Parbat area. Direct damages included complete or partial collapse of masonry structures, disruption of civil engineering structures, wide spread landsliding (Fig. 2a), rock and debris fall (Fig. 2b), localized liquefaction and disruption of communication and waterways. Indirect damages were predominantly caused by the ensuing landsliding and rock fall. These included loss of scanty but fertile agricultural land, damage to water storages and pipes, disruption of telephone and electricity lines and disorder of relief work by aftershocks and loss of roads and bridges. The relief work further slowed down as the visibility was reduced to less than 35 meters by dust clouds generated by landsliding. The psychological effects (fear, panic, disorder) were growing with each aftershock and worsening weather conditions. People were sleeping outdoors in snow and below freezing temperatures.

The first earthquake (Nov. 2nd, 5.5M) caused major damage in Muthat, Tato, Raikot, Jal and Tatta

Pani villages. According to UNICEF estimate (the News, Nov. 19, 2002), 11 people were killed, more than 40 seriously injured, over 4000 became homeless, several missing, and hundreds of cattle heads were killed. The first fatality occurred when 4 passengers alighted the bus they were traveling in to clear the rockfall on Karakorum Highway (KKH) when another landslide occurred and swept away one passenger into the Indus River and injured the other three. Aftershocks continued for the next three weeks with six aftershocks measuring more than 4.0 on Richter scale occurring within 48 hours of the main shock. It was one of the aftershock (M 5.3) that killed 10 more people and seriously injured another 30, and initiated wide spread landsliding blocking the KKH and hindering the relief work for weeks. In fact the authors witnessed several aftershocks and subsequent landsliding at the time of the present investigation. Damage to the masonry structure was limited to the collapse of few boundary walls and partial collapse of roofs (Fig. 2c). Dislodging of plaster and development of cracks in walls and plasters of few houses was commonly observed.

The November 21st earthquake was more severe (6.4 M) and damaging. Pakistan Seismological Department in Peshawar recorded a total of 53 aftershocks since the first major earthquake within the month of November. Most of the devastation occurred in Mushkin, Dushkin, Turbaling, and Harchu villages (Fig. 1). At least 23 people were killed, more than 100 seriously injured and an estimated additional 7000 people became homeless. The loss of livestock ran into several hundreds. Similarly the second phase of tremors washed away whatever was left of the agriculture land. This time major landsliding was a common phenomenon, which seriously disrupted the already rundown communication and rescue operations. An estimated 1000 houses were completely flattened, with dozens partially damaged. Major portions of the KKH were swept away between Chilas and Raikot and the Astor road not only lost several sections but also was covered with rubble at many other places.

GEOLOGICAL MANIFESTATIONS

Landsliding, rock fall, and soil creep were a common observation. Landsliding was seen to be the most dominant effect probably due to dry steep slopes (Fig. 2a). At Dushkin and Mushkin localized soil creep was slowly turning into mudflow as more

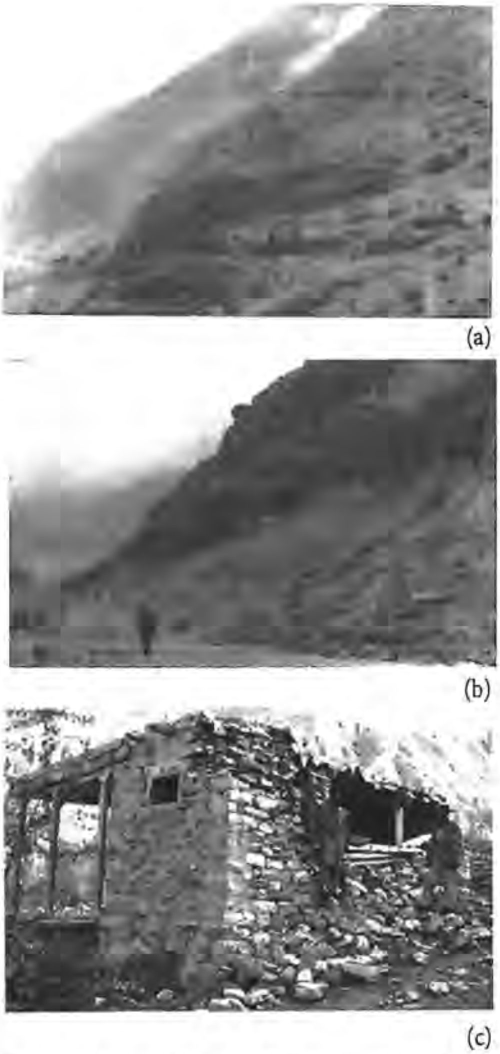


Fig. 2. Recent photos of earthquake effects. a) landsliding at Tatta Pani, b) huge boulders sitting on top of loose sediments ready to roll down, c) Damage to civil structure at village Lichar (cracks are visible to the left and right of the window).

and more water was diverted (possibly by earthquake) into the substratum. A few hundred meters upslope of the Mushkin and the Jal sliding areas, liquefaction has produced large pools of loose mud, sand and water. Ground fissures or cracks or any other evidence of surface faulting were neither found nor reported by the locals. Some boulders within the known fault zones had developed minor cracks. It was not possible to establish if these cracks were in response to movement on the fault plane or they were simply fractured during sliding. Large cracks in overhanging glacial sediments were, however, observed at many places. They seemed to have been freshly opened and may have been developed in direct response to the earthquakes or indirectly due to the loss of material at their foot by rock sliding. No evidence of any volcanic activity, as feared by the local people, was found. The existence of any significant melt in the subsurface has been ruled out by recent studies (Sarker et al., 1999; Park and Mackie, 2000; Meltzer et al., 2001) as well.

Apart from the above-mentioned observations, the authors had extensive talks/discussions with not only the local people but with officers of police and military who were assisting the rescue operations. Few of the interesting points that were noted during these discussions are: "Loud rumbling sounds are heard with every quake". Researchers believe that such a phenomenon happens when earthquake waves directly transfer the elastic wave energy from the ground to the air. There is considerable loss of energy but human ear is quite sensitive, so that small amplitude of vibration in the air is heard as a loud sound. "Rocks brought down by landslides are warmer than normal". It can simply be explained by the fact that the subsurface temperature remains unaffected by the change in atmospheric temperature, so the deeper parts of rocks that are brought down by the landslides will have higher temperature. It is simply as if we pump out underground water to the surface, during winter it is warmer than normal and cooler than normal in summers. Additionally, the widespread presence of hot springs in this area may be dissipating "extra" heat into the surrounding rocks as compared to the other areas. Some people described "seeing strange lights in the sky during an earthquake". Earthquake lights is currently the hot topic in seismology and several credible incidences have been reported worldwide (Davis, 1978; Ouellet, 1990; Corliss, 1995). One of the more logical explanations of the cause of earthquake lights is the piezoelectric effect. Certain materials, including quartz, respond to changes in pressure by changes in electrical voltage across their surfaces. The idea is that, as quartz-bearing rocks are stressed, they might produce such high voltages that lightning-like discharges could occur in the air above.

CAUSES

An earthquake, by definition, is the vibration of the earth. This 'vibration' can be produced by a moving train or heavy machinery, by an explosion, by volcanic eruption, by rising magma, or by motion on a fault. It is the motion on a fault that produces the most devastating and widespread earthquakes. Earthquakes from the other sources are of very low intensity and least magnitude and are usually harmless. Motion on a fault is of two kinds i.e. *creep* and *stick-slip*. If the opposite portions of a fault slip incrementally the result would be "creep". In the stick-slip case the fault blocks are locked together until the accumulated stress exceeds the binding strength and slip occurs abruptly. It is the stick-slip motion that gives rise to earthquakes. In other words, earthquakes are instantaneous release of stored energy. Therefore, for an earthquake to occur, it is essential that there exist a fault, albeit an active fault. The forces that cause the slip on a fault are provided by the prevalent tectonic regime.

The western Himalaya is dominantly experiencing a north-south convergence at a rate of 5.4 cm/year (Holt and Haines, 1993; Bernard et al., 2000). The dominantly north-south convergence results in generally east-west oriented structures. In NPM the structures are not oriented as expected. The original collisional suture i.e. the Main Mantle Thrust (MMT) is folded into a bow-shaped structure around the Nanga Parbat anticlinorium (Fig. 3) and is partially cut by the 70 km long Raikot fault on the western side (Riaz et al., 1997). The Raikot fault is an active fault with dominantly northwestward directed thrusting and minor right lateral strike slip motion. Both of these structures (i.e. NP anticlinorium and Raikot fault) are roughly N-S oriented (Fig. 3), almost 90 degrees off the expected E-W orientation. Such an orientation implies an east-west compression, contrary to the N-S compression caused by the northward drift of the Indian plate. Seeber and Pecher (1998) suggest it is probably related to radial spreading of the greater Himalayan arc. Alternatively, it may be related to transpression associated with strike-slip displacement along the Karakorum fault system

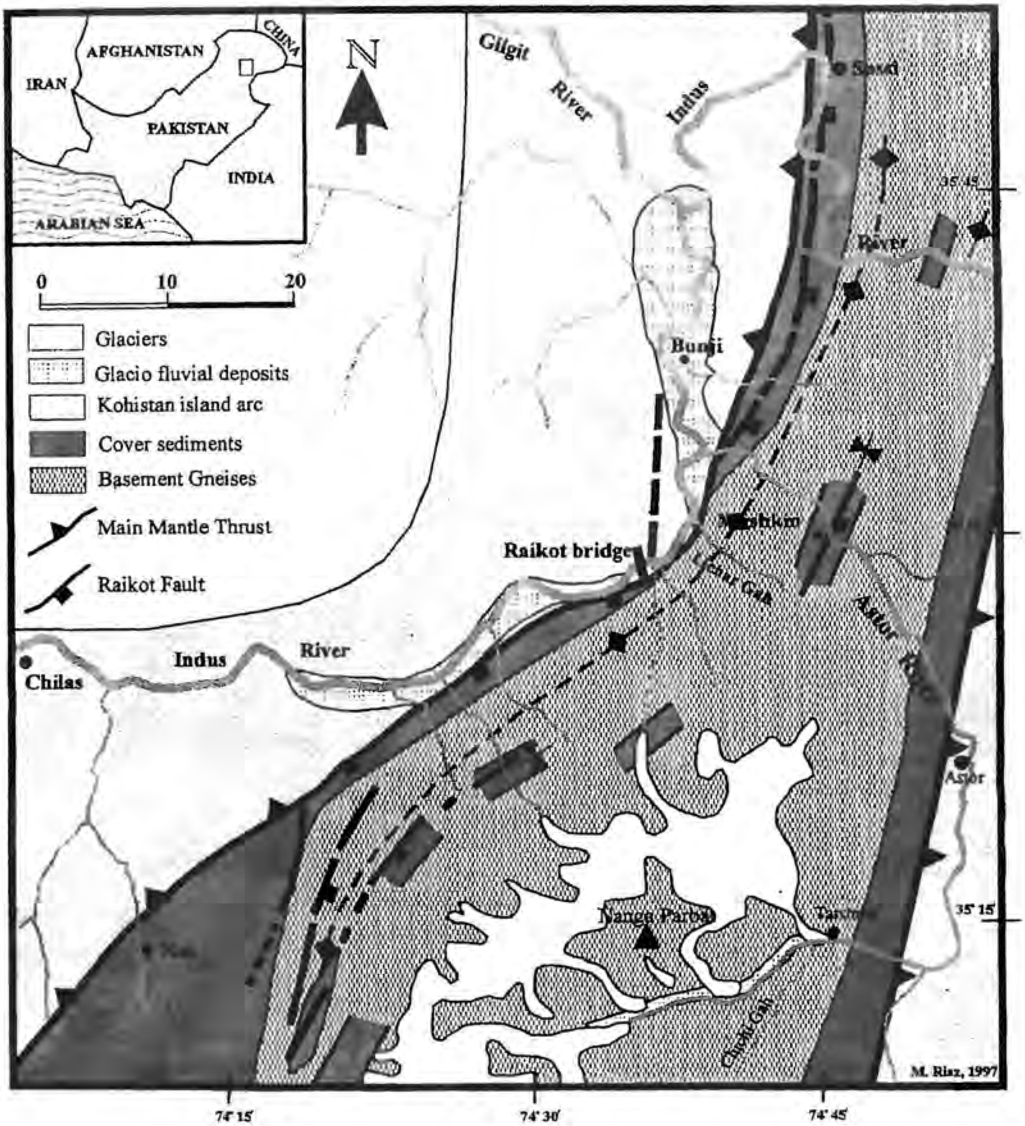


Fig. 3. Geological map of the western Part of the Nanga Parbat area.

(McCaffrey and Nabelek, 1998). In either case there is a strong east-west compression that keeps the Raikot fault active and thus the resultant seismicity.

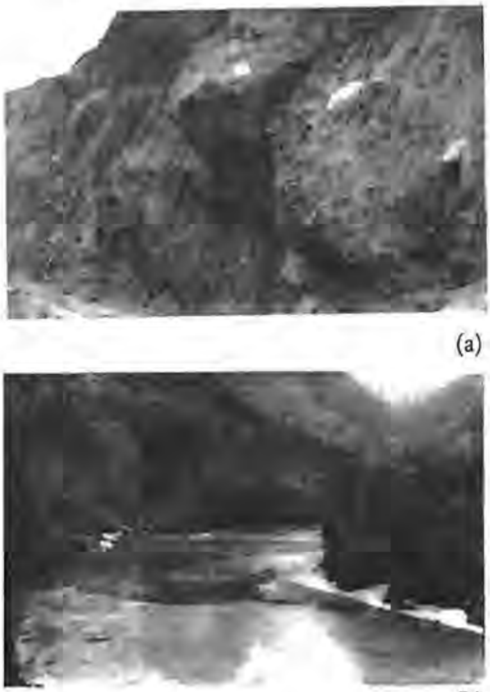
The Nanga Parbat Massif falls in the "seismically active zones" of Pakistan (Mirza, 1981). Records of the historical seismicity of this area is either not available or is poorly documented (e.g. Sverdrup et al., 1994). However, recent investigations indicate that, on average, the area is experiencing more than 300 seismic events every month (Meltzer et al., 2001). This number does include those events that do not originate in NPM. A vast majority of these events is instrumental i.e. they are not felt by human beings. Meltzer et al., (2001) show that out of 1500 seismic events recorded in the NPM area, 380 were clearly associated with the Raikot fault. The idea, as hypothesized by the local officials, that the earthquakes in the NPM area are caused by the subsurface gaseous buildup and subsequent sudden release is far from reality. Even though there are many hot springs with associated gaseous emission all along the length of the Raikot fault, but they have no contributing effect on the seismicity of the NPM. There is, however, evidence of microseismicity associated with the flow of the meteoric water concomitant with few of the hot springs (Meltzer et al, 2001). Various studies (Sarker et al., 1999; Park and Mackie, 2000; Meltzer et al., 2001) have ruled out any significant presence of magma in the subsurface at the NPM and thereby eliminated the possibility of earthquakes related to magma-movement.

CONCERNS

This area is not only home to most scenic mountains of the Himalaya, it also houses a considerable portion of the famous Karakorum Highway (Fig 4a). The importance of this highway is evident from the fact that it is the only land connection between China and Pakistan. Secondly, its strategic value is unsurpassable. Thirdly, its existence has helped the people of the region economically and socially by connecting them with the rest of the country throughout the year. Fourthly, it is the easiest route for tourists and professionals to see the fascinating and spectacular Himalaya, Karakorum and Hindu Kush Ranges. Work on Basha Dam, a hydro-power project, has recently been accelerated. The Dam site is located about 70 km downstream of Raikot (Fig. 4b). It is these two mega projects (KKH and Basha Dam) that are the prime targets of the seismic hazard prevalent in this area. A list of seismically induced potential risks are discussed below.

BASHA DAM RISKS

1. *Landsliding effects*: In December 1840, an earthquake in Nanga Parbat area (Drew, 1875; Butler, 1991) detached a block of rock, roughly measuring 300 X 500 meters, from the hanging-wall of the Raikot fault. The landslide made a



(a)

(b)

Fig. 4. Earthquake risks within the Nanga Parbat area. a) over-hanging boulders within loose glacial sediments along KKH, b) proposed Basha dam site .

300 meter high natural dam by blocking the flow of Indus in the narrow gorge just a few hundred meters upstream of the present day Raikot bridge. In the next six months the Indus built up a 60 km long lake behind the dam. The geological "scars" of this lake are still preserved in that area. In June 1841, there was another earthquake-triggered landslide that fell into this lake causing the water to spill over the dam. The dam failed releasing the water almost instantaneously. After traveling more than 300 km down the Indus the 25 meter wall of mud, rock and water wiped out an entire regiment of Sikh army at Attock. The regiment has taken advantage of the unusually dry river bed to establish a camp. The devastation continued downstream at least as far as Dera Ismail Khan (Drew, 1875). Yet another example is the loss of 2000 lives in 1963 when the Lake Vajont in Italy breached the dam after an earthquake induced landslide generated an over-the-dam-top wave (Pearce, 1991). Recent earthquakes in NPM initiated several landslides, if the same happens after the Basha dam is built and a wave is generated that may fail the dam or spill over it, the downstream devastation would be enormous.

2. *Peak Ground Acceleration (PGA)*: PGA is the maximum acceleration at which ground surface moves in response to an earthquake. PGA is maximum at epicenter and attenuate at farther distances from the epicenter. It is measured with reference to the acceleration due to gravity (g). Most dams are designed to withstand a 0.5g PGA. According to Brume's (1970) model, an earthquake of magnitude 7.0 on Richter scale in the type of rocks that are prevalent at NPM would easily produce PGA as great as 2g at the epicenter and would have very little attenuation within a distance of few tens of kilometers. Therefore, any sizeable earthquake in the area has the potential to shake the dam to failure. Such a PGA has the additional potential of generating "tsunami type" effects in the lake behind the dam. Luckily the dam will be housed on the footwall of the Raikot fault so the PGA would be 2-3 three times less than the PGA on the hanging wall side (e.g. see Brune et al, 1997). However, the shallowness (~8 km below sea level) of the brittle-ductile boundary beneath the Raikot fault (Meltzer et al., 2001) limits the occurrence of earthquake foci to shallower depths as well, which in turn increases the possibility of a higher PGA.

3. *Triggered Earthquakes*: A number of man-made activities trigger the release of pre-existing tectonic stress in the form of earthquakes (Fig. 5). For example, the impounding of reservoirs behind large dams (Adams, 1974; Simpson, 1976; Simpson and Negmatullaev, 1978; Chander and Sarker, 1993; Schwartz et al, 1996; Talwani, 1997), large-scale surface mining (Gibowicz, 1995; McGarr, 2001), high pressure fluid injection in the subsurface (Davis and Frohlich, 1993; Genmo et al., 1995), secondary oil recovery (Rothe et al., 1983; Nicholson and Wesson, 1992) and underground explosions have all contributed to increased earthquake activity. This type of seismicity is called "triggered or induced earthquakes" (Simpson, 1986).

   Orientation of principal stresses varies with the tectonic environment. In thrust fault environment the minimum compressive stress (σ_3) is vertical, in regions of normal faulting the maximum compressive stress (σ_1) is vertical and the intermediate stress (σ_2) vertical in strike-slip environments (Fig. 5). Mega engineering projects can alter the stress regime through increases in solid (elastic) stress or fluid (pore) pressure (Fig. 5). Numerous studies (Adams, 1974; Buchbinder et al., 1981; Meade, 1991; Packer et al., 1980) have shown that impounding of reservoirs leads to increased seismicity in the area. In NPM the reservoir will be located on the footwall of the Raikot fault and, when full, the more than 3 billion tonnes of water will

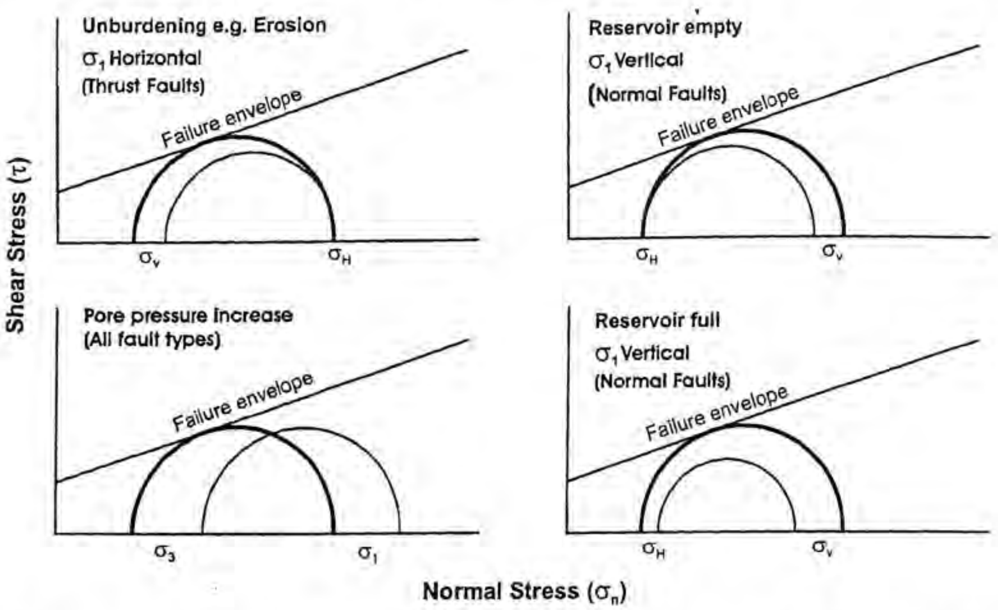


Fig. 5. Various environments in which change in stress leads to failure. Thick semicircle indicates the changed stress environment and thin semicircle denote original stress state. Intersection of semicircles with the failure envelope leads to failure. σ_H and σ_V refer to horizontal and vertical component of stress.

effectively change the state of stress (i.e. σ_3) and may enhance movement on the fault triggering earthquakes. The proposed height of the Basha Dam is 200 meters above river bed (Montreal Engineering Company, 1984). According to a study by Allen (1982) any new dam that will impound water to depths exceeding 80-100 m can cause a magnitude 6.5 earthquake. The magnitude 6.1 earthquake triggered by Hsinfengkiang Dam in China (Wang et al., 1975) and 6.5M earthquake at Koyna Dam in India (Gupta and Rastogi, 1976) have in fact come uncomfortably close to disastrous failure during similar impounding. Similarly the NPM rocks have an efficient network of fracture porosity, which can distribute the dam water over a wider area thereby increasing the pore pressure. An increased pore pressure tends toward failure regardless of tectonic stress environment (Bell and Nur, 1978; Martin, 1975; Athavale, 1975).

4. *Seiches*: The closeness of the fault to the dam and, therefore, of the potential epicenter creates yet another danger, that is, 'seiches'. The word 'seiche' comes from Switzerland and is used to designate a standing wave set up on the surface of an enclosed body of water such as a lake, pond or tank. A closer-to-the-lake epicenter means that the lake has maximum tendency of developing a seiche than creating a free wave. A sustained seiche may break the dam or spill over it and start a flooding event.

KARAKORUM HIGHWAY RISKS

1. *Landsliding effects*: The KKH is built on slopes that are, at places, inclined more than the angle of repose with the consequence that even a passing truck starts the landsliding. The effect of an earthquake at such places is obvious. At other places the KKH is built on glacial outwash. Such rocks are susceptible to minor changes in

water content. Since earthquakes can change underground water movement (Derr and Persinger, 1992), an increase in water content of the glacial sediments will eventually start a landsliding event. In the vicinity of the NPM the Raikot fault cuts across loosely packed Holocene sediments, any motion on the fault will have the potential to start severe landsliding within these sediments.

2. *Rock Fall*: All along the KKH there are many places where giant boulders are sitting on top of loose sediments (Fig. 2b). A substantial earthquake wave may easily dislodge these boulders and not only damage the road but may destroy life and property as well. Similarly, earthquake induced higher meteoric water content of the foundation sediments of these boulders can destabilize these boulders and cause sudden rock fall.

CONCLUSIONS

The structural and tectonic setting of the Nanga Parbat area is such that earthquake hazard will remain in future. Lack of adequate seismic monitoring in this area hinders any short term earthquake prediction. Probabilistic long term prediction of large earthquakes is also not possible because no historical record of major earthquakes of the area is available. Basha Dam may be a cheap source of energy but its location requires cautious deliberation. These recent earthquake are forewarning to the planners to thoroughly evaluate the risks versus benefits of the dam before they tame the Lion River.

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