ABSTRACT

The Kashmir Nappe Zone is an asymmetrical synclinorium flanked by the Panjal Thrust and the Zanskar thrust, with the oldest stratigraphic basement floor composed of the Precambrian Salkhala series and the Dogra slates (Wadia, 1931). The sedimentary sequence is formed by the Panjal Volcanics (Panjal trap and Agglomeratic slates) and Triassic limestone. The sediments covering the synclinal basement of Kashmir are mainly of two types, namely, Plio-Pleistocene Karewas and the Holocene/Recent Alluvium (Wadia, 1931). The Alluvial plains/lowlands along with the Karewa highlands/terraces form an interesting combination of geological formations within the Kashmir valley. The surrounding hills, mountain ranges, the presence of wetlands, reclaimed swamps, and rivers contribute to the variability of soils within the region.

IS Code (IS 1893: 2016) designates seismic zones IV and V to the areas in the Kashmir valley. The region has suffered huge damages owing to devastating earthquakes in the past, the most significant being the M_w 7.6 2005 Kashmir earthquake. Landslides, flooding of rivers, ground fissures and cracks, huge ground movements, damage to built structures, and loss of life have been reported in previous earthquakes in Kashmir (Iyengar et al., 1999; Ahmad and Shafi, 2014). Moreover, liquefaction has occurred in many regions of Jammu and Kashmir both in the recent and the historic past during earthquakes (Bhat et al., 2005; Sahoo et al., 2007; Hough et al., 2009; Sana and Nath, 2016).

In view of the distinctive characteristics of the Kashmir region, the primary purpose of this study is to understand the behaviour of the deposits in the Kashmir Region and develop simplified recommendations aimed at guiding the selection of suitable foundation levels and/or ground improvement levels for future constructions within the area. The proposed guidelines are intended to assist planners and designers in taking appropriate decisions for the urbanisation and future town planning endeavours in the region. This study involves geotechnical and geological characterization of the region, assessment of seismic hazards, estimation of dynamic parameters of the deposits using geophysical tests, seismic site characterization and ground response analysis, liquefaction hazard assessment, bearing capacity assessment, and ultimately the determination of vulnerability zones.

Extensive geotechnical data for about 700 locations within the Kashmir valley was used to characterize the geotechnical properties of the soils in this region. The variation of the geotechnical properties within the geological units especially Karewa highlands and Alluvial

floodplains has been studied in detail. Maps for the various soil properties have been created to understand their spatial distribution within the region. The geotechnical database was combined with the geological information for the region to create seven transverse and five longitudinal comprehensive 2D cross-sections for the basin.

Seismic hazard assessment for the Kashmir region. using deterministic as well as probabilistic approaches has been performed. An earthquake catalogue has been prepared and subsequently, seismicity parameters (a, b-value, λ, M_C, and m_{max}) have been estimated for the complete Kashmir region. Spatial distributions for the peak ground acceleration (PGA) and peak spectral acceleration (PSA) at 0.2s and 1s have been presented in the form of contour maps at bedrock. Seismic zonation of the Kashmir region was carried out based on the distribution of PGA within the region. The Kashmir region has been divided into five zones ZA-ZE representing high to low seismicity zones. The mean PGA values derived from PSHA at 2475-year return period for the five zones are 0.514g, 0.456g, 0.379g, 0.258g, and 0.175g. The southern, northwestern and northernmost parts of the region including the districts of Pulwama, Shopian, Kulgam, and Budgam fall under high seismicity zones. In contrast, the central parts including the districts of Bandipora and Ganderbal fall under low seismicity zones. Seismic hazard curves, uniform hazard response spectra (UHRS) and disaggregation results have been presented for each of the ten districts as well as for each seismic zone

An extensive geophysical testing program was carried out which included tests at ~192 sites to determine dynamic soil parameters within the complete Kashmir region. Multichannel Analysis of Surface Waves (MASW) was performed to estimate shear wave velocity (V_s) and microtremor records were obtained to estimate the frequency response of the soil deposits. The V_{S30} (average shear wave velocity over 3m depth) varies from as low as 150-200m/s in the alluvial floodplains to as high as 350-500m/s in the Karewa highlands. On the other hand, the hilly regions show much higher values of ~500-900m/s indicating a close relationship of V_{S30} with geology. The horizontal-to-vertical-spectral ratio (HVSR) response of the soils is varied, with fundamental frequency (f_0) ranging from as low as 0.2Hz in the deep sedimentary deposits to as high as 20 Hz in the shallow region. Different groups of HVSR curves – clear, broad, and flat peaks were observed in the Kashmir region.

With regards to the exceptional nature of the physiography as well as topography of the region, the results obtained through geophysical tests suggest high variability. Fractured zones in fault lines have been detected in this study showing very high amplification due to the low velocity characteristics. Such zones may contribute to concentrated increased hazard when subjected to favorable earthquake ground motions and must also be considered during the urban planning and construction processes. Joint inversion analysis of the dispersion and HVSR curves has been conducted to estimate the depth of the bedrock depth in the region. It is concluded that the Karewa deposits and Alluvial plains are deep sedimentary deposits with depths as large as 900-1300m. The shear wave velocity of the bedrock below the soft sediments is estimated to be ~1100-1900m/s. The depth of bedrock is shallow in the hills and mountains.

Although the conventional single-proxy approach for seismic site characterization has the advantage of being simple and based on a readily available parameter (V_{S30}), it neglects various key elements of site response (Castellaro and Mulargia, 2014). The results of the field testing in Kashmir reveal glaring anomalies in the behaviour of the deposits in the region pointing out the insufficiency of the parameter V_{S30}. V_{S30} completely lacks information pertaining to the actual variation of V_S with depth, the frequency dependence of response, and the influence of soil below 30m depth which can be critical in deep sedimentary deposits (Regnier et al., 2014). Consequently, a site classification scheme has been proposed in this study for the Kashmir region by modifying specific parameter ranges in Di Alessandro et al. (2012) classification which is based on the predominant frequency of the site, the HVSR shape, and V_{s30}.

1D nonlinear ground response analysis has been conducted for the 192 sites in the Kashmir region. The ground response analysis of the soils conducted in this study considers the actual depth of geological bedrock determined from the joint inversion analysis as the depth of input motion. The nonlinear behaviour has been captured by conducting a parametric study utilizing input motions of varied intensity (PGA) grouped into five intensity groups (M1-M5). Amplification factors have been recommended for each intensity group and each geological unit. The response spectra at the surface reveal that the deep deposits amplify the long-period (low-frequency) motions and deamplify the short-period (high-frequency) motions. This result is crucial since the impact may be particularly detrimental to tall buildings having longer fundamental periods due to the double resonance phenomenon in the soft soil deposits subjected to low-frequency earthquakes.

The expanded Srinagar Metropolitan Region – Greater Srinagar – in the Master Plan-2035 by the Town Planning Organization of Srinagar was selected for further detailed analysis including liquefaction hazard analysis and bearing capacity assessment. The liquefaction hazard assessment has been conducted considering the $PGA_{bedrock}$ corresponding to 2475 years return period (10% probability of exceedance in 50 years). Both pseudo-probabilistic (PP), as well as simplified performance-based methods (sPBEE), have been used and the results from both methods have been compared. Simplified performance-based liquefaction triggering procedure allows engineers to adopt a risk-targeted strategy by utilizing the return period of liquefaction in place of the ground motion. Reference loading parameter maps at seven selected return periods (108, 225, 475, 1033, 2475, 4950, and 20000 years) were developed. Liquefaction hazard index (LHI) was estimated using three parameters, namely settlement (S), liquefaction potential index (LPI), and liquefaction severity number (LSN). Finally, LHI based zonation was conducted for the study area. It was concluded that young Holocene alluvial sediments deposited in low-energy fluvial environments are the most susceptible to liquefaction having the lowest factor of safety (<1) and the highest potential of liquefaction (~0.99). The sPBEE method in general overestimates the hazard in terms of settlement in moderate to high seismicity areas.

The bearing capacity of the soils at each site in the Greater Srinagar region has been assessed both under static as well as seismic loading conditions. The ultimate bearing capacity is in general less than 300kPa in the Jhelum floodplains indicating the low strength of the soils. The Karewa highlands and hills show much higher capacity (>300 kPa). The seismic bearing capacity ratio (SBCR) computed using Richards et al. (1993) and Choudhury and Subba Rao (2005) methods are lower (<0.86) in the Karewa deposits suggesting the critical nature of these deposits under seismic loads. Consequently, the bearing capacity hazard index (BCHI) has been determined at each location.

Finally, vulnerability zones (VZ-A to VZ-D) have been defined based on the integrated hazard index (IHI) computed by combining LHI and BCHI through the analytical hierarchy process (AHP). The Jhelum floodplains fall within the most critical category of VZ-D with the highest hazard of liquefaction and low bearing capacity. Deep foundations (e.g., piles) and deep ground improvement is imperative in the plains to prevent excessive settlements and bearing capacity failures in structures. Site-specific issues of lateral spread need to be assessed on land near the banks of rivers.

The Karewa highlands fall in categories VZ-B and VZ-C showing lower potential for liquefaction and good static bearing capacity yet significant chances of significant bearing capacity reduction during earthquakes. Integrated use of shallow foundations and ground improvement may be effective solution in such areas. There is an added hazard of landslides and slope stability issues in the highlands which needs to be duly considered in foundation design.

The deep sedimentary deposits (Karewas and Jhelum floodplains) in general, can have a significant influence on the performance of structures existing on the ground in several aspects. Low-frequency amplification is critical for the multi-storeyed buildings on these deposits and a Mexico City-like disaster may be in waiting in event of a future earthquake of bolstering characteristics. Large ground deformations associated with the top 20-30m of the soft soils may lead to significant damage to structures if not incorporated adequately in design. The softened layers further filter out the high-frequency waves, amplifying the low-frequency components. In this respect, the characteristics of the soils like thickness, stratification, geotechnical properties, and stiffness play an important role in the response towards seismic waves. Proper damping measures must be provided in the construction of tall buildings on these deep sedimentary deposits.

The hills and mountains are designated VZ-A category suggesting that liquefaction is highly unlikely and static bearing capacity is quite significant. Shallow foundations may be sufficient in these areas, although extra provisions for slope stability issues and high-frequency amplifications need to be suitably made.

The vulnerability zones delineated in the Greater Srinagar region are intended to provide basic information about the geotechnical as well as seismic hazards in the region. In this study, we recommend certain measures to mitigate seismic hazard effects in the different vulnerability zones including ground improvement techniques and the selection of appropriate types of foundations with a proper reinforcement design.