

Improvements in the integration of remote sensing and rock slope modelling

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Abstract Over the last two decades, the approach to the investigation of landslides has changed dramatically. The advent of new technologies for engineering geological surveys and slope analyses has led to step-change increases in the quality of data available for landslide studies. However, the use of such technologies in the survey and analysis of slopes is often complex and may not always be either desirable or feasible. In this context, this paper aims to improve the understanding of the use of remote sensing techniques for rock mass characterization and provide guidance and on how and when the data obtained from these techniques can be used as input for stability analyses. Advantages and limitations of available digital photogrammetry and laser scanning techniques will also be discussed in relation to their cost and the quality of data that can be obtained. A critique of recent research data obtained from remote sensing techniques is presented together with a discussion on use of the data for slope stability analysis. This highlights how data use may be optimized to reduce both parameter and model uncertainty in future slope analyses.

Keywords Remote sensing · UAV · LiDAR · Slope stability analysis · Conventional and numerical modelling

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1 Introduction

The use of remote sensing techniques allows acquisition of detailed information on both the slope and discontinuity geometry for study of landslide susceptibility and potential rock slope instability mechanisms. Several authors have discussed the use of digital photogrammetry (DP) and laser scanning (LS) in the study of natural and engineered slopes (Ghirotti and Genevois 2007; Coggan et al. 2007; Lato et al. 2009; Sturzenegger and Stead 2009a, b; Salvini et al. 2013; Francioni et al. 2014, 2015; Spreafico et al. 2016). These techniques allow the acquisition of very detailed information on the structural setting and slope geometry, particularly important in the case of steep inaccessible slopes. These data can provide very useful input parameters for stability analyses, especially when considering the wide range of software now available for both conventional and numerical methods of slope analyses (Stead and Coggan 2012; Stead and Wolter 2015).

The principal aim of our research is to show the use of remote sensing techniques for providing the necessary data for the varied methods of slope analysis. Long- and short-range terrestrial laser scanning and four approaches to photogrammetric survey will be presented, i.e. tripod, aerostatic balloon, helicopter and unmanned aerial vehicle (UAV) or drones. The data obtained from these different survey techniques can be used in conventional (kinematic, limit equilibrium and rockfall) and more sophisticated numerical (continuum, discontinuum and hybrid and rockfall run out) methods of analysis. The potential use of other forms of remote sensing in slope investigations including airborne and mobile laser scanning, aircraft photogrammetry, thermal and hyperspectral imaging and full waveform analysis will also be briefly addressed.

Among conventional methods, kinematic analysis remains the simplest method to study rock slope stability and can be extremely useful in preliminary assessment of potential instability mechanisms. Results from this analysis are strictly related to the geometric orientation of discontinuity surfaces relative to the slope. It is important that structural domains be identified and that the measured discontinuity parameters representative of the area be assessed. In this context, DP and LS are ideally suited to collect input data that are more representative of the study area, which may often be inaccessible to conventional methods of discontinuity data collection. As part of the analysis, it is essential that the variation in discontinuity sets and their orientation within a slope be assessed and the effect of structural geology on slope stability be fully considered. The use of remote sensing methods allows such spatial variations in structure (with slope height and along the slope) to be investigated more comprehensively and efficiently. Francioni et al. (2015) showed how interpolation of remotely sensed data using GIS techniques can be used to perform a more rigorous deterministic kinematic analysis of slopes.

When using limit equilibrium methods, the geometry of discontinuities and slopes is considered together with force and/or moment equilibrium conditions. DP and LS data can be integrated with conventional engineering geological surveys and used for deterministic and probabilistic stability analysis. The geometry of the rock blocks and the discontinuities obtained from remote sensing techniques and the physical characteristics of discontinuities and rock mass from both engineering geological survey and close-range LS/photogrammetry can be used to calculate the factor of safety of the blocks within the slope (Salvini et al. 2011, 2013). Conventional limit equilibrium slope stability analysis can also be supplemented by rockfall calculations for risk and hazard assessments. This is particularly important for the definition of areas that can be affected by potential rockfall and for the subsequent creation of hazard maps (maps highlighting area of potential instability and/or

rockfall). DP and LS can play a key role in defining the geometry and topography of the slope and the land cover which are all essential input data in rockfall run out simulation.

Numerical modelling has been increasingly used in recent years for stability analyses (Brideau and Stead 2010; Brideau et al. 2011; Stead and Coggan 2012; Francioni et al. 2014, 2015; Stead and Wolter 2015; Spreafico et al. 2016, 2017). The reliability of a numerical model is, however, connected to the quality of input data and the assumed constitutive models and failure mode. DP and LS can greatly improve the quantity and quality of the available data for slope analysis and can also be used, where appropriate, to create sophisticated stochastic discrete fracture networks (DFN) for incorporation into numerical models.

2 Remote sensing sensors

2.1 Digital photogrammetry

In the last two decades, the availability of new survey techniques and software processing tools has resulted in a marked increase in the use of DP.

Conventional acquisition methods include independent convergent, image fan and image strip models (Fig. 1a–c). These methods are explained in detail by Birch (2006), and their application discussed by Sturzenegger and Stead (2009a, b), the choice of method being decided according to site-specific slope conditions. Figure 1a shows the independent convergent model; the advantage of this method is that almost 100% of the images are used to build the model and if multiple models are required to cover the slope, very little overlap is required between models. Figure 1b shows the image fan method; this is similar to the independent method with the exception that the images are captured from specific camera locations (which are not independent). In this way, there are fewer unknowns to be determined (since the camera positions are the same) and the precision of the models is greater; this can be used also with high focal length lenses for long-range photogrammetry (Sturzenegger and Stead 2009a, b; Birch 2006). The last method is the image strip setup (Fig. 1c) where a series of parallel images with a typical 60% overlap is required. The high degree of overlap between images results in precise orientation of the model, significantly reducing the number of control points required. This method, in addition to being suitable for aerial photogrammetry, is also used in terrestrial photogrammetry when the stations and the outcrop are not very far apart (as the distance becomes larger, depth accuracy is reduced) and the slope is not very high. A typical example of the use of this method is in the survey of underground tunnels when the distance between the camera and the rock wall is small and the acquisition of a series of parallel images is the easiest way to proceed.

The coordinates of the camera location or the coordinates of ground control points located in the surveyed area are required to scale/georeference the photogrammetric models. In recent years, the use of structure from motion (SfM) imaging techniques (and software) has increased significantly making the routine use of photogrammetry in engineering practice easier and even more attractive. Although SfM still requires the use of ground control points to scale/georeference the model, the creation of the 3D model is much easier and faster. This is due to a highly redundant bundle adjustment based on matching features in multiple overlapping photographs (Fig. 1d). An introduction to this technique is given by Westoby et al. (2012), while applications of SfM techniques in

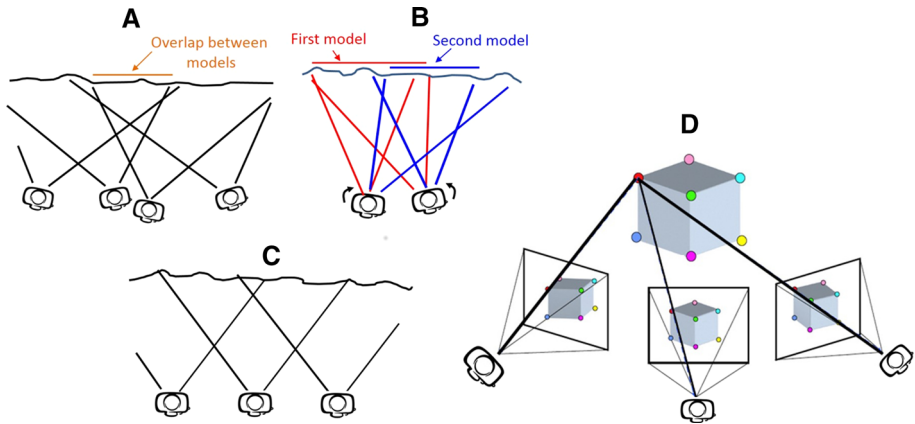


Fig. 1 Photogrammetric acquisition methods (Birch 2006) and structure from motion. **a** Independent convergent model. **b** Image fan method. **c** Image strip method. **d** Structure from motion

engineering practice have been recently presented by Lucieer et al. (2014) and Salvini et al. (2015b).

Another type of acquisition technique is the use of stereo cameras rigidly mounted that allow the acquisition of photographs from two cameras with a known baseline (distance between the cameras) (Firpo et al. 2011; Francioni et al. 2014). In such cases, the baseline is known and if the camera is calibrated, it is possible to reconstruct a scaled 3D photogrammetric model.

2.2 Laser scanning

LS allows the remote acquisition of information from an observed object including both morphological characteristics (altitude, spatial coordinates, etc.) and physical properties, e.g. the intensity of the reflected signal that can be correlated with the object material, temperature, humidity, etc.

LS can also involve both short- and long-range acquisition. Long-range laser scanners (up to 6 km) are particularly useful for wide and high rock slopes. It is possible to set up the laser scanner at a considerable distance from the slope, hence decreasing the number of occlusions when working with very elevated slopes. Moreover, because of accessibility issues, sometimes it is not possible to set up the instrument close to the slope, and without a long-range laser scanner, the acquisition would not be possible. The recent use of long-range LS for landslide analysis is documented by Barbarella et al. (2015).

Short-range laser scanners are fast and very precise with a wide vertical field of view and for these reasons have mostly been used in engineering geology in underground mining and for small rock slopes, where the instrument can (or has to) be set close to the slope (Francioni et al. 2013, 2014).

Time-of-flight and phase difference are the two types of measurement principles by which laser scanners obtain geometric and physical data. An introduction to these techniques, and laser scanner specifications, are highlighted by Beraldin (2004) and Fröhlich and Mettenleiter (2004). Time-of-flight has been the most used measurement technique to date; it allows for measuring the geometry and the reflectivity of an object from a few metres to kilometres in distance. The newly available phase difference measurement

terrestrial laser scanners (full waveform LS) have seen considerable research in the last few years. With this technology, it is possible to capture additional metrics of the rock slope surface, which allow significantly reduced uncertainties in change detection (Afana et al. 2013). Using this approach, geometric and radiometric target surface information can be obtained and, at the same time, retain the spatially rich detailed point clouds.

The advent of full waveform LS makes the LS techniques more attractive, but it has to be noted that the cost of full waveform LiDAR technology is currently significantly higher than of time-of-flight instruments and DP.

3 Remote sensing platforms

3.1 Ground-based platforms

Ground-based remote sensing instrument platforms such as tripods, hand-held devices and vehicles are commonly used in engineering geology. Although these systems are simple to use and cost-effective, they have significant limitations related to the slope elevation; when a survey has to be conducted at the bottom of a high slope, occlusions can seriously compromise the final model (Lato et al. 2009; Francioni et al. 2014). Sturzenegger and Stead (2009a, b) highlighted the importance of understanding possible bias related to the use of this technique and how the results can be affected by occlusions. Nevertheless, this method has been successfully used by several authors in the analysis of rock slopes (Haneberg et al. 2006; Bonilla-Sierra et al. 2015; Havaej et al. 2016). In the following sections, the most common types of platform for slope surveys are presented.

3.1.1 Ground-based digital photogrammetry with hand-held camera or tripod

A hand-held camera or tripod are the simplest and most convenient photogrammetric survey methods. The use of a tripod results in acquisition of high-quality photographs and reduces the distortions related to camera vibrations. Another advantage of the use of a tripod is the possibility to perform long-range photogrammetry (Sturzenegger and Stead

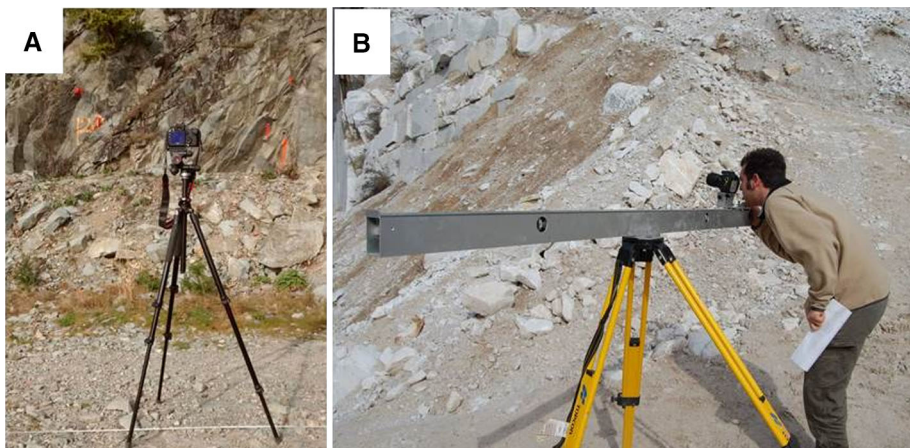


Fig. 2 Photogrammetric image acquisition using **a** a tripod and **b** a tripod with a reamed bar

2009a, b). It is also possible to use a tripod together with a reamed bar in order to maintain a constant line of sight and to precisely control the distance between sequential photographs (Salvini and Francioni 2013). Figure 2a, b shows the application of this technique with and without a reamed bar, respectively, in two case studies, a rock outcrop along the “Sea to Sky Highway” in British Columbia, Canada, and in a Carrara marble quarry, Italy.

A GigaPan (2016) robotic tripod may be used for both producing high-resolution panoramas of rock slopes and conventional acquisition of images for photogrammetry.

The use of hand-held camera survey technique has increased markedly with the advent of SfM techniques as they overcome some of the limitations related to the position of the camera, and using a consistent number of images, it is possible to obtain a detailed 3D model of the study area.

3.1.2 Ground-based laser scanning with tripod

Ground-based LS or terrestrial LiDAR is a survey technique for rapidly obtaining high precision slope geometry and deriving geological structure. One of the most difficult steps in using terrestrial LS is the point cloud registration which allows for the integration of several point clouds into a unique reference system (Francioni et al. 2014). Francioni et al. (2014) showed how this problem can be solved using an integrated topographic system. Moreover, some of the most recent software for point cloud management has built-in modules for the automatic registration of point clouds based on the recognition of common points between different point clouds (ICP–iterative closest point, Besl and McKay 1992).

Figure 3 shows two 3D representations of an outcrop located along the Sea to Sky Highway, BC, Canada, obtained using a tripod and a Riegl VZ4000 scanner (very long-range laser scanner with online waveform processing; Riegl 2014). Figure 3a shows the 3D model of the road cut visualized using the RGB information gained from the internal digital camera of the laser scanner. Figure 3b shows the same outcrop visualized as the wave amplitude (dB). The use of waveform analysis (in this case wave amplitude) allows recognition and highlighting of different rock types. It is clearly shown that the amplitude generated from the overlying basalt columns in the 3D model has a higher value compared to the lower competent formation beneath. Using the same theory as applied in the airborne LiDAR, this technology allows for recording different object echoes. Figure 4 shows the acquisition of the photographs (Fig. 4a), RGB point cloud (Fig. 4b) and the visualization of the four echoes registered by the Riegl VZ4000 laser scanner (Riegl 2014) for a geological outcrop located along the “Sea to Sky Highway” (Fig. 4c). This facility is important for filtering the point cloud based on the different arrivals (first, last or single) and obtaining more information where there is vegetation or objects located along the LiDAR line of sight.

3.1.3 Ground-based mobile laser scanning

Mobile LS refers to the use of LS from moving platforms. The common utilization of this technique is through the use of wheeled vehicles (the instrument is usually mounted on the vehicle roof) for road or scene mapping purposes. However, mobile laser scanning systems are not restricted to wheeled vehicles as they can be mounted on any moving platforms, such as trains and boats. The main advantage of this technique is the speed with which it is possible to survey entire streets or buildings. Moreover, in case of coastlines, the use of a boat can allow scanning of cliff faces from the sea. Since the LS data are acquired from a moving platform, georeferencing the data can be more complicated. For this reason, when

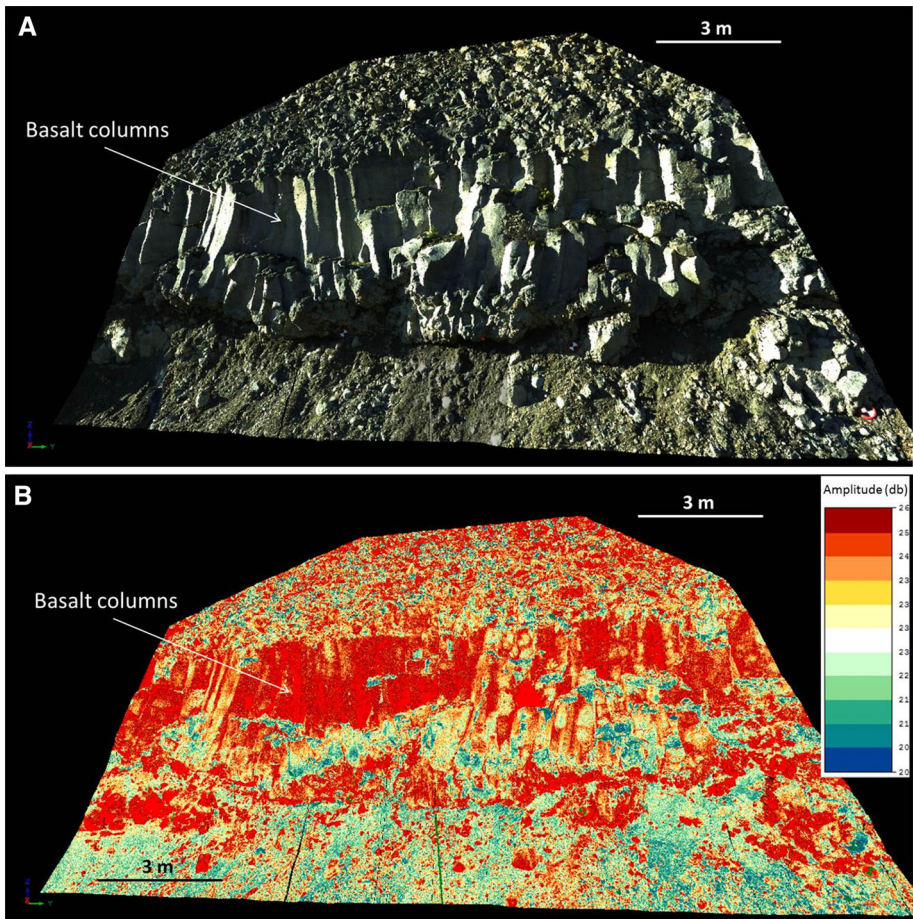


Fig. 3 Full waveform LS survey of a road cut along the Sea to Sky Highway, BC, Canada. **a** RGB coloured slope model. **b** Wave amplitude coloured slope model

using this type of platform LS instruments are supplemented by GPS and an inertial measurement unit (IMU).

The use of mobile LS in engineering geology and especially in the study of landslides has been presented by Michoud et al. (2015) who describe an interesting case study in High Normandy, France. They tested boat-based LS capabilities by scanning 3D point clouds of unstable coastal cliffs showing the potential use of boat-based LS to detect rockfalls and erosional deposits including multi-temporal acquisitions, to monitor large slope changes.

New-generation LS is very flexible and can be also hand-held or used on platforms such as backpacks, thereby providing the ability to map areas while walking geological traverses.

Hand-held and backpack LS has to date not been widely used in the study of rock slopes but has seen a wide range of general applications including heritage site mapping, crime scene investigations and civil engineering projects. In engineering geology, the most important application to date is related to underground tunnel surveys (Eyre et al. 2016). Hand-held LS has the advantage of being very rapid and easy to use but currently results in

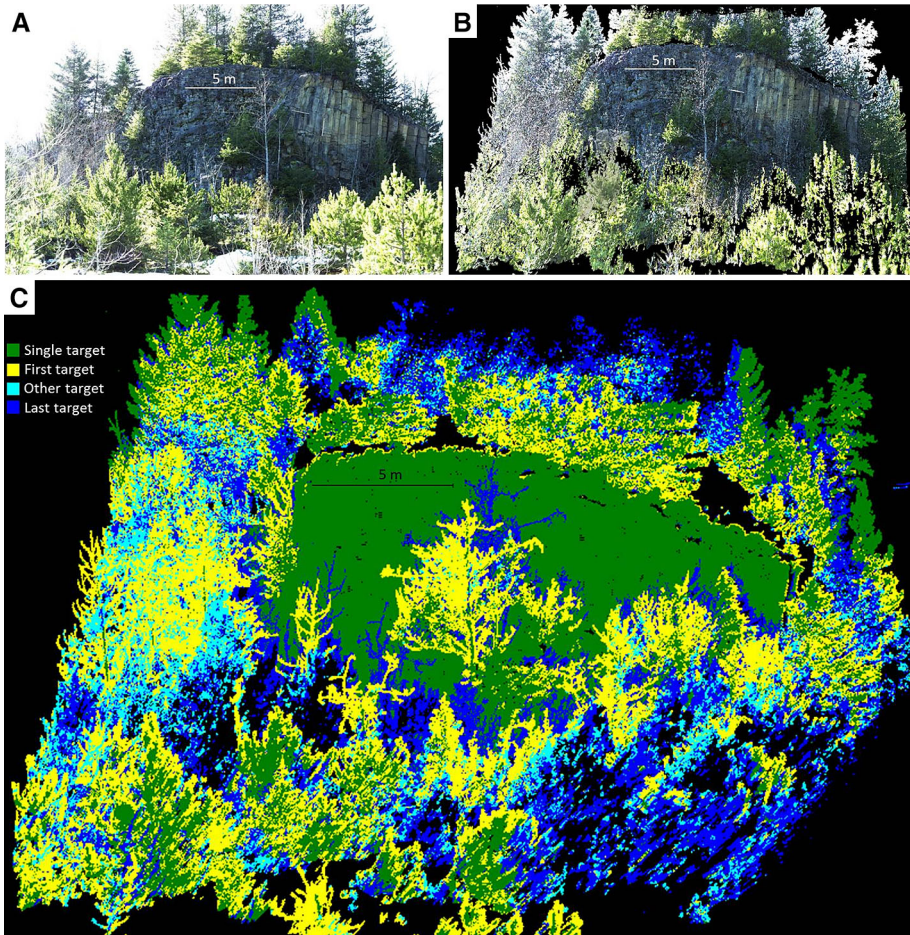


Fig. 4 LS survey. **a** RGB photograph. **b** RGB point cloud. **c** Different registered echoes from natural targets

less precision and resolution than traditional LS. It has limited range, making it ideal for tunnelling applications, but less applicable to slope and landslide analysis that requires greater distance.

3.2 Airborne platforms

Airplane, satellite, aerostatic balloon, helicopter and UAV are the most common airborne platforms currently available. Due to the high spatial resolution achievable with the new digital aerial photo-cameras and LS devices, airplane and satellite data can be used in the photo-interpretation of geotechnical projects at a large scale. However, despite the high quality of photographs and point clouds, the point of observation at the nadir is sub-optimal in the study of natural and artificial rock slopes characterized by very steep or even vertical slope sections. This problem can be overcome using platforms that allow change in the

point of observation such as an aerostatic balloon, helicopter or UAV. This also significantly reduces most of the occlusion problems highlighted for the ground-based platforms.

3.2.1 Airborne digital photogrammetry using aerial or satellite imagery

Aerial photogrammetry refers to imaging acquired through aerial or satellite platforms. In airplane and satellite photogrammetry, the camera is usually pointed vertically towards the ground. Multiple overlapping photographs of the ground are taken as the aircraft/satellite flies along a flight path. These photographs are processed either using a stereo-plotter or in automated processing for digital elevation model and orthophoto creation. These techniques are therefore used in numerous types of cartographic application, from military and regional small-scale maps, to that of medium- and large-scale technical maps (topographic, geological, geomorphological, land use, etc.). Airplane/satellite photogrammetry is very useful in regional engineering geological mapping and for detecting landslide-related geomorphic landforms (Wolter et al. 2016; Mantovani et al. 2016; Clayton et al. 2017; Donati et al. 2017).

3.2.2 Airborne digital photogrammetry using an aerostatic balloon

Of the platforms presented, the use of the aerostatic balloon has been far less common in engineering geology. DP with an aerostatic balloon can be carried with one single camera (Take et al. 2007) or stereo-pairs (Firpo et al. 2011; Francioni et al. 2014). Firpo et al. (2011) and Francioni et al. (2014) showed the use of an aerostatic helium-filled balloon carrying an apparatus that consists of an aluminium bar with two camera slots for the study

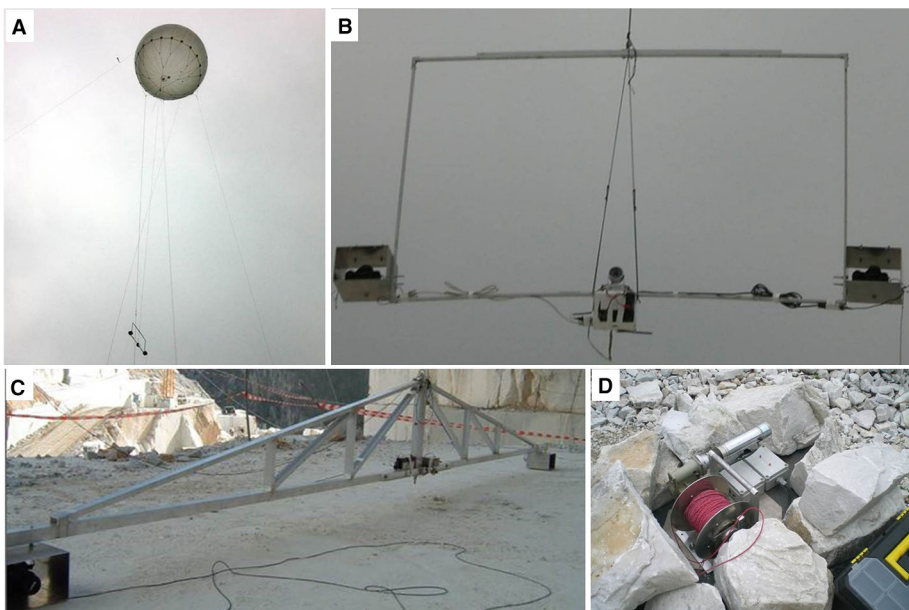


Fig. 5 Equipment used for digital terrestrial photogrammetry with an aerostatic balloon. **a** Aerostatic balloon. **b** 2-m-long photogrammetric frame (Francioni et al. 2014). **c** 5-m-long photogrammetric frame (Firpo et al. 2011). **d** Electrical winches for driving the system

of high steep quarry slopes in Carrara (Italy) (Fig. 5a–c). The geometry and length of the apparatus can vary depending on the baseline that is used, and more camera slots for a video camera may be added to capture in real time the slope face during image acquisition (Fig. 5b, c) (Firpo et al. 2011; Francioni et al. 2014). Four electrical winches are used to drive the balloon (Fig. 5d), while image acquisition is controlled by a PC-driven radio system which guarantees synchronous data acquisition (Firpo et al. 2011; Francioni et al. 2014). In this way, stereo-pairs can be acquired simultaneously and used to build a scaled photogrammetric model using the image strip (the baseline being perfectly known by using the frame) or independent convergent models. Francioni et al. (2014) described the use of an aerostatic balloon in a complex slope in the Apuan Alps showing the possible use of this technique and highlighting some of the complex procedures involved. Balloon used to date for photogrammetric purposes can reach up to 300 m from the ground (Firpo et al. 2011; Francioni et al. 2014). However, the area to be imaged must be accessible and sufficiently wide (Francioni et al. 2014). Weather conditions can also be a major limitation in the use of this method, which is best conducted in the absence of rain and, especially, wind.

3.2.3 Airborne digital photogrammetry using a helicopter

The aerostatic balloon can be used only if appropriate site and weather conditions persist and a suitable inexpensive source of helium gas is available. When these conditions are not present or in the case of slopes higher than 300 m, this technique cannot be utilized. In such cases, helicopters can provide an ideal data acquisition platform. The photogrammetric equipment described in Salvini et al. (2011) and Salvini et al. (2013) consist of an aluminium or steel frame adapted to fit a helicopter landing skid supporting two digital cameras and two GPS antennas at its extremities. The equipment is connected and controlled in real time from operators in the helicopter. In this way, it is also possible to use differential GPS (the power source being located in the helicopter) which helps to know the position of the camera and the orientation of the frame at the moment of the image acquisition. In this case, stereo-pairs are also acquired simultaneously and used to build a scaled photogrammetric model through image strip or independent convergent models. Occlusions can be considerably reduced with a careful work plan as it is possible to check the photograph acquisition in real time from the helicopter. Figure 6 shows the photogrammetric equipment developed by Salvini et al. (2013) and utilized in the analysis of a rock slope sited in Northern Italy.

Recent research has seen an increasing use of hand-held cameras in helicopter platforms to obtain high-quality SfM models (Gauthier et al. 2015). Digital SLR cameras now contain in-built GPS or conveniently mounted GPS adaptors. The use of hand-held cameras in the helicopter is well demonstrated by Vallet et al. (2000), Copons and Vilaplana (2008), Gauthier et al. (2015).

Helicopter platforms for DP have two main limitations, the first being the high costs involved and the second the difficulty in maintaining the stability and direction of the aircraft throughout the photogrammetric survey. Subsequently, this can create problems for the orientation of the photographs. However, with the acquisition of a considerable number of images, use of topographic survey to define the coordinates of ground control points and SfM software, this problem can be mitigated.

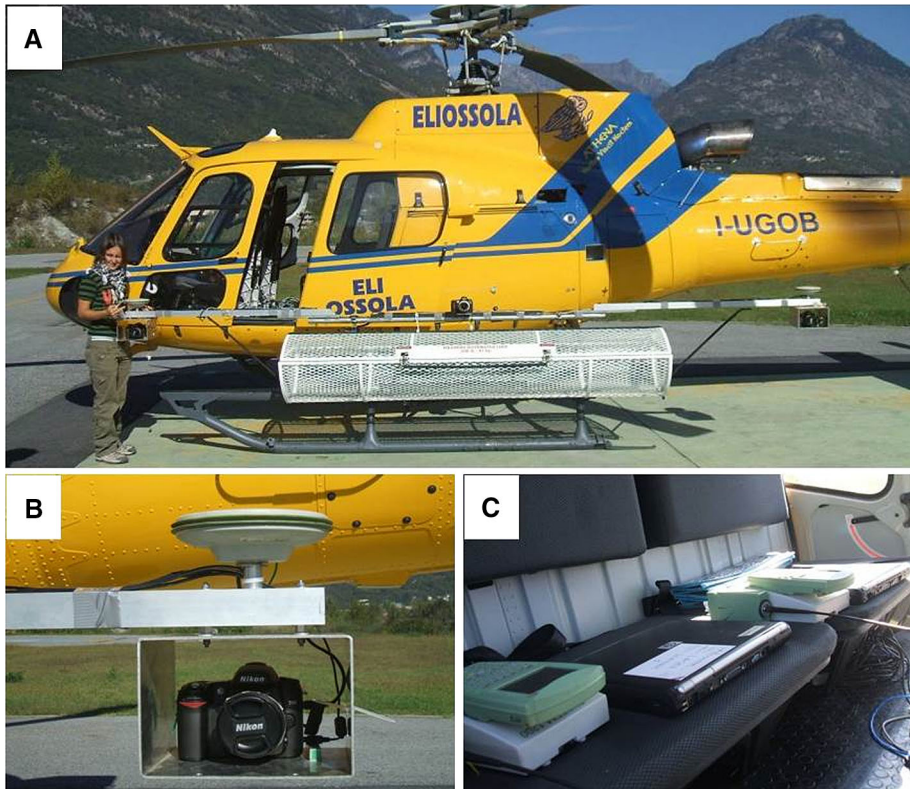


Fig. 6 Equipment used for digital terrestrial photogrammetry with a helicopter. **a** Steel frame adapted to fit a helicopter landing skid. **b** Digital camera and GPS antennas. **c** GPS data receivers and laptop for real-time photograph visualization

3.2.4 Airborne digital photogrammetry using an UAV

UAV systems are now routinely used in a wide variety of engineering and geoscience fields and include both fixed wing and multi-rotor options. UAV systems are highly flexible and provide an ideal platform for the acquisition of high-resolution photographic images along pre-programmed flight lines/paths. They overcome most of the limitations noted for the other platform providing increased spatial close-range coverage of inaccessible rock slope outcrops with reduced occlusions. Basically, the use of a UAV allows acquisition of areas that could not be surveyed with any other vehicle or methodology. Moreover, remote control of the UAV reduces the need for hire of a helicopter and operators, the cost of which may be significant. This makes the UAV method less expensive than the aerostatic balloon or helicopter.

Although UAV-based photography is the most common and inexpensive technique used at present, UAVs are increasingly being used to capture thermal, hyperspectral and light detection and ranging (LiDAR) imagery. An on-board GPS-IMU system provides the positions of the UAV camera at the moment of image acquisition, and independent convergent SfM methods are used to build the photogrammetric model. Figure 7 shows a

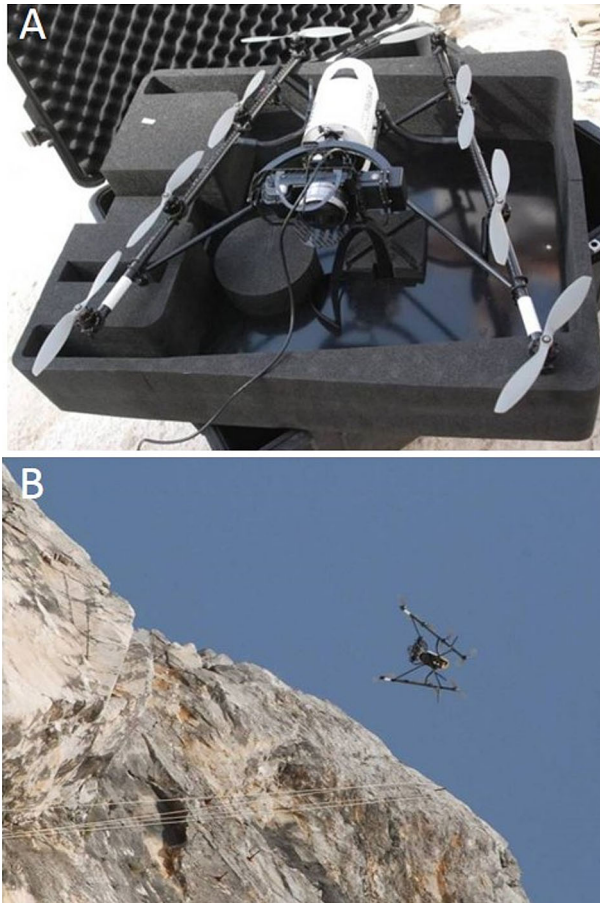


Fig. 7 UAV survey (after Francioni et al. 2015). **a** Falcon 8 UAV with gyro-stabilized digital camera Sony NEX-5 N. **b** Drone during the flight

Falcon 8 UAV (Fig. 7a) used during the survey of the Lorano open pit in the Carrara marble district, Italy (Fig. 7b) (Francioni et al. 2015).

The use of the UAV in the earth sciences and engineering geology is well documented in the recent literature (Haarbrink and Eisenbeiss 2008; Niethammer et al. 2010; Francioni et al. 2015; Salvini et al. 2015a; Assali et al. 2016; Westin 2017; Donati et al. 2017). The most important disadvantages in using the UAV technique is that it can be used only in the absence of wind/rain. This can present a major problem where local wind eddies exist along high mountain slopes. In case of multi-rotor options, it can also be difficult to acquire photographs maintaining the same line of sight (Francioni et al. 2015) and this can generate misalignment of photographs and major potential errors during their orientation. Obtaining a large number of photographs and using SfM software can, however, reduce these errors and make the UAV technique easier and more attractive. An additional current limitation in the use of the UAV that especially affects multi-rotor systems is the often limited battery life which can require the UAV pilot be within close range of the take-off/landing area. Where spatially extensive slopes require surveying, multiple battery packs may be

essential. The advent of inexpensive UAV systems represents the most interesting and promising innovation regarding remote sensing techniques as it provides a very powerful and flexible instrument for the acquisition of photographs (Colomina and Molina 2014; Francioni et al. 2015; Westin 2017; Donati et al. 2017). Their use will, most likely, become more frequent in the coming years, and it is important to continue studies on their utilization in the field of engineering geology, particularly with respect to change detection/slope monitoring and multi-sensor capabilities. A potential future disadvantage in the use of UAV technology is the increasing flight restrictions in their use due to abuse of the technology from recreational use. In some countries, it may become increasingly difficult to obtain approval for UAV flights.

3.2.5 Airborne LiDAR

Airborne LiDAR devices emit up to 150,000 pulses per second, and a sensor measures the amount of time it takes for each pulse to bounce back (or return). An IMU integrated with a differential kinematic GPS provides information about the position and attitude of the sensor. Airborne LiDAR offers advantages compared to traditional measurement systems such as the ability to penetrate vegetation cover (first–last pulse mode), the possibility to record data at night and over a large survey area. Aerial LiDAR is widely utilized in engineering geology for landslide hazard mapping and modelling, change detection, cliff erosion and rockfall run out (Jaboyedoff et al. 2012; Lato et al. 2016; Piacentini et al. 2015). The use of this technique to detect geomorphic and major structural features for identifying palaeo-landslides has been recently shown by Clague et al. (2015) and Francioni et al. (2017). Figure 8 provides an example of airborne LiDAR and GIS for highlighting landslide-related geomorphic features at Mount Burnaby, British Columbia, Canada.

Recently, as a result of the full waveform systems, aerial LiDAR is also being utilized for the characterization of surface material from the analysis of the physical backscattering measurements (Sumnall et al. 2016).

3.2.6 Airborne LiDAR using an UAV

With advent of UAV solutions, small LS devices have been installed with the possibility to scan any type of slope surface. This type of LS acquisition presents the same advantages and limitations discussed in Sect. 3.2.4 for DP with UAV. However, it should be noted that accuracy, precision and resolution of this technique are poorer than that obtained using ground-based systems. This type of platform offers much more flexibility and overcomes limitations related to occlusion and point of observation. The use of UAV LS in engineering geology is not well documented to date but is an area of significant potential future research.

4 Remote sensing and rock slope stability analyses

A remarkable quantity of data can be obtained through the use of terrestrial remote sensing techniques. This information can be used for different types of slope analyses, varying from simple kinematic admissibility tests, to more complex numerical simulations.

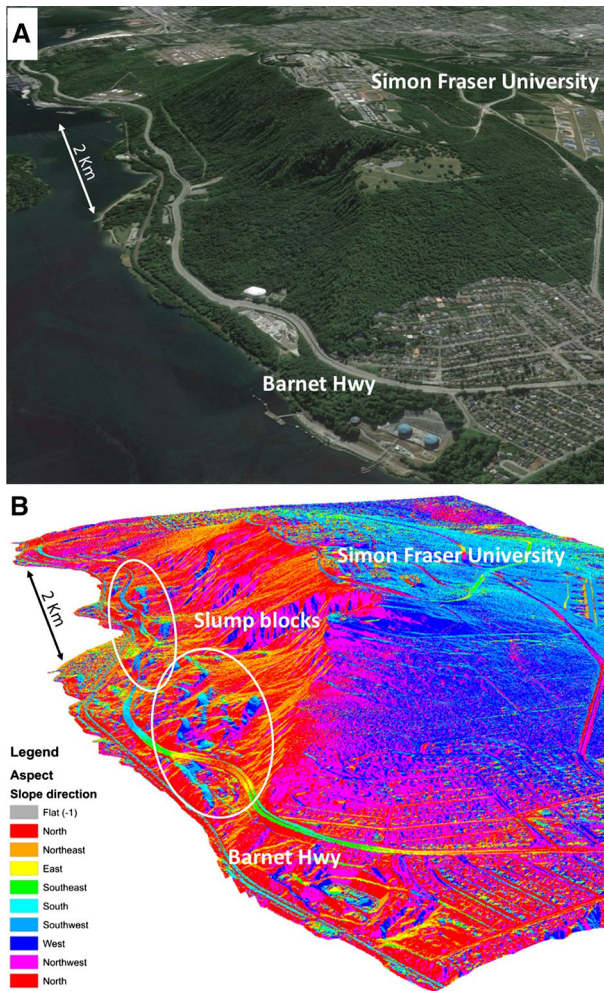


Fig. 8 **a** 3D view of Mount Burnaby and Simon Fraser University, situated at the top of the mountain. View to the southeast. **b** 3D representations of LiDAR aspect maps with highlighted slump blocks on the north face of Mount Burnaby (after Francioni et al. 2017). View to the southeast

4.1 Remote sensing and conventional methods of slope analysis

Conventional methods of slope analysis can include kinematic analysis, limit equilibrium calculations and run out analysis (Stead et al. 2006).

Kinematic analysis investigates the likelihood that unfavourably oriented discontinuities will generate discontinuity-controlled instability such as planar, wedge or toppling slope failures. The kinematic test considers the relative slope and discontinuity orientations and the effective friction angle along the discontinuity surfaces to determine whether a block can potentially move or not. This type of analysis can be carried out using a stereonet and/or 2D/3D vector analysis applied to 2D/3D rock structure models. Although a very simple analysis, it is a very useful preliminary tool allowing for a first estimation of potential failure and identification of potential key blocks. Stead et al. (2006), Brideau et al. (2011)

and Francioni et al. (2015) noted that results of this analysis are influenced to a large degree by reliability of the discontinuity survey and the accuracy of the slope topography. Recent developments in available commercial software allow for including all the measured discontinuities in the rock slope analysis (instead of just considering the mean joint set orientations obtained from joint surveys at the slope toe). This makes the use of remote sensing techniques highly relevant because the data from remote sensing are representative of the entire slope from the toe to the crest. Figure 9 highlights this concept showing a comparison of two kinematic analyses that were performed with engineering geological (Fig. 9a) and remote sensing data (Fig. 9b) in the Lorano open pit (Carrara, Italy) (Francioni et al. 2015). The results clearly show the difference in the two data sets in relation to the different spatial areas covered by the two surveys. The conventional engineering geological survey was performed only in accessible areas, while the remotely sensed data from DP covered the entire slope. Figure 10 shows a photograph of the Lorano open pit (Fig. 10a) and the 3D model obtained using UAV and SfM techniques (Fig. 10b).

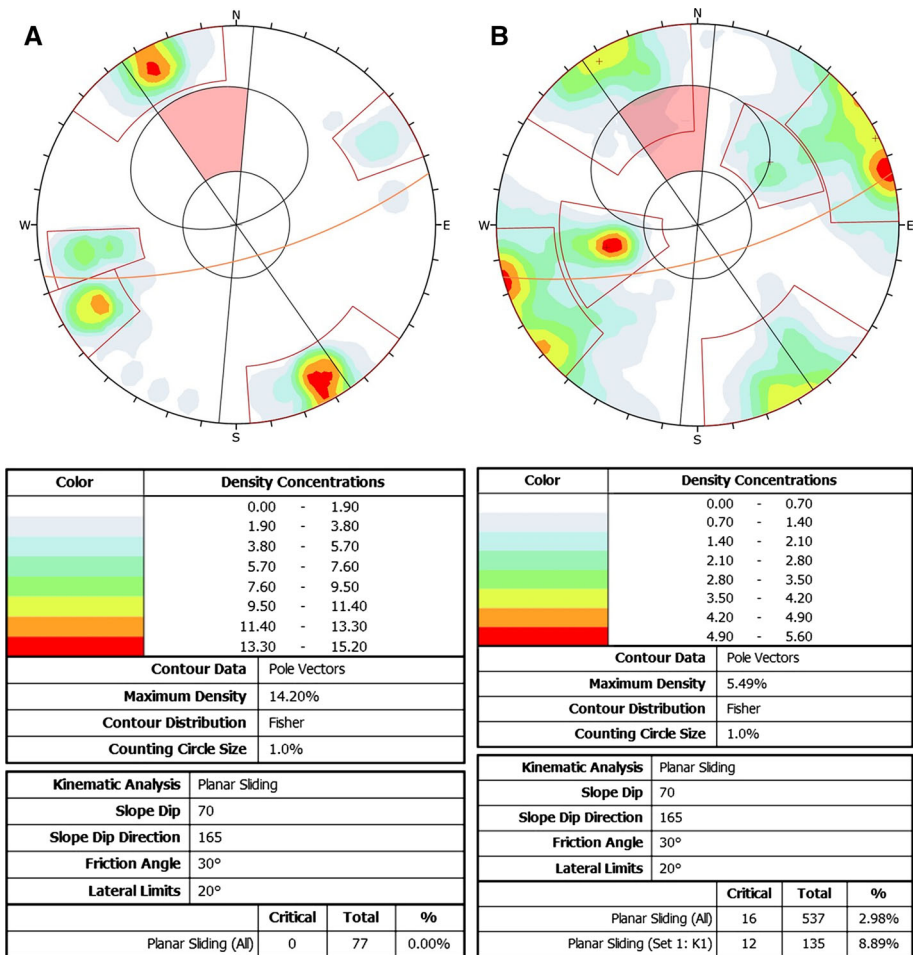


Fig. 9 Kinematic slope stability analysis performed using a engineering geological data (93 measurements) and **b** remote sensing data (537 measurements) in the Lorano open pit (Carrara, Italy)

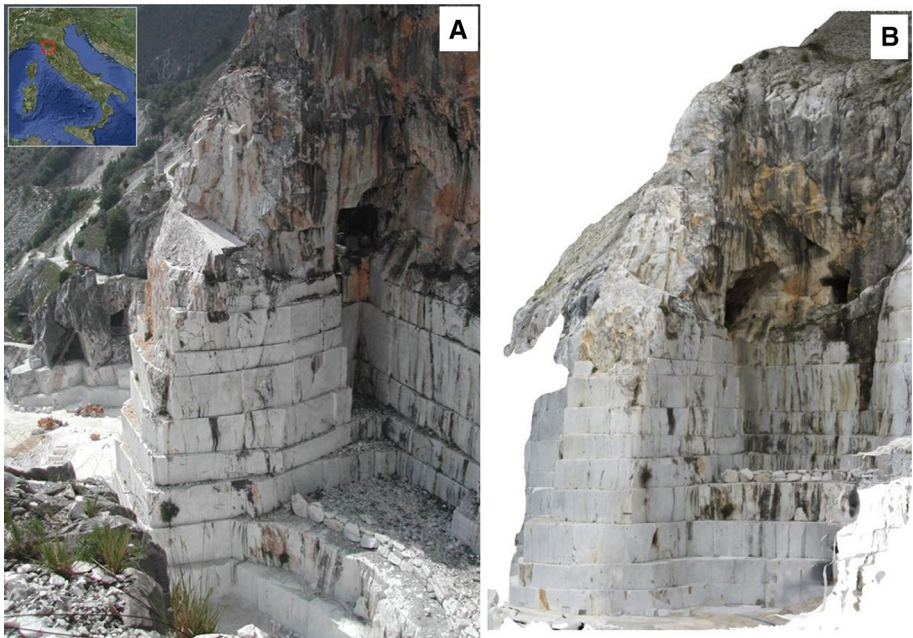


Fig. 10 Lorano open pit. **a** Photograph of the open pit buttress and **b** SfM 3D model

Recent developments in kinematic software allow highly interactive kinematic stability analysis of slopes with semi-probabilistic methods of failure modes. The assigning of discontinuity attributes (roughness, persistence, infill, spacing, etc.) is also supported. Kinematic analysis of a slope should always consider the measured spatial location of major structures as determined using remote sensing; this practice, combined with the use of structural domains, avoids the identification of “fictitious” failure modes indicated on a stereonet but not observed in the slope face. It is emphasized that wherever possible remote sensing methods should be supplemented with field mapping and the use of photographic site observations. Oppikofer (2009), Brideau et al. (2011) and Francioni et al. (2015) showed that remote sensing and kinematic analysis can be usefully integrated with Geographic Information Systems (GIS) for developing thematic maps. These thematic maps can clearly illustrate how the results of a kinematic slope failure analysis can change with location in the slope, depending on the topographic detail recorded/available. Jaboyedoff et al. (2004), using the same approach, developed a code designed to integrate structural data into the digital surface model.

Limit equilibrium methods are routinely used to identify the slope hazard due to translational and rotational movements occurring along a distinct failure surface(s). These analyses consider force and/or moment equilibrium conditions and can be performed by stereonet, or preferably 2D/3D rock structure models. They may also be used to provide a preliminary assessment of rock slope toppling failure. Analyses are carried out to calculate either a factor of safety (FoS) or, through back analysis, a range of shear strength parameters at failure. The results of this type of calculation are based on the geometry of slope (or potential unstable block, depending on the scale of work), material properties, forces involved (water pressure, seismic forces, external forces) and discontinuity mechanical properties. In this context, the use of remote sensing techniques plays an

important role in the definition of the discrete location of the discontinuities that form the failure surface(s) and rear release (tension crack) of unstable blocks (a necessary assumption in the limit equilibrium methods), the shape of the potentially unstable block and therefore the true potential failure volume (Salvini et al. 2011, 2013). Figure 11 shows an example of this method applied to a rock slope located in Northern Italy along the Domodossola–Iselle railway (after Salvini et al. 2011). Using a photogrammetric survey carried out with a helicopter (Fig. 11a), detailed photographs of the rock slopes were acquired (Fig. 11b) allowing definition of the geometry of blocks and discontinuities (Fig. 11c). This information was used to calculate the deterministic FoS using limit equilibrium software (Fig. 11d).

The volume of blocks, together with the location (in term of coordinates) of each potential unstable block can also be used for rockfall simulation. Rockfall analysis is based on the study of the slope geometry and the characteristics of potential falling blocks. It is possible to determine the kinetic energy, velocity, “bounce height”, end points and lateral dispersion of potential falling blocks for the entire slope. Having a good representation of the slope morphology, potential unstable block geometry and land cover are crucial for this type of simulation. Figure 12 shows an example of combined use of remote DP and rockfall run out simulation in the Grotta delle Felci Cliff (Capri Island, Italy). The location (Fig. 12a) and geometry (Fig. 12c) of rock blocks were determined from a helicopter-based photogrammetric survey and the data used for an improved understanding of the lateral dispersion of the potentially unstable blocks (Fig. 12b) in addition to their kinetic energy, velocity and “bounce height” (Fig. 12d). This approach can be very important in planning protection work (either active or passive), or proposing monitoring systems

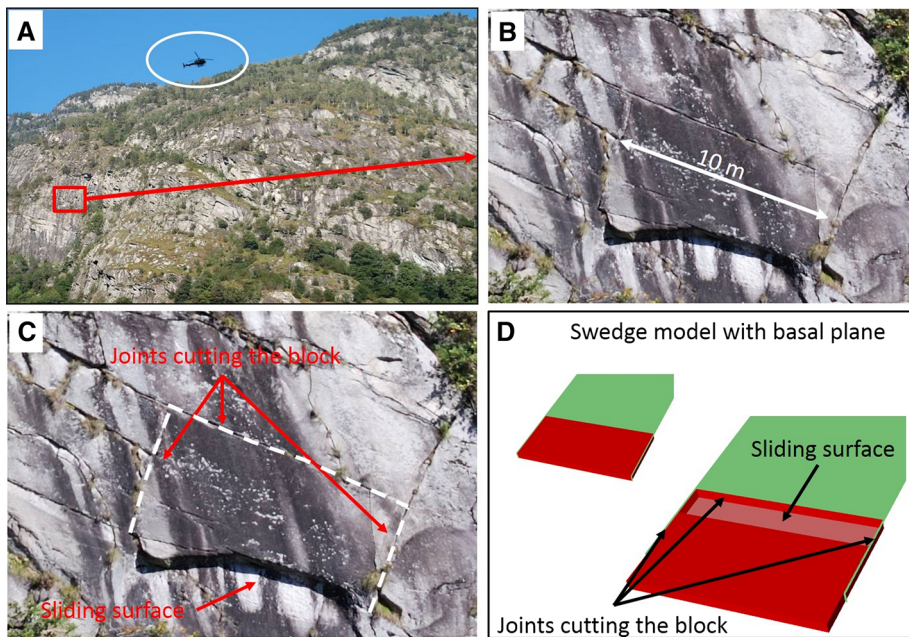


Fig. 11 DP used for limit equilibrium analysis. **a** Photogrammetric survey with a helicopter. **b** Example of detailed photographs acquired during the survey. **c** Geometry of block and joints gained from DP. **d** Calculation of block FoS using DP data

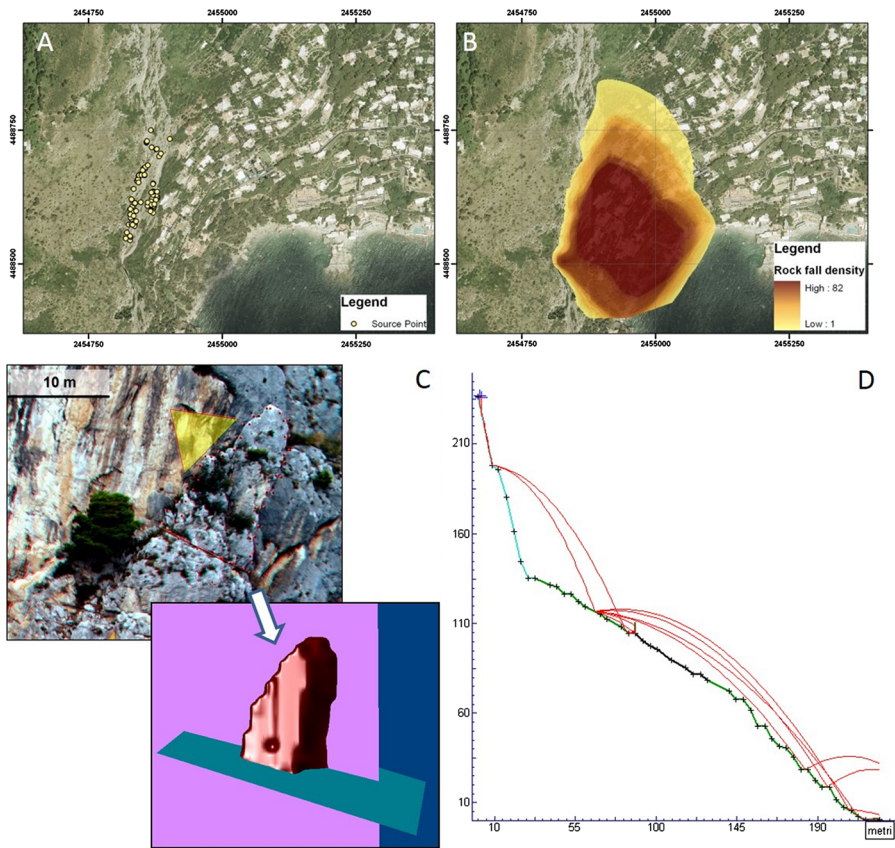


Fig. 12 Use of DP data for defining the rockfall run out simulations. **a** Location of potential unstable blocks. **b** Lateral dispersion of blocks in case of failure. **c** Example of block geometry reconstruction using the stereoscopy and the 3D modelling. **d** 2D Simulation of block fall with possible calculation of kinetic energy, velocity and “bounce height”

(Salvini et al. 2011, 2013). Rockfall modelling represents a very powerful tool for the study of risk mitigation, especially where rock slopes are located above infrastructure such as roads, train tracks and working areas. Moreover, multi-temporal survey (e.g. with DP, LS, LiDAR and radar interferometry) can be used for defining debris volume and for change detection (spatial and temporal) analyses (Rosser et al. 2007; Blasone et al. 2014); thermal images and/or LS data can be used to locate seepage that can be included in both conventional or more sophisticated analyses (Vivas et al. 2013; Gigli et al. 2014).

4.2 Remote sensing and more sophisticated numerical methods of slope analysis

Although limit equilibrium methods are the simplest and most widely used slope analysis technique, their use should, in general, be limited to uncomplicated case studies. More sophisticated numerical methods are better suited for the study of slopes of more complex slope geometry and structural geology. Similarly, material anisotropy, nonlinear behaviour, in situ stress, groundwater and brittle fracture can all influence the slope stability and often

can only be realistically considered using sophisticated numerical simulations. These techniques of analysis, usually called numerical modelling analyses, can benefit significantly from remote sensing data, especially where 3D variations in the slope geometry and structure are important in the slope behaviour. Currently, the most widely used 3D numerical codes for slope stability analysis are continuum (finite difference and finite element) and discontinuum (distinct element) codes. Havaej et al. (2015) described the application of a recently introduced 3D lattice spring code that utilizes a lattice-based structure, consisting of point masses (nodes) connected by springs. The lattice spring model simulates rock fracture through the breakage of springs in shear and tension and once the spring fails in either tension (normal spring) or shear (shear spring), the tensile strength and cohesion reduce to zero (Havaej et al. 2015).

The advantages of the combined use of remote sensing and 3D distinct element methods (DEM) in rock slope investigations have been recently described by Francioni et al. (2014) and Spreafico et al. (2016). Figure 13 shows an analysis undertaken using two models (with different spatial resolution) of the same slope using a DEM. The principal objective of the study by Francioni et al. (2014) was to highlight the advantages and limitations of using terrestrial remote sensing data in a 3D DEM. The first model was obtained from a topographic map (Fig. 13a–c), and the second model from terrestrial LS (Fig. 13d–f). These simulations demonstrated that the values of strength reduction factor (SRF) obtained from the stability analysis can be significantly influenced by the measured geometry of the slope (Francioni et al. 2014).

The use of remote sensing data and the 3D finite difference method (FDM) was illustrated by Francioni et al. (2015) in order to understand the stress-induced damage in

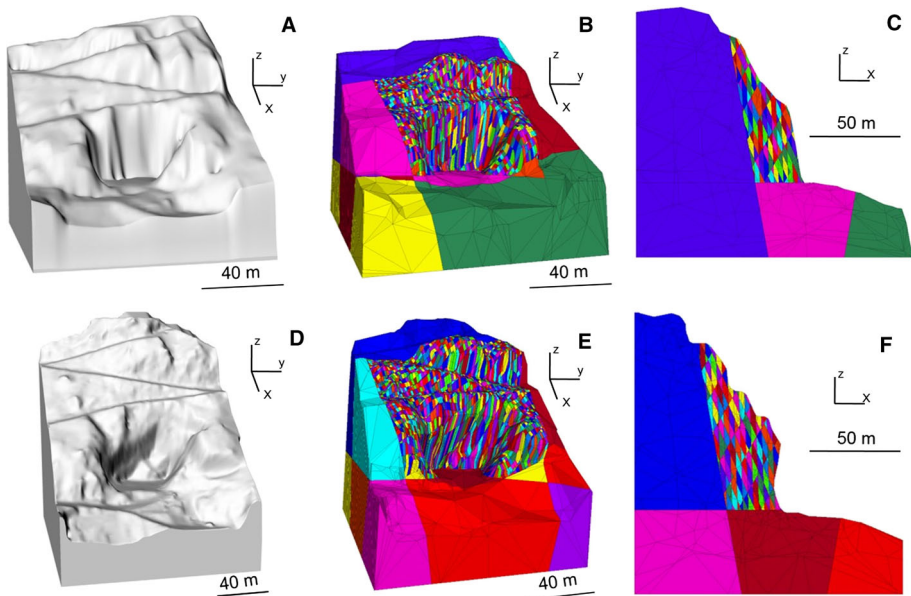


Fig. 13 3D rock slope models obtained from DP (after Francioni et al. 2014). **a** Initial model from topographic map, **b** 3D distinct element model based on topographic map, **c** 2D section, **d** initial model from terrestrial laser scanning, **e** 3D distinct element model based on terrestrial laser scanning and **f** 2D section. Colours represent the distinct elements (blocks) generated by interaction between different joint sets and the topography

surface-mined areas. Simulations were done using the slope geometry derived from DP and LS. In this case, it was possible to increase the understanding of stress-induced damage in the Lorano open pit (Carrara, Italy) due to the excavation processes (Fig. 14a, b). The detailed information on the structural geological setting of the entire slope obtained from DP and LS was also used in DEM analysis. Measured data from a conventional engineering geological survey (e.g. scan line or window) can often only be used in discontinuum modelling of simple rock slopes assuming continuous or persistent joint sets. The data determined from remote sensing techniques, however, can allow for more sophisticated deterministic (using only joints visible on the DP/LS model) or stochastic discrete fracture network, DFN, analyses (Elmo 2006; Hamdi et al. 2015; Tuckey et al. 2013). Figure 15 shows the differences between the DEM models created using continuous joint sets (Fig. 15a, b) and a DFN (Fig. 15c, d).

It must be emphasized, however, that the time needed for data processing are significantly longer when dealing with accurate and detailed slope geometry and that such detailed data are useful in complex cases but may be unnecessary in simple slopes where a large-scale topographic map can still be suitable (Francioni et al. 2014). Havaej et al. (2016) clearly showed the advantages of using terrestrial photogrammetry and LIDAR in developing DFN for a slate quarry slope at Delabole, Cornwall, UK. Detailed data were used to investigate the influence of different stochastic generated DFN on simulated slope failure mechanisms, the results agreeing with observed slope behaviour.

Havaej et al. (2015) showed the use of ground-based photogrammetric and airborne LiDAR data in the analysis of the Vajont slide, Italy, using a lattice spring approach. The landslide model was built using the airborne LiDAR data, while the sliding surface, discontinuity orientations and locations were derived from combined field analysis and long-range terrestrial photogrammetry. The use of this 3D-brittle fracture software, together with airborne and terrestrial remote sensing data, allowed the authors to improve the understanding of the importance of kinematics, internal damage and groundwater levels on the failure of the 1963 Vajont slide.

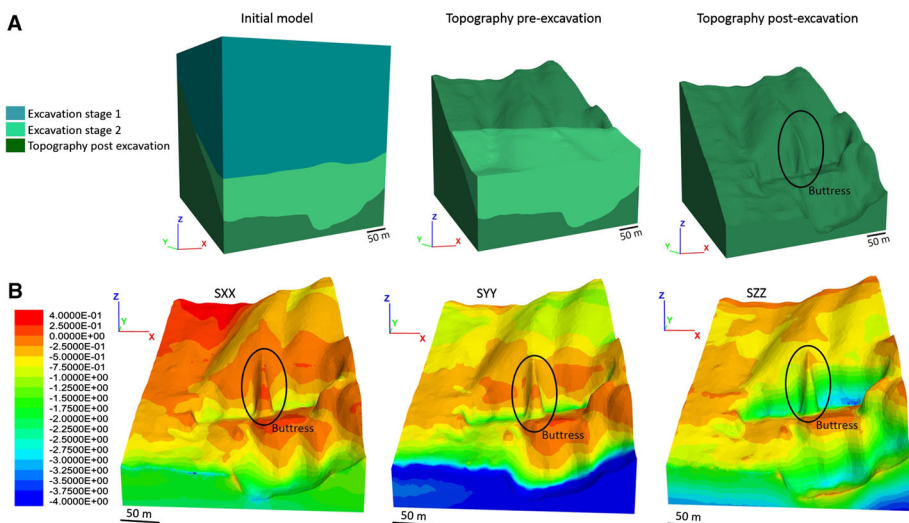


Fig. 14 3D rock slope models obtained from DP and LS (after Francioni et al. 2015). **a** Initial model and topography pre- and post-excitation. **b** Stress analysis

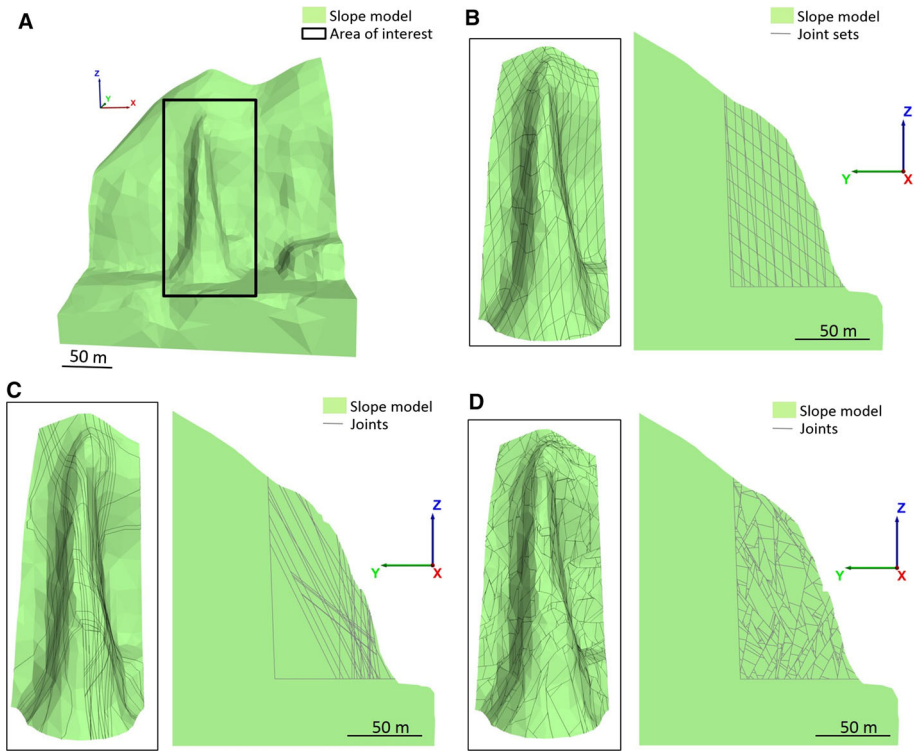


Fig. 15 3D rock slope models obtained from DP and LS. **a** Initial 3DEC model. **b** 3DEC model using continuous persistent joint sets. **c** 3DEC model using a deterministic approach. **d** 3DEC model using a stochastic DFN approach

Wang et al. (2003) and Lorig et al. (2009) showed the use of particle flow codes for the analysis of rock slopes. Although this method showed good results for 2D simulations, its use in 3D modelling remains computationally expensive. Eberhardt et al. (2004) used hybrids methods, using a finite element mesh to represent the intact joint bounded blocks and discrete elements to simulate joint behaviour to explain the failure mechanism of the Randa rock slide (Switzerland), and Styles et al. (2011) applied it to the back analysis of the Joss Bay Chalk Cliff (UK). Vyazmensky et al. (2010) and Styles et al. (2011a, b) incorporated discrete fracture networks into hybrid numerical models to realistically simulate rock slope deformation in the Palabora, South Africa, and Bingham Canyon, USA, open pits, respectively.

As previously mentioned, apart from slope geometry information DP and LS can also be used for defining discontinuity roughness angles and joint roughness coefficient (Haneberg 2007; Kim et al. 2015, 2016). Höfle et al. (2009), Kurz et al. (2012) and Park et al. (2016) recently showed how it is possible to use LS intensity signal and hyperspectral imagery to locate seepage and rock weathering/alteration zones. Moreover, rock mass heterogeneities can also be remotely detected to develop ubiquitous joint rock mass models (Sainsbury et al. 2016).

Table 1 DP platforms: advantages and limitations

DP	Advantages	Limitations
DP with hand-held camera and tripod	Simple and economic to use	Presence of occlusions in the case of very high slopes
	Full control of the camera. In case of tripod, photographs can be acquired with great precision without problems related to vibrations and stability. Wind does not usually affect the survey	Not possible to use in case of inaccessible areas not facing the object under study. Lighting conditions and distance to outcrop can compromise the survey
DP with aerostatic balloon	Overcomes problems related to elevation, steepness and complex geometry of slope	Requires experienced user
	With favourable weather conditions photographs can be acquired with high precision without problems related to the stability of the frame	Maximum elevation of 300 m. Cannot be used where difficult access exists and the slope area is not viewable. Unfavourable weather conditions prevent data acquisition Use of helium gas is expensive compared to the use of hand-held camera and tripod methods
DP with helicopter	Overcomes problems related to elevation, steepness and complex geometry of slope	Very expensive in terms of helicopter time requiring careful flight planning
	Does not need an accessible area facing the slope under study	Can be difficult to keep the vehicle stable and in the same direction during data acquisition (this can create major errors during the orientation process; obtaining a large number of photographs and using SfM techniques can reduce these errors)
	It is possible to check the photographs acquisition in real time from the helicopter	Weather conditions can limit surveys including wind, sun glare on light colour outcrops and restricted visibility due to cloud
	Differential GPS and IMU control allows calculation of the position and attitude at the moment of the photograph acquisition. Hardware-mounted or hand-held cameras can be used	
DP with UAV	Overcomes problems related to elevation, steepness and complex slope geometry	Prone to instability during the photograph acquisition which can result in misalignment of photographs and major error during the orientation process. Acquiring a large number of photographs and using SfM techniques can reduce these errors

Table 1 continued

DP	Advantages	Limitations
	Does not require the area to face the object under study	Weather conditions can limit the use. Limited battery life requires careful flight planning and may limit application in remote areas. UAV regulations may restrict use or preclude use in some cases. High number of photographs that require processing may necessitate use of high end graphics works station to limit computer run times
	Cheap UAV platforms now readily available	
	Freely available software for data acquisition, flight planning and data processing	

5 Final remarks and discussion

In this paper, we show how remote sensing data can be successfully used to define the morphology and structural setting of both natural and engineered slopes, the shape and volume of potential unstable blocks and the geometry of the potential failure surfaces.

The selection of a specific survey technique for a given site remains a complex and challenging problem which requires knowledge of the terrain, the objective of the project, the availability of funding and technologies approved for use in the region (Lato et al. 2015). For this reason, it is important to recognize that the methods described should wherever possible be considered as complementing each other rather than being competitive.

In this context, Tables 1 and 2 summarize, respectively, the DP and LS platforms currently available; highlighting their advantages and limitations. Airplane and satellite-generated data are not included in these tables because as previously mentioned, due the nadir point of observation they are not optimal for deterministic study of natural and engineered rock slopes. Figure 16 provides a comparison of the DP remote sensing platforms discussed in this paper in relation to their cost, simplicity of use and ability to avoid occlusions.

It has been shown how the information gained using these remote sensing techniques can be usefully applied within different types of conventional and numerical analyses and can play a key role in the final results of the model simulations. Figure 17 presents additional information that can be retrieved with LS and DP and the improvements in terms of input parameters that these techniques can offer conventional and numerical analyses of slopes.

It should be noted that, wherever possible, integrated use of different remote sensing with conventional mapping and monitoring investigation techniques is recommended as this allows for the validation of the data and an understanding of the advantages and limitations of the proposed methodology.

The integration of slope monitoring systems with conventional and numerical analyses is a crucial aspect in the study of landslides. This is highlighted by new research on slope monitoring using remote sensing techniques that have been recently proposed by Sharma et al. (2016), Travelletti et al. (2016), Salvini et al. (2015b) and Kromer et al. (2015a, b).

Table 2 LS platforms: advantages and limitations

LS	Advantages	Limitations
Ground-based LS	Simple to use	The LS instruments are expensive
	Slope geometry and geological structure can be rapidly obtained with high precision	Presence of occlusions in the case of very high slopes Not possible to use in case of inaccessible areas not facing the object under study
Mobile LS	Slope geometry and geological structure can be rapidly derived	The LS instruments are expensive
	Survey of long slope section can be very fast	Presence of occlusions in the case of very high slopes Precision and accuracy of point cloud can be lower when compared to ground-based platforms Registration of point clouds can be complicated (Michoud et al. 2015)
LS with UAV	Slope geometry and geological structure can be rapidly obtained	High cost of LS instruments to be mounted on the UAV
	Overcomes problems related to elevation, steepness and complex slope geometry	Precision and accuracy of point cloud decrease significantly when compared to ground-based platforms
	Does not need the area to face the object under study	Weather conditions can severely limit use. Limited battery life requires careful flight planning and may limit application in remote areas. UAV regulations may restrict use or preclude use in some cases
	UAV platforms now available	
	Freely available software for data acquisition, flight planning and data processing	

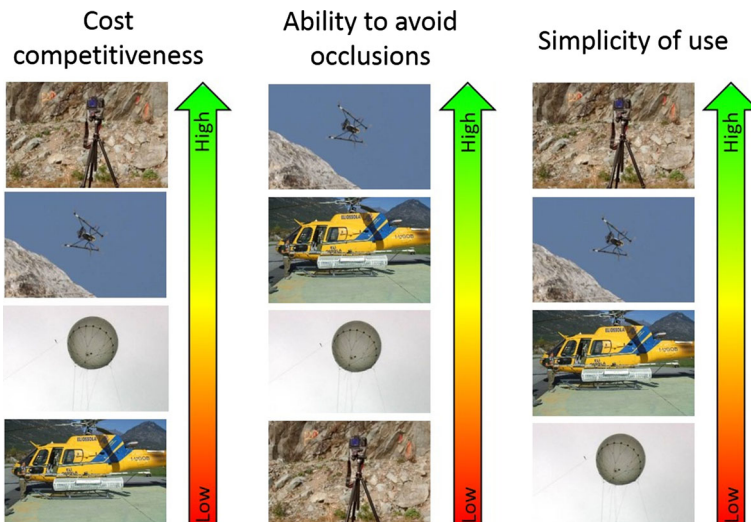


Fig. 16 Comparison between DP platforms

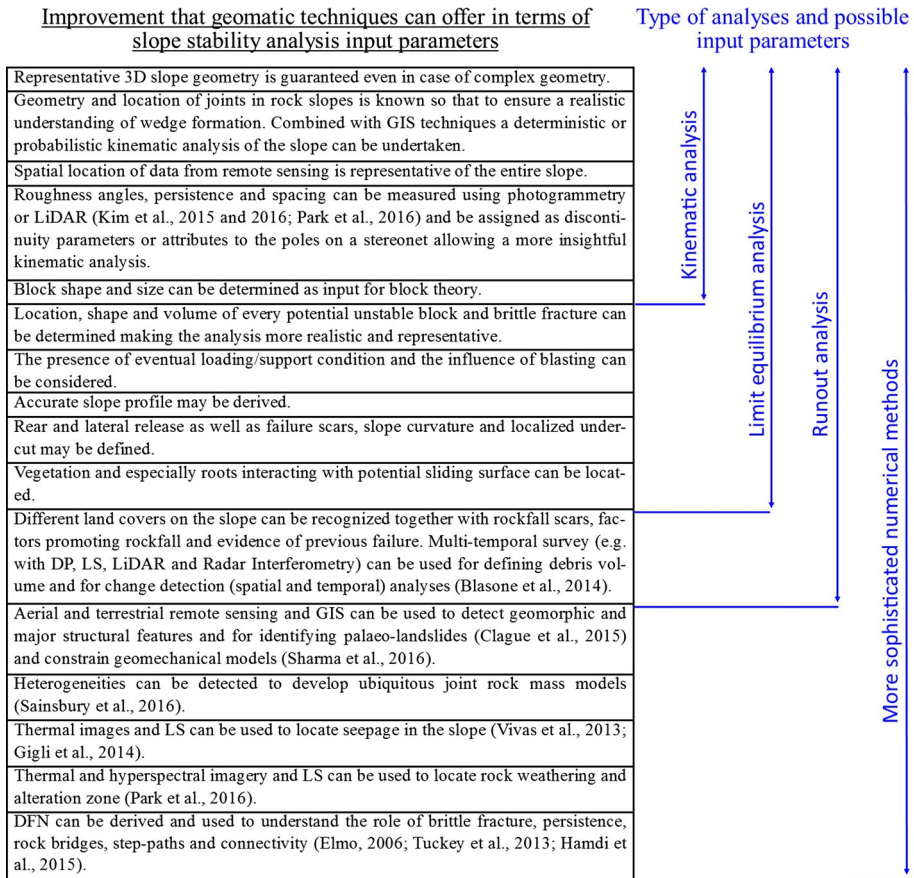


Fig. 17 Improvement that geomatic techniques can offer in conventional and numerical slope analyses

The results obtained from this research will improve the understanding of landslide behaviour.

6 Conclusions

This research presents international examples of the application of remote sensing techniques in the study of rock slopes and landslides and highlights the importance of incorporating the data gained from these techniques in subsequent stability analyses. We demonstrate the use of the different methods of remote sensing surveys and illustrate how each data set can be important in improving the precision and reliability of rock slope analyses.

With regard to DP, considerations of cost and flexibility often make the use of the hand-held camera or tripod the most convenient and effective photogrammetric solution. UAV systems are, however, increasingly seen as the preferred option as they are the least expensive aerial option and also provide the maximum ability to avoid occlusions.

With regard to LS, their use is simple and the results are very precise and reliable (especially in the case of full waveform LS). The cost of the equipment is the main limitation of these techniques especially when compared to DP. Occlusions can still be a problem when dealing with very high slopes and ground-based platforms. UAV LS systems can overcome this problem, but accuracy, precision and resolution of data decrease considerably when compared to ground-based platforms.

All the described remote sensing survey techniques can provide data sets suitable for incorporation into the varied methods of slope stability analysis. These data can overcome many limitations related to input parameters and the difficulties in reducing model and parameter uncertainty. Multiple methods of numerical analysis can be performed with remote sensing-derived data, and stochastic methods can be used to perform multiple simulations in order to better calibrate model results.

In kinematic analysis, the use of remote sensing techniques can result in more representative structural geological assessment of rock slopes; with continuing development in kinematic and block theory approaches, remote sensing data will be more efficiently utilized in slope design and remediation.

In limit equilibrium analysis, the use of specific block and discontinuity geometry directly available from DP and/or LS will lead to more reliable slope analyses as a result of decreased uncertainty related to the block volume and discontinuity inclination. Moreover, the block volume, location and shape together with data concerning the slope geometry and land cover will also allow more detailed and realistic rockfall run out simulations and the construction of more reliable hazard and risk maps.

Remote sensing data when incorporated into more sophisticated numerical models provide improved slope geometry input and also the possibility to include deterministic and/or stochastic representation of discontinuities (especially relevant to future improvements in the 3D analysis of complex slopes). This allows improved analyses and increased scope for model calibration. However, the use of complex geometry increases the simulation time significantly and it is important to understand when this approach is necessary and when it can and should be avoided.

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