

SPATIAL VARIATION OF SILT AND CLAY SEDIMENT DEPOSIT IN BHAKTAPUR CITY

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Abstract

3D geological subsurface model of the Bhaktapur City is prepared using RockWork2016, which is based on 3-D Geo-scientific information system (3-D GIS). The main aim of this study is to interpret the geological conditions of Bhaktapur city, providing subsurface geological database and its relevance to 2015 Gorkha earthquake damages. For this, the borehole data are collected from different sources and digitized in the RockWork2016 program for the generation of the 3-D attributed subsurface model. For the stratigraphy divisions of the soil, the unified soil classification system is used. From the interpretation of the developed attributed model, it is found that the central part or the core area of the Bhaktapur city has a deeper depth of the soft sediment-silt and clay rather than other surrounding parts of the city. This indicates the possibility of local soil amplification in the central part of the study area. The spatial variation of the subsurface sediment deposit is then co-relate with damage scenario caused by 2015 Gorkha earthquake.

Keywords: Database, Lithology, Stratigraphy, Soil amplification, 2015 Gorkha earthquake

1. Introduction

Bhaktapur is one of the culturally rich cities in Nepal where most of the historically important palaces, monuments, temples, stupas are situated. Most of these antiques are recorded in UNESCO world heritage. The importance of preservations of these important antiques of Bhaktapur city is increasing day by day from the earthquake. The ground response analysis done by different researchers (JICA and MoHA, 2002; Maskey and Datta, 2005; Paudyal et al., 2012; Bhandary et al., 2014; Chamlagain and Gautam, 2015; Gautam et al., 2016) have indicated the wide range of site amplification within the study area. Therefore, in order to preserve these antiques from earthquakes, the subsurface geological condition needs ample study.

The geological and geotechnical parameters are essential for any kind of infrastructure development

as well as assessing the seismic hazards. The use of state-of-art computer program is dominant in recent geological subsurface interpretation, which was previously limited in two dimensional (2-D) specialized map, cross-sections, and fence diagrams. Currently, with the advances in computer technologies, it is possible to construct three dimensions (3-D) subsurface models easily using 3-D Geo-scientific information systems (3-DGIS) which have efficient data-management capabilities (Rahman, 2007).

In the last 2 decades, the number of 3-D subsurfaces modeling studies has increased due to the use of computer software and 3-D GISs used by different disciplinary (Sinan et al., 2013). The 3-D subsurface modeling studies not only give the information of sediment deposit but it is also used in detecting ore locations (Feltrin et al., 2009). A number of 3-D GIS software are available for subsurface modeling (GoCAD, LYNX, TECHBASE, VULCAN, GEoBLOCK, MVS and RockWorks2016). This software has their own cons and pros but they have some common properties that are a basic requirement of a 3-D GIS.

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Recently, RockWork2016 has been used in different studies (Fufa, 2004, Zhu et al., 2003, Piya et al., 2004, Hack R et al., 2006, Rahman, 2007, Kelsey et al., 2012, Akiska et al., 2013 and Dong, 2014) due to efficient data management capabilities. It facilitates easy entry of different types of subsurface data such as lithological, geophysical and geochemical data. This software is comparatively less time consuming to develop a model (Rahman, 2007). Therefore, in this study, RockWork2016 software is used to see the lateral and vertical variation of the sediment deposit in Bhaktapur city.

In this study, a 3-D geological model was generated for Bhaktapur city using the borehole log data. Borehole data is collected from various organizations; Department of mine and geology, Department of water supply and sewage, Bhaktapur Municipality, private companies, and previously published and non-published research papers. The main goal of this study is to provide sufficient information on the variation of soil sediment deposit of Bhaktapur city, providing the subsurface database. Further, the 3-D geological model is inspected by slicing the model in order to understand the variation of soil deposits in the study area. Lastly, the 2015 Gorkha earthquake damage (based on literature) within the study area are interpreted with the outcome of the subsurface soil profile.

2. Geological Setting of the Study Area

The Bhaktapur city with an area of 6.88 sq km is located in the Bhaktapur district, Bagmati, central development region, Nepal. It lies a 13 km east of Kathmandu, between 27°36' to 27° 44' N latitude and 85°21' to 85° 31'E longitudes, with an elevation of 1401 m above sea level. The geographical boundary of the study area is delimited by Suryabinayak city in the south, Thimi city in west and Changunarayan city in the north. It consists of ten wards. The Bhaktapur city is located in the weak geological structure having a number of fault lines, with low bearing capacity and loose soil structure as physical limitations (Shrestha et al., 1999; Chapagain et al., 2010). The Thimi formation exposed at Phaidhoka, Bhaktapur shows that the sediment is relatively finer, indicating the deposition

might have occurred from suspension settling. The thin, parallel laminations of alternating silt, silty clay indicate widespread deposition over the sand beds (Paudyal, 2015). The basement of the district is formed by Precambrian to Devonian rocks, which are intensely folded, faulted and fractured igneous and meta-sedimentary rocks, and it is overlain by Quaternary fluvio-lacustrine deposit with the thickness of 550-600 m (Chapagain et al., 2010). The Kalimati clay is rich in organic matter, plant fossils, diatoms, and natural gases (Fujii and Sakai, 2001; JICA, 1990). The Kalimati formation with the clay layer of a minimum thickness of (<10 m) having low bearing capacity covers the area (JICA, 1990). Fault lines are spread around the city that possesses limitation for construction, making most of the settlement area vulnerable (Shrestha et al., 1999). In the study area, sticky clay constitutes top soil along with fine and coarse sand followed by clay with pebbles, cobbles, and boulders over consolidated hard rocks of quartzite, basalt, granite, etc. (BDC, 2011). The grain size of the core sample ranges from sticky clay (0-5m), cobbles and boulders (100 m) to the consolidated hard rocks of quartzite, basalt, and granite up to a depth of 300 m (Thakur et al., 2015). The geological map prepared by the department of mines and geology of the Kathmandu valley is as shown in Fig.1 in which the study area has Kalimati formation.

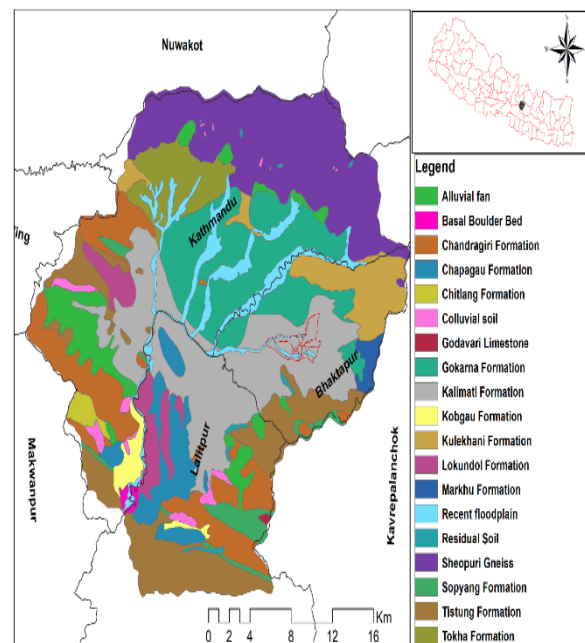


Fig.1. Geological map of Kathmandu Valley (DMG, 1998)

3 Material and Method

3.1 Acquisition of borehole data

The borehole data that are collected even lack much important information such as coordinate, elevation and engineering properties. Therefore, collected borehole data are reviewed minutely and entered in an excel sheet. The excel sheet contains information such as UTM coordinates, the surface elevation, the down-hole depth, the address and borehole IDs. The data are then plotted in the digitized map using ArcView GIS 3.2 (Fig. 2). The information of the borehole logs prepared in the excel sheet, with the standard template of RockWork2016 program, is imported in the RockWork2016 program and save as a point map. The lithological and stratigraphic information is directly entered into the RockWork2016 program.

3.2. Construction of geological model

Data acquisition of borehole logs of Bhaktapur city is very difficult. There is no any particular institution responsible for the borehole drilling and data management. The borehole log data is collected from different sources such as the Department of water supply and sewage, Bhaktapur city, published and unpublished reports. Most of the drilling of the borehole in Bhaktapur is done for drinking water supply purposes and very few drilling of the borehole is done for a geotechnical purpose. Out of 110 boreholes collected, 45 boreholes are deep borehole with a depth greater than 150m. Among these borehole logs, 13 boreholes reached up to bedrock level. The lithological data of each borehole logs are directly entered in RockWork2016 using the borehole manager window.

After reviewing the Moriyabashi and Maruo (1980), Katel et al. (1996), Yoshida and Gautam (1988), Sakai (2001), Piya et al. (2004) on the stratigraphic division of the Kathmandu valley, it seems that there is inconsistency in the classification of the soil profile. Various nomenclatures have been given for the same type of soil as per their own system of each worker (Piya et al., 2004). Previous researchers did not follow any standard system of soil classification, which causes the problems mainly during the analysis of engineering properties

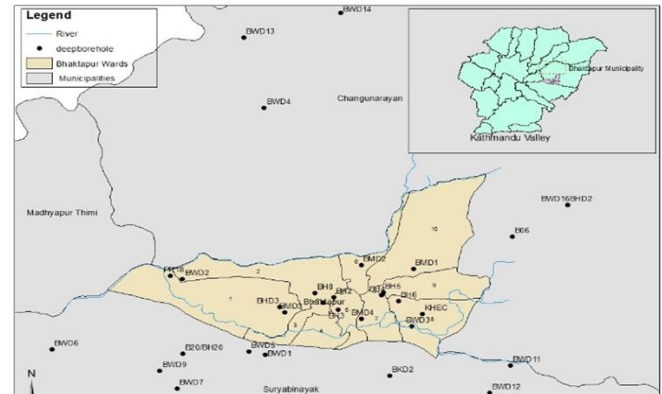


Fig.2. Location of boreholes in study area

of soil, such as density, shear modulus, modulus of rigidity; shear wave velocity, etc. (Paudyal et al., 2012). This ultimately effects on the engineering designs and to overcome this problem some sort of the standard should be followed. For this, available standards used for the soil classification are reviewed. The standards used in engineering practice for classification of soil are AASHTO classification, ASTM classification, and BS classification. Among these standards, soil types of each borehole are classified based on the unified soil classification system (USCS) (ASTM, 1996) for stratigraphic modeling. Using this soil classification system, the soil is classified into clay and silt, sand, gravel, and rock. This interpreted stratigraphic information was stored in the stratigraphy tab of the borehole manager. The stratigraphic individual vertical projection of borehole log that is generated in RockWork2016 is as shown in Fig. 3 and 3D lithological model and 3D stratigraphic model are shown in Fig.4 in vertical exaggeration (VE) 15. The 3D lithological model is done using solid modeling algorithm called "litho blend" and inverse distance weighted (IDW) interpolation method for the 3D stratigraphic model.

4. Result and discussion

4.1. 3D geological subsurface model

The attributed 3-D model provides a platform whereby the integration and visualization of data from many different sub-disciplines can be achieved. This attributed 3-D model can portray some of the natural heterogeneity of real geological systems (Royse et al., 2008, Sevnur et al. 2014).

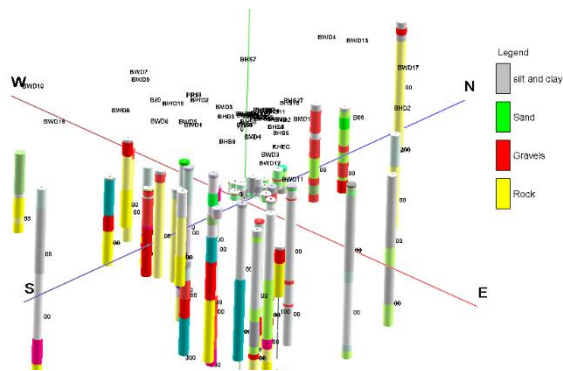


Fig.3. Vertical projection of borehole logs

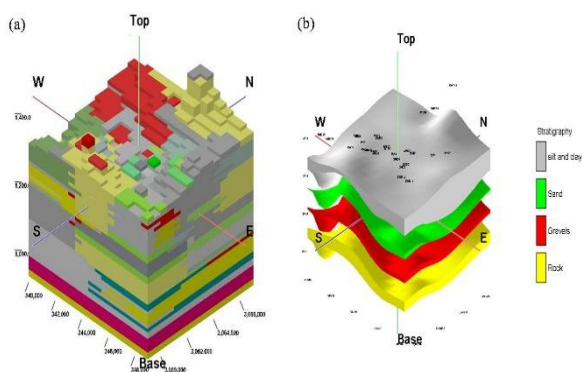


Fig.4. 3- D model (a) Lithological model (VE:15) and (b) stratigraphic model (VE:15)

The 3-D model, developed as described in the previous section, cannot display all attributes classification (litho-stratigraphy and engineering geological classification). It is possible to display all attributes at different depth by slicing the 3-D model. The resulting solid model can be sliced vertically (profile, section, and fence diagram) and sliced horizontally plan map (RockWork, 2016).

From the developed lithological and stratigraphy 3-D models, corresponding 3-D fence diagrams (lithological and stratigraphy fence) are developed as shown in Fig. 5, using the same grid dimensions as used for developing the attributed 3-D model. From this 3-D fence diagrams, as stated above, limited attributes can be studied. Observing the 3-D fence diagrams (lithological and stratigraphy fence),

it can be seen that the north-west corner is dominantly rich in sand overlain by the shallow depth of soft soil. Further, observing the northern part (Changunarayan area) and the southern part (Suryabinayak area), it shows the outcrop of the rock. In these parts, observing the borehole log, the rock strata is found at the depth that varies from 15 to 50m with overlain by coarse sediment. Besides these parts, the soil deposit is dominant. To understand the detail spatial geological condition in the core city area, the 3-D models sliced for detail analyses.

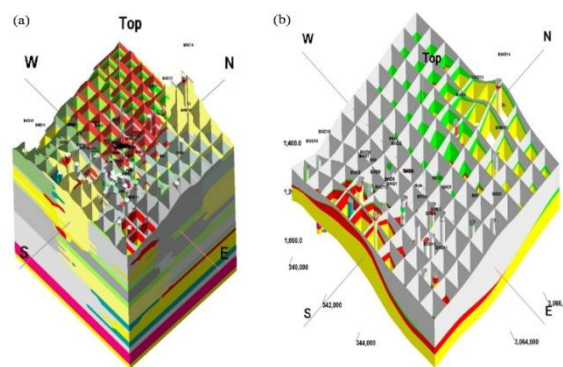


Fig.5. 3-D fence diagram: (a) Lithological (VE:15) and (b)Stratigraphy (VE:15)

Vertical slicing of the 3-D solid model is done to understand the vertical and lateral variation of coarse sediment (sand and gravel) and fine sediment (silt and clay). Therefore, six sections are chosen for the vertical slicing; three longitudinal sections (A-A', B-B' and C-C') that run from west to east and another three transverse sections (1-1', 2-2' and 3-3') that run from south to north (see Fig. 6). These sections pass through the core city area, densely populated area. Both lithological and stratigraphic vertical sliced at these six sections are generated from the corresponding 3-D model. The generated six sections are shown from Fig. 7 to 12. Observation of these cross-sections is mainly concerned on the spotting of the fine sediment, coarse sediment and bedrock, and its respective thickness.

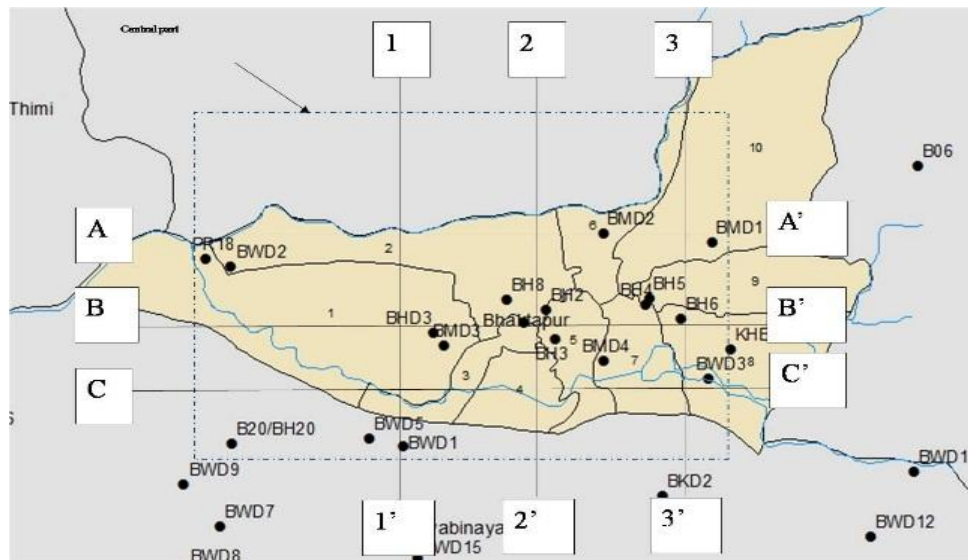


Fig.6. Showing the grid line for cross-sectional profile

Longitudinal Sections (A-A', B-B' and C-C')

The longitudinal lithological and stratigraphic cross-sections at A-A', B-B' and C-C' are observed (Fig. 7 to 9). For simplicity in observations, these sections are further divided into a western part, center part, and eastern part. These divisions are made in such a way that the central part covers all the portion of the core area of Bhaktapur city.

In the western part, looking at lithological sections, the coarser sediment like sand and gravel exist in the shallow depth in all the three sections (A-A', B-B' and C-C') with deeper depth dominated by fine sediments like silt and clay. In the same part, looking at the stratigraphic section, the depth of soft soil increases from section A-A' to C-C' with an almost constant depth of the coarse sediment.

In the central part, embedded coarse sediment at a different level within the shallow depth is observed in section A-A' which noticeably decrease in sections B-B' and C-C'. Another significant change between section A-A' and B-B' is the change of gravel layer to sand layer at the depth of 1190m, thickness almost the same. In section C-C', the rock layer in a certain portion is exposed. From the stratigraphic section, we see that the soil thickness and gravel thickness slightly decreases from section A-A' to C-C' but there is an increase of the sand thickness from section A-A' to C-C'. Another significance of the stratigraphic section is that the thickness of the soil increases from west to east direction.

In the eastern part, the fine sediment is dominantly present in sections A-A' and B-B' with a very thin depth of the coarse sediment in deeper depth. The embedded coarse sediment is spotted in section B-B' with fine sediment deposit. Section C-C' is totally different from sections A-A' and B-B' where coarse sediment within the shallow depth is observed and the rock layer is close to the surface. From the stratigraphic section, we see that the soil thickness decreases from sections A-A' to C-C' with almost the same thickness as the gravel. In the stratigraphic section, it also shows that the thickness of the soil increases from east to west direction in this part.

Transverse Sections (1-1', 2-2' and 3-3')

The transverse cross-section (1-1', 2-2' and 3-3') of the lithological and stratigraphic sections are shown in Fig. 10 to 12 is observed. As longitudinal cross-sections, these transverse cross sections are also divided into three parts; southern part, the central part, and northern part. In this sectional division also, the central part covers almost all the area of the core city area.

In the southern part of the lithological sections (1-1' and 2-2'), the rock layer is close to the surface of the ground with the shallow depth of the coarse sediment. The fine sediment is almost absent in these parts. In this portion, the fracture and weathered bedrocks like meta-sandstone, schist, and limestone are found within the shallow depth. While coming towards the central part from the southern part, the fine sediment is observed. Contrary to these

two sections, section 3-3' is totally different. In the southern part of section 3-3', the fine sediment is dominant with coarser sediment in the deeper depth. This indicates that moving from section 1-1' to 3-3' or from west to east directions, the fine sediment deposit is revealed. From the stratigraphic diagrams, we can also see that the fine sediment deposit thickness increases from sections 1-1' to 3-3' with the almost constant gravel thickness. In addition to this, in section 3-3' the sand layer is also observed.

In section 1-1', in the central part, the coarse sediment like gravel and sand is available in the shallow depth overlain by the fine sediment. Coming to section 2-2', there is a dominant presence of the fine sediment with an embedded thin layer of the coarse sediment within a shallow depth. However, coming to section 3-3', there is almost negligible coarse sediment within the shallow depth and this section is dominant with fine sediment.

From the stratigraphic cross sections (1-1', 2-2' and 3-3'), we see that the thickness of the silt and clay increases from sections 1-1' to 3-3' with the almost same thickness of the gravel. However, the thickness of the sand deposit decreases from section 1-1' to 3-3'. While moving from the central part to the northern part, it is seen that the soil deposit is dramatically decreased.

In the northern part, the coarser sediment gravel and sand are highly present throughout the depth in sections 1-1' and 2-2' with a very thin layer of the fine sediment. In contrary to these two sections, in section 3-3', there is dominant of the fine sediment in the shallow depth which is followed by the rock layer. From the stratigraphic cross sections, it can be observed that the thickness of the sand layer is dominant in sections 1-1', which decreases from 1-1' to 3-3' and contrary to this the thickness of the clay and silt increases from 1-1' to 3-3'.

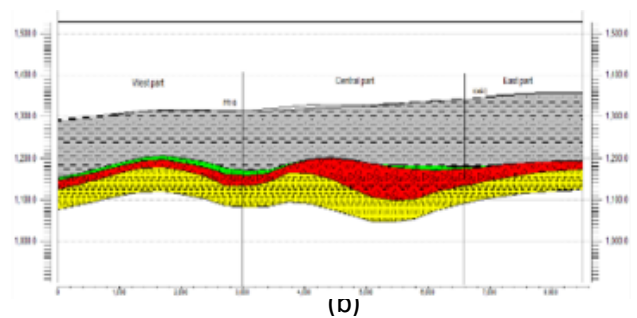
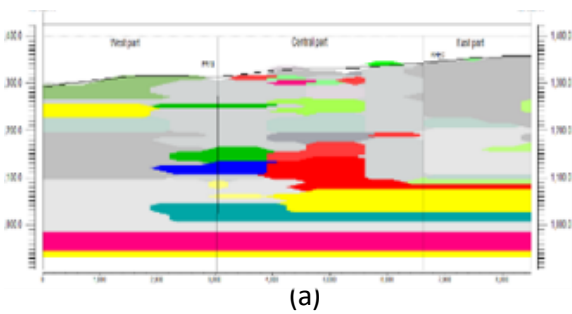


Fig.7. 2-D fencing Diagram at A-A'(a) lithological and (b) stratigraphic

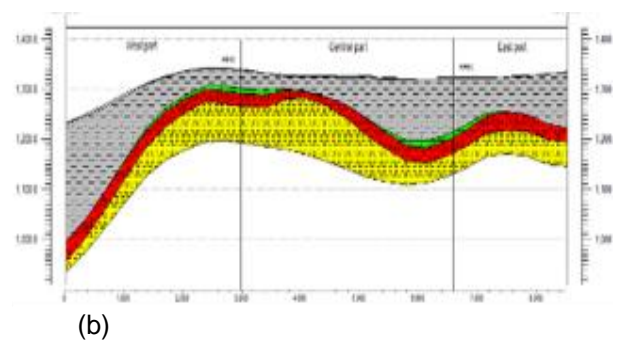
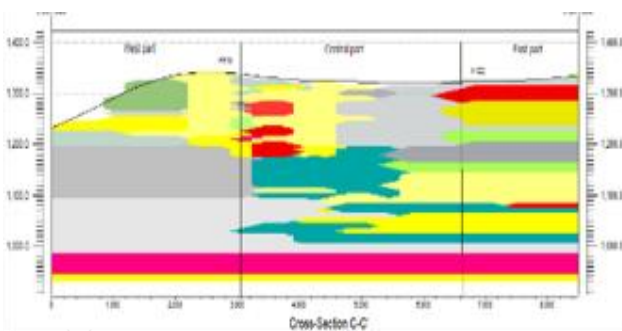


Fig.8. 2-D fencing Diagram at B-B' (a) lithological and (b) stratigraphic

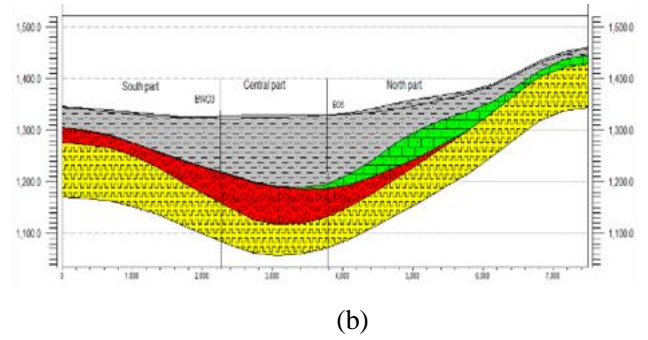
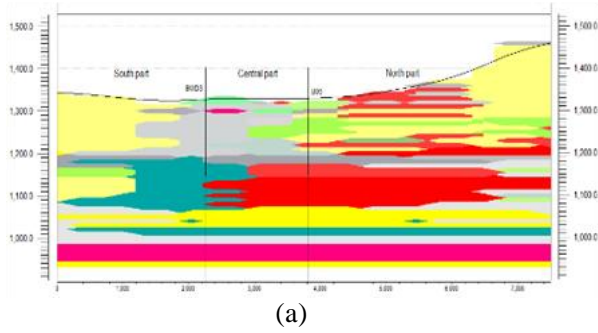


Fig.9. 2-D fencing Diagram at C-C' (a) lithological and (b) stratigraphic

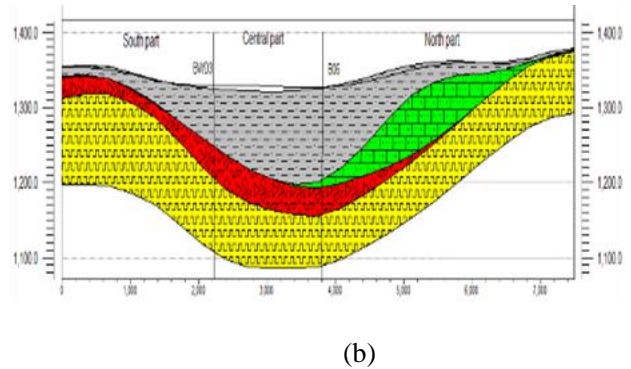
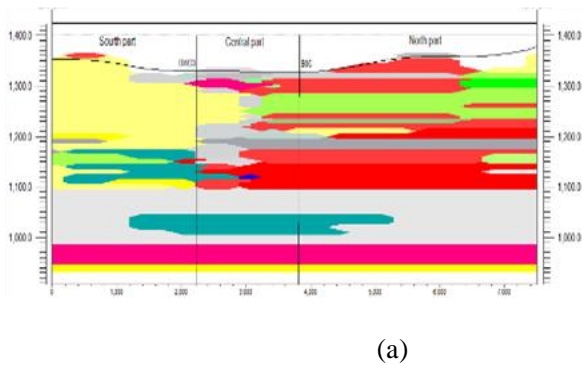


Fig.10. 2-D fencing Diagram at 1-1' (a) lithological and (b) stratigraphic

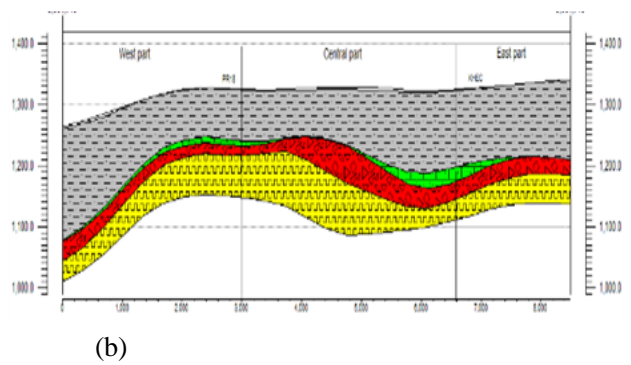
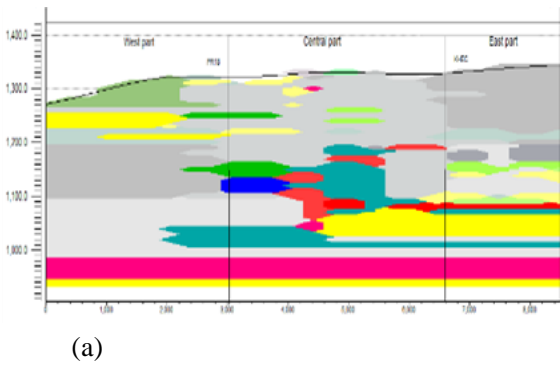


Fig.11. 2-D fencing Diagram at 2-2' (a) lithological and (b) stratigraphic

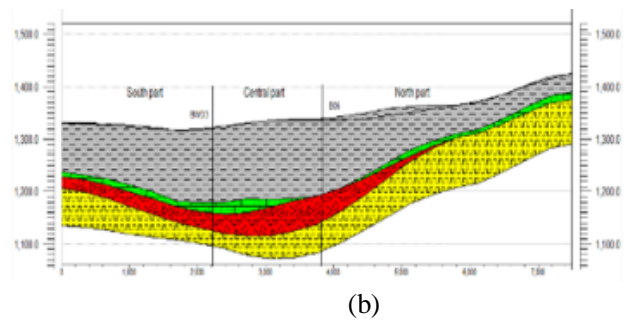
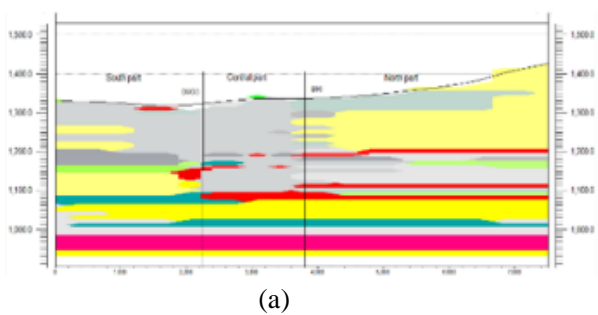


Fig.12. 2-D fencing Diagram at 3-3' (a) lithological and (b) stratigraphic

4.2 Earthquake damage scenario

Bhaktapur is potentially prone to earthquake hazard, as it is located in an active seismic zone along with other cities of the Kathmandu valley. Several big historical earthquakes have badly affected the city in the past. Numerous devastating historical earthquakes are still in our memory such as 1934, 1960 and 1988, along with the recent 2015 earthquake.

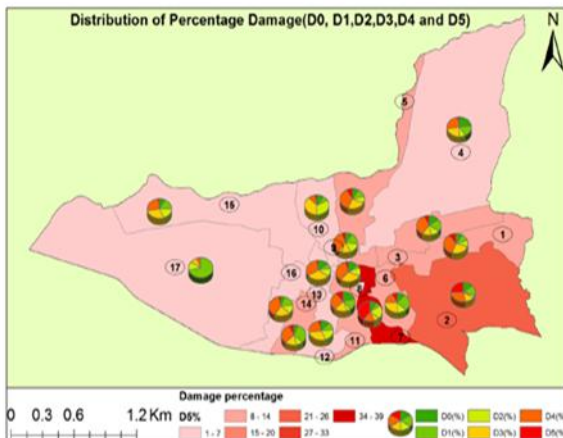


Fig.13. Building damage scenario

Shakya et al. (2016) carried out the rapid visual damage assessment of masonry buildings after 2015 Gorkha earthquake within the study area. During 15 days of data collection, altogether 3,979 buildings were inspected. The inspected damage buildings were graded according to EMS-98 (Grunthal, 1998) and GNDT I level approach (GNDT-1990, 1990). Fig. 13 shows the ward map of Bhaktapur city (ward 1 to 17) with color variation based on the percentage of building suffered from damage grade D5. The GIS map also shows the percentage of damages (D0 to D5) in the pie chart. From Fig. 13, it can be seen that maximum destruction is concentrated in the eastern part of the Bhaktapur city. Local soil condition has a vital role in the localized damages during the earthquake besides topographical effects. From the above section, it was observed that the thickness of the fine sediment deposit, probable cause for seismic wave amplification, in the eastern part of the Bhaktapur city is higher than in the western part. This signifies that during the 2015 Gorkha earthquake, this fine sediment deposit might have amplified effect in the

free-field seismic wave, although topographic reasons might be another cause for such destruction. This is just a preliminary co-relation drawn based on 2015 Gorkha earthquake that need to be verified from some sort of analytical or experimental research work.

5. Conclusion

3-D digital modeling of the subsurface is nowadays a well-established technique in many sub-disciplines. To assist in the recognition and identification of problematic ground conditions, 3D modeling is widely used in various fields. In this study, the subsurface geological database is prepared for Bhaktapur city, using the RockWork2016 program. The developed 3-D lithological and stratigraphy models are comprehensively studied using sliced diagrams. It is observed that the central part, the core area of the study, is deposited with the thick depth of the soft sediment, silt and clay, whereas surrounding parts are deposited with the coarse sediment like gravel and boulder. Further, the thickness of the soil in the central part increases as we go from west to east. The building damage scenario of Bhaktapur municipality caused by 2015 Gorkha earthquake was studied by the Shakya et al. (2016). The study had prepared the GIS map, showing the spatial distribution of building damage of grade D5. It shows that the maximum damage of grade D5 occurs in the eastern part of the City. The spatial distribution of buildings damage co-relate with the variation of fine sediment deposited within the study area.

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