Geotechnical applications for geohazards mitigation in dry land environment of Thar Desert, India

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Abstract

Dry land environment of Thar Desert in western India is characterised by sparse and highly variable rainfall, extreme variation in diurnal and annual temperatures and high evaporation, besides the typical arid-semiarid landscapes. Thar Desert forms the eastern-most extension of the vast Sahara- Arabian deserts. Thar Desert is dominated by southwest monsoon winds that despite carrying precipitable moisture fail to bring rains in this region due to atmospheric circulation pattern and abnormal sinking of atmospheric air masses. Nevertheless, the monsoon winds have continued to control the aeolian dynamics in the Thar region that created a variety of depositional dune- interdune forms and other erosional or deflationary landforms. Formation of sand dunes depend essentially on the strength and duration of high speed winds, sediment supply, moisture content and surface conditions. It is noteworthy that occurrence and distribution of fossil dunes in presently vegetated eastern desert margin areas with relatively higher rainfall (>500 mm annual rainfall) indicate the spatial expansion of former frontiers of the prevalent aridity and ecological fragile conditions of the terrain.

There have been persistent efforts to tame the harsh living conditions for human occupation of the Thar Desert since pre-historic times. Thar Desert has been one of the most populated dry land terrains in the world. Inhospitable terrain has several inherent geotechnical and geological hazards that include: extreme weather flash flooding events along the ephemeral drainage courses; mobility of sand leading to obstruction of paths and roads and enhanced siltation of water courses such as canals and water reservoirs; subsidence due to piping and tectonic causes (sites are particularly vulnerable where major lineaments intersect), higher propensity for gully erosion of silty-sand deposits, shrinking and swelling Tertiary bentonitic clayey deposits in western Thar, etc. Aspects of desertification and occurrence of brackish/ chemically contaminated groundwater with higher contents of fluoride, nitrates and calcium carbonates, pose problems to be addressed and demand sustainable geotechnical solutions. This paper provides an overview and attempts to enumerate inherent propensity of Geohazards and Geoenvironmental problems prevalent in the dry land conditions of Thar Desert and application of geotechnical knowledge and considerations with case studies that have been adopted and prognosticated for safe and sustainable development of the aridity affected region.

Nevertheless, geotechnical considerations that have facilitated inter-basin transfer of perennial Himalayan fresh-water of the Satluj River through Indira Gandhi Nahar Priyojna thereby addressing the scarcity and availability of potable quality water for the human settlements within the Thar Desert, impact of such huge import of water and consequent changes in water balance both in surface and groundwater regimes in ecologically fragile environment need to be assessed for creating vulnerable sites for inducing land subsidence and corrosive geochemical conditions adversely affecting life of construction material, etc.

Several major lineaments have been inferred that traverse through the region and support neotectonic movements, potential for seismic hazards, particularly in western and northern parts of the Thar Desert that have also shown subsurface dislocations Tertiary formations and occurrence of pull-apart basins hosting progressive thickening of Quaternary and sedimentary deposits. Besides formation of gypcrete and calcrete deposits are reported that form impervious layers hindering free percolation of surface water and favouring water-logged conditions.

The paper also discusses impacts of indiscriminate and adverse anthropogenic interference with the subsoil, excessive mining of ephemeral riverside sandy material and rapidly changing geologically inappropriate land-use practices that may aggravate desertification, trigger Geohazards and pose difficult challenges for disaster management.

1. Introduction:

Thar Desert is characterised by arid-semiarid ecologically fragile environment and occupies a unique tectonic-sedimentary domain in north-western [NW] India. It is confined essentially to West Rajasthan Shelf [WRS]. The tectonic disposition and basement configuration of intra-cratonic basins and sedimentary formations here range from the Precambrian Delhi Super group in the east, Late Proterozoic to Early Palaeozoic Marwar Super group of sedimentary rocks in the middle, to Mesozoic and Cainozoic cover sedimentary formations on the western and north-western fringe areas in western parts of Rajasthan and Haryana in north-western India. It is remarkable that successive geological young age of sedimentary formations is mapped from the Aravali Hill ranges on the east to the sand covered rocky plains on the west in the Thar Desert. Distinctive geomorphic expressions and relative lowering of relief are also deciphered and recorded in an east-west transect along northern parts of the Thar Desert (Wadhawan, 2010).

Palaeogene rocks in the Jaisalmer Basin of western India are represented by sandstone - shale sequence of the Sanu Formation (Palaeocene). These are capped at places by sand-clay/ bauxitic clays and pisolitic laterite. These in turn are overlain by the fossiliferous limestone-bentonitic clays and fullers' earth sequence of the Khuiala Formation (Lower Eocene) and the younger limestone-shale succession of Bandah Formation (Lower to Middle Eocene). Calcretised gritty conglomerates, ill-sorted and indurate pebbly-gravelly, ferruginous sandy and clayey fluvial deposits in the area are categorised as the Shumar Formation of Neogene (Plio-Pleistocene)/ basal Quaternary age. Geological mapping of Palaeogene-Neogene formations in NW India have helped reconstruction of the palaeo-geographic shore-line limits of the Tertiary sea. Such inferred basement disposition ostensibly had a bearing on the source of evaporate minerals and continuing salinity aspects of the present day inland lakes and playas in the region. Successive deepening of the sedimentation basin is also inferred from the geological logs prepared during the drilling probes for the Potash Mineral Investigation by Geological Survey of India in NW India (Virender Kumar et al., 2007).

2. Geohazards in Thar Desert:

Geohazards related to geostructures in dry land environment of Thar Desert include:

i) Extreme weather events, flash flooding and excessive siltation of reservoirs/ water retention ponds.
ii) Subsidence due to geotectonic setup and consolidation and super-saturation.
iii) Water logging due to absence of surface drainage and impeded subsurface flow.
iv) Wind erosion, deflation and sedimentation.
v) Greater propensity of gully erosion and piping / slumping of sand-silt strata.

vi) Geomaterials: in situ cracking/ shattering of geomaterials due to extreme diurnal temperature variations, leading to seepage and leakages from engineered geostructures.
vii) Salinity of soil and water and salt weathering.
viii) Occurrence of shrinking and swelling Tertiary bentonite clayey deposits in western Thar Desert.

i) Flash Flooding and Excessive Siltation of Reservoirs:

Extreme weather phenomenon, cloud burst with abnormal heavy rainfall and consequent flash flooding events along the otherwise ephemeral drainage courses is characteristic feature in dry land environment. River Luni is the only integrated drainage system in the Thar Desert. There have been instances of flooding due to unusually heavy rainfall in the catchment area, which was catastrophic particularly during July 1979 (Dhir et al. 1982). Besides excessive water discharge, huge sediment load is also transported during such events which results in siltation, reduction of the reservoir capacity and choking of the drainage and creation of water logged areas. Sharma et al. (1982, 1984); studied severe floods in the Luni basin and Kale (1999) and Kale et al. (2000) investigated slack water flood deposits in a back-flooded tributary of the Luni near Sindari gorge in Barmer district in the Thar Desert and inferred at least 17 mega-flood events in the past millennium. The consequent changes in the river morphology were also recorded. Another catastrophic event of cloudburst and very heavy rainfall in 2007 was experienced in Kwas area near Barmer where owing to absence of integrated drainage lead to inland flow towards local depressions and flooding of human settlements. Occurrence of thick gypcrete and carbonate rich hardpans in the area also contributed towards inhibited vertical drainage and percolation of water through the otherwise sandy deposits in the area. Engineers and engineering geoscientists must adopt an integrated approach and take such meteorological and terrain conditions into account while planning and designing geotechnical river training and constructing causeways, bridges and other structures on such drainage courses for safe and sustainable utilisation of available resources and risk reduction.

ii) Subsidence due to Geotectonic Setup, Consolidation and Super-saturation:

Thar Desert is traversed by several major lineaments that have been neotectonically active and shaping the geomorphic and geologic evolution of the dryland environment (Bakliwal and Ramsamy 1987; Kar, 1988a & b; Virendra Kumar and Wadhawan, 2001). Important amongst these are outlined in the following paragraphs.

Luni - Sukri Lineament:

It is a composite lineament system comprising a set of sub-parallel curvilinear lineaments, traversing east - west from Rann of Kachchh through the NE -SW trending Luni river and extending through Aravalli gap and beyond northeast of Ajmer. It delimits a rectilinear fault bound configuration of the Rann of Kachchh. It also defines a sharp contact between the Late Quaternary stabilised parabolic dune fields and the coastal sabkha environment of deposition along the Great Rann of Kachchh that experiences recent reactivation and repeated seismic activity. Ramsamy et al. (1991) interpreted a major NE - SW trending Quaternary arch along the Luni - Sukri lineament. It is also characterised by a graben along its crest and its extensions are manifested as tear faults in the Siwaliks towards the NE along the Himalyan foot-hills.

Jaisalmer - Barwani Lineament:

It is about 1000 km long tectonic lineament trending NNW - SSE to NW - SE. It is defining the southwestern boundary of the Aravallis northwest of Ahmedabad and show contrasting elevations and fault-line scarps within the Himatnagar Sandstone of Mesozoic age. It abruptly truncates the rocks of the Delhi Supergroup near Vadnagar - Palanpur in north Gujarat plains and marks western margin of the Tertiary basins north of Barmer and its NW extensions have been recorded to coincide with the Jaisalmer - Mari arch in the Afganistan region as well (Dasgupta, 1975). Further it coincides with major fault within Mesozoics sedimentary formations of the Jaisalmer area and delimits Gravity High Zone along NE of it and Low Gravity Zone on the SW of it implying thicker fill of sedimentary rocks in the SW. It also coincides with recently reactivated Kanoi fault along which earthquake of intensity 6.3 on Richter scale was recorded on 8th November 1991 (Dharman et al., 1993). Several circular features in the region are interpreted bearing direct linkage with this lineament as surface manifestations of the Tertiary domes and basins (Bakliwal and Ramasamy 1983).

Lathi - Rajkot Lineament:

It is estimated to be over 500 km long, N - S aligned curvilinear tectonic lineament. It traverses the Deccan volcanics of Saurashtra (Mesozoic- Cainozoic) and occurs as fault zone within the Mesozoic sedimentary rocks in the Kachchh and Jaisalmer region and cuts through the dune field's of Late Quaternary age thus implying its neotectonic reactivation. Ramasamy (1999) attributed the curvilinear nature of this lineament to be a reflection of the post-collision plate-tectonic phenomenon during Neogene all along its disposition.

Raisinghnagar-Tonk Lineament:

It is about 400 km long, NW -SE trending lineament and demarcates the dune covered pediplain over pre-Aravallis of the Jaipur region from dune free Bhilwara region. It delimits subsidence on north and northeast and confirms relative deepening of the Neogene/ Quaternary continental sedimentation in the Ghaggar basin along the northern margin of the Thar Desert.

Sardarshahar Fault:

It is aligned along N - S to NNE –SSW with a confirmed down-throw of over 400 m on the west, as recorded in the Quaternary sediments (inferred upto 700 m during subsurface investigations for potash mineralisation in Ghaggar basin). It is inferred to be active fault with frequent mild earthquakes recorded at seismograph observatory located at nearby Churu.

Considering geological, neotectonic - seismic set-up and geothermal gradient characteristics, the Thar Desert area in western India is categorised as the Quaternary tectonic domain undergoing extensional stress fields manifested in a series of normal faults and graben structures with moderate seismic activity and geothermal heat flow attributes. Such neotectonic movements have also been considered responsible for deviation of the river courses originating in the Himalayas such as the Saraswati, Indus, Sutlej and Yamuna, etc., affecting considerably the Mohanjo Daro and Harrapan civilisations and subsequent human settlements in the region. Post-Tertiary reactivation of Mari - Jaisalmer - Barwani lineament and earthquake ruptures/ dislocations along the Kanoi Fault in Jaisalmer area in 1991 confirmed continuing neotectonic activity (Dharuman et al., 1993).

In addition to the above lineaments, a wide variety of neotectonically induced geomorphic expressions have been recorded in semi-arid and arid drylands of Rajasthan and Gujarat such as lineament controlled alignment of certain dune fields and abrupt truncation of the different dune morphologic domains, reactivation of Kanoi Fault during the earthquake of 8th November, 1991 in Jaisalmer region (measuring 6.3 on Richter scale), unequal thickness of Quaternary formations in the contiguous blocks in northern and central Thar Desert, distinctive shearing and faulting of Quaternary formations and dislocation of Tertiary and overlying Quaternary strata inferred from subsurface probes in Bikaner - Ganganagar region, preferred and linearity controlled orientation of drainage courses, such as the Luni and Sabarmati river systems, etc. Several faults showing evidences of recent reactivation are manifested as prominent curvilinear tectonic lineaments, for instance, along the Luni - Rupangarh, Nawan - Alwar, Didwana - Dausa, etc. Intersections of these weak zones have created the pull-apart basins occupied presently by the salt lakes of the Didwana, Kuchaman and Sambhar (Sinha Roy, 1986; Dassarma, 1986). Further, it is reasonable to infer that the persisting salinity of these lakes could be linked through the tectonic lineaments/ shears with the subsurface halite bearing perennial source - the Hanseran Evaporite Sequences in the Bikaner - Nagaur - Ganganagar basin, geologically correlated to the Marwar Supergroup of rocks (Virendra Kumar and Wadhawan, in GEOSAS - 2001).

Geotechnical appraisal and causative factors of several reports of land subsidence in urban areas including those in Thar Desert were enumerated by Kasliwal, et al., 1990; Kasliwal, 2010. It is ascertained that Thar experiences mostly low intensity earthquakes (less than 4.5magnitude), primary cause for land subsidence is super-saturation of subsoil and consolidation/hydro compaction of clastic sediments and reduction in cohesion and bearing strength thus leading to flowage and foundation failure.

iii) Wind Erosion, Deflation and Sedimentation:

Wind erosion, intense deflation blow-outs and mobility of sand leading to obstruction of paths and roads and enhanced siltation of water courses such as canals and water reservoirs is prevalent in the western Thar Desert. Here it occurs seasonally during the hot dry months and is understood as normal processes of desertisation. However, such hazards assume challenging dimensions where overexploitation of land resources and inappropriate land uses particularly in ecologically fragile desert margin areas. Appropriate planning and designing, route alignments of engineering structures and creation of wind breakers, plantations to retard wind velocity and induce sand deposition and adopting measures to stabilise dunes in the upwind areas are some suggested remedial strategies that need to be applied for comprehensive land management in Thar Desert.

iv) Indira Gandhi Nahar Priyojna and aspects of Geohazards:

Besides strategic considerations, the scarcity and availability of potable quality water for the human settlements within the Thar Desert was addressing through application of Geotechnical knowledge that facilitated inter-basin transfer of perennial Himalayan fresh-water of the Sutluj River through construction of different stages of the canal and its distributaries network under the ***Indira Gandhi Nahar Priyojna*** **[IGNP].** Desolate and barren desert landscape has been transformed into a green vegetated region through the use of perennial sweet water of the IGNP main Canal which is 649 km long up to Mohangarh in Jaisalmer district. In addition to meeting drinking water requirements of the major cities and towns, it provides irrigation to about 525,000 ha of land in Ganaganagar, Bikaner, Jodhpur and Jaisalmer districts that constitute the heart of the Thar Desert. In order to prevent wind erosion and sand deposition, about a kilometre wide green belts of trees have been planted all along the main canal route. However, as there is no natural drainage in this part of the Thar desert region, threats of water-logging and salinity are prevalent owing also to occurrence of hard calcrete and gypcrete pans near surface in dryland. Nevertheless, impact of such huge import of water [estimated to be 57901 Mcm] and consequent changes in water balance both in surface and groundwater regimes in ecologically fragile environment need to be assessed for understanding land-water interactions thereby creating vulnerable sites for inducing land subsidence and corrosive geochemical conditions adversely affecting life of construction material, etc. It is imperative to learn from success and failure of major irrigation projects in other deserts of the world for application of geotechnical solutions for sustainable use of natural and engineered resources. Interpreting remote sensing data products particularly delineating tectonic weak-zones and lineaments intersection have helped decipher certain pull-apart basins that are inherently vulnerable to land subsidence and water-logging geohazards (Figure 1). Geotechnical avoidance of such vulnerable areas is recommended to obviate recurring application of remedial measures.

v) Greater Propensity of Gully Erosion and Piping / Slumping of sand-silt strata:

Piping term is applied to phenomenon where subterranean channels are developed by moving water through the incoherent sediments as a form of subsurface discharge of sediments mixed with water. It poses hazard of subsidence to engineering structures.
Subsidence due to piping and tectonic causes [sites are particularly vulnerable where major lineaments intersect] and higher propensity for gully erosion of silty-sand deposits are commonly reported from Thar where surface water has been imported and utilised through canals, distributaries and pipe lines. Regular monitoring and detailed understanding of the geomorphology of the area is imperative for applying suitable geotechnical remedial measures.

vi) Salinity of Soil, Groundwater and Salt Weathering:

Inland drainage, high evaporation and retarded groundwater movement is characteristic of the dry land environment of Thar Desert where abnormal concentrations of various salts is observed in vertical and lateral profiles of desert soils, interdune depressions, playa and saline lakes (Wadhawan and Sharma, 1997; Wadhawan et al 2004). As the capillary rise of water in surface sediments is generally very pronounced and leads to concentrations of salts in upper parts of soil. Most common salts include calcium carbonate ($CaCO_3$), hydrous calcium sulphate ($CaSO_4$. $2H_2O$) and sodium chloride (NaCl) in soluble and precipitable forms. Salt weathering processes attack and disintegrates and aids in decomposing the materials used in the geostructures, roads and buildings leading to reduction in their strength and durability. It is observed that the damaging effects of these salt aggressions are spatially variable owing to several geofactors including differing susceptibility of construction material to salt reactions and the workmanship. Geotechnical remedies lie in adequate planning and designing, observing high standards of construction and workmanship as per BIS Codes, use of sulphate resistant cement, building stones and aggregate with low initial salt content and avoiding creation of cracks/ gaps and crevices where deposition of salt would be facilitated, high quality control and regular monitoring for initiating corrective measures, etc.

vii) Shrinking and Swelling Tertiary Bentonite Clayey Deposits in western Thar:

Several horizons of bentonite clayey deposits are reported and have been mapped as upper Tertiary deposits in parts of Jaisalmer district in western parts of Thar Desert (Laul et al., 1984; Pareek, 1984). Bentonite is an assemblage of clays, rich in layered minerals belonging to illite, and montmorillonite (fullers' earth) and smectite groups. It is notorious for its capacity to absorb and loose water and thus swell or shrink according to variations in temperature and amount of water present in a system. Occurrence of such bentonite clays as foundation substrata has been reported to be damaging several segments of the Canal and its distributaries network in western parts of the Thar Desert.

3. Geomaterials for Construction in Dry land Environment:

Natural material needed for construction of engineering projects and geostructures such as irrigation schemes, canals and roads in dry land environments fall in the following four categories: hard rocks, sand and gravel; clays (for building bricks and tiles for lining of canals and fillers as impervious buffer) and mono-mineralic rocks/ minerals such as gypsum and limestone. Construction material is needed in bulk quantities and become expensive owing to transport costs if not available locally. Scarcity of these resources poses inherent difficulties in dry land environments. However, Thar Desert region is richly endowed with hard rocks belonging to the Malani Suite of Igneous rocks (variety of rhyolite and granite), as the aggregate of these rocks have high compressive strength and do not contain free mica or other salts that may decompose on weathering and cause damage due to subsequent volumetric changes by reactions with cement. It well recognised in aridity affected desert environment that accurate estimation of the limit load for geostructures such as tunnels, dams, highways and foundations is further complicated by the fact that the geomechanical behaviour of geomaterials is dilatants, nonlinear, heterogeneous, anisotropic and dependent on the pore pressures and ground water conditions. Concerted efforts in geotechnical R & D are required to arrive at reasonable and acceptable cost-effective solutions.

Rich cement grade limestone deposits of Tertiary (the Bandah and Khuyala Formations) and Eocambrian age (the Bilara Group of the Marwar Supergroup of rocks) are being utilised for manufacture of quick-lime and cement. Several locally available calcrete and hard pan clayey *Kankar* deposits [locally called *Murdh*] are found to be geotechnical suitable as sub-base or base layer for surfaced roads. Potential occurrences of such deposits were delineated based on detailed geomorphological mapping of the selected and specific regions in Thar Desert as excellent transport corridors and road construction material for rural connectivity and strategic requirements (Basu and Duara B. K. 1982; Basu, J. K., 1985; Wadhawan, et al., 1999 and Wadhawan, et al., 2004). River borne material deposited by ephemeral and mostly dormant inland flowing fluvial systems in dryland environment of Thar Desert provide fine grade aggregates, gravel and silt either as braided channel bedload or as palaeo-fan/ colluviums and bajada deposits derived from the rocky ridges of Jodhpur sandstone or Malani rhyolites. Geoenvironmental and geotechnical criteria for selection of river deposits for construction material were elaborated by Wadhawan et al., 2013. Besides, gypcrete and calcrete deposits occur as playa and lacustrine environments at several places in Thar Desert (Wadhawan and Sharma, 1997; Sundaram, and Rakshit, 1994). These form impervious layers hindering free percolation of surface water and favouring water-logged conditions.

4. Discussion and Conclusions:

Ecologically fragile dryland environment in Thar Desert offers a unique geoscientific set-up and provides challenging engineering situations and opportunities for application of geotechnical knowledge for sustainable regional development.

I. Detailed geomorphological mapping of the terrain will improve understanding of the available resource potential and help delineate occurrences of locally available suitable Geomaterials.
II. As the geomechanical behaviour of geomaterials is dilatants, nonlinear, heterogeneous, anisotropic and dependent on the pore pressures and ground water conditions. Concerted efforts in geotechnical R & D are required to arrive at reasonable and acceptable cost-effective solutions.
III. In the absence of natural integrated drainage in the Thar Desert region, threats of water-logging and salinity are prevalent owing also to occurrence of hard calcrete and gypcrete pans near surface in dryland.
IV. It is imperative that impact of such huge import of water [estimated to be 57901 Mcm] through the IGNP canals and irrigation distributaries and consequent changes in water balance both in surface and groundwater regimes in ecologically fragile environment need to be assessed for understanding land-water interactions thereby creating vulnerable sites for inducing land subsidence and corrosive geochemical conditions adversely affecting life of construction material, etc. It is imperative to learn from success and failure of major irrigation projects in other deserts of the world for application of geotechnical solutions for sustainable use of natural and engineered resources.

V. Geotechnical remedies lie in adequate planning and designing, observing high standards of construction and workmanship as per BIS Codes, use of sulphate resistant cement, building stones and aggregate with low initial salt content and avoiding creation of cracks/ gaps and crevices where deposition of salt would be facilitated, high quality control and regular monitoring for initiating corrective measures, etc.

VI. Engineers and engineering geoscientists must adopt an integrated approach and take such meteorological and terrain conditions into account while planning and designing geotechnical river training and constructing causeways, bridges and other structures on such drainage courses for safe and sustainable utilisation of available resources and risk reduction.

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WATERLOGGED AREAS AS WETLAND ALONG IGNP IN BIKANER DISTRICT