# Follow-up report of damage caused by the Gorkha Earthquake, Nepal, of April 25th, 2015

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Key Facts
- Hazard Type: Earthquake
- Date of disaster: April 25th , 2015
- Location of Survey: Kathmandu, Dhunche, Nepal
- Date of the field survey: July 11th to July 16th and October 31st to November 3rd, 2015
- Survey tools: Dynamic dual-frequency positioning system, Microtremor sensor, Surface wave survey measurement tool
- Key findings:
  1) Surface Wave Surveys near the damaged section of Araniko Highway identified the presence of a shallow soft soil layer, which is considered to be an organic soil deposit.
  2) Creeping nature of a landslide mass was clearly observed along Pasang Lhamu Highway at the southern limb of the Kuncha-Gorkha anticlinorium.

***Key Words :*** *Gorkha Earthquake, road damage, surface wave survey, micro-tremors, GPS monitoring*

## 1. INTRODUCTION

Gorkha Earthquake (Mw7.8) struck central Nepal on April 25th, 2015 at 11:56 a.m. local time (6:11 a.m. UTC), one of the worst natural disaster to strike cetral Nepal since the 1934 Nepal-Bihar Earthquake. The Japan Society of Civil Engineers (JSCE) dispatched reconaissance teams (an advanced body and the main team) to areas affected by the earthquake[1), 2), 3)], and one of worries they have highlighted in their report[3)] was signs of creeping ground observed at some locations. It is far from an isolated story that aftermaths of an earthquake are often more devastating than its immediate effect, especially in mountainous terrains. Large strains built up in soils and rocks can trigger post-earthquake problems discouraging attempts for quick reconstructions of infrastructures. This report follows up the authors' previous report[3)] highlighting geotechnical issues that may affect important rehabilitation activities.


**Fig. 1** Depressed section of Araniko Highway and ground offsets[3)] (Photo from Google Earth)

## 2. DAMAGE TO ARANIKO HIGHWAY

A section of the Araniko highway crosses a small valley at Kausaltar with an embankment. This section has sunken seriously in the Gorkha Earthquake. The location is about 2 km southeast of the Tribhuvan International Airport, Kathmandu. Several lines of vertical ground offsets appeared diagonally across this road making up a swath of ground offset lines (Fig. 1[3)]).

The offset lines that appeared on the ground are about parallel to each other trending in ENE to WSW direction. These offset lines disappear beyond their eastern and western ends, and were about 300 to 400 m long at the most, indicating that the failure was just localized within this short extent of the swath. While the maximum vertical offset of about 2m was reached near boundaries between the terrace and the valley, the sagging part of the highway embankment has been slightly pushed up as shown in Fig. 1[3)]. This ground deformation was responsible for the damage to a two-span continuous pedestrian overpass (Fig. 2), whose north pier rests exactly on the northeastern-most line of ground offset while the other two are on the relatively intact hill terrace. As the result, the


**Fig.2** Pedestrian overpass over Araniko highway at Kausaltar ($27^{0}$40.475' N $85^{0}$ 21.865'E) :
(a) dislocated bridge photo on May 3rd 2015 and
(b) demolished northern deck of the overpass on July 15,

northern pier was on an outward tilt, causing the joint between the pier and the deck to open up by about 40 to 45 cm. The opening was found to have been a little expanded during the two months of period between the surveys by the advanced and main teams. There could have been a good chance for any single supported deck of overpass to fall upon the highway with its spans expanded. Though it was a two-span continuous overpass, the northern half of the deck was demolished in view of the authors' previous report[3] (Fig. 2(b)).

The above sequence of events can be an indication that the ground may have moved a little even after the earthquake. Soil samples from boreholes drilled after the earthquake for reconstructing the highway reportedly had an inclusion of shallow organic soil as

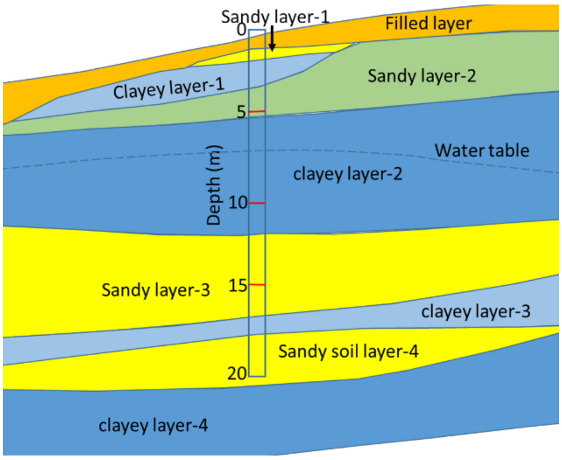


**Fig. 3** Soil profile estimated from borehole data (provided by JICA[4])

shown in Fig. 3 (JICA[4]); organic soil is particularly susceptible to instability conditions with a marked loss of shear strength in an intense shake.

A Surface Wave Survey (SWS) test was conducted along two lines shown in Fig. 4. Line 1 extends 72 m in the transverse direction of the highway, while Line 2 covers 210m stretch along the highway, both crossing some major lines of ground offset.

SWS test is a nondestructive geophysical method widely used to investigate sub-surface structures. Penetration depth of a surface wave that propagates along the free surface depends upon its wavelength such that the longer wave-length influences the deeper portion of the ground, thus reflecting mechanical nature of deeper soils. Given this nature of surface waves, both the number of geophones and the geophone interval are very important. The entire stretch of the line of geophones is to be at least two times the depth of interest, while the geophone interval determines the spatial resolution of the analysed 2D soil profile. In the authors' survey, total 24 geophones are lined up at every 1 m interval, and this fixed spread of geophones (land streamer hereafter) is towed along the ground surface. A 5 kgf hammer is used to generate surface waves by hitting vertically a rubber plate, maintaining the source and the end receiver offset of 1m. After acquisition of the data from every impact, the land stemmer is towed 1 m forward simultaneously. This process is repeated for the entire stretch of the measuring line. Fig, 5 shows the typical SWS test arrangement in this investigation.

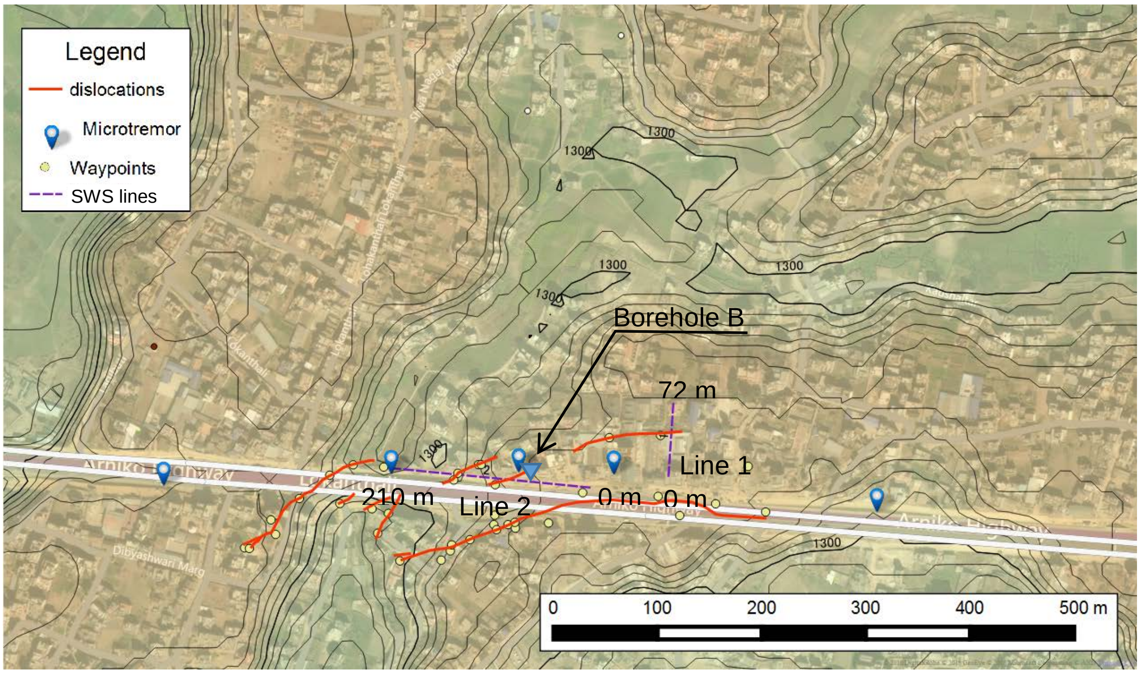


**Fig. 4** Surface wave Survey test profile lines 1 and 2


**Fig. 5** Land streamer of geophones

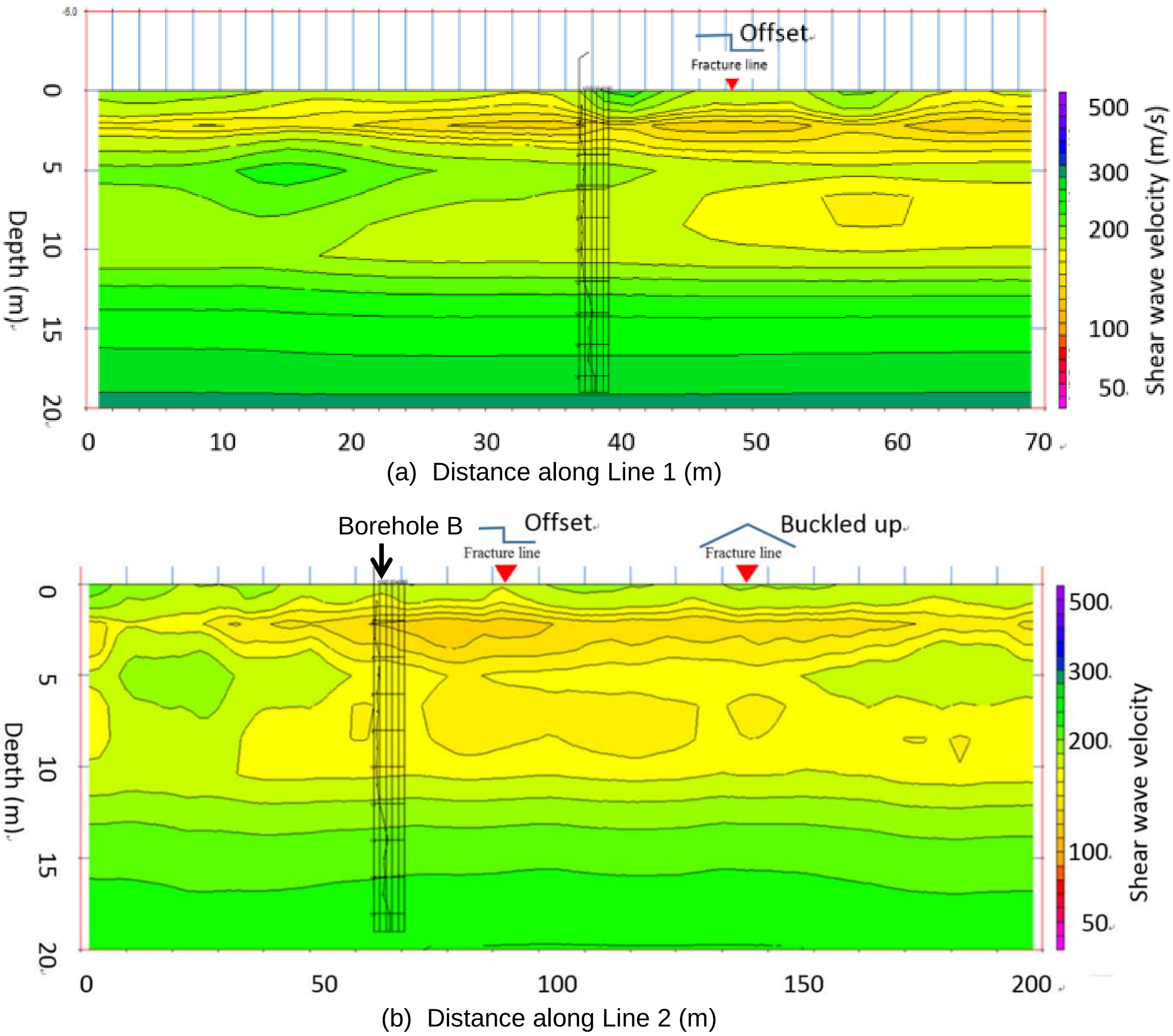


**Fig. 6** Estimated soil profiles along Lines 1 and 2

The result of SWS test along Line 1 is shown in Fig. 6(a). The back-analysed shear wave velocities for the uppermost surface layer of about 1 to 2 m thickness range from 160 to 180 m/s, indicating the presence of compacted gravel and/or filling materials. This uppermost layer caps a softer soil layer with its estimated shear wave velocity below 150 m/s. The thickness of this soft soil layer varies from location to location, but generally gets thicker as we go away from the highway and reaches around 4m at the very end of the line. The average depth of this layer corresponds to the organic soil taken from

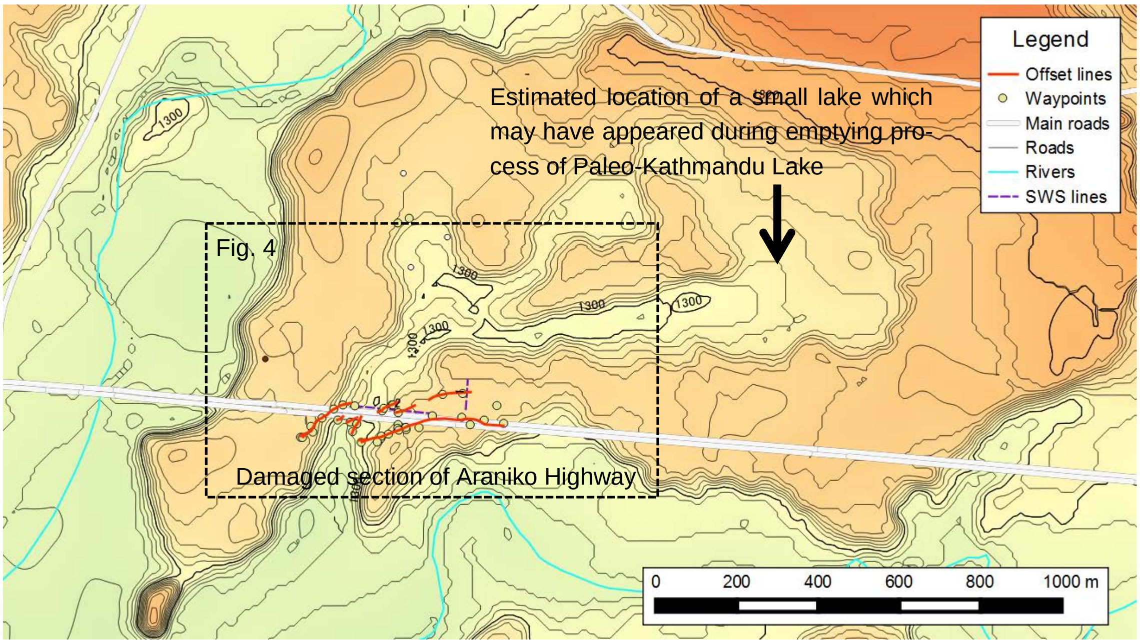


**Fig. 7** Estimated location of a small lake which may have appeared during emptying process of Paleo-Kathmandu Lake

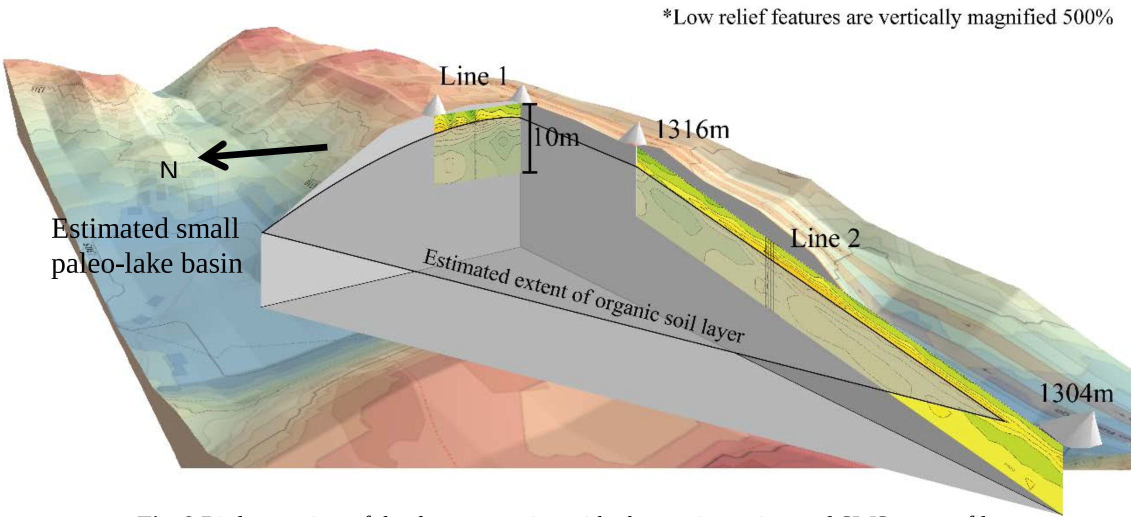


**Fig. 8** Birds eye view of the damage section with observation points and SWS test profile

Borehole B[4)] (Figs. 4 and 6), showing the likelihood that the organic soil layer reaches Line 1. A line of vertical ground offset crosses Line 1 at its 48m distance, and immediately below this point, there spreads one more soft soil layer underlying the softest soil layer. Similar soil profile was estimated for Line 2 (Fig. 6(b)). Below the capping soil with shear wave velocity ranging from 160 m/s to 180 m/s, a soft soil layer spreads across the entire stretch of Line 2. This soft soil layer is thickest near the vertical offset line and Borehole B, reaching 4 to 5 m below the ground surface. It is also noted that below both the line of ground offset and the buckled highway pavement, there spreads one more soft soil layer immediately beneath the softest soil layer.

It is probably premature to judge that the softest soil layer immediately below the uppermost soil cap is all organic soil to be sure, but at least the fact that there was an organic soil at Borehole B clearly indicates that there was a paleo-lake whose water was covering this area. Morphological feature of this area suggests the presence of the small paleo-lake basin just north of the damaged section of the highway as shown in Fig. 7. Though the Paleo-Kathmandu lake was formed over one million years ago with the tectonic uplift, the organic soil here may be much newer than the other surficial deposits covering the entire Kathmandu basin. When the Paleo-Katumandu lake was almost emptying, there yet remained a little amount of waters of small lakes and ponds which included the one that covered the northern part of the damaged highway section. Fig. 8 is a birds eye view map of the damage section together with SWS results. As we go towards the estimated small paleo-

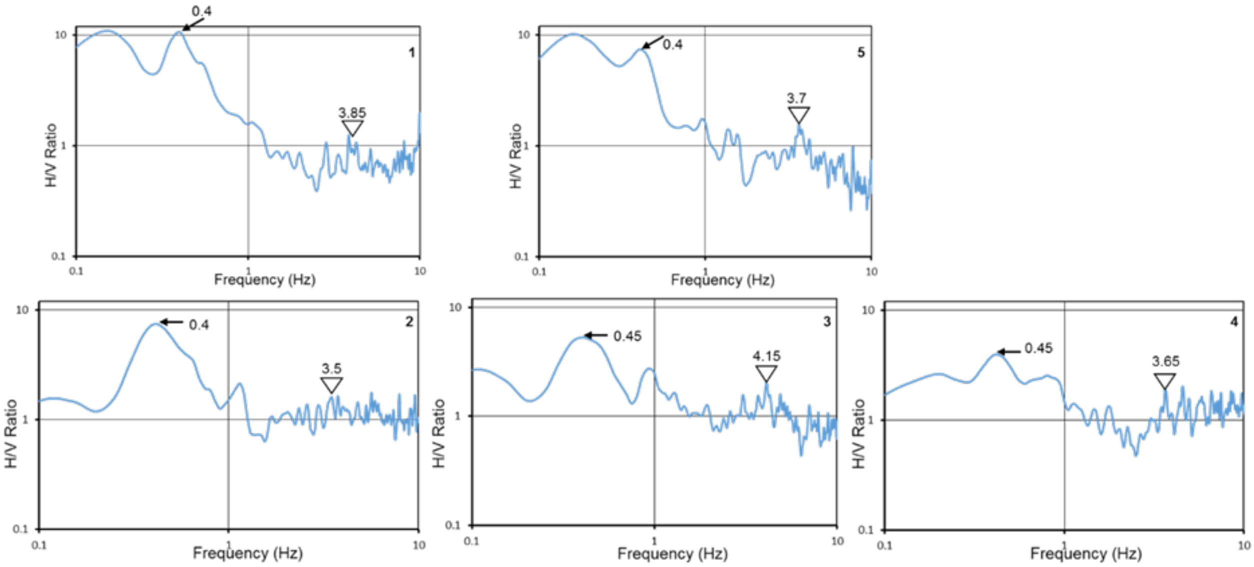


**Fig. 9** H/V spectral ratios at five locations

lake basin, the softest soil layer is getting thicker. Carbon 14 dating of the sampled organic soil, SWS and just a small number of borehole drilling may help us to estimate the presence of organic soils from micro-terrain features, which information is very necessary in mapping out plans for rehabilitating urbanized areas of Kathmandu.

Microtremor observation is conducted at five points along the highway (Fig. 4). Points 1 and 5 are located on the intact terrace, while Points 2, 3 and 4 are along the damaged section of the highway. As these points are lined along the busiest highway in Kathmandu, main source of ambient tremor can be predominantly vehicular movements and/or human activities. A portable device called Network Sensor (CV374-AV, Tokyo Sokushin Co. Ltd.) consists of three servo type accelerometers (VSE-14C, Tokyo Sokushin Co. Ltd.) for two horizontal (X, Y) and one vertical (Z) components, each having the velocity cover-range of 2 cm/s over the frequency range of 0.2 to 100 Hz.

Horizontal-to-vertical (H/V) spectral ratios, which can provide relevant information concerning site conditions and/or site amplification, were obtained at these five points as shown in Fig. 9. It is noted that in all H/V spectra, a common predominant frequency of 0.4 to 0.45 Hz appears. Though the graphs are smoothened by Parzen window with band width of 0.05 Hz for a higher frequency range from 1 to 10Hz, multiple peaks appear probably reflecting rather local soil profiles. H/V ratios for these peaks are rather small scattering around 1.0, and they alone do not seem to provide any clear clue to identify the subsoil structure. However it is noted that the subsurface organic soil layer together with the underlying soft soil layer may have a resonance frequency of around 3.5 Hz given their average shear wave velocity of 100 to150 m/s and thickness of about 10 to 12 m.


**Fig. 10** Creeping section of Pasang Lhamu Highway: Black and white arrows show that the road constructed in 2003 (black arrows) has carried over about 30m horizontal distance from its original location (white arrows).

## 3. DAMAGE TO PASANG LHAMU HIGHWAY

Pasang Lhamu Highway, a twisty mountain road, is one of the important highways of Nepal that connects Kathmandu to China via Dhunche. Many landslides have been observed along Pasang Lhamu Highway. Among them, a landslide at Ramche is found crucial for maintaining this road (Fig. 10). This massive landslide mass was detached from the hill slope of about 2100m above sea level in a rainy season of 2003. A temporary road was quickly constructed across this zone for the important traffic of this highway not to be suspended long. However the detached mass has been moving inch by inch towards the Trishuli River around 1300m below this road. The satellite images taken at different times show that this temporary road has been carried down

**Table 1** GPS measurement data at Ramche landslide on July 14$^{th}$ and November 1$^{st}$, 2015

| | Measurement on June 14$^{th}$ | | | Measurement on November 1$^{st}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Point ID | Ellipsoidal height(Z) | Longitude (Y) | Latitude (X) | Ellipsoidal height(Z) | Longitude (Y) | Latitude (X) | dZ | dY | dX | Total dis-placement (cm) | Moving direction azimuth |
| REF | 2001.7178 | 324369.507 | 3100221.539 | | | | | | | | |
| 1 | 2015.9812 | 325109.1492 | 3100945.428 | 2015.9855 | 325109.1604 | 3100945 | 0.0043 | 0.0112 | 0.0015 | 1.209049 | 82.37185 |
| 2 | 2013.1505 | 325217.9598 | 3100996.518 | 2013.1171 | 325217.9752 | 3100997 | -0.0334 | 0.0154 | 0.0129 | 3.897602 | 50.04836 |
| 3 | 2012.5992 | 325244.3199 | 3101084.913 | 2012.5663 | 325244.2812 | 3101085 | -0.0329 | -0.0387 | 0.0864 | 10.0225 | 335.8716 |
| 4 | 2011.9942 | 325277.0743 | 3101162.532 | 2011.9643 | 325277.0505 | 3101163 | -0.0299 | -0.0238 | 0.0194 | 4.285802 | 309.1844 |
| 5 | 2011.4167 | 325314.8458 | 3101227.664 | 2011.3625 | 325314.7921 | 3101228 | -0.0542 | -0.0537 | 0.0281 | 8.130769 | 297.622 |
| 6 | 2014.7622 | 325330.3356 | 3101266.62 | 2014.7299 | 325330.2841 | 3101267 | -0.0323 | -0.0515 | 0.0367 | 7.101007 | 305.4745 |
| 7 | 2016.0828 | 325350.2638 | 3101291.537 | 2016.0262 | 325350.1954 | 3101292 | -0.0566 | -0.0684 | 0.0674 | 11.14669 | 314.5781 |
| 8 | 2014.2099 | 325342.1236 | 3101331.004 | 2014.1426 | 325342.0548 | 3101331 | -0.0673 | -0.0688 | 0.0404 | 10.43786 | 300.4219 |
| 9 | 2009.5402 | 325305.9835 | 3101411.039 | 2009.4288 | 325305.8337 | 3101411 | -0.1114 | -0.1498 | -0.025 | 18.83481 | 260.5253 |
| 10 | 2016.8584 | 325300.9334 | 3101514.004 | 2016.7779 | 325300.8321 | 3101514 | -0.0805 | -0.1013 | 0.0038 | 12.94464 | 272.1483 |
| 11 | 2016.8675 | 325280.1502 | 3101571.3 | 2016.8521 | 325280.1322 | 3101571 | -0.0154 | -0.018 | -0.011 | 2.611819 | 238.5704 |
| 12 | 2022.4657 | 325244.8754 | 3101666.762 | 2022.4373 | 325244.8723 | 3101667 | -0.0284 | -0.0031 | -0.0142 | 3.190313 | 192.315 |
| 13 | 2028.0851 | 325187.1982 | 3101744.659 | 2028.0751 | 325187.2117 | 3101745 | -0.01 | 0.0135 | 0.0371 | 4.072665 | 19.99551 |

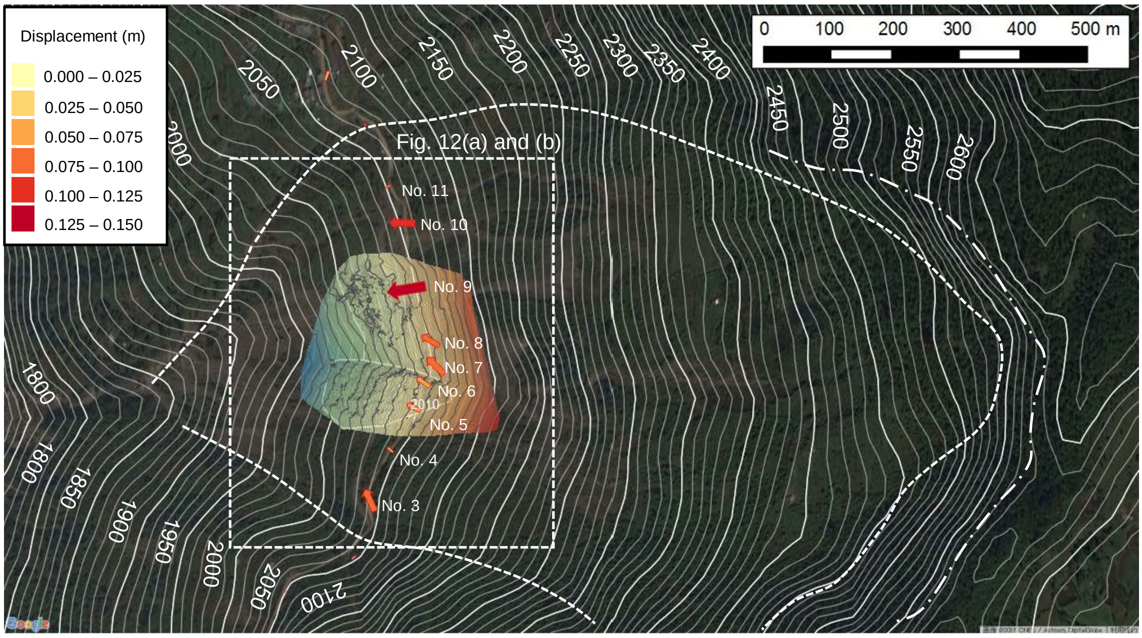


**Fig. 11** Vectors of creeping displacements over 4 months period from July 2015 to Nov. 2015. (Photo from Google Earth)

the slope over about 30m horizontal distance[3].

Geologically, the landslide is at the southern limb of the Kuncha-Gorkha anticlinorium formed by alternating bands of metasandstones and chlorite-phyllite[5]. Thick loosely packed colluvium with huge boulders are situated on the rocky slope.

To measure the movement rate of this landslide mass, GPS measurement for precise dynamic dual-frequency positioning was conducted twice over a 3.5 months period (July 14$^{th}$, and November 1$^{st}$, 2015, Table 1) along the creeping section of this highway. A reference station was taken at a N28.01564°, E85.21363 ° on an outcrop of sandstone on a stable mountain ridge. Then survey nails were driven at 13 locations along the highway. The movements of three orthogonal displacement components (X, Y and Z) for each of these 13 points were measured twice on mid-July 2015 and 1st November 2015 (Table 1 and

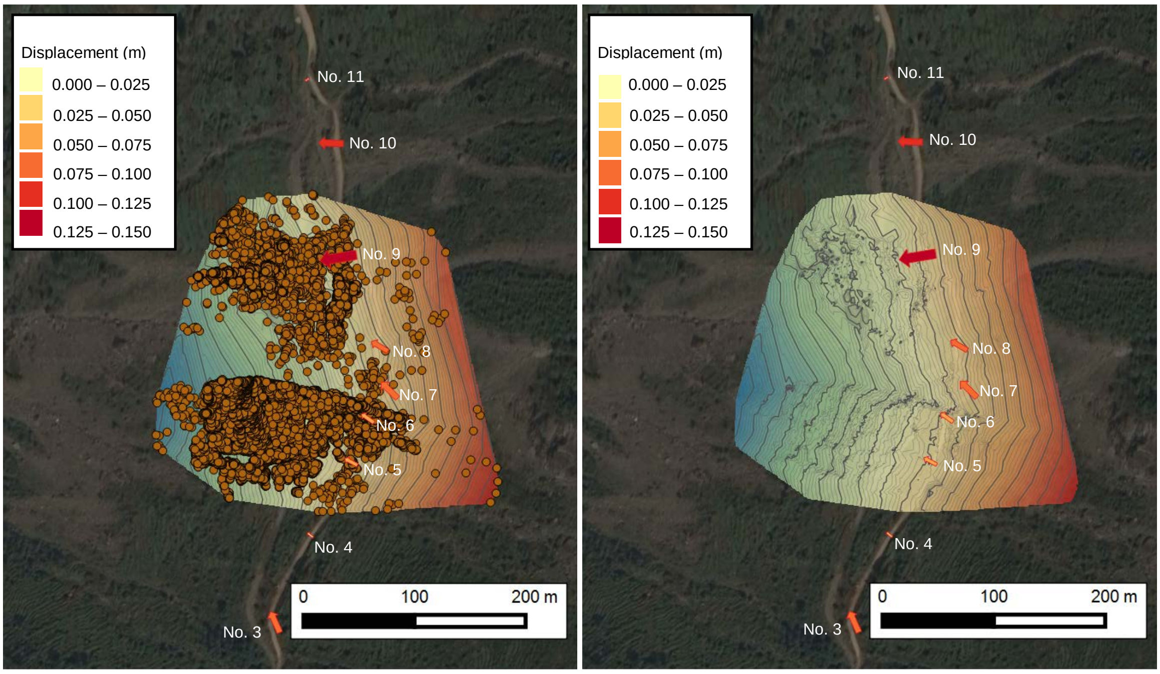


**Fig. 12** Micro terrain model (right) for a fraction of the creeping slope extracted from photos: Stereo-photogrammetry software allows to detect dots on the left figure automatically/ manually from photos for creating the 3D image shown on the right figure. (Photos from Google Earth)

Fig. 11). Given GDOP values ranging from 2.3 to 4.7 for these two surveys, the expected errors are at most 0.009 m and 0.007 m at Points 3 and 13, respectively. The largest lateral displacement of 0.15 m was reached at Point 9 with an expected maximum error of 0.003 m. Therefore, at least the observed displacement for Point 9 is considered to have statistical significance indicating clear creeping nature of this landslide mass. The vertical displacement component of Point 9 is 0.11 m, indicating that the displacement vector here dips 0.11/0.15 radian towards the Trishuli River, which inclination is a little larger than the average slope inclination of about 1/2. It is empirically known that vectors of creeping displacement observed on the surface of a coherent landslide mass can be about parallel to the slip surface lying below. This empirical knowledge suggests the possibility that the highway crosses a little higher part of one of coherent landslide masses making up the entire slope.

To see detail morphological features of the coherent landslide masses, it was originally planned to fly a drone to take aerial photos for stereo-photogrammetry. However Nepal moved to limit drone flights after the earthquake, and only photos from available ground photo spots were used. Due to this limitation, the extracted image-based 3D terrain model covers only a small fraction of the entire creeping slope as shown in Figs. 11 and 12. However the extracted 3D image shows small scarps in the middle of these landslide masses suggesting that they are not a single coherent mass but multiple.

The micro-terrain shown in Fig. 12 can be a reflection of local surficial soil movements to be sure, but by no means, does it show the entire picture of the creeping landslide masses. Fig. 11 also shows contour lines of the slope extracted from 30m by 30m resolution digital terrain model from JAXA[6]. As can be seen from a set of these contour lines, major lines of convex and concave breaks of the mountain slope, shown by white dot-and-dash and broken lines, respectively, immediately below the mountain ridge indicate that the entire landslide mass can be rather deep seated. If drone flights were not limited, we would be able to obtain significant information for mapping out necessary tactics for either stabilizing the slope or rerouting the highway. Moreover if we had more GPS survey points covering the whole landslide mass, a least-squares minimization of the difference between the measured slip vectors and dips of the hidden slip surface would enable a rational estimation of the entire geometric features of the slip surface[7]. Water of a gorge was found flowing across the highway indicating the subsurface soil of the landslide mass at this elevation is soaked up. Seasonal change in groundwater flows here is to be investigated.

## 4. SUMMARY

The authors conducted a surface wave survey, SWS, at the damaged section of the Araniko highway at Kausaltar, which crosses a small valley with an embankment. The estimated soil profiles for a 72 m and a 210 m stretches in the transverse and longitudinal directions of the highway indicated the wide-spread presence of weak shallow soil, that covers a area where offsets and cracks appeared in the earthquake. The weak soil is considered to be an organic substance from soil samples taken from a borehole near the highway, and a terrain map of this area shows a low-lying depression north behind the damaged section of the highway, maybe suggesting the presence of the small paleo-lake, which had been drying/emptying leaving organic substance over its entire shallow water area. The aothors' previous report[3] showed that both the damaged section of Araniko highway and the biggest cluster of damaged houses/ buildings were found where the east-west trending parallel firinge pattern of InSAR showed some clear disturbances. If they were a reflection of the presence of subsurface weak soils, rehabilitation plans for these areas should be carefully made taking into acount the weak nature of the hidden subsoils.

Pasang Lhamu highway is increasing its importance particularly after the earthquake and its largest aftershock hit very hard Araniko Highway, which has been of crucial importance to Nepal as it had been carrying a very large amount of goods from China. Actually China did supply its petro assistance of 1300 KL of oil through this Pasang Lhamu highway to Nepal[7], which country has been facing an economic and humanitarian crisis caused by a blockade in the country's south, leading to acute shortages of fuel and medicine. However as has been reported herein, this twisty mountain road has some unpaved narrow dangerous sections on creeping slopes. Actually on November 4th, 2015, three days after the authors' survey at this section, a bus skidded off the road and fell some 150 metres at the exact location of the authors' survey. At least 35 people were killed and more than 50 others were injured[8]. Its direct cause was surely the over-crowded vehicle due to the fuel shortage crisis. However we need to recognize that people need to risk passing through these dangerous sections of the highway by their over-crowded and over-loaded vehicles. All the more because of this difficult situation, monitoring of creeping behaviors of slopes along the highway is of crucial importance for taking necessary safety measures.


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