“Structure-from-Motion” photogrammetry: a novel, low-cost tool for geomorphological applications

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1. ‘Structure-from-Motion’

Presently, methods for surveying, at high resolution, complex landforms and landscapes are accompanied by high start-up and data acquisition costs. In addition, issues of portability may be introduced given the relative remoteness and inaccessibility of many field sites, particularly in high-mountain regions.

‘Structure-from-Motion’ (or SfM), represents a solution to the above, and requires little more than a consumer-grade digital camera and GPS for effective implementation. Operating under the same basic principles of stereoscopic photogrammetry, the user moves around, through, or over the landform or landscape of interest, acquiring multiple overlapping, offset images. For best results, a small camera baseline, and high degree of scene overlap is recommended.

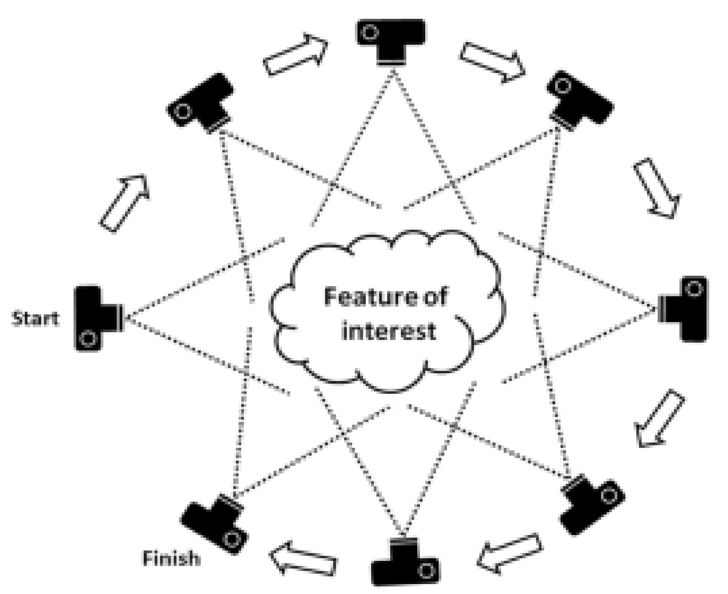

Fig. 1. Instead of a single stereo pair, the SfM technique requires multiple overlapping images as input to 3D reconstruction algorithms

Traditional softcopy photogrammetric methods require the 3D location and pose of the camera(s), or the 3D location of ground control points (GCPs) to be know to facilitate scene triangulation and reconstruction. The SfM approach requires neither of the above to be known prior to scene reconstruction. Instead, fully automated feature extraction and matching algorithms (Lowe, 2004) and bundle adjustment software (Snavely. 2008) employing an iterative, least-squares solution are used to simultaneously estimate camera pose and reconstruct scene geometry.

Output data are fixed into a relative co-ordinate system. A network of GCPs, visible in the resultant point cloud and surveyed used dGPS, is required to transform the data into absolute co-ordinates, permitting the extraction of useful metric data. The SfM workflow employed is outlined in Fig. 2.

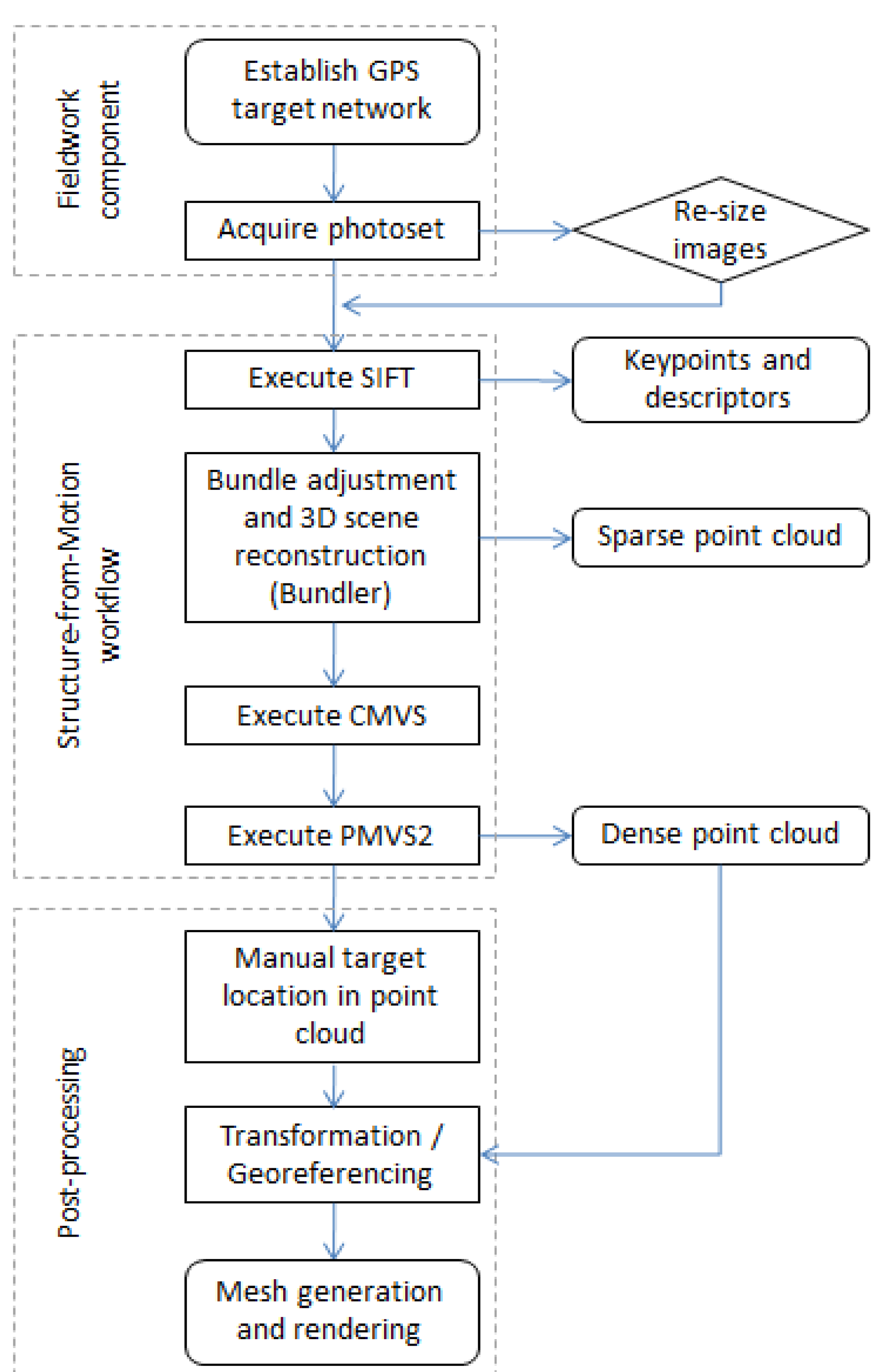

Fig. 2. From photograph to high-resolution, georeferenced 3D model: the SfM workflow. Note: all software listed is freely available and will appear with a Google search. Henri Astre’s ‘SFMToolkit’ application bundle was used for this work (Astre, 2011).

2. Comparison with Terrestrial Laser Scanning

Given the recent emergence of the SfM technique, performance was gauged against a contemporary high-resolution surveying method. This was achieved through direct comparison of DTMs created of a local landmark using SfM and Terrestrial Laser Scanning (TLS). Constitution Hill (Aberystwyth, Wales; Fig. 3a) is ~80m high, and comprises topographically complex terrain, including near-vertical cliff faces, rockfall debris, with land cover including grasses and low shrubs.

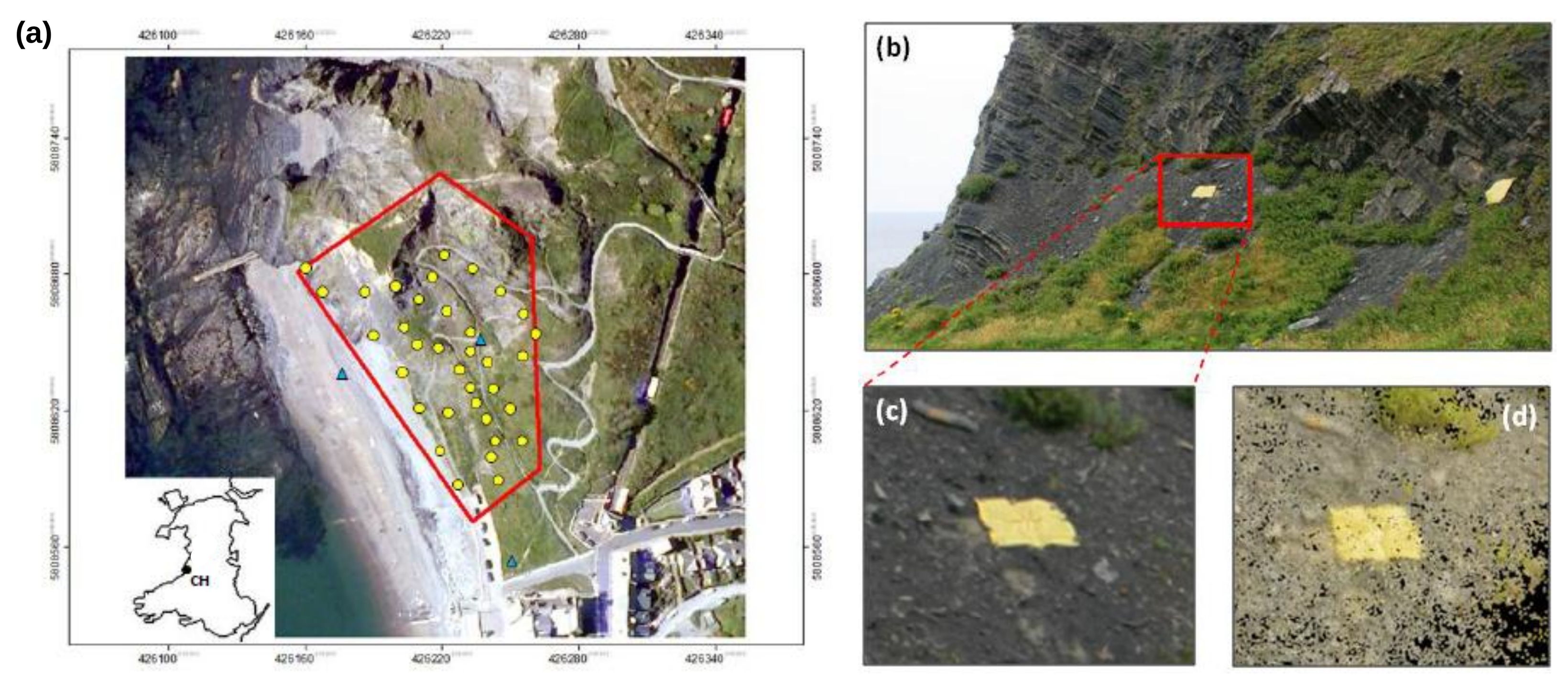

Fig. 3. Constitution Hill, Aberystwyth, UK. **a)** Overview of the study site (red). Yellow circles = GCPs, Blue triangles = TLS location; **b)** GCPs, as viewed *in situ*; **c)** GCP close up, as appearing in an input photograph, and; **d)** as resolved in the dense point cloud.

Thirty-five $1m^2$ GCPs were placed across the site (Fig. 3b-c). TLS data were acquired at a scan resolution of 1 cm. For SfM input, a total of 889 photographs were acquired across the site using a Panasonic DMC-G10 (12MP) . TLS data were not transformed, though retained accurate scaling and rotation. GCP centroid locations, as extracted from the TLS data, were used to transform the final, dense point cloud produced using SfM (with transformation residuals of 0.124m, 0.058m and 0.031m for xyz, respectively).

Following the manual removal of outliers and scan artefacts, the TLS data numbered 11.5×10^6 points. Sparse point cloud reconstruction using SfM produced 1.7×10^5 points, whilst subsequent dense reconstruction significantly increased the final dataset to 11.3×10^6 points. An example of reconstruction density and detail produced using SfM is displayed in Fig. 4. Although the spatial coverage attained using SfM was poorer than TLS, notable topographic elements such as near-vertical cliff faces were resolved faithfully.

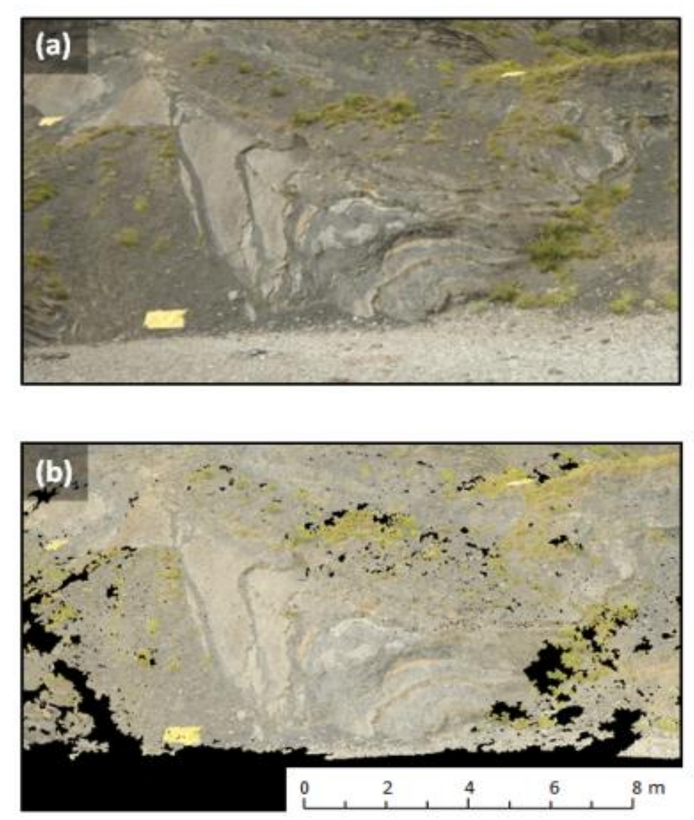

Fig. 4. Bedrock fold structure, as it appears in an input photograph **(a)**, and reconstructed in a significant amount of detail in the dense point cloud **(b)**.

A DEM of difference (DoD; in the vertical dimension) was created by decimating both datasets to $1m^2$ resolution and subtracting the SfM data from its TLS counterpart (Fig. 5). These data reveal that 85.6% of cells falling in the range -0.5 – 0.5 m. Spatially, the largest discrepancies correspond to the steepest zones of the site, where small horizontal transformation errors result in large vertical displacements, as well as areas of dense vegetation, or interpolation. Across the remainder of the site, z_{diff} values were minimal.

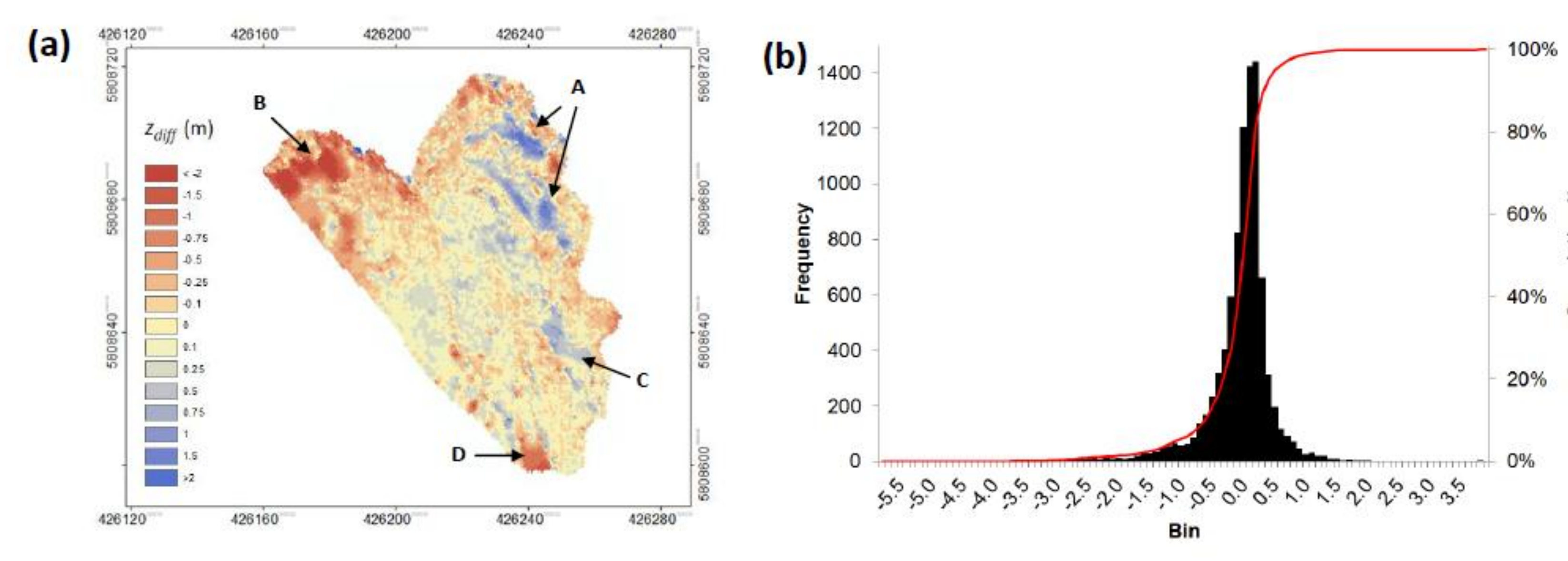

Fig. 5. SfM vs. TLS results. **(a)** DoD shown as the spatial representation of the z_{diff} frequency distribution, and; **(b)** z_{diff} frequency distribution histogram. **A** = headwall at highest point of survey area; **B** = near-vertical cliffs; **C** = dense vegetation cover; **D** = interpolation errors.

3. Application: Dig Tsho moraine dam complex

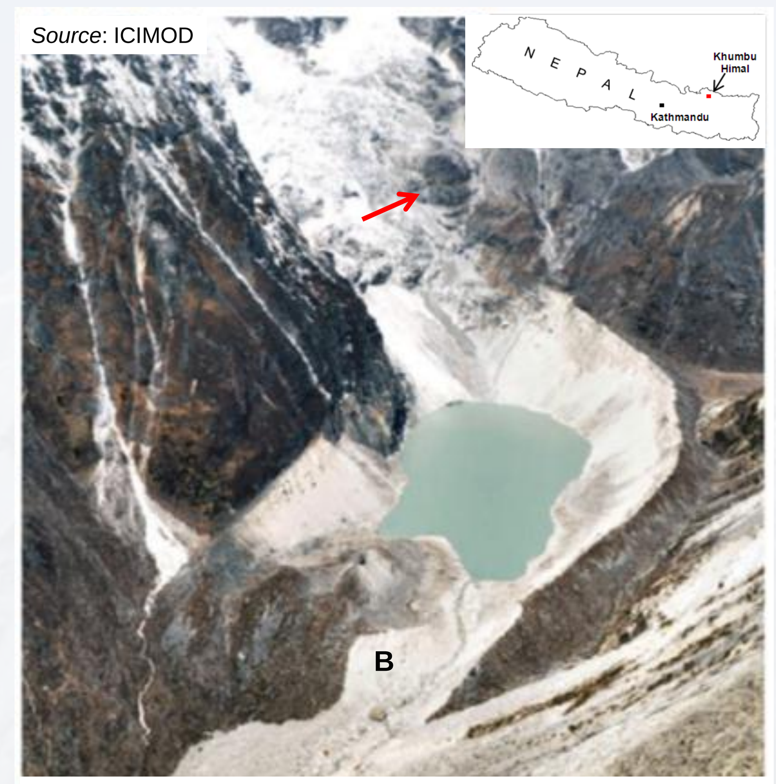

Fig. 6. The Dig Tsho moraine-dammed lake complex. Arrow shows ice avalanche source area. **B** = moraine breach.

The workflow outlined in previous sections was applied to the Dig Tsho moraine-dam complex, located in the Khumbu Himal, Nepal (Fig. 6; 4,400m). The dam failed in 1985, when an ice avalanche from the receding parent glacier produced a displacement wave which triggered its failure (Vuichard and Zimmerman, 1987).

The construction of high-resolution DTMs was required for the extraction of precise metric data pertaining to drained basin bathymetry and dam topography. A GCP network was established at the site, and ~1600 photographs were taken of the terminal and lateral moraine for use as input to SfM processing (achieved by processing in three ‘batches’ , application of transformation data, and merging into a final point cloud).

The final DTM, constructed through the interpolation of 13.2×10^6 points is shown in Fig. 7a.

Significant topographic detail is resolved, including the breach (40 m high, 70 m wide), relict spillways, and a sizeable perched boulder in the centre of the moraine.

Morphometric analysis of the data permitted the extraction of volume-stage and area-stage curves for the drained water volume (Fig. 8), as well as geometric data including cross-sectional elevation profiles of the dam structure and breach for use as input to advanced dam breach modelling.

Finally, the volume of material removed during the GLOF was achieved through reconstruction of pre-GLOF dam topography (Fig. 7b, c).

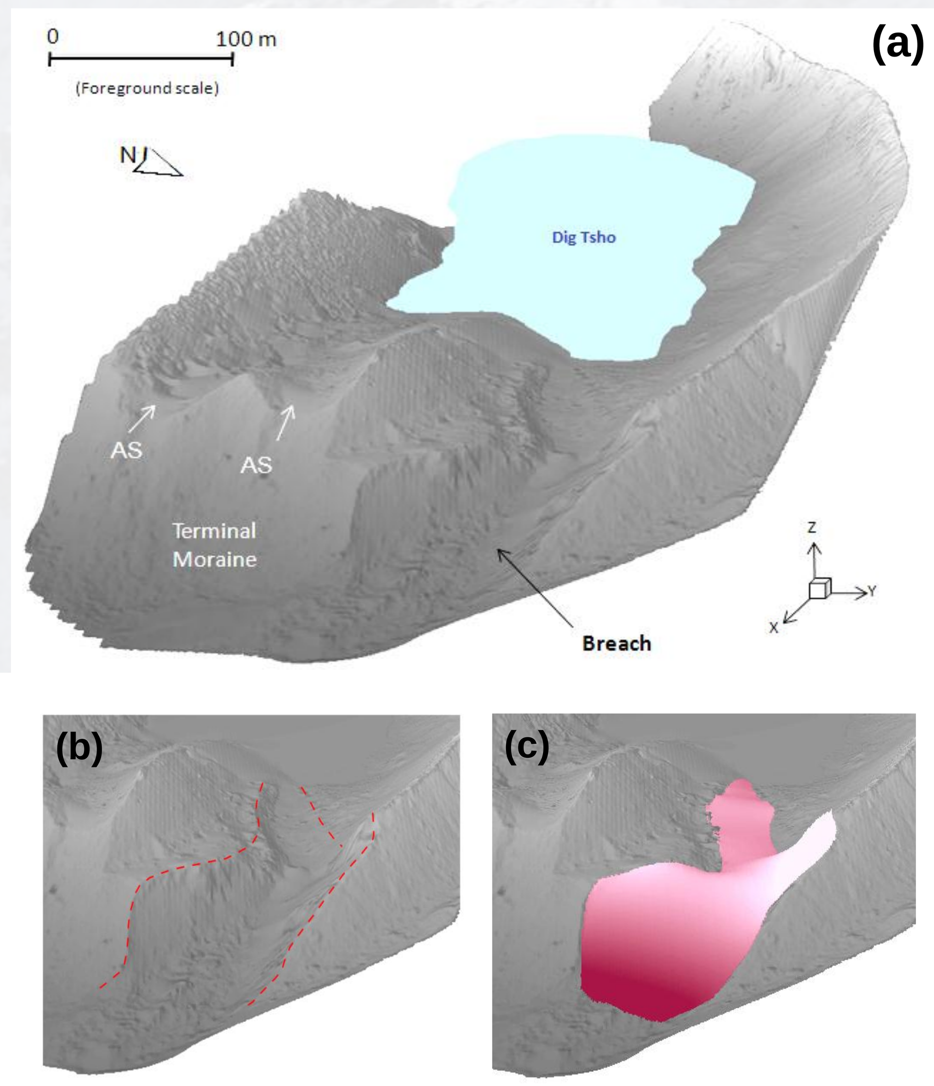

Fig. 7. **(a)** Hillshaded DTM of the moraine-dammed lake complex; **(b)** post-GLOF breach geometry (red dashes show lateral extent), and; **(c)** reconstructed pre-GLOF geometry.

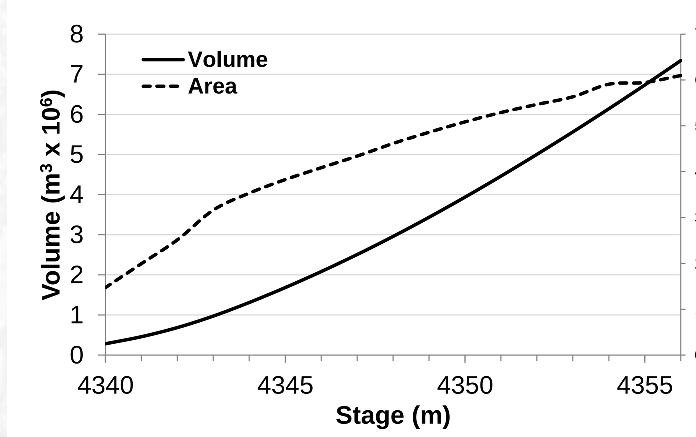

Fig. 8. pre-GLOF volume-stage and area-stage curves.

4. Summary

Issues of portability and high start-up costs typically accompany many high-resolution topographic surveying methods. In contrast, the ‘Structure-from-Motion’ photogrammetric method requires little more than a digital camera and GPS to implement, and is capable of producing point cloud output which rivals TLS (set at 1 cm scan resolution) in both density and reconstruction detail. Due to its versatility, this makes SfM a powerful tool for high-resolution topographic surveying in remote regions. However, errors caused by interpolation in areas of ‘dead-ground’, and the presence of vegetation are significant limitations of the method. The SfM technique was used to construct a high-resolution DTM of the breached Dig Tsho moraine dam complex, facilitating the reconstruction of pre-GLOF moraine geometry and extraction of bathymetric data.

References

Astre, H. (2011). SFMToolkit. Available: http://www.visual-experiments.com/demos/sfmtoolkit. Accessed 09 January 2012.
Lowe, D. (2004). Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision*, **60(2)**, 91-110.
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Vuichard, D. and Zimmerman, M. (1987). The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences. *Mountain Research and Development*, **7**, 91-110.

See also: GM2.2 - Friday, 15:45, Room 2:
“Close-range photogrammetric reconstruction of moraine dam failures”