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Evaluation of Unusual Damage Caused by Amplified Seismic Waves Passing Through Around Quetta Basin Using Aftershock System Analysis

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Abstract
A total of 1200 aftershocks of Ziarat-Pashin earthquake of October 29, 2008 recorded till January 27, 2009 were seismically analyzed and the results indicated the presence of earthquake seismic waves amplifying geological structures around Quetta basin in the Ziarat -Pashin region, which acted like amplifiers, amplifying the magnitude of passing seismic waves and releasing relatively many times more energy, causing stronger shaking of certain locations even though being far away from the epicenter. The amplification was greatest for high-frequency waves and was less powerful at lower frequencies, which, in fact facilitated the focusing of seismic waves which caused intense shaking and resultant severe damage. Muddy structures were vulnerable because the seismic waves passing through such loosely packed muddy structures, cohesion less particles in alluvial soils or slits and sandy soils got amplified manifold. Therefore many collapsed houses were found near these mountains and hills of subduction zone.

Introduction
Both earthquake disasters of Pakistan, Muzaffarabad earthquake of October 08, 2005 in Kashmir and Ziarat earthquake of October 29, 2008 near Quetta in Balochistan, have left trails of anomaly in the pattern of destruction, loss of life and damage to property and civil structures. For instance, some areas, which were located: several kilometers from the epicenter of the 2008 Balochistan earthquake of 6.4 magnitude experienced anomalously concentrated damage with Mercalli intensity VIII, which is the intensity almost as large as that experienced in the vicinity of the epicenter. Similarly, the mountain trails or hilly tracks

representing the subduction zone of the boundary of the Indian tectonic plate with Eurasian tectonic plate passing through Balochistan have shown colossal damage in the form of all collapsed houses near these mountain trails and hilly tracks.

Our national vision for disasters in Pakistan is to build a safer and disaster resilient Pakistan. This supreme goal can only be achieved by developing a holistic, pro-active, multi-disaster oriented and technology-driven strategy for disaster management through collective efforts of all Government Agencies and Non-Governmental Organizations (NGOs).

Several kilometers from the epicenter of the October, 2008 earthquake of Ziarat, Balochistan, which measured 6.4 on the Richter scale there should not have been any serious damage to many areas near Ouetta basin which were geographically far away from the epicenter, which was near Ziarat. But, the areas around Quetta basin were shaken with a surprising intensity, equal to that felt around the epicenter. This research paper is about the research work focused on these surprisingly unusual shaking results that have caused a very serious damage in certain specific areas.

The purpose of analysis of seismic records from aftershocks was to assess and evaluate the severe damage that resulted from the interaction of the passing seismic waves with the several underground structures at depths of few kilometers, formed by the faults on the northwestern edge of the Quetta basin. The check of vulnerability of subduction zones of boundary of tectonic plates near Quetta was also envisaged to determine the cause of intense earthquake tremors and damage due to intense shaking as seismic waves passed through loose medium of alluvial soils and sandy soils where muddy houses were raised for abode.

It was also planned to evaluate the effect of reinforcement of loose structures by cement to ensure cohesion of particles in civil structures. Both effects of loose and reinforced structures to seismic waves were to be observed in the interaction of the passing seismic waves through the geology of the area recorded in the continuous series of aftershocks.

Research Methodology

Aftershock analysis was planned for this research work and the data recorded by the Pakistan Meteorological Department (PMD) was available. Temporary four digital seismic monitoring stations were installed by PMD after the Ziarat Earthquake of October 29, 2008 to measure the number and magnitude of the aftershocks. The locations of these stations were Kuch, Kan Depo, Gogai and Ziarat and were well within 40 km from Ziarat to record the frequency of occurrence of various magnitudes of tremors for 13 weeks from October 29, 2008 to January 27, 2009. The recorded data was then analyzed in terms of the seismic waves interaction with rocks, alluvial soils, sedimentary basins considering the wave characteristics of reflection, diffraction, refraction and interference (constructive as well as destructive). Percentage-wise categorization and the effective frequency component and its interaction with material in terms of attenuation by the rocks was carried out for the investigative results to address the problem of anomalous shaking that caused more damage in certain areas.

Results

The Ziarat earthquake of Balochistan near Quetta of magnitude 6.4 in 2008 has been shown geographically on the map of Pakistan in fig. 1 based upon the recorded data by the Geological Survey of United States of America (USGS).

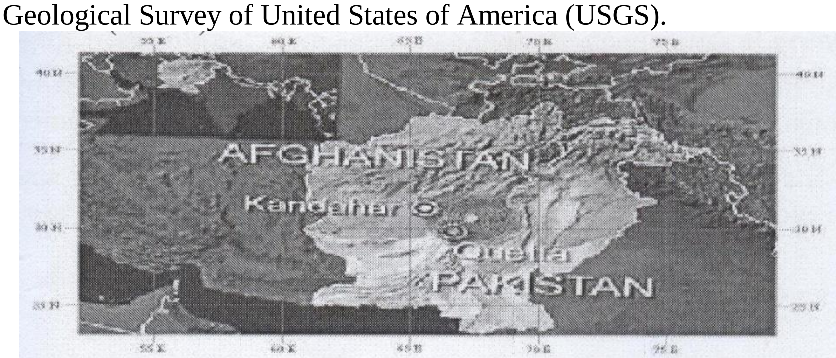

Fig. 1: United State Geological Survey shows the epicenter of October 29, 2008 Ziarat Earthquake near Quetta in Balochistan, Pakistan. ***(Source: USGS)***

As obvious from fig. 1, the epicenter was at latitude 30.61 N and longitude 67.43 E along North East (NE) axis passing through Quetta and the earthquake belonged to shallow category. The foreshock of magnitude 5 occurred at 04:33 PST at 30.51 N and 67.48 E and remained in NNE direction from Quetta at the distance of 60 Km. Intensity of main shock was VIII Merrcalli damage scale in and around Ziarat-Pashin area. At Quetta, the horizontal component of Peak Ground Acceleration (PGA.) was 0.17 m/sec and the vertical component was 0.06 *ml* sec .

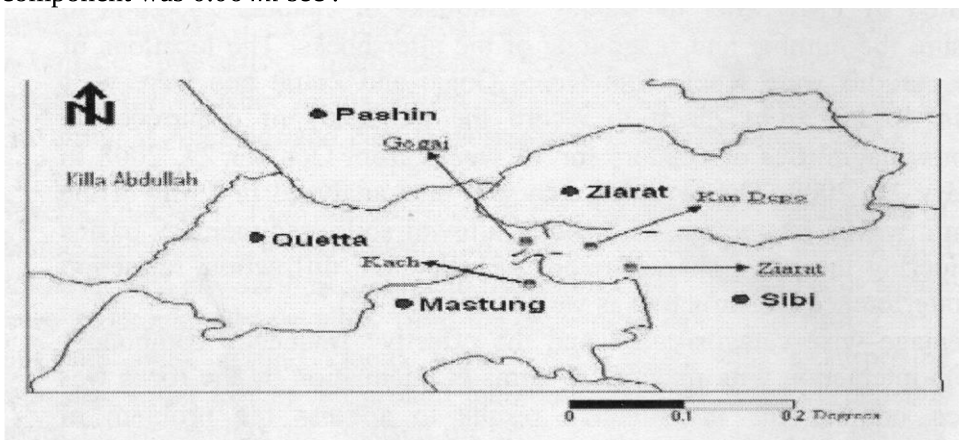

Fig. 2: Four Digital Seismic Monitoring Equipments were deployed by Pakistan Meteorological Department (PMD) to collect data on aftershocks of Ziarat earthquake of 2008.
(Source: PMD)

Temporary four digital seismic monitoring stations were installed to measure the number and magnitude of the aftershocks. The locations of these stations are shown in fig.2 and the stations were arbitrarily named as Kuch, Kan Depo, Gogai and Ziarat within 40 km from Ziarat.

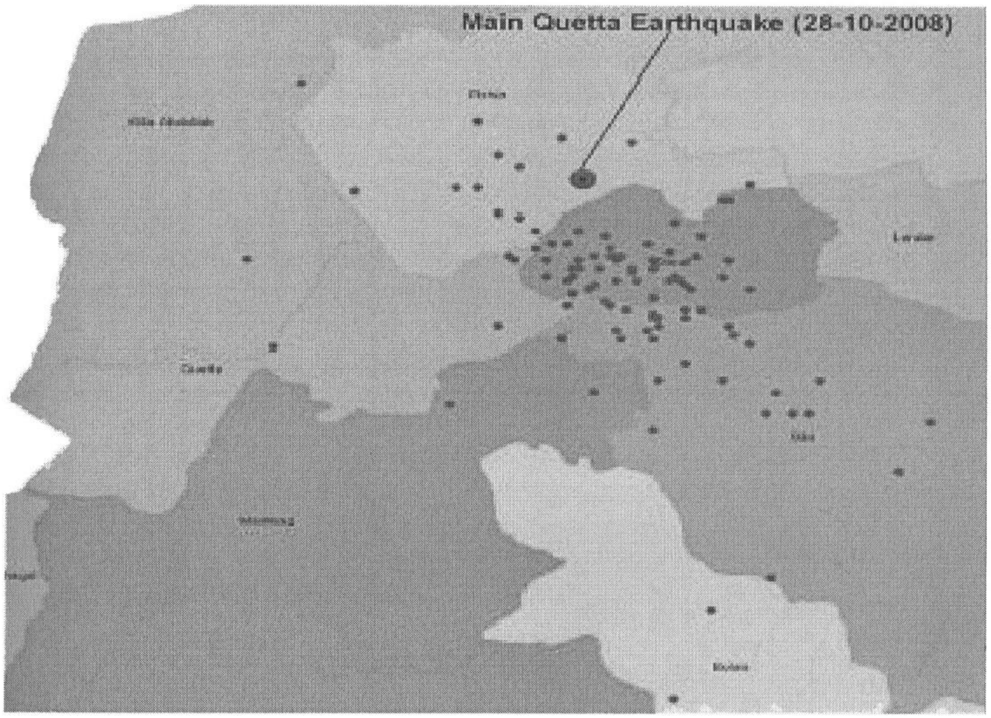

Fig. 3: The distribution of aftershocks in Ziarat-Pashin area near Quetta with comparative reference to main geographical areas of Pashin, Ziarat, Sibi, Mastung and Quetta in Balochistan.

(Source: PMD)

The data on number and magnitude of aftershocks for the total period of 13 weeks after main shock on October 29, 2008 are shown in table 1.

Table 1: Number and magnitude of aftershocks (on weekly basis)

Sr. No.	Dates of the week	Number of aftershocks	Minimum magnitude	Maximum magnitude
1st	29-10-2008 to 04-11-2008	535	2.2	4.7
2 nd	05-11-2008 to 11-11-2008	145	2.7	4.6
3rd	12-11-2008 to 18-11-2008	081	2.7	4.9
4th	19-11-2008 to 25-11-2008	074	2.9	4.4
5th	26-11-2008 to 02-12-2008	052	2.7	4.5
6th	03-12-2008 to 09-12-2008	073	2.7	4.5
jib	10-12-2008 to 16-12-2008	076	3.0	4.3
8th	17-12-2008 to 23-12-2008	050	2.9	4.5
9th	24-12-2008 to 30-12-2008	027	2.4	4.3
10th	31-12-2008 to 06-01-2009	025	2.7	4.3
11,B	07-01-2009 to 13-01-2009	037	2.7	4.6
12th	14-01-2009 to 20-01-2009	014	2.7	3.6
13,h	21-01-2009 to 27-01-2009	011	2.9	4.3
Total	29-10-2008 to 27-01-2009	1200	2.2	4.9

(Evolved by the Author)

Trend of aftershocks revealed that the force component causing aftershocks was not coincidental with the South-West to North-East axis of Monsoons in Pakistan along which the energy transport in summer usually takes place dominantly with the pumping of winds and clouds from the Arabian Ocean. But the component of force acting in the area was North-West to South-East (NW-SE) direction which is also the direction of the possible rupture line in the area. The spinning direction of Earth Globe is also from west to east and that component is reflected in the North-West to South-East (NW-SE) direction coinciding with the rupture line in the area. The majority of the aftershocks are also found concentrated along the rupture line and there are only few events of aftershocks which can be designated as outliers as they are, in fact, located far away from the rupture line. These outliers are easily recognizable from the results of aftershocks shown in fig.3. These outliers are the outcome of the triggering of the local faults in the area when the maximum shaking was indeed along the fault line and the villages like Warn, Kan Depot, Ahmedoon, Tangi and Khanozai along it suffered maximum damage.

Table 2: Percentage of occurrence of aftershocks in the range of 3.6 to 4.9 recorded during the period of 29 October, 2008 to 30 January, 2009.

(Evolved by the Author)

Magnitude of Aftershocks	Percentage of Frequency of Occurrence	Remarks
4.9	2 %	High magnitude but low frequency
4.7	16%	High magnitude and high frequency
4.6	4 %	High magnitude and low frequency
4.5	28%	High magnitude and very high frequency
4.4	7 %	High magnitude and low frequency
4.3	17%	High magnitude and high frequency
4.2	7 %	High magnitude and low frequency
4.1	5 %	High magnitude and low frequency
4.0	4 %	High magnitude and low frequency
3.9	5 %	Low magnitude and moderate frequency
3.7	1 %	Low magnitude and low frequency
3.6	4 %	Low magnitude and moderate frequency

The results of table 2 clearly show that 90% aftershocks are in the range of 4.0 to 4.9 i.e. higher magnitude and only 10% are in the range of the magnitude below 4.0 i.e. 3.9 to 3.6 of lower magnitude.

The recorded Earthquake Incidences in Richter scale (R/S) for Balochistan in the recent past based on data extracted from Pakistan Meteorological Department, Quetta Station are shown below in table 3.

Table 3: Past record of earthquakes around Quetta, Balochistan.

(Evolved by the Author)

Year	Area (Place)	Magnitude (R/S)	Year	Area (Place)	Magnitude (R/S)
1909	Kech	7.2	1987	Quetta, Chaman	5.6
1935	Quetta, Mach	7.0	1990	Quetta, Kalat, Khuzdar, Mastung, Kalat, Nushki, Surab	5.8-6.1
1935	Quetta, Mastung, Kalat	7.5	1992	Khuzdar, Nal, Quetta	5.7
1941	Quetta	5	1993	Quetta/Pishin, Makran/Gwadar	5.7
1945	Pasni/Makran	8.6	1995	Quetta	5.2
1952	Loralai	5.8	1996	Quetta	5.3
1954	Khuzdar, Nal, Wadh	5.7	1997	Quetta, Mastung, Mach, Sibi, Harnai	5-6.2
1955	Quetta	6	1998	Quetta, Dalbandin	5.3
1956	Kalat, Barkan	6	1999	Barkan	5.2
1957	Khuzdar	5.5	2000	Quetta, Sibi, Ziarat, Harnai and Duki	6
1975	Quetta	5.4	2002	Balochistan Boarder	6
1978	Quetta, Nushki	5.3	2003	Naukundi, Musa Khail	5.3
1983	Khuzdar	6.5	2004	Sibi	5.5
1986	Khuzdar	5.4			

This record also shows that the tremors are 90% along the main boundary fault line of Indian tectonic plate subducting the Eurasian plate. Quetta and Khuzdar are both along the main fault line.

Fig.4: Earthquake events around Quetta (Sept. 2006 to Sept. 2008)

(Source: USGS)

The findings of this research concentrate over the Quetta basin which is alluvial in characteristics as it is formed, like Lorlai basin, by the local tributaries. The resultant alluvial layers were then deposited in the basin, which now provide the cohesion-less particles of the soil which trigger amplification of passing seismic waves through Quetta basin. The basin covers the districts of Quetta, Mastung, Pishin and partly Qila Abdullah and Kalat. The research effort on the local geological structure around Quetta basin coupled with the results of the analysis: of aftershocks has led us to identify and locate the underground geologic structures around Quetta basin which have acted like amplifiers of the vibrations of the seismic waves passing through these structures. The amplified and focused vibrations that emerge while passing through such structures have resultantly produced concentrated spots of damage far from the epicenter.

The analysis of aftershocks has further verified the existence of such local geological structures around Quetta which act like waveguides to the propagation of the magnified waves emerging from the magnifying pockets of geological structures under the Quetta basin. The basement of the Quetta basin and the dip of Chilton Hills fault on the northern side form an arc of a convex structure which runs below the ground surface for about 3 kilometers. However, the structure is not smooth and regular in shape but have deformities which further facilitate wave-guiding effect. Such wave-guiding effect is also experienced in summer in Hyderabad district in somewhat similar way but with respect to wind flow where the ventilators on the roof tops of the houses are used to catch the air flow and compress it by convergence through narrow passage down in the room which was kept cool in spite of scorching heat of the sun outside. Similar converging effect is shown by the irregularities in the geological structure underground and the passing seismic waves converge as the light converges after passing through a lens. This, in fact, results in the focusing of the waves at many different points on the surface. This focusing of the seismic waves at these points acts like amplifiers causing unusually strong shaking which results in severe damage as if these locations were near epicenter. These findings can greatly help us in deciding which buildings should be reinforced first in earthquake retrofitting.

The observational data revealed that the amplification of seismic waves was frequency dependent and was directly proportional to the resonant frequency of the structures. Several structures around the Quetta Basin, with resonant frequencies in the upper range of infrasonic frequencies, that is, from 6 Hz to 16 Hz, showed severe shaking resulting in huge damage. This confirms the fact that the underground lenses selectively amplify the higher frequency range of 6 to 16 Hz as compared to lower frequencies of 1 Hz to 5 Hz.

Other findings of this research work showed that the pattern of shaking is also dependent on the angle of incidence of the seismic waves along the interfacing layers of the ground subject to reflection, refraction and diffraction having a specific critical angle of the structure under consideration. The effect of the amplification recorded 21° away from the critical angle was three times smaller than the maximum effect. So the critical angle, as in the phenomenon of refraction is the source of guidance in determining the intensity of shaking of the ground resulting in the damage of structures. This also indicates that the waves from other earthquakes will not be focused to the same extent as those from the October 29, earthquake of 6.4 near Quetta if they pass through the lens at a different angle.

The present Ziarat earthquake of 6.4 has the past of seismically active record starting from 1931 to 2008. Very close to the present epicenter, there have been two major earthquakes above magnitude of 7 i.e. Shahrigh earthquake of magnitude 7 on 25 August 1931 at latitude of 30.30 N and longitude of 67.80 E in which every building was damaged and all railway stations in the area were severely damaged. The other earthquake was Mach earthquake on 27 August 1931 two days after Shahrigh earthquake at the latitude of 29.3 N and longitude of 67.8 E with the magnitude of 7.4. Apart from this, there have been four earthquakes particularly in the Ziarat area of magnitude of 4.9 in 1983, 6.1 in 1984, 6.0 in 1985 and 6.4 in 1997.

Discussion of Results

Through around the basin at some specific critical angle, both the particular geometrical shape as well as the material making the sedimentary layers of the basin were found to act like an amplifier to amplify the vibrations which caused intensified ground shaking resulting into severe destruction of the geological structures including both, the muddy abodes on the ground as well as the civil structures, including roads, bridges and culverts.

The Quetta basin as well as the Quetta city itself is geometrically like a bowl of rock similar to Kyoto city of Japan which is also physically like a bowl surrounded by hills and mountains. This research paper has evaluated the focused seismic energy which remains trapped within such basins. These findings have also proved the fact that the seismic waves also exhibit the similar wave characteristics of reflection, refraction, diffraction and constructive or destructive interference when they pass through different materials. The seismic waves move slower in the sedimentary layers of the basin and therefore are amplified to cause intense shaking as the particles in the sedimentary layers are cohesion-less and encourage amplification of shaking. However, when the seismic waves conduct through solid rocks they move faster and are attenuated. This difference in the speed of the seismic waves in sedimentary material as compared to the solid rock in the Quetta basin, in fact, makes the structure to bend the seismic waves exactly in the same way as the glass lens bends the light and can concentrate the light at some point where the amplified light even can burn the area by generating more heat energy by focusing the light at some point.

The Quetta basin which is like a bowl acts like a parabolic dish antenna where once the seismic waves enter the basin, they are reflected off the peripheral boundaries of the basin and become completely trapped and the energy so concentrated results into more intense shaking causing severe damage around basin. In the light of these valuable findings, the specific software or computer simulation can be developed for these complex sedimentary layers of the Quetta basin. Slow travel of the seismic waves occurred in some areas which were found to be loosely packed sedimentary rocks which were causing amplification of shaking resulting in more damage in those particular locations. The other relevant finding of this research work was that the lenses for light are regularly shaped but the equivalent lenses in the geological structure are irregularly shaped and therefore, the seismic waves were actually bent into some odd directions.

Conclusion

The data on number and magnitude of 1200 aftershocks for the total period of 13 weeks after main shock on October 29, 2008 were analyzed. There were fcur Digital Seismic Monitoring Stations that were deployed by Pakistan Meteorological Department (PMD) to collect data on aftershocks of Ziarat earthquake of 2008 within the area 40 km from Ziarat. The collected data was analyzed to investigate and assess the effects of the geological structures on the seismic wave's amplitudes passing through or around Quetta basin. 175 aftershocks on 29 October, 2008 were in the range of 2.2 to 4.7 and many of the aftershocks were found well correlated with the damage pattern that was caused by the main shock because the peak values of body waves, Primary wave, P and secondary wave, S showed close correlation. However some areas in and around the Quetta basin showed more than three times higher amplification intensifying the shaking in the area resulting into more severe damage as compared to other surrounding areas in the vicinity. The doubling of the phase was also clearly noted from some events in Quetta basin. Also in the severely damaged areas, the Body waves, P and S waves arriving late were found to be several times larger in the magnitude than the first arrived waves. But, these large magnitude waves were found to show a rapid decrease in their magnitude in slightly damaged areas. In the case of Quetta basin, the critical path for converging the coming energy from the epicenter near Ziarat was lying towards the Quetta basin, which indicates the fact that even a slight change in the epicenter of main shock from near Ziarat would have certainly changed the destruction pattern achieved now. Seismic records from aftershocks suggested that the severe damage resulted from the focusing of seismic waves by several underground amplifying structures at depths of about 3 kilometers, formed by the faults on the northwestern edge of the Quetta basin. The involvement of a convex geological structure of the basin causing convergence similar to focusing of rays selectively in Quetta basin is realized. However, such focusing effects of certain geological structures were found several times smaller in the other areas of Quetta basin on the surface proving the constructive and destructive interference of the seismic waves with the geological structures of the basin.

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