# Appendix G Change Detection Parameters

## Tushare

### *Introduction*

Parameters employed for the M3C2 assessment at Tushare were based on the best estimate parameters provided by the plugin (Table G 1). Registration error associated with alignment of the individual scans was not directly entered into M3C2 but considered in the global level of detection (LOD) threshold applied to the whole cloud as described below.

**Table G 1. Parameters used in M3C2 surface change assessment from 2012 to 2017**

| Parameter | 2012 to 2016 | 2016 to 2017 |
|---|---|---|
| Core Points | 2012 dataset subsampled to 0.69 m | 2016 dataset subsampled to 0.79 m |
| Normals (m) | 2.746 | 3.176 |
| Projection (m) | 1.373 | 1.587 |
| Max Depth (m) | 56.440 | 60.734 |
| Registration Error | Not included | Not included |

The level of detection ($LOD_{95\%}$), referred to as distance uncertainty in CloudCompare, achieved for the comparison of the 2016 and 2012 and 2016 and 2017 datasets is included in Table G 2. This calculation is inherent to the M3C2 and considers the effects of surface roughness, position uncertainty and user defined registration error (Lague et al. 2013).

**Table G 2. Level of detection parameters for change detection using M3C2 plugin**

| Parameter | 2016-2012 | 2017-2012 |
|---|---|---|
| Minimum $LOD_{95\%}$ (m) | 0.0025 | 0.0010 |
| Distribution | Gaussian | Gaussian |
| Mean $LOD_{95\%}$ (m) | 0.0482 | 0.0397 |
| Median $LOD_{95\%}$ (m) | 0.0363 | 0.0310 |
| Standard Deviation $LOD_{95\%}$ (m) | 0.1828 | 0.1451 |

Higher distance uncertainty ($LOD_{95\%}$) is associated with higher surface roughness values on the vegetated talus cone at the base of the slope, vegetated slopes to the east of the main failure and in the rough debris at the base of the slope along with the upper source area (Figure G 1). In contrast, reduced distance uncertainty is associated with more planar, unvegetated areas as observed in the midslope rock face (Figure G 1). Non-significant changes (34% for 2016-2012, 37% for 2017-2016) correspond to areas of low point density (exterior edges of point clouds), occluded areas and truly stable areas.

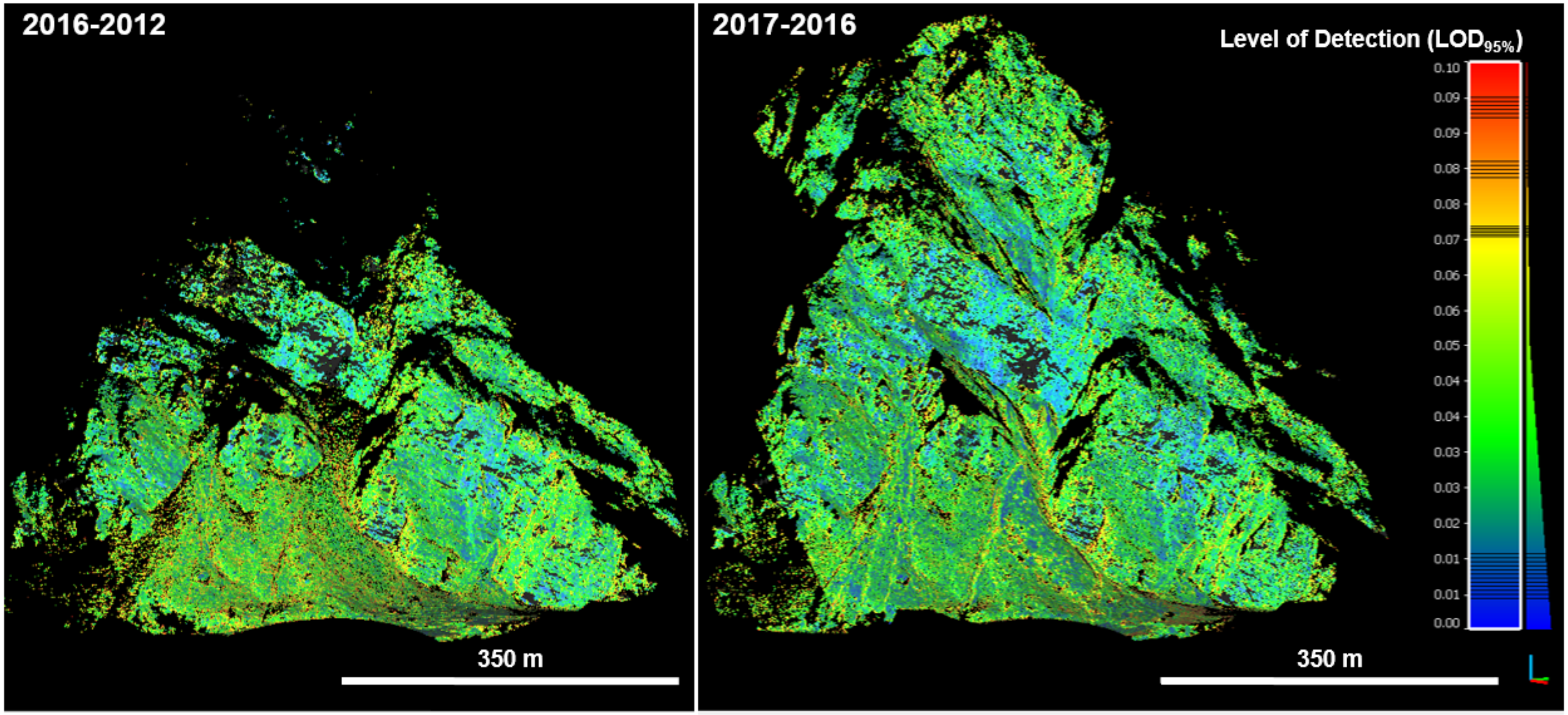


**Figure G 1.** **Spatially variable level of detection at 95% ($LOD_{95\%}$) for surface change between the 2012 and 2016 datasets (left) and 2016 and 2017 datasets (right). Both plots use the same scale (0.00-0.10 m).**

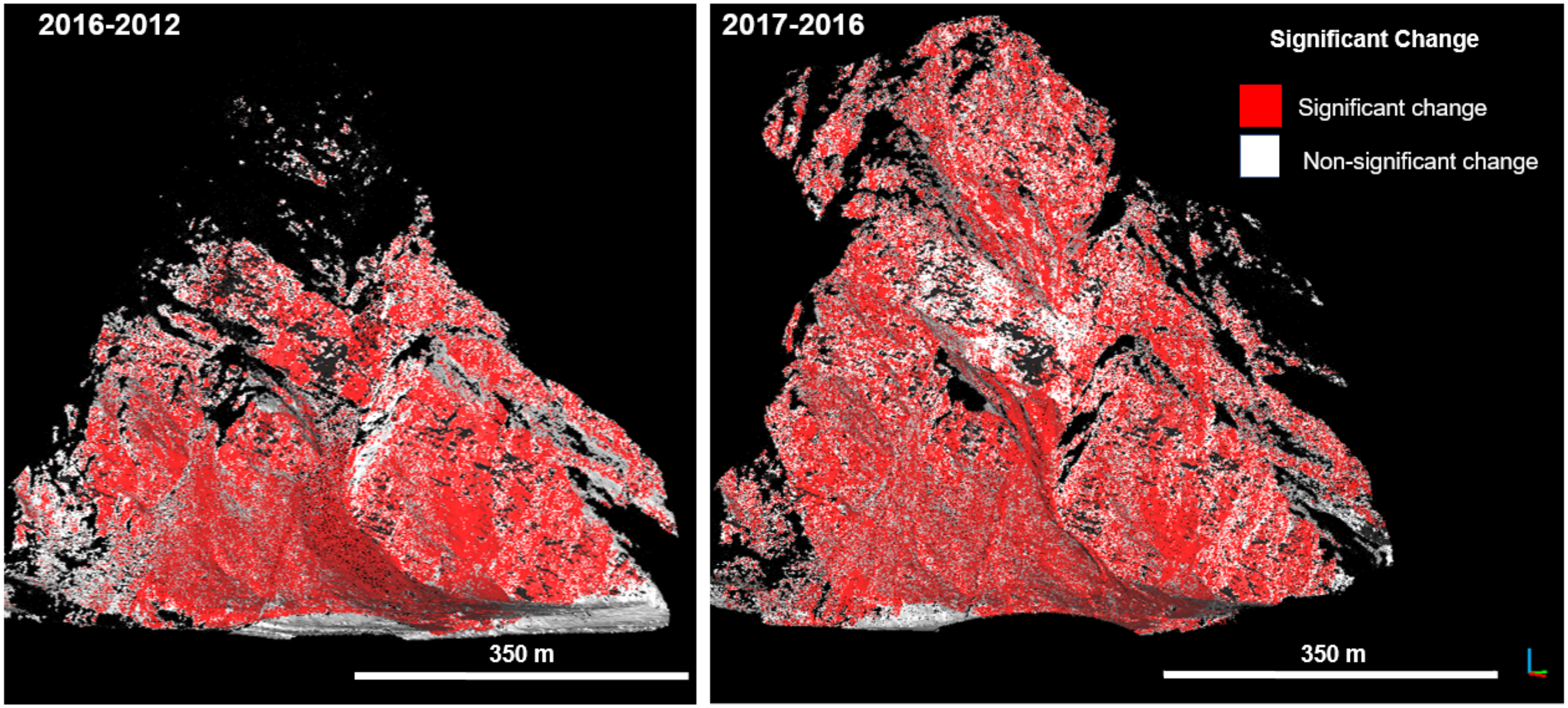


**Figure G 2.** **Significance of change measured between the 2012 and 2016 (left) and 2016 and 2017 datasets (right). Red indicates areas where the measured change exceeds the spatially variable $LOD_{95\%}$ shown in Figure G 1.**

Scalar field calculations were used to subtract the spatially variable $LOD_{95\%}$ from the measured M3C2 distances and then filter by significance to isolate surface change measurements exceeding the local LOD.

In addition to the variable LOD defined by M3C2, the accuracy and precision of the scanners (Riegl VZ-4000: accuracy, 0.015 m, precision: 0.010 m (at 150 m); Riegl VZ-1000: accuracy 0.008 m, precision 0.005 m (at 100 m) (RIEGL Laser Measurement Systems 2017a, 2017b) and registration error (0.013 m to 0.072 m error standard deviation as reported by the multi-station adjustment (MSA) statistic in RiSCAN Pro (RIEGL 2016) were considered. Using Gaussian statistics, the 95 percentile of the normal distribution lies within 1.96 standard deviations of the mean. As a conservation estimate, a LOD of 0.14 m (1.96*0.072 m) was employed.

For the purposes of visualizing the change detection results concurrently with the geomorphic mapping, DEMs of difference (DoD) using rasters from the TLS datasets were also produced. In the DoDs, the LoD is assigned as the raster cell size. DoDs present change where the point density exceeds 4 points/cell as calculated in CloudCompare using the number of neighbours approach. In addition, DoDs are masked to exclude all surface change measurements where the slope angle exceeds 60° given the limited application of this method to near-vertical slopes (Lague et al. 2013).

### *Comparison of Results by Method*

Measurement of surface change derived from the DoD and M3C2 illustrate the same patterns of erosion and deposition but vary in the extreme (minimum and maximum) values as a result of the methods of calculation inherent to each method. The DoD is derived from elevation differences along the z-axis whereas M3C2 uses a cylinder projected along the surface normal.

The magnitudes of change calculated using M3C2 are assumed to be more accurate due to the improved calculation of surface change at subvertical slopes. Table G 3 and Table G 4 summarize the differences in magnitude calculated using the different algorithms for the 2012 to 2016 and 2016 to 2017 change detection periods, respectively. Generally, it was found that the DoD method overestimated surface change compared with the M3C2 method.

**Table G 3. Comparison of maximum surface change calculated using DoD and M3C2 methods between 2012 and 2016 at Tushare.**

| Location | Maximum Surface Change (m) [1] | |
|---|---|---|
| | DEM of Difference (DoD) | M3C2 |
| Main debris deposit | 11.76 | 9.52 |
| Erosion into upper debris apron | -8.12 | -7.25 |
| West rockfall | -13.98 | -12.07 |
| East rockfall | N/A [2] | -17.02 |
| Pre-2012 rockfall source | -9.66 | -6.31 |
| Pre-2012 rockfall talus cone deposition | 2.97 | 2.40 |
| Pre-2012 rockfall talus cone incision | -2.24 | -1.88 |
| Erosion into lower debris apron | -5.21 | -4.53 |
| Erosion into lower west debris apron | -6.93 | -4.89 |
| Riverbank (upstream, east) | -7.54 | -9.67 |
| Riverbank (downstream, west) | -6.41 | -5.77 |

1. Negative values indicate erosion and positive values indicate deposition
2. Not measured in detail – visual observations only

**Table G 4. Comparison of maximum surface change calculated using DoD and M3C2 methods between 2016 and 2017 at Tushare.**

| Location | Maximum Surface Change (m) [1] | |
|---|---|---|
| | DEM of Difference (DoD) | M3C2 |
| Upper source area erosion | -2.50 | -2.25 |
| Upper source area deposition | 3.25 | -2.95 |
| Incision of landslide debris | -4.94 | -4.41 |
| Slumping of landslide debris | -4.53 | -3.29 |
| Deposition of debris flow debris | 5.46 | 4.15 |
| Gully incision | -4.36 | -4.62 |
| Riverbank (downstream, west) | -5.38 | -3.83 |

1. Negative values indicate erosion and positive values indicate deposition

### *Change Detection Parameters Used at Select Windows*

**Table G 5. Parameters used in M3C2 surface change assessment from 2016 to 2017 in the upper source area**

| Parameter | 2016 to 2017 |
|---|---|
| Core Points | 2016 dataset subsampled to 0.28 m |
| Normals (m) | 1.125 |
| Projection (m) | 0.562 |
| Max Depth (m) | 21.990 |
| Registration Error | Not included |

**Table G 6. Parameters used in M3C2 surface change assessment from 2016 to 2017 on the rockface**

| Parameter | 2016 to 2017 |
|---|---|
| Core Points | 2016 dataset subsampled to 0.097 m |
| Normals (m) | 0.3889 |
| Projection (m) | 0.1944 |
| Max Depth (m) | 11.2445 |
| Registration Error | Not included |

**Table G 7. Parameters used in M3C2 surface change assessment from 2016 to 2017 on the east rockfall**

| Parameter | 2016 to 2017 |
|---|---|
| Core Points | 2016 dataset subsampled to 0.48 m |
| Normals (m) | 1.906 |
| Projection (m) | 0.9531 |
| Max Depth (m) | 14.4180 |
| Registration Error | Not included |

## The Last Resort (TLR)

The parameters employed for the M3C2 assessment at TLR were based on the best estimate parameters provided by the CloudCompare plugin (Table G 8). Registration error associated with alignment of the individual scans was not directly entered but ranged from 0.0339 m to 0.0975 m error standard deviation as reported by the MSA Statistic in RiSCAN Pro (RIEGL 2016). The results are shown in Figure G 3.

**Table G 8. Parameters used in M3C2 surface change assessment from 2016 to 2017 at TLR.**

| Parameter | Value |
|---|---|
| Core Points | Full 2017 point cloud |
| Normals (m) | 9.62 |
| Projection (m) | 4.81 |
| Max Depth (m) | 117.30 |
| Registration Error | Not considered |

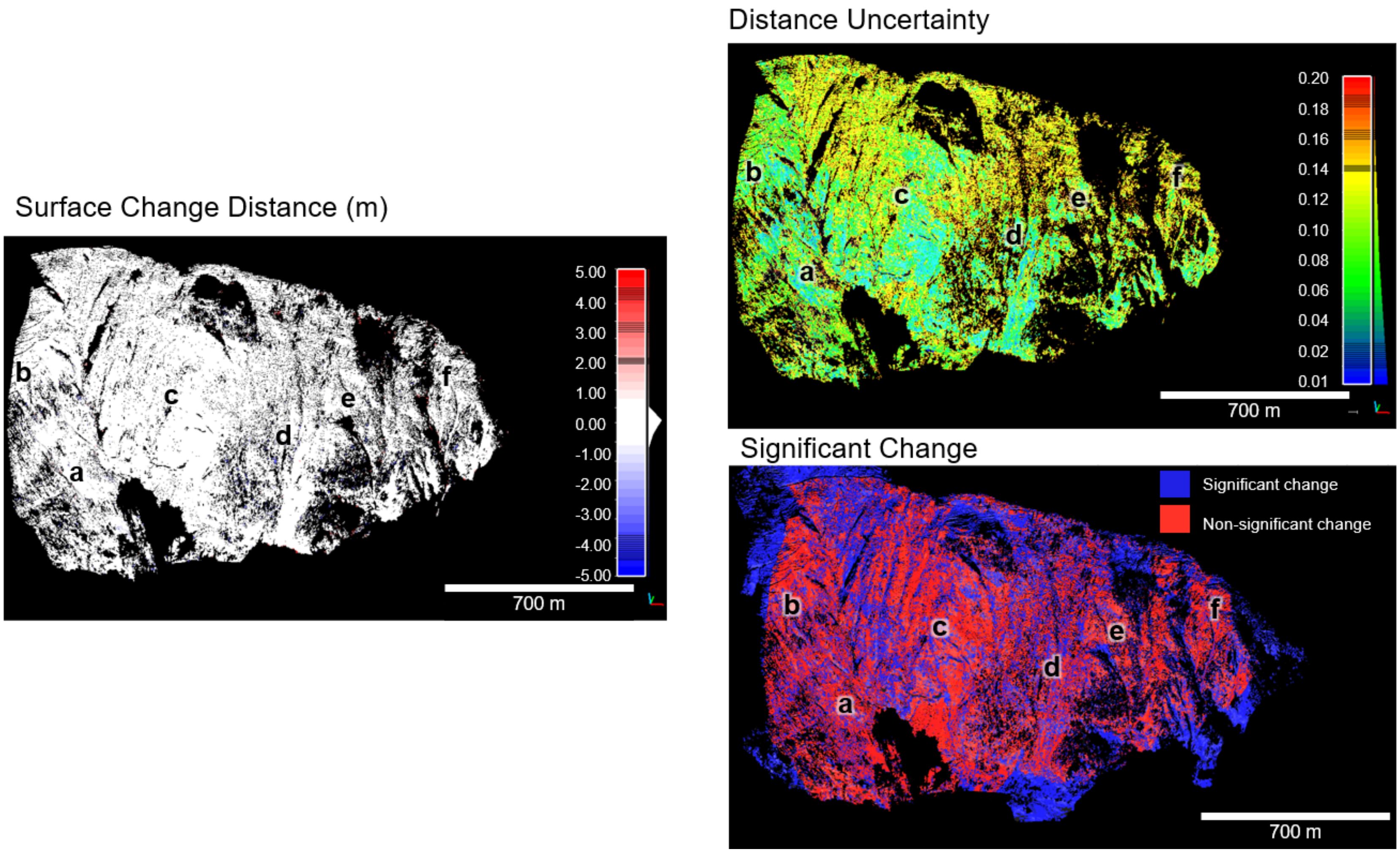


**Figure G 3. Change detection results at TLR using the M3C2 algorithm. At left is change greater than 0.5 m between 2016 and 2017. At right are distance uncertainty and significant change. Non-significant change is identified where point density is too low to facilitate accurate measurement or where change is less than the $LoD_{95\%}$.**