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A ground investigation to inform earthquake hazard assessment in the Kathmandu Valley, Nepal

Une enquête au sol pour éclairer l'évaluation des risques sismiques dans la vallée de Kathmandu, au Népal

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ABSTRACT: When designing ground investigations there is usually a requirement to fill large gaps in existing knowledge. In the developing world, specifically in seismic prone areas, this systematic lack of information affects the ability for practitioners to assess seismic risk. This paper presents the rationale and results of a ground investigation undertaken in Central Nepal to inform seismic hazard assessment, as part of the EPSRC funded project Seismic Safety and Resilience of Schools in Nepal (SAFER). Geological information and geotechnical parameters are presented. Downhole methodology has been used to derive an *in situ* shear wave velocity profile for seismic response analysis in a region which is currently reliant on seismic shear wave velocity correlations. This research presents discussion and comparison of velocity profiles obtained at other locations in the Kathmandu Valley and introduces new information on the basin topography.

RÉSUMÉ: Lors de la conception des enquêtes du terrain, il est généralement nécessaire de combler les lacunes importantes concernantes les information initiales. Dans les pays en développement, en particulier dans les zones à risque sismique, ce manque systématique d'informations affecte la capacité des professionnels à évaluer le risque sismique. A ce propos, cette étude présente la logique et les résultats d'une enquête sur le terrain entreprise dans le centre du Népal avec l'objectif d'améliorer l'évaluation des aléas sismiques, dans le cadre du projet SAFER (Seismic Safety and Resilicience of Schools in Népal) financé par l'ESPRC. Les informations géologiques et les paramètres géotechniques sont présentés. La méthodologie Downhole a été utilisée pour établir des profils de vitesse d'ondes transversales in situ afin d'obtenir l'analyse de la réponse sismique dans une region qui actuellement utilise uniquement des corrélations de vitesse d'ondes transversales sismiques. Cette recherche présente une discussion et une comparaison des profils de vitesse obtenus dans différents endroits de la vallée de Kathmandu et introduit des nouvelles informations sur la topographie du bassin.

Keywords: Nepal, site investigation, boreholes, seismic hazard assessment, developing countries.

1 INTRODUCTION

In 2015 a high magnitude earthquake occurred in Nepal with a moment magnitude of M_w 7.8, known as the Gorkha earthquake (e.g., Goda et al., 2015). Strong shaking and damage were experienced in Kathmandu and surrounding areas (e.g., Goda et al., 2015; Ohsumi et al., 2016). Engineering seismologists have explained that local soil characteristics effecting ground motion are not well understood in this region (e.g., Tallett-Williams et al., 2016; Poovarodom et al., 2017; Rajaure et al., 2017; Stevens et al., 2018). Isolated cases of liquefaction and lateral spreading are occurring, which have not yet revealed a systematic damage pattern (Asimaki et al., 2017). The basement topography, referring to the bedrock boundary beneath Kathmandu Valley, is also contributing to the unusual damage patterns, due to amplification effects commonly seen in basins (Asimaki et al., 2017). The basement topography has been derived using microtremor data by Paudyal et al. (2013).

The Kathmandu Valley is lacking detailed geological and geotechnical information to inform these seismic studies. In earthquake resilient engineering design, the parameter often used for soil classification is the average of shear-wave velocity from the surface to 30m depth (V_{S30}), according to relationship in (CEN 2004, clause 3.1.2). In the Kathmandu Valley, few locations have known prior P-S logging i.e. shear-wave velocity measurement (see Gilder et al., 2018).

To overcome this, V_S is often correlated with the Standard Penetration Test blow count (SPT-N) or other geotechnical parameters. Studies in Kathmandu are relying on these correlations and the sparse data available to produce V_{S30} maps of the Valley (Gautam & Chamlagain, 2016; Gilder et al., 2018). The systematic lack of data affects the accuracy of these generated maps.

The SAFER project (Seismic Safety and Resilience of Schools in Nepal) commissioned two new boreholes, undertaken in April 2018 in the Kathmandu Valley, with the aim of adding to the existing data. This paper describes the results of the site investigation.

2 GEOLOGY OF THE STUDY AREA

The Kathmandu Valley is an intermontane basin situated in a large syncline between the Sheopuri Lekh mountain range (north) and Mahabharat Range (south) in the Lesser Himalayas (e.g. Dill et al., 2001). The Lesser Himalayan belt is made up of largely low metamorphic grade rocks of slates, phyllites, quartzites and crystalline limestones (Stöcklin, 1980). Bounding the north of Kathmandu Valley is a higher grade, high temperature gneiss (Stöcklin, 1980).

The study area, however, is characterised by soft, semi-consolidated clays, silts, sands, and peats which represent a younger fluvio-deltaic depositional system (Sakai et al., 2008) discharged into an intermontane paleo lake (Yoshida & Igarashi, 1984). Figure 1 shows the basin sediments according to an engineering geological perspective modified from Shrestha et al. (1998). Further stratigraphic divisions are suggested by (Sakai et al., 2008), which are related to the terraces produced at different stages of the lake extension, separating the Gokarna Formation in Figure 1(a) into Gokarna, Thimi, and Patan Formations (north to central Kathmandu). Steady oscillations of water level fall and rise have produced a range of sediment grain sizes representing the delta front, delta plain and prodelta deposits, the latter referred to as the “Kalimati Clay”. However, a thick deposit of black clayey silt beds also referred to as the Kalimati Formation (Shrestha et al., 1998) exists beneath the entire valley, representing an older lacustrine environment. These lake deposits are rich in coalified matter, pollens and algae (e.g., Dill et al., 2001).

The sediment pile is approximately 200-650m thick, Sakai (2001) describe boreholes where the basement depth has been proven with core extraction. However, for the most part the depth is derived from wells drilled for groundwater resources (JICA, 1990). The published record describing the strata divisions lack detailed engineering description. Research, along with other international projects and consultancy boreholes amount to a total of “449 boreholes and 124 boreholes with corresponding SPT-N values” (JICA, 2017). To best investigate the geotechnical variation, BH-1 was placed within the Gokarna Formation (or where the Patan Formation is outcropping if according to Sakai et al., 2008), and BH-2 was placed in the Kalimati Formation.

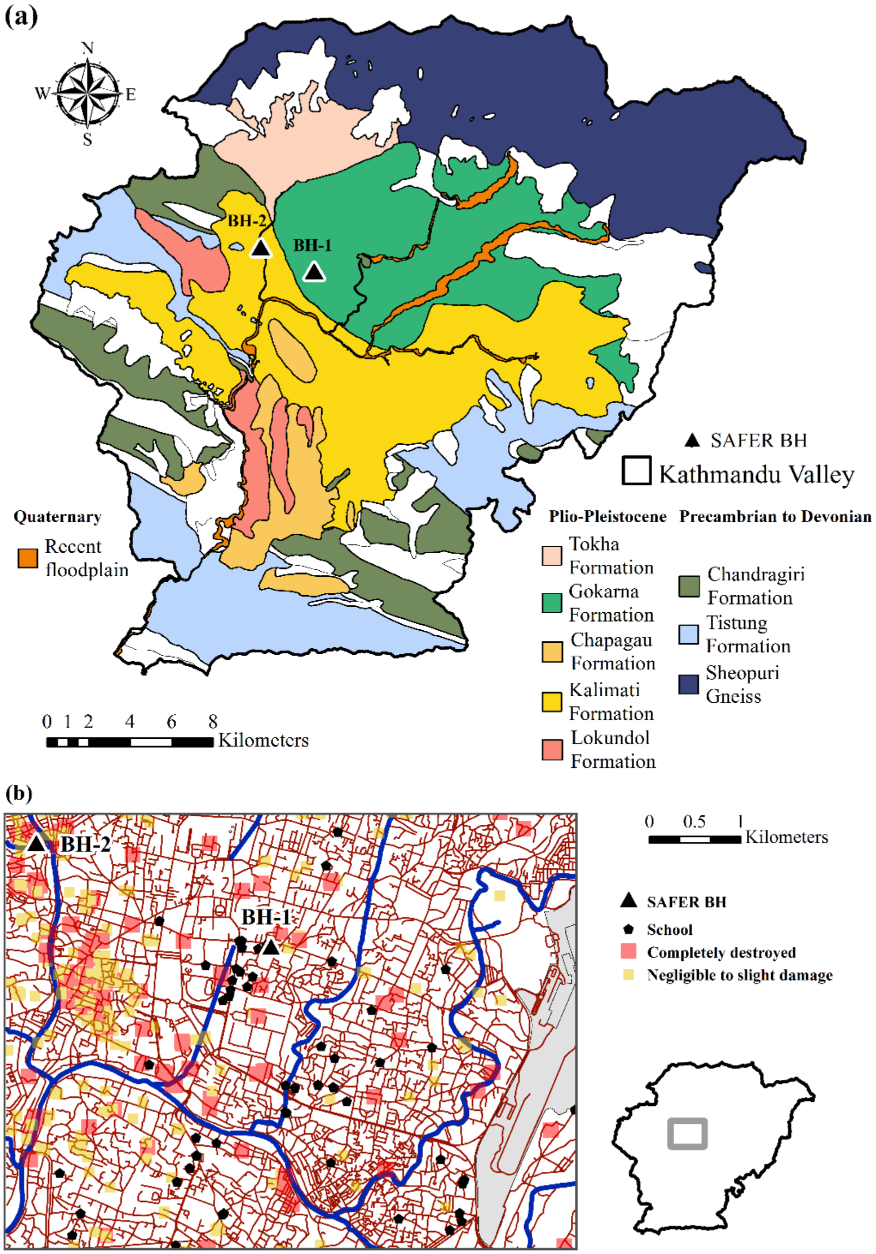

Figure 1(a) Simplified engineering geological map after (Shrestha et al., 1998) showing BH-1 and BH-2 residing in Gokarna and Kalimati formations respectively. (b) Recorded damage after the 2015 earthquake, zones of higher damage located within in Hyumat and Dallu in Kathmandu City, located either side of the Bishnumati River (running north to south) with lesser amounts of damage to settlements distributed across the remainder of this part of the city. Information provided by Copernicus (2015) [EMSR125] Kathmandu Grading Map and hydrology from Kathmandu Overview Map.

3 SITE INFORMATION

Data scarcity in the region meant that the site selection process for the two boreholes required careful consideration. The rationale for the selected locations for the boreholes was partly based on the work presented in Gilder et al. (2018) which describes the location of measured V_{S30} within the valley. Figure 1(b) shows the location of the schools in the study area, as improving the seismic resilience of Nepalese school infrastructure is a key aim for SAFER. Figure 1(b) also indicates areas of recorded damage after the 2015 earthquake. The position of the boreholes was optimised by considering these factors.

Investigation Details

The boreholes were progressed using rotary open hole drilling methods and recovery was obtained during driving of the SPT split spoon sampler. The works were designed to incorporate SPT sampling at 1m increments. BH-1 also incorporated PS-logging at 1m increment similar to the downhole techniques described in ASTM (2017). BH-1 was set within the grounds of an existing school at a ground level of 1309 m OD. BH-2 was located within 100 m west of the Bishnumati River on an area of disused land at a ground level of 1286 m OD. Directly south of this site is a steep slope, reaching a discrete topographic high of 1318 m OD at approximately 185 m south. From the top of this slope, the prominent Swoyambhunath Stupa (Buddhist Temple) can be seen to the west, also at an elevation above the general ground levels in this part of the city.

Ground Conditions

The results of the ground investigation have been presented in Figure 2. Full descriptions and photographs of the underlying soils are available from the Bristol University Research Data Repository (Gilder et al., 2019). Logging is, where possible, according to BSI (2015). Given that only open holing was available during this investigation, continuous soil records could not be observed. Some engineering horizons were obtained from changes in drilling progress.

At BH-1, underneath an initial layer of Made Ground, an interbedded sequence of whitish grey, occasionally silty, micaceous, sand with low gravel, and dark grey or greyish brown, thinly laminated, sometimes organic, silts and clays were encountered. The consistency of the silt and clay layers ranged from very soft to soft.

The silts and clays contained microscale (<1 mm) laminations. This was evident due to the occurrence of organic material, present as black near microscopic discrete particles disseminated throughout the laminae. The laminations were distinguished from the remaining inorganic grey or greyish brown constituents. These silts and clays contained a sheen owing to the abundance of microscopic sized micaceous crystals. Locally thin laminae (2-3mm) of black, likely high organic, low bulk density peat, with some rare recognisable plant remains were observed. The sands encountered at BH-1 contained the major constituent muscovite mica, ranging in grainsize from large intact plates of 3mm to more commonly <1mm. The light colour of the sands is given also by quartz. The sands are for the majority sub rounded to angular and medium grained. Where gravel is present, it is commonly fine, rarely of a medium grain size.

At BH-2 below the Made Ground, the soils comprise an initial layer of whitish grey clay and coarse sand, over dark grey organic clayey silt. This silt is representing the Kalimati Formation. This was underlain by bluish grey, medium grained, meta-sandstone, noted as weathered between 10.76 m to 10.85 m, proven to 20.0 m depth. Thorough classification of the discontinuity state of the meta-sandstone was not carried out: the length of core recovery was in total 0.80 m. The silts at BH-2 were generally darker in colour than at BH-1 and exhibited a sticky consistency. Groundwater was encountered at 2.37 m below ground level (bgl) in BH-1 and 2.50 m bgl at BH-2. The simplified logs are presented on Figure 2(a).

Geotechnical Testing

The authors observed SPT-N values were taken over three 150 mm increments (by the site investigation team) which is equivalent to the guidance given in ASTM (2011). For comparison BSI (2006) requires six intervals at 75 mm. The SPT-N values are presented as uncorrected values of penetration over the final 300 mm. At several depths in BH-1 the SPT penetrated both cohesive and granular units. Also, 'running sands' were encountered between 19 m and 25 m, therefore SPT's were not carried. Within BH-1, tests in the clays and silts gave SPT-N values ranging between 1 and 21 (Figure 2(b)). In the sands SPT-N values ranged between 7 and greater than 50. In BH-2 little increase in strength was observed in the organic clayey silts with SPT-N ranging between 2 and 8. The Atterberg Limit tests carried out on both sites are shown on Figure 2(c). Cohesive materials plotted close to or below the A-Line indicating that the soils are on the boundary of being a silt or clay, but are for the majority medium plasticity, silts (BSI, 2015).

Geophysical Testing

The geophysical testing was performed by direct method (see e.g., Kim et al., 2004 or ASTM, 2017). The seismic source was generated by striking a wooden block with a hammer, located 2.5 m from the borehole location. The borehole was installed with PVC pipework and the downhole receiver was positioned vertically inside the borehole. Water was not introduced to the test hole. The measured travel time (t) for each wave type, obtained in the inclined path from source to receiver, was corrected to the travel time, $t_c = (D)(t/R)$, where D is the depth below ground, t is the arrival time of the wave and R is the distance from the source of the seismic wave to the receiver (e.g., Kim et al., 2004). The average shear-wave velocity is equal to the slope of the line obtained by plotting t_c versus depth, across a particular depth interval. Calculated P-wave and S-wave velocities for each interval are also shown on Figure 2(d). The P-wave velocity generally increases with depth from 323 m/s to 1493 m/s, except for a portion between 11 m and 16 m. The S-wave velocities are between 133 m/s and 232 m/s in the clays and silts. In the sands the S-wave velocities are between 307 m/s to 475 m/s.

4 DISCUSSION

This investigation revealed two key findings. The first is the presentation of a new V_{S30} value at BH-1: 257 m/s. This is in line with previous records in similar material in Kathmandu. At a location south of BH-1, at Singha Durbar in the Gokarna Formation, JICA (2002) recorded a V_{S30} of 230 m/s. JICA (2002) recorded a V_{S30} of 180 m/s in the "Kalimati" at New Road, west of the BH-1 site, which is the material found at BH-2.

The second key finding is regarding the depth of the Kathmandu basement. Referring to Figure 1, at approximately 1km to the west of BH-2, the Tistung Formation is outcropping. Further outcrops, to the west and south include the Tistung and Chandragiri Formation, both known to contain horizons of meta-sandstone (Shrestha et al., 1998). The basement topography near BH-2 is currently estimated using microtremor to be at 96 m bgl (Paudyal et al., 2013). Additionally, a HVSR study undertaken alongside this study indicates a V_S of 470 m/s from 11.5 m to 90.0 m depth at BH-2, with V_{S30} of 327 m/s (Pokhrel et al., 2019). This could be considered a little low for an *in-situ* meta-sandstone. The core recovery in BH-2 also makes interpretation difficult. The HVSR technique is also known to have limitations (Bard, 1999). The meta-sandstone found at BH-2 can be interpreted as being either *in situ* highly fractured rock, which is possible due to the huge variations in basement topography seen via the outcrops, or a boulder. The final interpretation is difficult due to the limited data available.

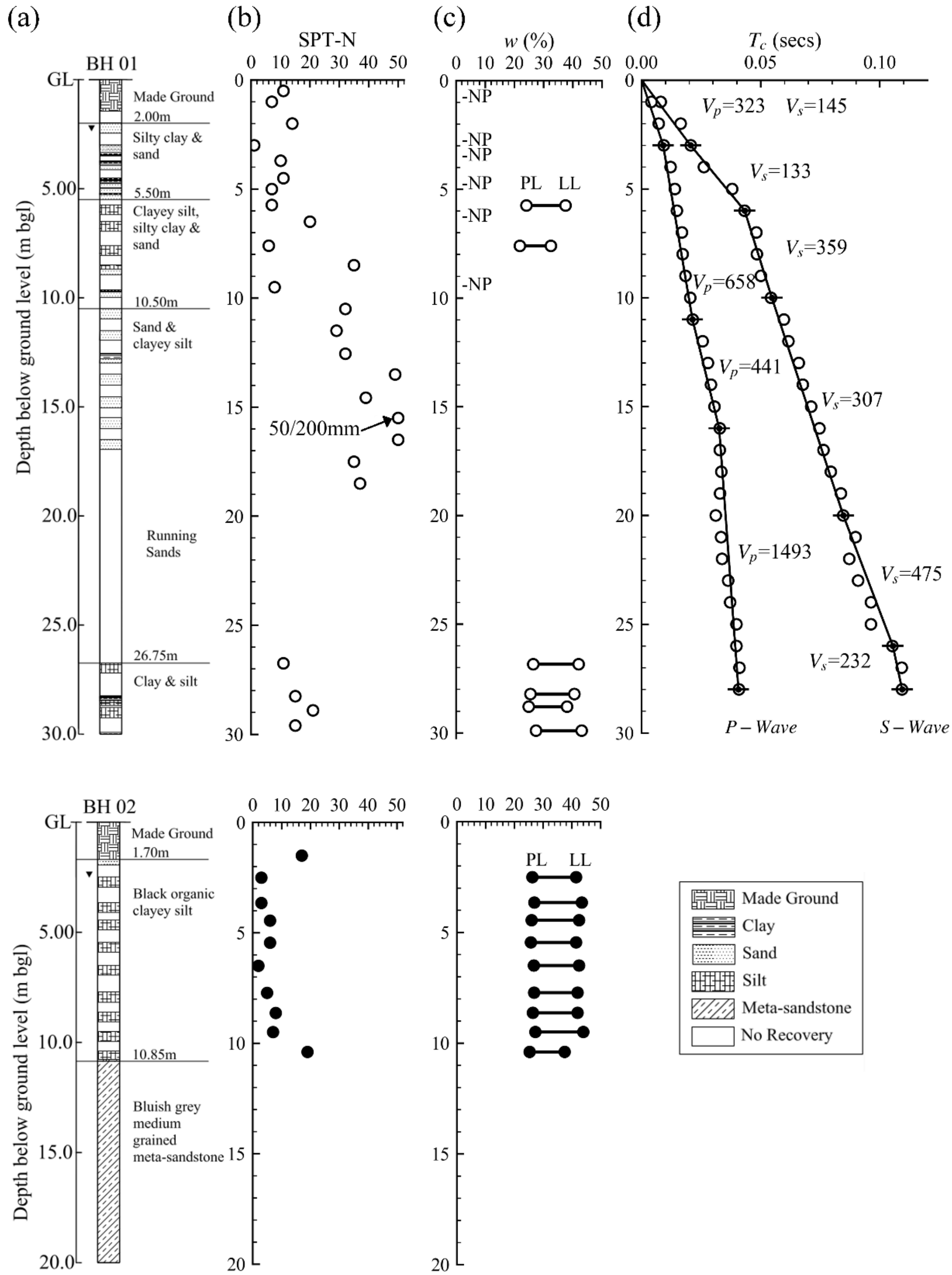

Figure 2. From left to right: (a) borehole records for the two sites. (b) recorded SPT-N (c) Atterberg Limits and (d) shear-wave velocity with depth.

5 SUMMARY

This paper has produced detailed geotechnical information from two major geological units of the Kathmandu Valley, Nepal. Earthquake resilient engineering design relies on the knowledge of the V_{S30}, and the work presented has provided a further measurement for a "data poor" region. Two new detailed borehole logs have been presented with accompanying SPT and Atterberg limits. For BH-1 new downhole V_S data have been reported. Further, geological and geotechnical investigation is needed to improve the calibration of amplification and seismic hazard assessment studies. Due to the interbedded nature and sensitive organic soils, any new investigations in the Kathmandu Valley would likely benefit from the use of boreholes coupled with Cone Penetration Testing.

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Data Availability: the data to reproduce Figure 2 and some site photographs can be sourced from the University of Bristol Repository (Gilder et al., 2019).

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