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Seismic potential and neotectonic studies at Karachi, Gadap and Hub areas, southern Kirthar Fold Belt, Pakistan

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The dream of accurate and reliable earthquake prediction has not yet come true; however, state of the art knowledge enables humanity to at least recognize earthquake prone areas. In this regard, neotectonic studies have been conducted in the Karachi, Gadap and Hub areas to locate earthquake environmental effects (EEEs) and to assess the seismic potential. Possible active faults manifestation were studied in the recent sediments to understand the intensity of seismic activity. The southern Pakistan has experienced some major and strong earthquakes in the past such as the Makran-1945, Anjar-1956, Bhuj-2001 and Awaran-2013 with magnitude 7.0 – 7.7Mw. However, only ground shaking was observed in the southern inner part of Karachi Arc area and no EEEs such as neotectonic deformation features, surface ruptures and liquefaction were observed during the major and strong earthquakes caused by the distant seismogenic sources. The lithological studies of the Quaternary sediments exposed in the Karachi, Gadap and Hub area have not revealed the existence of any distortion, off set in the sedimentary strata, paleo-liquefaction and fault propagation. It indicates the absence of seismogenic sources and no strong or major earthquakes have been occurred in this area in the Quaternary time except few minor to light (magnitude: 3-4.9Mw) crustal scale earthquakes.
Keywords: Neotectonic, Earthquake Environmental Effects, active faults, Kirthar Fold Belt

Introduction

Neotectonic is the study of young tectonic movements occurred or still ongoing in a particular region after its orogeny or geological study of recent crustal movements, especially those caused by earthquakes [1]. Neotectonic study is the only reliable tool to provide sufficient information on moderate to large-scale paleoseismic events. Deformations caused by earthquakes are recorded by deformed sediments and the intensity of paleoseismic events is determined by the degree of deformation experienced by these sediments [2]. Keeping in view the tectonic pattern and dynamics, the geological structures leading to neotectonic deformation are determined. The intensity assigned to a seismogenic structure is the basis for assessment of seismic potential of that particular structure. Seismic events associated with active structures repeated over thousands of years. The instrumental and historical records spanning over few centuries are insufficient to distinguish seismogenic sources and assess their seismic potential. In this case, only neotectonic studies can provide important samples for seismic analysis and modeling [2]–[4]. Neotectonics is of great significance in providing evidence for the location of large earthquakes in the active fault zone. The study of Neotectonics is carried out by various workers from different fields, such as geomorphology, seismology, structural geology, geophysics, and engineering geology [5]–[8].

The neotectonic studies have been conducted in the Gadap, Karachi, Hub, Layari and Malir Rivers areas of Karachi Arc, southern Pakistan (Figure 1) with the aim to locate the EEE, to check the tectonic disturbance within the recent sediments and to evaluate the seismic potential. The present work will provide basis for seismic hazard assessment, and earthquake resistant engineering. This work will help in recognizing earthquake prone areas and quantifying seismic hazards associated with seismogenic structures responsible for seismic activity within the Karachi Arc as well as for Karachi city for the safety of public and property. The study also provides preliminary assessment of potential for seismic hazards and permanent ground displacements.

Regional Geology and Literature Review

The area under study is a part of major tectonic zone called Sulaiman-Kirthar Fold Belt (Figure 1). The fold belt forms the eastern part of Baluchistan Province, extending about 850 km from South Waziristan to the Arabian Sea in the North-South direction. The width of the mountain system varies from about 390 km in the north to about 190 km in the south. In the west, the Ornach-Nal Chaman Fault bounds this mountain belt, while vast Indus plain bounds it in the east [9], [10]. The

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fold belt has a faulted contact in the west while it gradually loses its amplitude and merge with the fore-deep zones in the east and south [11]. The Sulaiman-Kirthar Fold Belt includes the Sulaiman Fold Belt, Sibi Trough and Kirthar Fold Belt. The study area is the southern part of Kirthar Fold Belt. The Kirthar Fold Belt is a north-south trending folded zone between Quetta and Karachi. The belt has straight upright anticlines that are the product of distributive sinistral Cenozoic transpressive wrench faults [12]–[14].

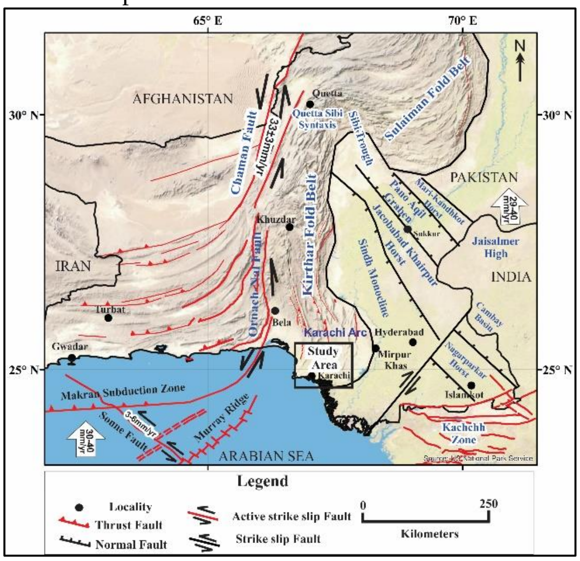

Figure 1. Regional tectonic framework of Sulaiman-Kirthar Fold Belt, southern Pakistan (modified after [15], [16])

The southern parts of Kirthar Fold Belt represent a divergent wrench regime. It is marked by open arcuate structures known as Karachi Arc (Figure 2). It shows relatively less brittle deformation as compared to the northern part of Kirthar Fold Belt. The Karachi Arc is bounded by Bela-Khuzdar block to the west and by Indus foreland to the east. In the south, the arc terminates in Murray Ridge area where tertiary rocks are covered by Quaternary sediments of Indus delta and submarine fans [17]. Wedge shaped Bela Khuzdar block is sandwiched between Ornach-Nal Fault in the west and Mor Range thrust in the east. The Bela block moved north ward and rotated anticlockwise resulting into the formation of Khuzdar Knot and Karachi Arc [14].

The major faults in northern part of Karachi Arc are Kirthar, Pab, Khud and Mor Faults (Figure 2). In Karachi Arc area, the Kirthar Fault is a north-south trending thrust in the frontal part of the Kirthar Range, and extending from northern Kirthar Range to Dureji in the south with variable dip of 65° and 43° toward east respectively. South of Dureji, the Kirthar Fault movement is compensated by folds, crosscutting strike slip faults and some local faults. Pab Fault is another important feature at western limits of Kirthar Fold Belt. The north-south trending and westward dipping fault zone runs more or less parallel to the Mor Range. Surjan Fault, located in the frontal part of the Karachi Arc is a westward dipping high angle fault, which extends from Jhimpir to Ranikot area. Some north-south trending faults with limited aerial extent collectively constitute Jhimpir-Meting Fault Zone. A number of northwest and northeast trending strike-slip faults in the western parts of the Kirthar Fold Belt represent conjugate sets formed because of compressional deformation. To the east of Karachi Arc Indus foreland is characterized by recent sediments laid down by River Indus, which are lying over a relatively less deformed Tertiary sequence.

Sarwar and Dejong [12] identified the Arc as Karachi Arc; characterized by arcuate pattern of north-south trending gentle folds but the most detailed mapping of the southern Pakistan was conducted by Hunting Survey Corporation [18]. According to Schelling [10] the tectonic deformation in the frontal part of Karachi Arc is from Pliocene/Pleistocene to Holocene, and he proposed the thin-skinned tectonic style for Karachi arc. Pervaiz et al., [17] assessed the Peak Ground Acceleration (PGA) of 0.2 for a imaginary site near Karachi city. They believed that the faults of the Katchchh zone do not extend in the Karachi Arc and there is no major earthquake risk to Karachi city. Sarwar [19] placed the Hyderabad graben under Karachi Arc.

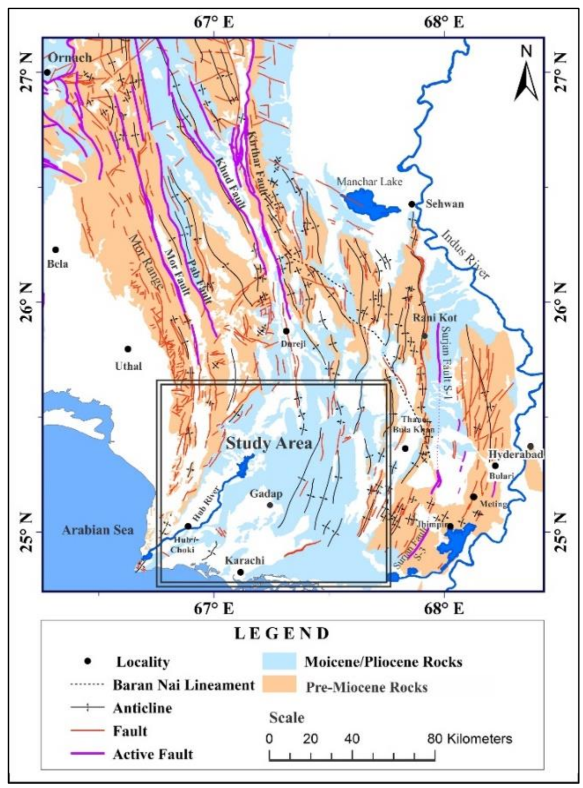

Figure 2. Geological Map of Karachi Arc showing the location of Study area [modified after 15].

Different authors [20]–[25], have documented historical seismicity of Karachi and surroundings areas. Bilham et al., [26] documented a review of historical seismicity near Karachi and argued that in spite the location near to active faults any seismic event has ever produced documented damage in

Karachi city. Bilham recommended further geological work for better understanding that whether the Karachi is safe and is at aseismic setting or short incomplete history. Sarwar and Alizai [9] concluded that the entire Karachi Arc is seismically active. They extended the southern wrench boundary fault to the south of Karachi Arc.

The area is comprised of a variety of rocks ranging in age from early Paleocene to Holocene [27], [28]. These rock units are variegated in lithology and age. The Paleocene to Eocene rocks are dominantly limestone with minor calcareous shale. Middle Miocene to Quaternary rocks are composed of sandstone, shale, conglomerate and alluvial sand, silt and clay.

Methodology

Satellite data was specially processed and interpreted for neotectonic studies. To provide input for the database, active faults were identified on the bases of LANDSAT and SPOT satellite images, published geologic maps at different scales, and seismicity catalogues. The absolute age of Quaternary sediments is undefined in the area, so the relative age and stratigraphic position of sediments were used to distinguish the recent deformation characteristics. Probable neotectonic signatures of certain areas were earmarked and the Quaternary strata exposed in that areas was studied in detail to understand the intensity of seismic activity in recent years. Detailed fieldwork including geomorphological and neotectonic studies were carried out, which mainly include analysis and interpretation of landform, slopes, excavation of trenches at selected sites, nature of rocks and drainage pattern. The geomorphological deformations were analyzed in quaternary strata, and its correlation with bedrock lithology were studied. Possible fault plane exposures were examined and measured laterally and vertically. Stream banks, ridges, terrace surfaces and hill slopes were studied to locate any offset features. Mapping of tectonic geomorphological features were carried out to locate any possible active fault traces and related surface features

Results

Neotectonic and Geomorphological Studies

Quaternary sediments are mainly exposed in the valleys of Hub River, Layari Nala and Malir River. (Figure 3). These sediments have been investigated thoroughly. The older alluvial Quaternary sediments occupy the major part of these valleys and low land while the very recent alluvial deposits occur along the current streams. Gravel/boulder beds represent the older Quaternary sediments, which are in erosion phase while the younger Quaternary deposits are composed of gravel, sand, silt and clay. The gravel / boulder beds in these valleys are peneplained and the present streams have carved through these sediments. No change in flow direction of both deposits have been observed which indicates that the ancient drainage system developed in the valley is not different from the current drainage system. The valley fill material was laid down by the paleo-drainage while the recent gravel, sand and silt deposits along the streams have been deposited by the present drainage.

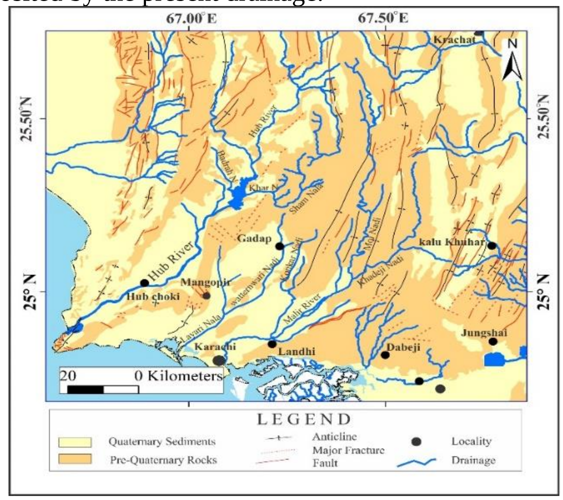

Figure 3. Geological and drainage map of the Gadap, Hub Choki and Karachi area.

The repeated processes of erosion and subsequent deposition have resulted into the development of three terrace levels that are not separated by any structural disturbance. It suggests that the area experienced only non-tectonic uplift or sea level changes since the deposition of older alluvial Quaternary sediments. These three terrace levels are the Alluvial fan terrace "A, B and C". First two generations i.e. "A & B" alluvial terraces are older, while "C" is the living terrace (Fig-4).

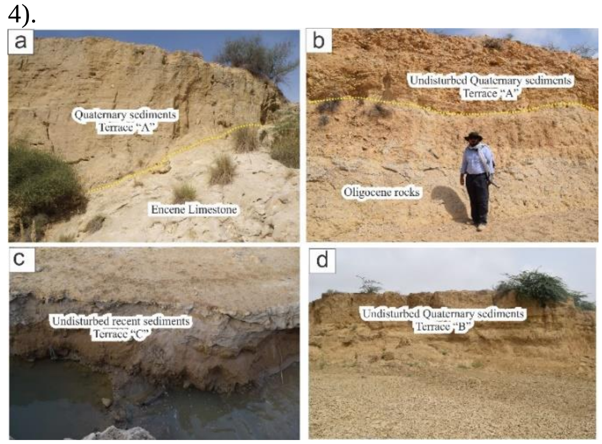

Figure 4. (a) Undisturbed terrace "A" lying over Eocene limestone near Hub Choki area. (b) Undisturbed Terrace "A" over Oligocene rock along Sona Fault, Jhil Range. (d) Undisturbed recent sediments (terrace "C") exposed along Malir River in Karachi. (d) Un-deformed terrace "B" exposed near Mangopir area, Karachi

The Terrace "A" is composed of clast-supported conglomerate with matrix of grit and coarse sand. It is the oldest one and constitutes higher ground in the area (Figure 4a). The "B" is composed of gravels with lenses of grit, silty sand and clayey silt. The top layer is generally finer while lower parts are represented by gravel, grit and conglomerate. It is cemented by calcite at places (Figure 4d). The Terrace "C" is the recent one and comprised of loose sand, silty sand and gravel/ boulders. It occurs as point bars, lateral bar or channel bars along current streams (Figure 4c). The thickness of terrace "A" is ranging from 1 to 5 m, thickness of "B" varies and maximum thickness of 7 m is observed while "C" occur as living terraces along streams. During rainy season, the streams carry heavy bed load that is deposited along the stream courses as braided islands, point bars, channel bars or crevasse splays. The sediments deposited in one season are eroded away during later torrential rains. The sand bars along the coast can also be regarded as living terrace.

Detailed studies of these terraces material have been carried out and no neotectonic signature has been observed. At certain places erosional surfaces or paleo-topography gives an impression of abrupt truncation of outcrop, however no signature of deformation is associated. The cross-stratification in some sediments and sedimentary slopes at the basin margins give pseudo impression of tectonic tilt (Figure 5a, 5c). The sediments of Terraces "A and B" are cross-stratified and margins of the trough type cross- stratification give a pseudo impression of tilt in horizontal strata. The gravel / boulder beds seem to be tilted and abruptly abutted against older rocks. The sharp contacts of older rocks and gravel have been studied carefully and no deformation is associated with the sedimentary features (Figure 5b). The Mangopir area, Gadap area and catchment streams of Hub, Layari and Malir Rivers have been investigated and seismites could not be located in the recent Quaternary sediments.

Columnar joints in the gravels are a common feature along the steep or vertical stream banks. These joints are of non - tectonic origin and are developed by lateral dilation and influence of gravity (Figure 4d). The sediments lose their water content after deposition that result into reduction of volume and subsequent development of desiccation cracks. The gravel beds have undergone early stages of diagenesis as depicted by their lithification and cementation. The calcium carbonate bearing water that cemented the gravel beds percolated through the desiccation cracks and material filled in the cracks experienced relatively higher degree of cementation as compared to their surroundings. The cemented joints form a positive signature. The cemented lenses within the gravel beds (A & B) are also marked by joints of non - tectonic origin, as these joints are irregular and do not follow the trends of tectonic joints recorded in the Manchar Formation of Pliocene age. These joints were developed by load release and temperature changes.

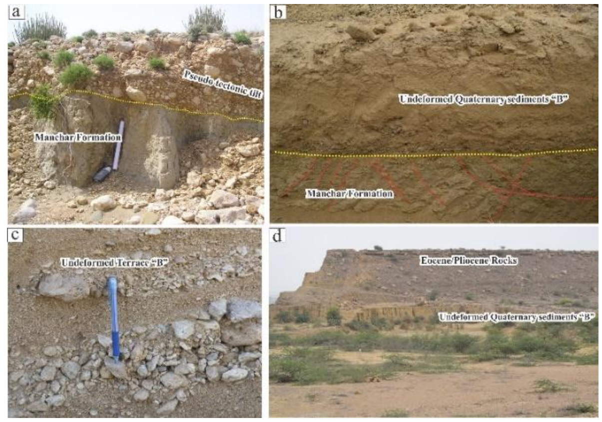

Figure 5. (a) cross-stratification and pseudo impression of tectonic tilt in the Terrace "A" layer lying over deformed sandstone of Manchar Formation of Pliocene age exposed at Mol Nadi area (b) Un-deformed Quaternary sediments over Manchar Formation Mangopir area exposed by trenching. The fractures/faults in the underlying sandstone are not extending in the upper terrace layer "B". (c) Cross-stratification in the recent sediments in a tributary of Hub River. (d) Un-deformed valley fill terrace-B exposed near Mangopir area characterized by columnar joints.

Sedimentation in some areas appears as abrupt truncation of sedimentary units along fractures or fault planes. These areas have been investigated in detail. The Quaternary sediments along or over the abrupt truncation are devoid of any signature of tectonic deformation. The sediments are horizontal and no shearing, jointing, offset or colluvial wedges are associated. The quaternary sediments along Khar Nadi, Konkar Nala and Badrah Nala have also been investigated and no tectonic deformation has been observed (Figure 3).

The Sona Fault cutting across the Jhil Range is located at the eastern margin of the study area. The dextral strike-slip fault is very noticeable, because the limestone of the Gaj Formation seems to be adjacent to the alluvium, forming a topographic discontinuity. The dextral slip brings Nari Formation of Oligocene age against Gaj Formation of Miocene age. The dislodged counterpart of limestone has been moved to southeast without a significant change in strike. The strata of Nari Formation lying under limestone in north and brought against limestone across the fault has been pedimented and covered with alluvium laid down by the streams draining the fault blocks with positive topography.

The streams across faults provide a cross-section for the investigation of fault. The alluvial layers on and along the faults do not record any signature of recent slip. Field evidences clearly show that no major or even moderate earthquakes have occurred in this area, because even moderate earthquakes events can produce surface cracks in the epicenter area, and such cracks are not observed in the quaternary sediments.

The EW trending active faults of the Katchchh Zone have been reported to extend up to Jhil Range [9], [19]. However, un-deformed Quaternary sediments over the Sonne Fault clearly reveal that the fault has not experienced any recent movement. The dextral faults of Jhil Range are part of characteristic strike-slip faulting of Kirthar Fold Belt caused by transpression. Instrumental seismicity of the area also support this idea.

Liquefaction Potential

The southern inner part of Karachi Arc drains into the Arabian Sea by a network of southward flowing seasonal streams (Figure 3). The drainage pattern of the area is dendritic, and the upper part of the main drainage system is located in the northern Hilly areas. The northern hilly terrain is mainly composed of limestone, shale with subordinate sandstone. The permeability of the rock units is low. The gradient and absolute relief in hilly terrain is high, so most of the rainwater is contributed to surface runoff. The tertiary and secondary streams of dendritic drainage pattern constitute tree like distribution and these streams join at the boundary of hilly terrain to constitute outlets, which turn into major streams of the area. Due to low rainfall and permeability, the groundwater in the study area is very low. The Terrace-A shows moderate infiltration; however, water is lost and contributed to runoff by interflow. Infiltration is low in Terrace-B due to cemented nature of the gravels. Shale is predominant lithology in the bedrock and cannot act as aquifer due to impervious nature. The sandstone units are well cemented and have limited exposure for recharge; consequently, these are also not good aquifers.

Young, loose and water saturated sand is supposed to be more susceptible to liquefaction (Terrace C). Unsaturated silty sand is one of the constituent of "Terrace B" sediments. Although "Terrace B" sediments do not fulfill the criteria strictly, yet these have been investigated in detail due to presence of finer facies. No paleo-liquefaction, slumping, and sand flow were observed in Terrace "B" Quaternary sediments. Liquefaction cannot occur in coarse facies, i.e. conglomerate and gravel. The finer phases are not sorted and contain gravel or pebble-sized debris. Cementation also minimizes the liquefaction. Because of the induration and lack of groundwater, bedrock cannot liquefy. All these characteristics observed in the field indicate that there is very limited possibility of liquefaction under seismic loading.

Seismicity

The catalogues of instrumental seismicity complied by ISC (International Seismological Center, UK.), NEIC (National earthquake information center, USGS) [29], [30] and MSSP (Microseismic Studies Program) [31] have been reviewed and effects of different seismogenic sources on the study area were examined. Based on these catalogues minor to moderate (3-5.9Mw) seismic events with occasional occurrence of strong (6-6.9Mw) and major (7-7.9Mw) earthquakes (Figure 6) characterizes the regional area around Karachi Arc.

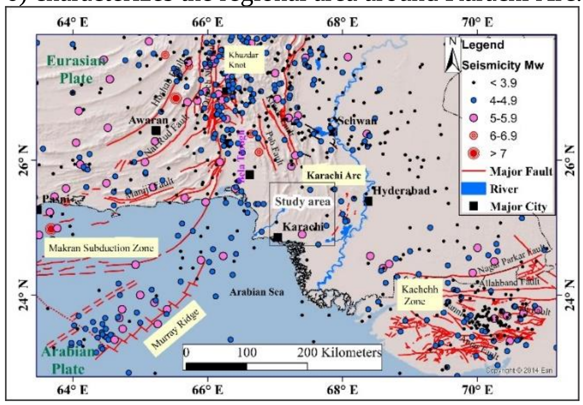

Figure 6. Regional seismicity around Karachi area [31], [32]

The central Katchchh Zone shows the highest frequency of earthquakes. Most earthquakes are light to moderate, but the Katchchh Zone has also experienced major earthquakes. Earthquake events occur frequently in central Katchchh and rarely in its western part. The Makran Subduction Zone and Murray Ridge area exhibits a cluster of epicenters. The events are very shallow to shallow and recent. Awaran earthquake of magnitude 7.7 (2013) also occurred along Hoshab Fault to the NW of study area while some epicenters are related to Nai Rud Fault (Figure 6).

The frontal and northern parts of Kirthar Thrust Fold Belt also show more occurrence of earthquakes while highest frequency of occurrence of seismic events in Kirthar Fold Belt is exhibited in northern most part. The northern Karachi Arc is characterized by moderate seismic activity but the active faults of this part such as Kirthar, Khud, Pab and Mor faults are not extending in the study area. Earthquake environmental effects such as, surface faulting, ground rupture, surface tectonic uplift, liquefaction and subsidence have not been observed in the study area during any major or strong events in the distant seismogenic sources such as Katchchh zone, Makran Subduction Zone, Murray Ridge and Ornach-Nal Fault Zone.

The Gadap, Hub, Malir and Layari River sites are characterized by few minor to light (< 4.9Mw) seismic events of crustal scale (Figure 7).

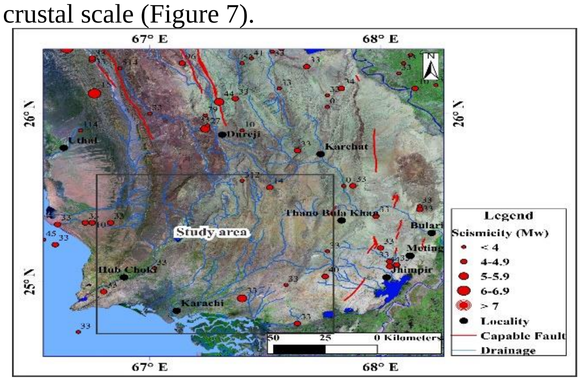

Figure 7. Landsat-ETM showing the seismicity of Karachi Arc area [31], [32]

Only one event of magnitude 5.3Mw (17th December, 1985) with focal depth more than 33km was recorded at location 67.4ºE and 24.9ºN [31]. The epicentral area has been thoroughly investigated to check tectonic disturbance within the recent sediments. The Quaternary sediments have not shown the existence of any distortion, off set in the sedimentary strata and paleo-liquefaction. Intensity survey also carried out in the epicentral area, which did not reveal a single report of damage to property within this area. The facts and investigations clearly show that modern seismicity of the area is low and could not cause any surface faulting or ground rupture even above the point of energy release i.e. at epicentral location.

Shear wave velocity (Vs30)

Lithology is one of the important factors that not only control morphology of the fault but also greatly influence the location of brittle deformation and seismicity. Propagation of seismic waves is influenced by variation in lithology. The stratigraphy plays an important role in propagation and attenuation of seismic waves as different rock units behave differently when seismic waves propagate through them. Reflection, refraction and attenuation of the seismic waves are also controlled by different lithologies. Most seismic damage is caused by ground amplification. Under the same magnitude and shallow depth, deformation will change with the change of ground stiffness. The brittle regime can accommodate aseismically a significant amount of earthquake effects [33].

The shear-wave velocity (Vs) of the area is a good indicator of the different types of lithological layers. The averaged shear wave velocity of up to 30 m depth (Vs 30) is an important parameter in building codes. It is widely used in site classification and plays very important role in the analysis of sites [34]. In general, a lower Vs-30 would be subject to a greater damage from an earthquake. The slope of topography or gradient is diagnostic of Vs 30, as competent materials mostly maintain a steep slope and younger soft sediments are deposited in the basins that lies in low gradient areas. The Vs 30 values of Karachi Arc are presented in Figure 8, which has been adopted from global Vs 30 database of Environmental System Research Institute (ESRI) and USGS [35]. According to Figure 8, the rocks that have shear velocity in the range of 320 to 520 m /s occupy the study area. By comparison with already defined criterion by the National Earthquake Hazards Reduction Program (NEHRP) the rocks of Gadap and Karachi area belong to Stiff and dense soil (Table 1).

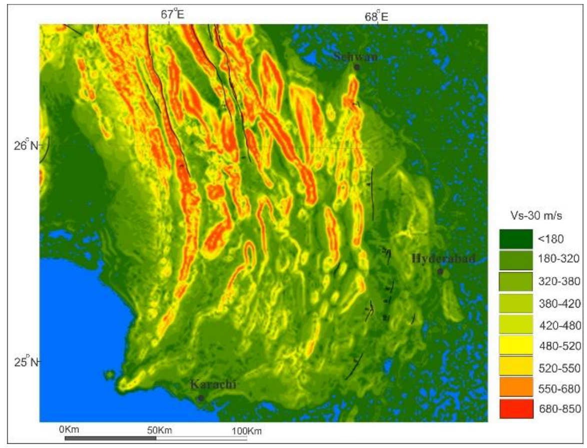

Figure 8. Shear wave velocity map of Karachi Arc (modified after [34], [35]

Category	Shear Velocity Vs 30	Type of Soil
A	>1500m/s	Hard Rock
B	760-1500	Rock
C	360-760	Very dense soil and soft rock
D	180-360	Stiff soil
E	<180	Soft clay soil
F	Liquefiable soil	

Table 1. Soil classification according to shear wave velocity “Vs 30” (adopted from [35])

Discussion

The Northern and frontal parts of Karachi Arc are characterized by minor to moderate seismic activity while the southern inner part is tectonically stable block. The capable faults such as Kirthar, Khud and Pab Faults characterized by moderate seismicity in the northern part of the arc are not extending southward in the study area. The undisturbed alluvial terrace deposits of three different cycles (A, B & C) clearly reveal the seismic stability of this geoblock in the Gadap, Hub, Malir and Layari Rivers areas. The instrumental seismicity of the area also supports this idea. Only minor to light (< 4.9Mw) events are located in the area with focal depth more than 30km that cannot be related to any fault (Figure 6 & 7). The basement generates occasional minor to light (3 to 4.9Mw) events but the absence of shallow seismicity, capable faults and neotectonic features suggest that the sedimentary cover in the area is presently inactive. No neotectonic activity have been found in the study area, neotectonic movement is usually related to active seismic area and active fault zone. The area under study is tectonically stable and the deformation has progressed towards east in the frontal part of Karachi Arc.

Active seismogenic sources such as Makran Subduction Zone, transform boundary fault (Chaman-Ornach-Nal Fault) and Katchchh Rift Zone are located about 230, 120 and 200km receptively around the area under study. Some major and strong seismic events occurred along these seismogenic sources such as the Makran event in 1945, Anjar event in 1956, Bhuj event in 2001, Awaran event in 2013 with magnitude 7.5Mw, 7.0Mw, 7.7Mw and 7.0Mw respectively. During these earthquakes, only ground shaking was observed in the Karachi and Gadap area and no EEEs such as neotectonic deformation features, surface ruptures and liquefaction were observed. The intensity survey in the study area also did not reveal any major damage to property during the earthquakes generated by distant seismogenic sources. The Jhil Range dextral faults have very limited strike length and the undisturbed Quaternary sediments along these faults have not experienced any recent deformation.

Conclusions

- Lithological studies of Quaternary sediments show no off set in the sedimentary strata, deformation, slumping and paleo-liquefaction. It is indicating that no major earthquakes have been occurred in Quaternary time.
- No seismogenic source is traversing the inner hind part of Karachi Arc. The arcuate fold-Thrust belt is convex to the east and the tectonic deformation has progressively been shifted to its eastern frontal part in Tertiary time.
- Any major or strong event along the Makran Subduction Zone, Katchchh Rift Zone and Ornach-Nal Fault Zone can cause minor to moderate seismic activity in the southern inner part of the Karachi Arc.

Acknowledgment

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References

1] Pavlides SB, (1989). Looking for a definition of neotectonics. Terra Nova 1:233–235. https://doi. 10.1111/j.1365-3121.1989.tb00362.x.

[2] McCalpin JP, (2009). Paleoseismology. Academic Press, vol. 95. https://doi:10.1016/S0074-6142(96)80076-3

[3] Cemen I, Yilmaz Y, (2017). Neotectonics and earthquake forecasting Eos 98. https://doi.org/10.1029/2018EO070105

[4] Serva L, Vittori E, Valerio C, Esposito E, Guerrieri L, Michetti AM, Mohammadioun BCG, Porfido S, Tatevossian RE, (2016). Earthquake Hazard and the Environmental Seismic Intensity (ESI) Scale. Pure and Applied Geophysics. https://doi.org/10.1007/s00024-015-1177-8.

[5] Vita-Finzi C, (2014). Misattributed tsunami 3: The Mw7.7 2013.9.24 SE Pakistan earthquake Proceedings of the Geologists' Association 125, pp.368–372. https://doi.org/10.1016/j.pgeola.2014.03.005

[6] Vita-Finzi C, (1986). Recent Earth Movements-An Introduction to Neotectonics. Orlando, FL: Academic Press 226.

[7] Liu Z, and Bird P, (2008). Kinematic modelling of neotectonics in the Persia-Tibet-Burma orogen Geophysical Journal International 172(2): 779–797. https://doi.org/10.1111/j.1365-246X.2007.03640.x

[8] McCalpin J, (2013). Neotectonics in Geographic information systems (GIS) and natural hazards pp. 730–732. https://doi.org/10.1007/978-1-4020-4399-4_252 https://doi.org/10.1016/j.geog.2018.03.004

[9] Sarwar G, Alizai A, (2013). Riding the mobile Karachi arc, Pakistan: Understanding tectonic threats Journal of Himalayan Earth Sciences 46(2): 9–24.

[10] Schelling DD, (1999). Frontal structural geometries and detachment tectonics of the northeastern Karachi arc, southern Kirthar Range, Pakistan Geological Society of America 328: 287–302. https://doi.org/10.1130/0-8137-2328-0.287

[11] Humayon M, Lillie RJ, Lawrence RD, (1991). Sulaiman Fold Belt and foredeep, Pakistan Tectonics 10(2): 299–324.

[12] Sarwar G, Dejong KA (1979). Arc Oroclines, syntaxes: the curvatures of mountain belt in Pakistan. In: Farah A, DeJong KA (eds) Geodynamics of Pakistan. Geological Survey of Pakistan, Quetta pp. 341–349.

[13] Banks CJJ, and Warburton J, (1986). Passive-roof duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan Journal of Structural Geology 8(3–4): 229–237.

[14] Ahmed R, and Ali SM, (1991). Tectonic and structural development of the eastern part of Kirthar Fold Belt and its hydrocarbon prospects Pakistan Journal of Hydrocarbon Research 3(2): 19–31.

[15] Nabi A, Liu X, Gong, Z, Pervaiz K, Ali A, Ashraf S, (2018). Episodic Uplift along a Quaternary Fault, A Signature of Active Deformation in Frontal Part of Karachi Arc, Southern Pakistan International Journal of Economic and Environmental Geollogy 9(3): 6-12. (http://www.econ-environ-geol.org/index.php/ojs/article/view/132

[16] Ahmed S, Solangi SH, Jadon SK, Adeel MZ, (2018). Tectonic evolution of structures in Southern Sindh Monocline, Indus Basin, Pakistan formed in multi-extensional tectonic episodes of Indian Plate Geodesy and Geodynamics 9(5): 358–366.

[17] Pervaiz K, Butt K A, Hussain J, Mehmood M, (2002). Peak ground acceleration assessment of an imaginary site at Hawks bay near Karachi Geological Bulletin University of Peshawar 35: 27–41.

[18] Hunting Survey Corporation L, (1961). Reconnaissance geology of part of West Pakistan Toronto, Ontario, Canada.

[19] Sarwar G, (2004). Earthquakes and the Neo-Tectonic Framework of the Kutch-Hyderabad-Karachi Triple

Junction Area, Indo-Pakistan Pakistan Journal of Hydrocarbon Research 14: 35–40.
[20] Banerji SK, (1957). Earthquakes in the Himalayan region, Indian Assoc. for the Cultivation of Science, Calcutta.
[21] Bakr MA, Jackson O, (1964). Geological Map of Pakistan,: 2,000,000 Geological Survey of Pakistan, Karachi.
[22] Menke W, and Jacob KH, (1976). Seismicity patterns in Pakistan and northwestern India associated with continental collision Bulletin of Seismological society of America 66: 1695–1711.
[23] Seeber L, Armbruster J, (1979). Seismicity of the Hazara Arc in Northern Pakistan: Decollement vs. Basement Faulting. In: Farah A, DeJong KA (eds) Geodynamics of Pakistan. Geological Survey of Pakistan, Quetta pp, 131–142.
[24] Quittmeyer RCC, Jacob KHH, (1979). Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran Bulletin of the Seismological Society of America 69(3): 773–823, 1979.
[25] Quittmeyer RCC, (1979). Seismicity variations in the Makran region of Pakistan and Iran: Relation to great earthquakes Pure and applied geophysics 117(6): 1212–1228. https://doi.org/10.1007/BF00876216
[26] Bilham R, Lodi S, Hough S, Bukhary S, Khan AM, Rafeeqi SFA, (2007). Seismic Hazard in Karachi, Pakistan: Uncertain Past, Uncertain Future," Seismological Research Letters 78(6): 601–613. https://doi.org/10.1785/gssrl.78.6.601.
[27] Malkani MS, and Mahmood Z, (2016). Revised stratigraphy of Pakistan, 127ed. Quetta: Geological Survey of Pakistan.
[28] Shah SM, (1991). Lithostratigraphic units of the Sulaiman and Kirthar Provinces, lower Indus Basin, Pakistan, no. 519. Geological Survey of Pakistan Information Release.
[29] International Seismological Center (ISC).http://www.isc.ac.uk/, Accessed on Dec. 24, 2018.
[30] National Earthquake Information Center (USGS). http://earthquake.usgs.gov/regional/neic/, Accessed: Dec. 20, 2018.
[31] Microseismic Studies Program (MSSP). Microseismic network by Pakistan Atomic Energy Commission 2018.
[32] International Seismological Centre, On-line Bulletin, Internatl. Seismol. Cent. Thatcham, United Kingdom, 2016. http://www.isc.ac.uk,
[33] Perfettini H, Avouac JP, Tavera H, Kositsky A, Nocquet JM, Bondoux F, Chlieh M, Sladen A, Audin L, Farber DL, Soler P, (2010). Seismic and aseismic slip on the Central Peru megathrust Nature 465:78-81. https://www.nature.com/articles/nature09062
[34] Wang SY, Wang HY, and Li Q, (2017). An alternative method for estimating Vs(30) from a shallow shear-wave velocity profile depth Soil Dynamics and Earthquake Engineering 99: 68–73. https://doi.org/10.1016/J.SOILDYN.2017.05.002
[35] National Earthquake Hazard Reduction Program NEHRP, (2003). https://earthquake.usgs.gov, Accessed: Dec. 31, 2018.