TOWARDS A MODERNIZED GEODETIC DATUM FOR NEPAL FOLLOWING THE APRIL 25, 2015 MW 7.8 GORKHA EARTHQUAKE

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Abstract: *Along with the damage to buildings and infrastructure, the April 25, 2015 Mw 7.8 Gorkha earthquake caused quite significant deformation over a large area in central Nepal with displacements of over 2 m recorded in the vicinity of Kathmandu. In this paper we consider options for a modernized geodetic datum for Nepal that will have the capacity to correct for the earthquake displacements and ongoing tectonic deformation associated with Nepal's location on the India/Eurasian plate boundary. In the scenario we present here, the datum would be based on ITRF2014 with a reference epoch set some time after the end of the current sequence of earthquakes. We have developed a preliminary velocity field by collating GPS derived crustal velocities from four previous studies for Nepal and adjacent parts of China and India and aligning them to the ITRF. We developed preliminary patches for the co-seismic part of the deformation using published dislocation models. By combing the velocity and co-seismic models we have developed an NDM that can correct coordinate for both the effect of the earthquakes and continuous deformation associated with Indian / Eurasian plate boundary.*

High order control would be a CORS network based around the existing Nepal GPS Array. Coordinates for existing lower order control would be determined by readjusting existing survey measurements and these would be combined with a series of new control stations spread throughout Nepal.

1 INTRODUCTION

Currently Nepal uses a classical datum (the Nepal-Everest datum) developed in 1984 by the Military Survey branch of the Royal (UK) Engineers in collaboration with the Nepal Survey Department (Spence 1987). However, Nepal is located at the conjoint of two converging plates and due to the regular convergence of these plates the existing passive geodetic control network had become distorted with time. This combined with the effect of the April 25, 2015 Mw 7.8 Gorkha earthquake, which caused significant deformation over a large area centered on the Kathmandu Valley means that the integrity of the current Nepal-Everest datum cannot be assured. In this paper we consider options for a modernized geodetic datum for Nepal that will have the capacity to correct for the earthquake displacements and ongoing tectonic deformation associated with Nepal's location on the India/Asia plate boundary.

2 SEMI-DYNAMIC DATUMS

Modern semi-dynamic datums are based on a version of the International Terrestrial Reference Frame which is based on four techniques, (Satellite Laser Ranging, Very Long Baseline Interferometry, DORIS: Doppler and GNSS). This produces a global datum with unparalleled accuracy but it is not suited to use as a national datum because it lacks a mechanism to produce stable coordinates. In semi-dynamic datums, stable coordinates are produced by projecting each coordinate to its position at a common date called the reference epoch. In order to make this technique work we need a model of how the earth is moving due to plate tectonics. In stable areas, the effect of earthquakes will be small and the motion of the points will follow the motion of the tectonic plates. In areas that are located on the boundaries of tectonic plates, the motion is more complicated. In this case a mathematical model called a National Deformation Model, is used to calculate the trajectory of points. This usually includes a way of estimating the constant or secular velocity of each point and a way of calculating the effect of any earthquakes that may have occurred between the time that the coordinates were measured (epoch of observation) and the reference epoch. The effect of earthquakes is an instantaneous offset while the effect of the velocity increases linearly with time. This process is illustrated in Figure 1, which shows the trajectory of a point effected by a constant velocity and two earthquake shifts.

In contrast, older classical datums such as the Nepal-Everest datum, which were usually established before the reality of plate tectonics was widely accepted, establish fix coordinates for a network of control points with no mechanism to correct for tectonic motion. As a result the marks will drift off their true position. Thus the datum will become distorted as the bearings and distances between marks calculated from their coordinates become increasingly different from what we would measure on the ground.

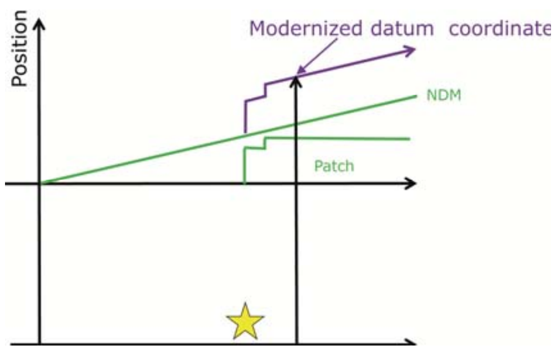

Figure 1 Schematic diagram of a dynamic datum. Green shows the secular velocity and co-seismic contribution to the deformation model. The purple line shows the deformation model with both contributions.

3 POSSIBLE OUTLINE FOR A SEMI-DYNAMIC DATUM FOR NEPAL

Normally, a dynamic datum is aligned to a realization of the ITRF that is current at the time that the datum is released. In the case of Nepal, the datum would be based on be ITRF2014. For the reference epoch, we propose to use a date after the end of the current sequence of earthquakes is over.

The Deformation model is the tool that allows coordinates to be projected either backward or forward in time to the reference epoch. As shown in Figure 1, a deformation model contains two distinctly different elements. The first is a model of the variation of the long term (or secular) crustal velocity across the country and the second is a model or models of the co-seismic deformation associated with any large earthquakes. Both the velocity model and the co-seismic deformation models are grid files so that the estimates of the velocity or co-seismic shifts can be determined using a process of linear interpolation (Stanaway et al. 2012).

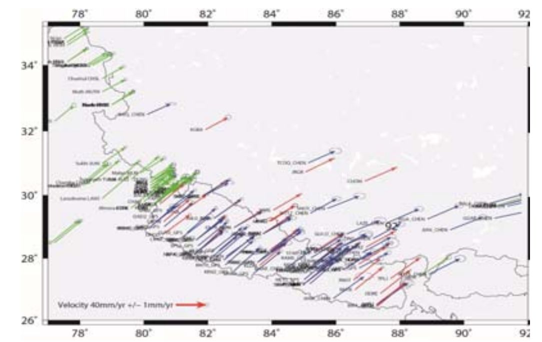

Figure 2 separate solutions transformed into ITRF2008. red is from the Ader et al, (2012) study, Black is Jade (2004), Blue is Jade et al (2014) and Betenilli et al. (2006)is green.

Our model of the velocity field for Nepal was developed by combining published velocities for Nepal and adjacent parts of China and India from four geodetic studies in the Nepal region. These include 96 measurements from Betenilli et al. (2006), 70 from Jade et al. (2014), 38 from Ader et al. (2012), and 228 from Banerjee et al. (2008). In addition we included 1000 official IGS13 velocities for IGS stations. The five studies provide good coverage of the Nepal area but, because each study was conducted separately over a period of 10 years, they are in several different realizations of the ITRF (ITRF 2000, ITRF2005 and ITRF2008). The velocities are shown in Figure 2.

These velocity solutions were then aligned consistently with ITRF2014, using a least square technique from (Snay et al. 2015). Using these velocities we developed a grid file that covers the region from 80°E to 89°E and

26°N to 31°N (Figure 3). While Figure 3 shows velocity vectors on a half degree spacing the actual gridded velocities have a spacing of 20 points/degree (0.05°).

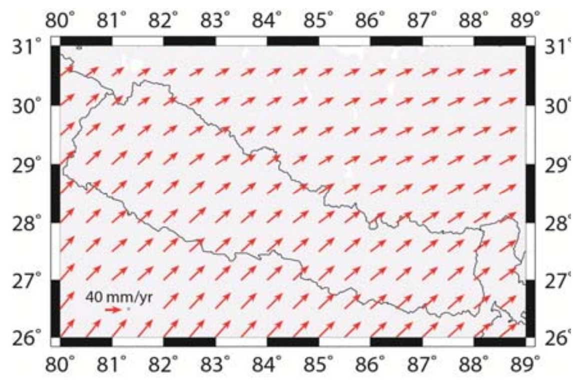

Figure 3 Velocity grid for Nepal

An NDM also must include patches or gird files that can be used to predict the earthquake deformation at any point. We have developed preliminary patches for the co-seismic part of the 25th April 2015 Gorkha Earthquake and the 12th May ML 6.8 aftershock using published dislocation models (Galetzka et al., 2015). Figure 4 and 5 shows the co-seismic slip from the 25th April 2015 Gorkha Earthquake and the 12th May ML 6.8 Aftershock. Note that the Kathmandu Valley has moved by up to 1.9 m.

The velocity grid and the two earthquake patches have been combined to make a preliminary national deformation model (NDM) for Nepal. This model would form a key part of a semi dynamic datum for Nepal and be transformation coordinates from the epoch of observation to reference epoch of Nepal's national datum.

In order to test the effectiveness of a semi-dynamic datum to correct for the deformation from the April 25, 2015 Mw 7.8 Gorkha Earthquake, we adjusted GPS

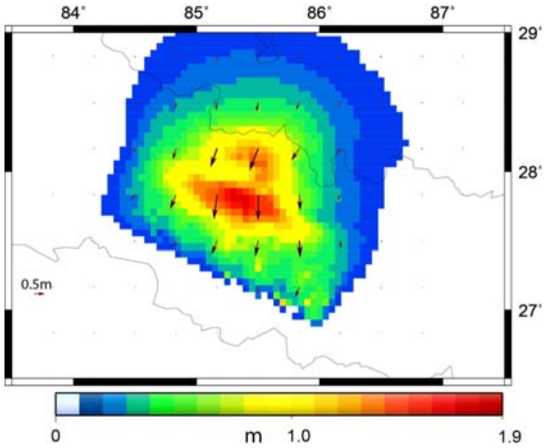

Figure 4 Predicted displacement associated with the 25th April 2015 Mw 7.8 Gorkha Earthquake

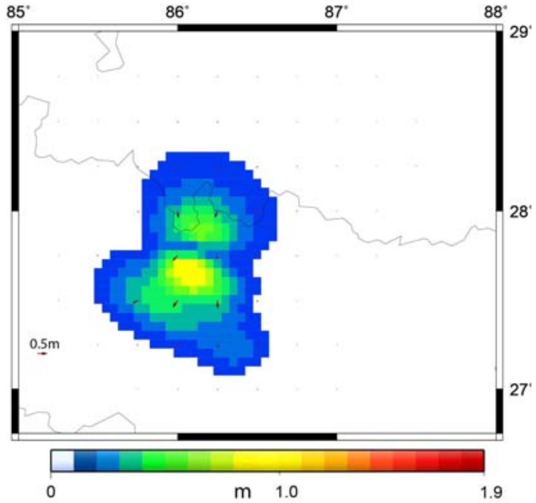

Figure 5 Predicted displacement for the Mw 7.3 12 May Aftershock

data that contained both pre and post-earthquake measurements using a version of the Land Information New Zealand's (LINZ) Survey Net Adjustment (SNAP) program (LINZ 2013) which has been modified to support the option for a modernized datum for Nepal. These test points (See figure 6) define a polygon extending about 40 km in the NW SE direction centered on Kathmandu. Between these points there are nine GPS baselines, three of which were recorded in April 2013, before the earthquake and six of which were observed on 08 May 2015, in the period between the 25th April 2015 Gorkha Earthquake and the 12th May ML 6.8 aftershock.

The first adjustment was conducted without using a deformation model while, in the second adjustment, the deformation model was used to correct all the measurements to pre-earthquake values. The Standard error of unit weight for the adjustment which does not apply the NDM is more than a factor of 3 times greater than the SEUW for the model which does apply the NDM. This difference demonstrates that the deformation model is effective in correcting for crustal deformation between the two surveys. The improvement in the SEUW due to applying the NDM is significant the 99.99% level of confidence.

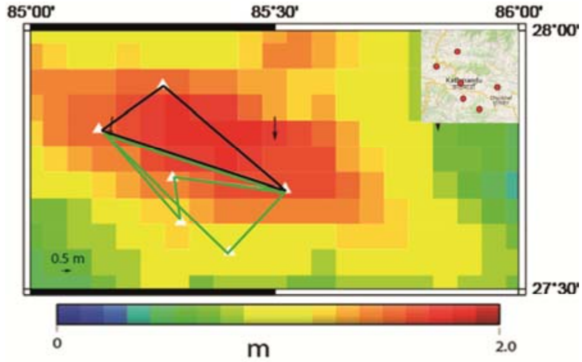

Figure 6 Location of test points plotted on a map of maximum displacements from the 25th April 2015 Gorkha Earthquake. Arrows show vector displacements. Black lines show baselines from the pre earthquake survey and green lines show the show baselines from the post earthquake survey. Inset shows a map of the test points.

Of course least square adjustments require control. Top level control for a new Nepal datum could be based on a CORS network with coordinates being rigorously aligned to the ITRF. This network could adopt as many of the existing Nepal GPS Array (http://www.tectonics.caltech.edu/resources/kmlnepal.html) stations as possible. A preliminary evaluation of the stations in the array indicates that 20 of these sites maybe available to act as a CORS network for Nepal. Coordinates for existing lower order coordinates would be determined by readjusting existing measurements combined with new surveying data using software that can apply the deformation model correctly..

4 CONCLUSIONS

Because of the effect of the 25th April, 2015 Gorkha earthquake, significant earth deformation has occurred in a large area of Nepal centered on the Kathmandu Valley. As a result, the geodetic control in this region is significantly distorted with published geodetic control coordinates being displaced from their true position on the ground by up to 2 m. Correcting these distortions will require a new geodetic datum. In this paper we consider the possibility of Nepal adopting a semi-dynamic datum, which would be based on ITRF2014 and include a national deformation model capable of correcting for the recent earthquakes and normal tectonic motion. We demonstrate that it is possible to develop a deformation model for Nepal incorporating the Gorkha earthquake and the variation of the long term (or secular) crustal velocity across the country using published information. While this model is preliminary our test shows that its use does a good job of correcting survey measurements for the effect of the earthquake.

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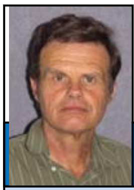

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