Triggering Mechanisms of Gayari Avalanche, Pakistan

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Triggering Mechanisms of Gayari Avalanche, Pakistan

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Abstract A massive snow avalanche occurred on April, 2012 at Gayari, located in NE part of Pakistan, close to India and China Border. The catastrophic avalanche killed nearly 148 people, majority of which were Pakistan army personnel destroying army base camp. To mitigate its future hazard, different triggering mechanisms have been investigated in this study. We contemplate that the avalanche was triggered due to snow pack existence on favorable slope in combination with different meteorological conditions and anomalous ground vibration. The avalanche occurrence clock was advanced by two earthquakes: M4.1 at a distance ~ 125 km that occurred about 21 hours before and another comparatively larger (M5.6) earthquake that occurred comparatively at larger distance (~ 370 km) and longer time (~ 25 days) before which have significantly changed the loading conditions. The latter event (M 5.6) has imparted maximum peak dynamic stress and cumulative seismic moment a month before the avalanche. Interestingly the avalanche occurred within the seismic coda of M2.8 earthquake from Hindu Kush region, located at 560 km distance. Although the size and its expected impact on avalanche might be minor but its role in instantaneous triggering cannot be ruled out. Even smaller events at larger distance have been reported to cause snow avalanches in same environments. The presence of cracks within the avalanche, were further weakened by persistence of extremely low temperature (lowest in the past decade), causing high precipitation rate along with altering the mechanical properties of the weak layer within the snow pack. Robust wind pressure pattern highest and lowest in March and April, 2012 respectively might be responsible for abrupt changes in loading conditions.

Keywords Avalanche · Stressing rate · Natural Hazard · Triggerring Mechanisms

Introduction

Snow avalanche is large body of snow mass that flow over unstable slope (ZARUBA and RAPP, 1981; Hewitt, 2009; Fort et al, 2010), typically starts when a huge glacier is detached from its main body and moves downward at extremely high

velocity (Davies and McSaveney, 2002). It is a main hazard source in mountainous region for infrastructures (roads, buildings) and peoples during winter season (Pérez-Guillén et al, 2014). Relationships between snow properties and meteorological conditions are controlling factors in slope failure (Perla, 1970; Mahboob et al, 2015). Snow avalanche stability depends on the structure and strength of snow layers that may vary under outside conditions such as; temperature, precipitation and wind. Snowpack develops over the winter and consists of different layers with widely varying physical properties which evolve accordingly with heat, water vapour content and radiative fluxes driven by the varying weather conditions. Avalanche formation depends on the characteristics of terrain and existence of snow depths over weak layers together with external triggering factors, which include earthquakes, explosions, the passage of skiers and cornice collapses (Davies and McSaveney, 2002; McClung and Schaerer, 2006). Extra load may disturb mass balance of snowpack, corroborate in weakening and nucleation process of avalanche (McSaveney, 2002; Podolskiy et al, 2010). Human activities (Jones and Jamieson, 2001; McCollister et al, 2003; Faillettaz et al, 2004), weather conditions (Mahboob et al, 2015) and earthquake shaking (Podolskiy et al, 2010) have been suggested as main triggering mechanisms of avalanches. Moderate to large earthquake (magnitude > 4.0) triggered widespread avalanches either co-seismically or instantaneously. Mostly within the rupture length of earthquake, shear stress applied to sliding surface is large enough than shearing resistance that may triggered by static or permanent stress changes (Meunier et al, 2007; Lacroix et al, 2014). However, many studies reported triggering of events in relative low (i.e., 1 to 3 bar) stress increase (e.g., Stein and Lisowski, 1983; Oppenheimer et al, 1988; Toda et al, 1998; Anderson and Johnson, 1999). Multiple ground motion cycles during earthquake shaking may weak snowpack resistance by fracturing or development of cracks. Additionally, some observations showed delay in time between earthquake shaking and avalanche triggering. This is due to indirect triggering, earthquake activated process such as change pore pressure, stress weakening or development of cracks. Thus, evaluating the snow slope failure requires a complex system of variables, compose a number of different factors, with scales variation in time and space (Latarnser and Schneebeli, 2003; Schweizer, 2008).

Snow catalog is normally based on visual observations or news reports, after occurrence of the avalanche. These catalogs are incomplete and have poor resolution in time and space (Latarnser and Schneebeli, 2002). For better understanding a snow avalanche, a world wide seismic monitoring system has been established in different tectonic environments such as; Canada (Schaerer and Salway, 1980), France (Leprettre et al, 1998), Japan (Kishimura and Izumi, 1997), Spain (Surin et al, 2000), Norway (Lied et al, 2002), Switzerland (Biescas et al, 2003; Van Herwijnen and Schweizer, 2011), and Iceland (Bessason et al, 2007). The major advantage of seismic monitoring system is to provide the accurate time of avalanches for events of different sizes, regardless of visibility conditions. In Northern Pakistan largest snow glacier exists over higher terrain and within the strong shaking zone of Hinud Kush which is several hundred kilometers away from glacier. Unfortunately, no seismic snow avalanche monitoring system exist. The 7th April, 2012 avalanche in Gayari area of Saltoro Valley in northern Pakistan have killed 148 people majority of them are soldiers. Although our infra-sound and seismic monitoring system are far (i.e., in Islamabad ~ 374 km) from the avalanche site but have detected a clear signal on both seismic and infra-sound array.

The main goal of this study is to improve our understanding of snow avalanche dynamics and its triggering. We study an avalanche occurred on 7th April 2012 in Giyari area of Saltoro Valley in northern Pakistan possibly triggered by an earthquake in Hindu Kush Region. We compare the Infrasound and seismic data show that the origin time of earthquake and avalanche. The azimuth and apparent trace velocity of avalanche, using infrasound and the seismic data have been computed using seismo-acoustic array. We got a tremor signal after the avalanche occurrence. We present the seismicity data before and after the avalanche and calculating stress distribution in the past 24 hrs, one year before the avalanche, which shows that maximum stress accumulates in the glacier before avalanche occurrence. In addition, for weather condition satellite DEM data of Gayari glacier was also analyzed for temperature and precipitation of last 20 years at different locations.

Data and Methods

Data from local seismic network of CES (Centre for Earthquake Studies) and PMD (Pakistan Metrological Department) was used to study the seismic characteristic of snow avalanche. The seismic network consist of 25 broad band sensors deployed all over Pakistan. Signal at least on three stations and has good SNR (signal to noise ratio greater than 3) are located regularly using SEISAN software. Additionally, CES has a four element Seismo-Acoustic array with an aperture of 1km, located at Islamabad. The shape of array is a triangular geometry with ~ 500 m separation between each element. This particular facility further supplement and augment our conventional seismic network operating throughout the Pakistan (Figure 4). For any weak signal, Seismo-Acoustic array enhances it, as compared to that of conventional seismic network.

Snow avalanches have low frequency (< 20 Hz) infrasound waves, which pass through the atmosphere with speed of sound. Acoustic waves produced by avalanches have been discussed by many researchers, but still use of Infrasound for avalanche monitoring is uncommon (Bedard Jr, 1994; Comey and Mendenhall, 2004; Scott et al, 2007). Acoustic waves are not easily measured and are strongly affected by noise (i.e. both natural and artificial). Avalanches generate signals of 1-5 Hz frequency (e.g. Bedard Jr, 1994; Ulivieri et al, 2011). Both acoustic and seismic data were band pass filtered between 1 and 10 Hz frequency range. For processing Seismo acoustic array data, we used MatSeis 1.12 software a MATLAB based toolbox. It offers a time-distance profile plot by integrating origin time, waveform, travel-time, and arrival data. Graphical plot controls, data manipulation, and signal processing functions offer a user friendly environment (Hart, 2004; Hart and Young, 2010). Infra Tool is a MatSeis GUI tool, which help processing infrasonic-array data using different technique described by Young et al (2002). Infra Tool processing creates a new time series of correlation/f-statistic, azimuth, and velocity. Once processing is complete, new detection algorithms of Hart (2004) scan the results for signals based on a set of threshold criteria. Infra Tool was used in this study for calculation of correlation/F-Statistic, trace Velocity (km/s) and azimuth (deg) computation of avalanche signal. Frequency Slowness Analysis (i.e. correlation, azimuth and slowness) were used for determining coherency in a signal reached at an infrasound array (Young, 1975).

Good SNR (signal to noise ratio) required for processing data on traditional seismic network, with were not possible to perform such type of analysis. Contrary, infrasound array amplifies the signal within noise on the basis of their coherency over different stations (McLaughlin et al, 2000; Brown et al, 2001; Whitaker et al, 2002; Garcés et al, 2002; Noble and Tenney, 2003). It calculates azimuth and inter co-relation between the seismic array stations. Whenever, a consistent similar azimuth having some correlation above a threshold within certain duration is achieved signal is said to be detected (Whitaker et al, 2002). Time delay of signal within different elements with constant spacing, inverted for apparent slowness or velocity. Two automated signal-processing routines for Infrasound signal detection are Hough Transform and Inverse Slope. Both methods were used to find the representative slope for a specified number of data points. The slopes are then used in combination with their associated correlation values to determine an infrasonic signal. Processing infrasound array data using frequency slowness analysis gives us three outputs per processing step: correlation, azimuth and trace velocity (or slowness).

DEM data is considered as the primary input for glacier avalanche studies. High-resolution Global-DEM 30-m horizontal resolution were used to generated from the ASTER satellite covering the whole gayari glacier (NASA, 2020 (accessed October 11, 2020; DAAC, 2015), as show in Figure 1. We analyze different metreological conditions such as; temperature, precipitation and wind speed data of the region to find out any abnormal behavior, we analyze climate data from different sources. The historical spatial distributed data sets of Climate research unit (CRU) also provided in by the world bank organization were used to find out variations in temperature and rainfall at different latitudes and longitudes within the region. This data is monthly averaged for the period 1991-2016 (Harris and Jones, 2017; CRU, 2016 (accessed November 10, 2020). The other data we analyze is the gridded data sets of temperature, precipitation and wind speed downloaded from National data center, he other data we analyze is the gridded data sets of temperature, precipitation and wind speed downloaded from National data center, Physical sciences labratory data bank where different types of gridded data sets of climate variables are avaiable in netCDF format The temperature and the precipitation data is of 0.5° and 0.5° grid of CPC global temperature data sets and GPCC global precipitation data set (GPCC, 2016 (accessed November 10, 2020; CPC, 2020 (accessed November 05, 2020) and wind data sets is of 2.5° and 2.5° grid from NCEP reanalysis of 40 years of climate variables (Kalnay et al, 1996), this data covers daily, monthly mean and annual variation in the climates variables within the grid. We take several points in the region to find out variations of climate variables.

Results

The location of Gayari snow avalanche is in high terrain and difficult to access, along with close to boundary of India, China in extreme NE of Pakistan as show in Figure 1. The rescue operation was difficult due to harsh weather conditions. The avalanche signal on infrasound array located (375 km away from avalanche) in Islamabad was clearly recorded (Figure 2, 3). The quality of signal was very good and clear as at midnight there was no air due to convection process and no microbaroms. Only that part of signal with co-relation co-efficients greater than 80% on array components have been

used for computation. The accurate determination of origin time and location is only possible when three infra sound array is available. Unfortunately, we have only one infra sound array in Pakistan. For origin time approximation the consist arrival time on array were taken (i.e, 21:25:30 GMT), if we use average sound velocity as 290 m/s and distance as 374 km then yield origin time as 21:04:00 GMT. The avalanche azimuth and apparent velocity calculated by infrasonic processing (i.e. infratool) based on frequency slowness analysis as 57.201° and 0.374 km/s (Figure 3). On the basis of calculated origin time, we draw travel time curve on the time series of infrasonic data, the S-phase arrival time is clearly co-relating. The recorded signal having maximum power as 0.031 Pa. Although the exact location from small aperture array was not possible, but azimuth 57.201° clearly and exactly correspond to avalanche location.

On analyzing same data on seismic stations, additional to avalanche an event with clear *P* and *S* phase as shown in Figure 4, occurred just before the avalanche. The event was recorded on nearly all stations, which was located in Hindu Kush region with magnitude of $2.8 M_L$. It was deeper (~ 200 km depth) event, so high velocity (i.e. 9.1 km/s) computed on basis of first arrivals on different stations. The avalanche signal was also clear on seismic stations upto 435 km distance (Figure 4). On basis of four stations, with clear first arrivals, avalanche velocity calculated as 5.1 km/s. The velocities difference (~ 4.0 km/s) between event and avalanche corresponded to the expected avalanche occurrence time ~ 25 sec late as that of first arrival from the event. Avalanche is a moving and extended source but unfortunately our seismic station are away from source and was not able to capture its moving velocity. The recorded velocity of an avalanche might represent body wave velocity that generated after the interaction between avalanche and earth. Compare to earthquake an avalanche consist number of sources that deposited mass along the track. So, clear phases was not possible to identify within the seismic signal.

The size of avalanche computed as $1.5 M_L$ (local magnitude), using calibrated local magnitude scale of Mushtaq et al (2019) developed for Punjab, Pakistan. Compare to earthquake, magnitude of an avalanche may not a good representative of its size because their seismic energy depend on it flow type regime. For magnitude calculation the types of snow are also important because wet snow generate larger seismic signal with long coda wave compare to that of dry powder snow, having low density mass being involved (bieras et al., 2003). The inverse is true in case of infra-sound signal that is, larger signal produced by powder snow as compare to wet snow (kogelnig et al., 2011). The type of avalanche sometime inter changes with each other. Inter stations co-relation co-efficient are poor and have no consistent phase may be because of 1-3 Hz frequency content, have strong interaction with local tectonic structures. Avalanche on seismic array at Islamabad start within the coda of *S*-phase of earthquake. This make further complication, in additional to local geology interactions. Comparing CE14 and CE11 stations respectively to close (351 km) and away (462 km) from avalanche and vice versa in case of Hindu Kush $2.8 M_L$ earthquake, as shown in Figure 5. In case of CE14 station, avalanche within the coda of earthquake, whereas at that of CE11 both are separated ~ 115 sec from each other.

We located all events within 24 hours (12 hours before and after) of the avalanche time, with clear *P*–, *S*– arrivals, good signal to noise ratio and recorded on minimum three stations. Because of some small events were missing in our catalog that were further added. Majority of these events were located in Hindu Kush region (~ 550 km away from

avalanche location), whereas couple of events located within 200 km from avalanche (Figure 6). Average event occurrence rate before (0.75 events/hour) were higher than that of after (0.3 events/hour) i.e. 22.5%. A significant accelerated rate that is, events rate during the occurrence of avalanche time is respectively 62.5% and 85% higher than that of average event rate and after the avalanche occurrence. This increase in earthquake rate start nearly three hours before the avalanche time (0.7 and 2 events/hour earthquake rate exist 6 hours and 3 before the avalanche time). We extend the seismicity pattern from time period of 01 day to 01 year before and after the avalanche time. First the threshold magnitude or completeness magnitude for the catalog was calculated as $3.5 M_L$ (local magnitude) using maximum curvature (Wiemer and Katsumata, 1999) and Ogata technique (Ogata, 1983). The slope of frequency magnitude, which is b -value of Gutenberg Richter law (Gutenberg and Richter, 1954) were close to 1, depict same ratio of large to small events production. Normalized cumulative number and seismic moment consist one accelerating sequence (Figure 11), an event of magnitude M_L 5.6, occurred twenty five days before and at 370 km away from avalanche in Hindu Kush region. This event release maximum seismic moment ($\sim 24\%$) in this region within that time period. Additionally, the event have cluster of aftershock decay with time, with aftershock duration as ~ 10 days (Figure 12). The avalanche occurred after 15 days of the aftershock sequences, within the reference seismicity or ambient stress condition of the region, not in the relaxation phase of aftershock sequence. At smaller distance (i.e. $< 2*L$, L is rupture length) both static and dynamic stress disturb the state of stress condition on neighboring faults (e.g., Harris, 1998; Stein, 1999; King and Cocco, 2001). While at large distance (i.e. $> 2*L$), the static stress changes become negligible, whereas the triggering mainly controlled by dynamic stress changes (e.g., Hill et al, 1993; Prejean et al, 2004; Brodsky and Prejean, 2005; Gombert and Johnson, 2005; Peng et al, 2009; Wu et al, 2011). For quantitative dynamic stress, we first calculated ground motion (peak ground velocity, PGV) at avalanche location of the corresponding events using NGA relationship of Chiou and Youngs (2008) as seismic station were far the avalanche location. This relationship is most suitable for the tectonic environment of the study area. These ground motion were further converted into dynamic stress using Hill and Prejean (2007) approach (Figure 12). The peak transient stress produce by the plane wave passing from certain region propositional to peak particle velocities and it corresponding phase velocity as; $\sigma_d = G \cdot \dot{u} / v_s$ (Jaeger et al, 2009), where G , $\dot{u}$ and v_s are the shear modulus, peak ground velocity (PGV), phase velocity. Using G - value as 35 GPa and v_s as 3.5 km/s, the peak dynamic stress calculated at avalanche location varies between 0.2 and 9 KPa. For 10 months before avalanche, its stressing rate was 0.37 KPa/month. This change from 0.37 to 1.2 KPa/month (correspond to 69% monthly stressing rate increase), nearly one month before the avalanche time. It was the maximum stressing rate at avalanche location during two years time period. An additional of ~ 1.5 KPa out of 8 KPa total stress (correspond to 19% stress step increase) received by avalanche, during the occurrence of 5.6 magnitude event.

Geomorphological and Climatological Data Analysis

DEM (Digital Elevation Model) data is considered as the primary input for glacier avalanche studies. High-resolution Global-DEM (i.e. 30-m horizontal resolution) were used, that were generated from the ASTER satellite covering the whole Gayari glacier (NASA, 2020 (accessed October 11, 2020; DAAC, 2015), as show in Figure 1. Topographic or DEM investigation show that the glacier have varying landscape (slope, aspect, etc.) Avalanche start from the maximum elevation (i.e. $\sim 6000\text{m}$) of the Gayari glacier, with slope vary at elevations. Two sharp slopes followed by gentle slopes in this region (e.g, Mahboob et al, 2015). The highest gentle slope ($\sim 5750 - 5500\text{m}$) act as a snowpack zone, where the second one ($\sim 5500 - 4000\text{m}$) act as favorable slope for avalanche triggering (McClung and Schaerer, 2006; Mahboob et al, 2015). From elevation 4250m to 5000m of the glacier there was a sharp slope from 30° to 50° , that were dangerous for avalanche triggering as more than 75 percent of the avalanches occur along such slopes. So most of the mass coming from peak of the glacier gets accumulated at this slope, then favorable meteorological conditions might triggered an avalanche at this position.

The average smoothed temperature and precipitation data of last 20 years time period of avalanche location and its surrounding are shown in Figure 14. The temperature of valley ranges from -3°C to -11°C annually. Precipitation were highest (75mm) at the avalanch location (i.e. $4000\text{ m} - 4500\text{ m}$) as compared to higher altitudes (i.e. greater than 5000 m). This depicted that maximum snow accumulation were occurred at highest point on the glacier at critical slope (30° to 50°). Comparing precipitation data for month of March of year 2012 with that of before (year 1991 – 2011) and after (year 2013-2016 – 2011) the avalanche, depict higher precipitation were observed in March 2012.

The cumulative temperature and precipitation for time period of 10 years at avalanche location, with their corresponding average values and standard deviation are shown in Figure 15. The average temperature in year 2012 were significantly ($\mu - 1\sigma$, with μ is mean, σ is standard deviation) lower than that of previous one and winter 2012 was coldest in the Gayari region. Similarly precipitation in first six months were higher ($\mu + 1\sigma$) than that of average one. We analyze wind speed data monthly and daily basis, and then convert that wind speed into pressure using Bernoulli's equation (Kalnay et al, 1996). In March 2012 the wind pressure was significantly high than the average wind speed. But in April 2012 it was opposite, i.e. wind pressure was very low than the average value (Figure 15, 16).

We also analyze the daily hourly wind speed data of uwind and vwind components of wind speed for year 2012. uwind is the horizontal component of wind speed and its value is positive for wind direction from west to east, the vwind is vertical component of wind speed and that value is positive for south to north direction. Figure 17 shows the variations in wind speed and pressure with hours in horizontal and vertical components. The speed and pressure of uwind was high in February and March compare to April 2012 exhibit low pressure. Additionally, the direction of uwind in the first three months of year 2012 was positive (i.e. from west to east) but in first 10 days of April the direction of uwind became negative (i.e. from east to west). On the other hand vwind speed and pressure was high throughout the winter season

and generally its direction remains positive (i.e from south to north) through out the year. Only, vwind speed reduced in month of April, 2012.

Discussion and Conclusion

The most important factors for avalanche triggering is the existence of favorable slope and formation of weak layer. Snow pack within the Gayari region meet both conditions that is; slope ($\sim 35^\circ - 50^\circ$) and formation of crack was detected in years 2011 at nearly 900m elevation upward from glacier terminus (Mahboob et al, 2015). According Mahboob et al (2015) there was no crevasse in year 2005, slowly formation of weak layer get started with time and became visible in year 2011. Although suitable environment were achieved in year 2011, but avalanche was not triggered because some additional shear stress was required. This supplementary stress might come from earthquake shaking and different meteorological conditions such as; temperature, wind pressure and precipitation (e.g., LaChapelle, 1968; Higashiura et al, 1979; Singh and Ganju, 2002; Podolskiy et al, 2010). Podolskiy et al (2010) compiled a database of earthquake triggered avalanches for different regions. They evaluated that events with $M \geq 5.0$ triggered confirm avalanche from 0 to 350 km distance, but however statistically even a smaller event ($M \sim 3.0$) can triggered an avalanche upto 250 km distance. In the same context Singh and Ganju (2002) reported that an event of magnitude 3.0 can triggered an avalanche upto distance 600 km using the data from Western Himalaya. Further, Parshad et al (2019) suggested that an earthquake with magnitude 1.4 also triggered an avalanche at zero distance using their empirical relation ($M = 0.0021 \times R + 1.4$, R distance in km, M magnitude of an event). Gayyari avalanche occurred within the S-phase of an earthquake with magnitude 2.8 that located ~ 500 km away from the avalanche. Although event have small magnitude but has high seismic body wave velocity (i.e. 9.2 km/s) due to its depth nearly 200 km. According to empirical relation provided by Parshad et al (2019) an event of magnitude 2.8, can triggered an avalanche upto 666 km distance (i.e., $R = \frac{M-1.4}{0.0021}$, with magnitude $M = 2.8$, yield distance R as $\frac{2.8-1.4}{0.0021} = 666$ km). Additionally, an event of magnitude 4.1 occurred in Xingjiang region of China with 21 hour before and at distance 125 km away from avalanche, that contributed the maximum stress (~ 0.0795 KPa), during a day of avalanche. Due to its higher magnitude and minimum distance from the avalanche, there might be possibility of delayed triggering mechanism within the weak layer that changed its shear strength. Couple of events with delayed avalanche triggering were discussed by Singh and Ganju (2002) for western Himalaya regions. According to their reported study an event of magnitude 4.1 could triggered an avalanches at 400 km distance with 5.8 hour delay after earthquake.

An avalanche failure clock may be further advanced by increase in average event occurrence rate before (0.75 events/hour) were 4.5 times higher than that after (0.3 events/hour) i.e. 22 %. Three hours before the avalanche events occurrence rate were further accelerated (i.e., 35% increase). Inertia response force of snow pack might produced fracture within the snow body by accelerated earthquake occurrence (Podolskiy et al, 2010).

Puzrin et al (2019) modeled the delayed triggering mechanism on the basis of slab release model on the same events of Western Himalaya discussed by Singh and Ganju (2002). According to this model slope failure and crack growth in glacier strongly dependent on their internal particles re-orientation and relaxation processes (e.g., Schweizer, 1999; Puzrin et al, 2019). Although three delayed avalanches triggered by earthquakes were well modeled and co-related by Puzrin et al (2019) but an upper bound for the longest possible delay time upon given conditions were missing in their study. Puzrin et al (2019) suggested a co-relation between avalanche delayed time (t_f) with that of different physical parameters or factors (such as; relaxation time t_r , initial shear fracture length l_o , stress ratio k) as;

$$t_f = t_r \ln \frac{l_o}{l_o - l_g} + \frac{t_r}{k} \ln \frac{l_{cr} - l_g}{l_o - l_g} \quad (1)$$

whereas,

$$l_{cr} = l_g + 2l_e \left(1 + \frac{1}{k}\right); l_g = \frac{2l_e}{k}; s = \frac{c_{max} - c_o}{c_o} \quad (2)$$

l_e and c are the characteristic length and cohesion respectively. The most important and contributing parameters in avalanche delay triggering are t_r , l_e and k , with their maximum and minimum values were taken from Puzrin et al (2019). Using maximum value of t_r (40 min) and l_e (0.1 m) leads to maximum t_f as 14 and 24 hours respectively (Figure 18). If the other meteorological conditions were not involved than the delay time of 21 hours is in accordance with that of slab release model modified by Puzrin et al (2019) with given parameters t_r , l_e and k as 40 min, 0.1 m and 0.1 values respectively. However, significant variation in t_f could be obtained with varying k values. Higher t_f can be achieve with lower k value and vice versa. Additionally, this parameter (k value) may also evolve with meteorological conditions too. The three month avalanche delay can be acquired from small k value (i.e., $k=0.005$) with t_r and l_e have their maximum values.

Lower the stress ratio ($k = \frac{\tau_g - \tau_r}{\tau_{p0} - \tau_g}$, $\tau_g = \rho g h \sin \alpha$) value will slow the shear fracture development, thus yield longer time delay for avalanche triggering and vice versa. For accelerating fracture growth the gravitational shear stress (τ_g) should be larger than residual shear stress (τ_r) but smaller than the peak strength (τ_{p0}). For mild slope or lower α value the τ_g is lower and longer time required for avalanche to be triggered. Avalanche triggering will be alter by density and height of the snow pack as both parameters are strongly dependent on meteorological conditions. Anomalous behavior of climatic variables (such as temperature, wind speed and precipitation) in year 2012 suddenly changed the value of τ_g (gravitational shear stress) that in turns increased value of stress ratio k and thus triggered avalanche earlier then expected time. Modulus of softening for snow reduced progressively as the pressure is increased, which suggests that snow elasticity decreases with increasing pressure. Shinojima (1967) discussed relationship between snow temperature and fundamental stresses. The viso-elastic properties of snow undergoes some physical changes due to temperature gradient and forces acting on it. Decrease in temperature, the co-efficient of elasticity calculated in terms of strain decreases that eventually lower the density of snow pack (Shinojima, 1967). Temperature gradient and precipitation in the region caused abnormal hardening and softening of snow.

In March and April, 2012 wind speed was respectively higher and lower than that of average value based on 10 years data. These significant monthly variations in wind pressure generated constant loading and unloading situation on the snow pack, that altered the normal pressure on the slope (Shinojima, 1967). High wind pressure drained maximum amount of water from the snow pack but conversely low wind pressure accumulated water within the snow body. Pore pressure and density fluctuation of snow pack changed shear strength of the weak layer. Moreover, the grain size of the snow pack were also changed by meteorological conditions gradient in the Gayari region leads to uneven grain size distribution, further unstable the snow pack. Strain rate with in the weak layer at that particular time get high.

Lower wind pressure in the month of April, also melted part of snow and changed its crystalline structure, that created an additional unbalance snow layer above the snow pack. Further unbalanced uploading was caused by changed in the direction of u-wind on the day of avalanche.

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Fig. 1 Location of Gayari avalanche that occurred on April, 2012 in NW part of Pakistan, close to India and China border.

Fig. 2 Location of Gayari avalanche (star), seismic stations (triangle) and acoustic array. Circle represents aperture of station separation, 1 km away from each other.

Fig. 3 Acoustic signal of avalanche recorded on seismo-acoustic array from nearly 500 km distance. The data was filtered between 0.5-3.0 Hz with amplitude of signal in counts. (A) Co-relation co-efficient between four elements were higher ($> 80\%$) at time of avalanche. (B) Trace Velocity of acoustic signal is 0.374 km/s at the time of avalanche. (C) Azimuthal angle of avalanche to acoustic array is 57° . (D) Acoustic signal recorded on one of the element of array the timing of the signal matches with avalanche time. (E) Different parameters of acoustic signal and their Standard deviations.

Fig. 4 Hidu Kush event and Avalanche record on different stations of CES, with their corresponding seismogram and apparent phase velocity computed using arrival time and distance. Dotted line show apparent velocity, event was deeper have higher velocity (9.1 km/sec) as compare to that of avalanche (5.5 km/sec). Different filters for event and avalanche were applied to enhance their corresponding signal.

Fig. 5 Location of Hindu Kush earthquake (M 2.8) and avalanche occurred on April, 2012. CE-11 (left) is the closest to event, CE-13 (central) and CE-14 (right) is the closest one to avalanche.

Fig. 6 Seismicity 24 hours before and after the avalanche release recorded by seismic stations of CES.

Fig. 7 Cumulative number of events, 12 hour and after avalanche. These events were manually picked and located, using minimum three stations. All these events were from Hindu Kush region. Three hours before the avalanche seismicity rate was significantly high (2 events/hour) as compare to average seismicity rate (0.7 events/hour). After Avalanche hourly rate 0.3 events/hour, which is lower than that of average of rate.

Fig. 8 Seismicity one month before (circle) and after (square) the avalanche recorded by seismic stations of CES.

Fig. 9 Seismicity one year before (square) and after (circle) the Gayari avalanche recorded by seismic stations of CES

Fig. 10 Frequency magnitude distribution of events occurred one year and after the avalanche (Wiemer and Katsumata, 1999). Threshold magnitude (i.e., $M_c = 3.5$) calculated on basis of maximum likelihood method and Ogata technique (Ogata, 1983).

Fig. 11 Cumulative number of events and their corresponding seismic moment for time period of one year before and after Gayari avalanche. A largest event (filled circle) of magnitude 5.6 occurred nearly 173 km away from avalanche, at Hindu Kush region. This event released maximum seismic moment (24% of the total seismic moment) nearly 25 days before the avalanche.

Fig. 12 Similar as that of Figure 11 but daily rate calculated on basis of events occurrence before and after avalanche. Maximum earthquake rate with clear aftershock decay observed for event of magnitude 5.6, occurred 25 days before avalanche. Horizontal dotted line show average or reference seismicity of the region. Inset figure at top show decay of aftershock sequence, avalanche was occurred within the average or reference seismicity rather than relaxation phase of aftershock sequence.

Fig. 13 Cumulative Dynamic stress computed using data one year before and after, within 500 km from the Gayari Avalanche. The average stressing rate was lower (0.26 kPa/month) as compare to that of average stressing rate one month were maximum (0.89 kPa/month). Inset figure show events with their corresponding distances from avalanche.

Fig. 14 Average precipitation (top) and air temperature (bottom) variation at different elevations of Gayari avalanche. Average precipitation was higher and average temperature was lower at different elevations.

Fig. 15 Comparison of cumulative precipitation, air temperature and wind pressure around Gayari Avalanche for ten years data. Average and corresponding standard deviation represented by solid and dotted line respectively.

Fig. 16 Comparison of wind pressure for the month of March and April before and after avalanche occurrence. Horizontal thick and thin dotted line show average and standard deviation, respectively. For the month of March average wind was extraordinary lower, contrary true for the month of April (i.e., extraordinary lower pressure).

Fig. 17 Hourly horizontal (top) and vertical (bottom) wind speed and their corresponding pressure during year 2012. Both wind speed were higher a month that suddenly decrease just before avalanche occurrence.

Fig. 18 Delay time dependency on different parameters (k , le and tr) given in equation 1 and 2. Two parameters are suppose to be constant and sensitivity of time delay was observed for third parameter. Horizontal dotted line show different time delay, three hours, twenty one hours and twenty five days. (a) Time delay and initial fracture length for different relaxation time for constant stress ratio ($k = 0.1$) and characteristic length ($le = 0.1$). (b) Time delay for different stress ratio (k) values, highest time delayed could be achieved with lower (0.005) k value, which correspond to the time of M 5.6 earthquake. Whereas time delay of twenty one hours could be achieved by with $k = 0.05$ value. (c) Time delay for different characteristic length (le) values. Time delay of twenty one hours that corresponds to M 4.1 could be achieved with stress ratio of 0.1 with characteristic length of 3 m.

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