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INSTRUMENTATION FOR MONITORING AND MITIGATION OF LANDSLIDES

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Abstract : Phenomena such as earthquakes, volcanoes, landslides, coastal erosion, glacial movements or subsidence following mining, water or oil extraction are all characterized by surface movements ranging from millimeters to meters, over spatial scales of meters to tens of kilometers and temporal scales of hours to years. Detecting the timing and amount of deformation is critical for understanding the physical causes and eventually warning of possible hazards. Monitoring of deformation of structures and ground surface displacements during landslides can be accomplished by using different types of systems and techniques. These techniques and instrumentation that can be classified as remote sensing or satellite techniques, photogrammetric techniques, geodetic or observational techniques, and geotechnical or physical techniques are presented in this seminar.

Keywords: **Landslides monitoring techniques, geodesy, photogrammetry, GPS, geotechnical techniques.**

1. Introduction

Landslides are downslope movements of rock, debris or earth under the influence of gravity, which may cover a wide range of spatial and temporal scales. Most landslides occur at steep slopes, but they can also happen in low relief areas in connection with excavations by rivers or construction work. Landslides can be triggered by natural environmental changes or by human activities. Earthquakes, volcanic activity, heavy rainfalls and changes of ground water level are typical natural triggering mechanisms for landslides, which amplify the inherent weakness in rock or soil. Landslides may result in severe human casualties, property losses and environmental degradation. Therefore, it is well justified that maintaining the stability of slopes is a critical aspect of any geotechnical engineering project. Monitoring the surface displacements of a slope can provide valuable information about the dynamics of the landslide phenomenon. The magnitude, velocity and acceleration of displacements can provide an indication of the stability of the slope. These movements, if detected early enough, can indicate impending catastrophic failure of a slope mass. Landslide hazard mitigation strategies comprise a range of activities including hazard mapping and assessment, real time monitoring and warning systems for active landslides, protective engineering measures, development of public awareness, and emergency planning. Mitigation measures benefit from the understanding of landslide processes and triggering mechanisms which build on the knowledge of geophysical and geological properties of the mass wastes and on models of slope deformation and of failure processes. In general, the information on landslide properties and the understanding of the processes is still inadequate. After an area is suspected of having a potential for failure, an observation campaign is established in order to determine the magnitude, direction and velocity of displacements. This campaign would also help to determine the frequency of the subsequent measurement epochs.

I. Literature Review

1. Patil Abhijit S. studied Western Ghats of Maharashtra frequently suffering from landslide disaster caused by steep slope areas and mountainous terrain. To mitigate this problem, landslide hazard zonation has significance as a fast and safe mitigation measure. This study has been carried out in the South-western Ghats of Maharashtra with the prime objective of delineating landslide hazard zones for the study area by using Analytical Hierarchy Process and Geographical Information System.

2. T V Ramachandra et al.investigated, it is found that Landslides triggered by rainfall can possibly be foreseen in real time by jointly using rainfall intensity-duration and Information related to land surface susceptibility Terrain analysis applications using spatial data such as aspect, slape, flow direction, compound topographic index, etc along with information derived from remotely sensed data such as land cover / land use maps permit us to quantify and characterize the physical processes governing the landslide occurrence phenomenon.

3. Praveen B. Gawali1 et al.studied Heavy rainfall triggered landslides are on the rise along the Western Ghats making it a matter of priority to identify landslide prone areas well in advance. The present effort is aimed at identifying landslide susceptible villages (LSV) around the Kalsubai region of Deccan volcanic province (DVP), Maharashtra, India from 8 weighted landslide parameters- rainfall, slope, lithology, land use and land cover (LULC), soil properties, relative relief, aspect and lineament.

4. Faraz Tariq et al. investigates the landslide hazard zonation along the MH SH-73 at Kelghar ghat between Medha and Mahabaleshwar hill station of Maharashtra. Remote Sensing and GIS were used for the landslide hazard zonation of this section. The ghat section was buffered 100 m on both sides to define the extent of study area based on the field investigation.

II. REMOTE SENSING OR SATELLITE TECHNIQUE FOR LAND SLIDE MONITORING

Remote sensing in the form of the photographic, scanning and processing system is one of the most appropriate means of recording existing ground conditions, of essaying their potential for engineering projects and also of evaluating the effect or potential effects on the environment. Satellite images in the optical region with high spatial resolution are used for producing landslide inventory maps and for mapping factors related to the occurrence of landslides such as surface morphology, structural and lithological properties, land cover, and temporal changes of these factors. .The satellite data are used complementary to aerial photography or as a substitute if no recent air photos are available. In addition, for hazard zonation at regional and national scales, satellite imagery is a more economic database. Another advantage of satellite-based remote sensing is the capability of repeat observations, which results in more frequent update of information on landslide characteristics than the conventional data sources. At the small scale of satellite imagery, only extremely large landslides can be identified directly. The value of satellite imagery is that the landslide susceptibility of an area can be determined indirectly from some of the features that are identifiable at those scales. Regional physiography, geologic structure, and most land forms as well as land-used practices and distribution of vegetation are evident on the satellite imagery.

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IV. Photogrammetric techniques for landslide monitoring

Photogrammetric techniques have been extensively used in determining ground movements in ground subsidence studies in mining areas, and terrestrial photogrammetry has been used in monitoring of engineering structures. The main advantages of using photogrammetry are the reduced time of fieldwork; simultaneous three-dimensional coordinates; and in principle an unlimited number of points can be monitored. The accuracy of photogrammetric point position determination has been much improved in recent years, which makes it attractive for high accuracy deformation measurements. The interpretation of aerial photography has proven to be an effective technique for recognizing and delineating landslides. It is an effective technique for recognizing and delineating the three-dimensional overview of the terrain from which the interrelations of photography, drainage, surface cover, geology materials, and human activities on the landscape can be viewed and evaluated. Aerial photographs present an overall perspective of a large area and boundaries of existing slides can readily be delineated on aerial photographs. Surface and near- surface drainage channels can be traced. Important relations in drainage, topography and other natural and man-made elements that seldom are correlated properly on the ground become obvious in photographs. Furthermore, soil and rock formations can be seen and evaluated in their undisturbed state. Recent photographs can be compared with old ones to examine the progressive development of slides and aerial photographs can be studied at any time, in any place and person. Terrestrial photogrammetry and ground-based photography is also being used for local-scale landslide monitoring. Sites that are too steep or too small to be confidently viewed from the air lend themselves to study on the ground, albeit at a distance. Terrestrial photogrammetry can effectively be used at unsafe or inaccessible sites, such as road cuttings and landslides. Special cameras with minimized optical and film distortions must be used in accuracy photogrammetry.

2. Ground-based geodetic techniques for landslide monitoring

Conventional ground-based geodetic techniques have been used for deformation monitoring of structures and landslides. Two basic methods for the design of a deformation survey can be used:

1. A horizontal or vertical control network is established in the area under investigation with control points located in the deforming region.

2. Total station instruments are used to measure angles and distances to target-prisms located on the moving mass. In both cases the aim is the computation of targetpoint coordinates and/or heights for each measurement epoch. From the comparison of these coordinates/heights, after all proper statistical and reliability tests, the horizontal and/or vertical displacement vectors of each control point can be determined

2.1 Triangulation and trilateration horizontal control networks

In triangulation and trilateration networks angles/ directions and distances are measured with the proper instrumentation. Manually operated theodolites have been traditionally used for angle measurement in high accuracy deformation surveying. Distances are measured using manually operated electronic distance measurement (EDM) instruments:

a. Electronic theodolites.

Over the last two decades, the technological progress in angle measurements has been mainly in the automation of the readout systems of the horizontal and vertical circles of theodolites (fig. 2). Various, mainly photo-electronic, scanning systems of coded circles with an automatic digital display and transfer of the readout to electronic data collectors or computers have replaced the optical readout systems. As far as accuracy is concerned, electronic theodolites have not brought any drastic improvements in comparison with accuracy optical theodolites. Atmospheric refraction is a particular danger to any optical measurements, particularly where the line-of sight lies close to obstructions.

(fig. 1)- Eica TM5100A high precision electronic Theodolite

b. Electronic Distance Measurement (EDM) Instruments.

Short range (several kilometers), electro-optical EDM instruments with visible or near infrared continuous radiation are used widely in engineering surveys. The accuracy (standard deviation) of EDM instruments is expressed in a general form as: s = ± (a + bS) where "a" contains errors of the phase measurement and calibration errors of the so-called zero correction (additive constant of the instrument and of the reflector), while the value of "b" represents a scale error due to the uncertainties in the determination of the refractive index and errors in the calibration of the modulation frequency. Typically, the value of "a" ranges from 3 to 5 mm. In the highest accuracy EDM instruments, the "a" value is 0.2 mm to 0.5 mm based on a high modulation frequency and high resolution of the phase measurements in those instruments. One recently developed engineering survey instrument is Leica DI2002 that offers a standard deviation of 1 mm over short distances. Over distances longer than a few hundred meters, however, the prevailing error in all EDM instruments is due to refraction problems during their propagation in the atmosphere. It is interesting to observe that the production of high accuracy EDM instruments (e.g. the Mekometer 5000) was discontinued due to a small demand and an extremely high cost.

c. Dual frequency instruments.

Only a few units of a dual frequency instrument (Terrameter LDM2 by Terra Technology) are available around the world. They are not really user-friendly in use but standard deviations of ±
0.1 mm ± 0.1 ppm may be achieved with them. Research in the development of new dual frequency instruments is in progress. d. Three-dimensional positioning systems. Two or more electronic theodolites linked to a PC computer create a three-dimensional (3D) (positioning) system with real-time calculations of the coordinates. The systems are used for the highest accuracy positioning and deformation monitoring surveys over small areas or for measurements for industrial applications. Leica TMS and UPM400 (Geotronics, Sweden) are examples of such systems. Positions (x, y, and z) of targets at distances up to ten meters away may be determined with standard deviations smaller than 0.05 millimeters. These systems can be used for landslide monitoring. In this case high accuracy theodolites measure horizontal and vertical angles to targets on the area under consideration. Standard deviations depend among others upon the accuracy of the instruments used but can be kept in low values

2.2 Vertical control networks and height determination

The traditional technique for height determination is differential leveling. It provides height difference measurements between a series of benchmarks. Vertical positions can be determined to very high accuracy (± 0.1 - 1 mm) over short distances (10-100's of meters) using accuracy levels. Two major classes of accuracy levels commonly used for making deformation measurements are automatic levels and digital levels:

a. Automatic levels

The old method of geometrical leveling with horizontal lines of sight is still the most reliable and accurate, though slow, surveying method. With high magnification leveling instruments, equipped with the parallel glass plate micrometer and with invar graduated rods, a standard deviation smaller than 0.1 mm per set-up may be achieved in height difference determination with balanced lines of sight not exceeding 20 meters. In leveling over long distances (with a number of instrument set- ups) a standard deviation of 1 mm per kilometer may be achieved in flat terrain.

b.Digital levels.

The digital automatic leveling systems with height and distance readout from encoded leveling rods have considerably increased the speed of leveling (fig. 3). There are several contradictory remarks on their performance as high accuracy levels and some improvements are expected to be introduced by the manufacturers but they can effectively be used in landslide monitoring if geodetic leveling is selected as the most suitable technique for height determination.

c. Zenith angle methods.

High accuracy electronic theodolites and EDM equipment allow for the replacement of geodetic leveling with more economical trigonometric height measurements. An accuracy better than 1 mm may be achieved in height difference determination between two targets 200 m apart using accuracy electronic theodolites for vertical angle measurements and an EDM instrument. This technique is especially more economical than conventional leveling in hilly terrain, and in all situations where large height differences between survey stations are involved. It can be used in landslide monitoring instead of geodetic leveling. The refraction error is still the major problem with increasing the accuracy of trigonometric leveling. Fig. 3. Leica NA 2003 automated digital level and section from bar-coded invar level rod d. GPS measurements. Height differences can also be computed with the use of GPS receivers. Height determination with GPS has somewhat worse accuracy than horizontal position. GPS control networks have been for land subsistence measurements. It must be noted that GPS provides geometrical height differences that must be transformed into orthometric in order to be compatible with measurements with the other techniques.

2.3 Total station instruments for landslide monitoring

In the past, any electronic theodolite linked to an EDM instrument and to a computer was considered to be a total surveying station which allows for a simultaneous measurement of the three basic positioning parameters, distance, horizontal direction, and vertical angle, from which relative horizontal and vertical positions of the observed points can be determined directly in the field. In recent years, the manufacturers of surveying equipment have produced integrated total stations. Different models of total stations vary in accuracy, range, sophistication of the automatic data collection, and possibilities for on-line data processing. The launch of the motorized theodolites (fig. 4) known also as surveying robots or robotic surveying systems introduced the possibility of collecting 3D positional information for automatic deformation monitoring. They can track a moving target and make automatic measurements of angles and distances to the target in motion. These instruments can make measurements at data rates up to 1 Hz and can operate autonomously once “locked” to the target that has been manually set by an operator. Current technology provides total stations that are able to measure angles with an accuracy of ± 0.15 mgon, and distances with an accuracy of ±1 mm + 1ppm to a range of 3,500 m. Total stations allow the measurement of many points with prism-targets on the surface being monitored within a short period of time. Using Automatic Target Recognition (ATR) technology each prism can be found and its center identified to provide precise target pointing. Such technologies are ideal for precise applications where the removal of error sources is desired. The ATR approach used by Leica uses nonactive prisms and hence does not require a power source at each prism, reducing the cost of each prism installation. Early automated vision systems were installed in accuracy theodolites by the 1980's. Its operating components consisted of an external video camera imaging system and a separate servo motor drive. Modern systems are more sophisticated being packaged internally and having an active beam sensing capability. An emitted IR signal is transmitted to the prism that passively reflects the signal back to the instrument. The return spot is imaged on a high-resolution (500 x 500) pixel CCD array. The centroid is located in relation to the current position of the optical cross-hairs (reticule). A series of targets are sighted so the instrument can be trained to their location at least once. With the approximate coordinates of each target prism stored in memory, the ATR system can then take over the pointing, reading, and measuring functions completely within the instrument. The user can program target search radius, data rejection thresholds, and other controls into the operating menus. The first commercial motorized total station was Georobot. Recent advanced systems include, for example, the Geodimeter 140 SMS (Slope Monitoring System) and the Leica APS and Georobot III systems based on the motorized TM 3000 series of Leica electronic theodolites linked together with any DI series of EDM. These can be programmed for sequential self-pointing to a set of prism targets at predetermined time intervals, can measure distances and horizontal and vertical angles, and can transmit the data to the office computer via a telemetry link. Similar systems are being developed by other manufacturers of surveying equipment. The robotic systems have found many applications, particularly in monitoring high walls in open pit mining and in slope stability studies. Generally, the accuracy of direction measurements with the self-pointing computerized theodolites is worse than the measurements with manual pointing.

2.4 Satellite-based geodetic techniques for landslide monitoring

The Global Positioning System (GPS) can be used as an alternative surveying tool to assist in geotechnical evaluations of steep slopes by providing 3D coordinate time series of displacements at discrete points on the sliding surface (fig. 2). Current GPS positioning techniques for monitoring applications typically include the use of either episodic techniques for small scale projects or continuous monitoring for regional scale projects .

(fig. 2) GPS measurements in a landslide area

Each of these techniques has associated trade-offs between system installation and maintenance costs, and the quality of the resulting coordinate time-series. GPS positioning is based on measuring the transit time of radio signals emitted by orbiting satellites. For a receiver to compute its stand-alone position, it must be in view of at least four satellites. Code Phase Positioning is widely used in navigation and low accuracy tracking applications, and relies on the measurement of the modulated GPS signal code phase, which exhibits a resolution of about 1m. The measurement is affected by several perturbations, which bring the achievable accuracy to about 5- 10m. GPS offers advantages over conventional terrestrial methods. Visibility among stations is not strictly necessary, allowing greater flexibility in the selection of station locations than for terrestrial geodetic surveys. Measurements can be taken during night or day, under varying weather conditions, which makes GPS measurements economical, especially when multiple receivers can be deployed on the deforming mass during the survey.

2.4 Episodic GPS deformation monitoring

GPS techniques are used to measure vectors in space among the points of a control network. In order to compute deformations, repeated GPS surveys must be done (for example every few weeks or months). A comparison of their results can give the observed displacements of the network points. Static, rapid-static or real-time kinematic GPS surveying techniques can be used. Precise static positioning using carrier phase differential GPS involves forming double differences to eliminate most errors common to both receivers, and integrating the measurement over time. The method thus requires collecting and post processing a relatively large amount of data, a sufficient amount of – 250 – computing resources, and is by definition non real time. Real Time Kinematic GPS (RTK GPS) delivers 3D coordinates with an accuracy of ± (5mm + 2ppm) in real-time with a frequency as high as 0.2Hz. Equipment which provide the accuracy achievable with RTK GPS and with the update rates that is possible with modern GPS receivers provide the ideal sensor for monitoring “high” and “low” frequency movements in structures (e.g. bridges and buildings) and landslides. Another possibility is using the rapid static positioning technique. In this way, the time for the measurements at each station is reduced to a few minutes. When using an episodic monitoring system there are lower establishment costs, but there are certain disadvantages as well.

These may include:

1. Discontinuous time series that does not always allow the extraction of the trend of the deformations from the noise existing within the observations.
2. Poor systematic error modeling due to short observation times.
3. Safety considerations for personnel re-entering site. Episodic GPS monitoring systems have less cost to deploy but require personnel costs throughout the lifetime of the measurement regime

3 Comparison of landslide monitoring methods

Each measurement technique has its own advantages and disadvantages. Remote sensing is a very helpful technique for regional ground displacement monitoring although the small scale of satellite imagery imposes some limitations. On the other hand the temporal coverage is very good. Satellite or/and ground based Interferometric Synthetic Aperture Radar (InSAR) techniques are capable of providing key information for monitoring of landslides and other geological hazards. The value- adding industry and research laboratories developed excellent tools for InSAR analysis, which should be adapted for fully operational use and for integration with conventional observations and predictive models. InSAR and GPS techniques are complementary, and GPS can "calibrate" the InSAR errors. Hence the integrated InSAR-GPS technique has the potential to measure deformations at sub-centimeter levels of precision with unprecedented spatial coverage. The development of such a system will result in a methodology based on the optimum combination of InSAR and GPS technologies and is still under research. Aerial photos provide the base for local displacement computations but the temporal coverage is rather poor, making this technique useful for comparisons over large periods of time. Terrestrial Photogrammetry can also be used even for real-time monitoring with the help of CCD sensors. Ground-based geodetic techniques, through a network of points interconnected by angle and/or distance measurements, usually supply a sufficient redundancy of observations for the statistical evaluation of their quality and for a detection of errors. They give global information on the behavior of the deforming mass. Geotechnical measurements give very localized and, very frequently, locally disturbed information without any check unless compared with some other independent measurements. On the other hand, geotechnical instruments are easier to adapt for automatic and continuous monitoring than conventional geodetic instruments. Conventional terrestrial surveys are labor intensive and require skillful observers keeping the cost of monitoring campaigns rather high, while geotechnical instruments, once installed, require only infrequent checks on their performance. Geodetic surveys have traditionally been used mainly for determining the absolute displacements of selected points on the surface of the object with respect to some reference points that are assumed to be stable. Geotechnical measurements have mainly been used for relative deformation measurements within the deformable object and its surroundings. Measurements with traditional geodetic techniques are done according to a periodic schedule, thus reducing the ability to appropriately model the observed phenomena. Furthermore, on-site instruments may require maintenance and cleaning, thus increasing safety hazards to personnel re-entering potentially hazardous areas.

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Table 1. Typical accuracy claimed by different deformation (landslide) monitoring techniques

Method of measurement	Displacement parameter	Distance between points	Typical accuracy
Metal tape or invar wire	Distance	< 30 m	0.5 mm / 30 m
Fixed wire extensometer	Distance	< 10 - 80 m	0.3 mm / 30 m
Inclinometer	Elevation angle	± 10° ±	(5-10 mm ± 1-2 ppm)
Triangulation Trilateration	Dx, Dy, Dh	< 300 – 1000 m	2 – 10 mm
Traverses	Dx, Dy, Dh	Variable	5 – 10 mm
Robotic total station	Dx, Dy, Dh	< 100 m	1-3 mm
Precise geometric levelling	Dh	10 m 100 m	0.1 mm 0.2 – 1 mm / Km
Electromagnetic Distance Measurement	Distance	Variable	± (1-5 mm ± 1-5 ppm)
Terrestrial Photogrammetry	Dx, Dy, Dh	< 100 m	± 10 mm
Aerial Photographs	Dx, Dy, Dh	Variable	10 cm
GPS L1/L2 static	Dx, Dy, Dh	< 50 Km < 1-2 KM	± (5 mm ± 2 ppm) ± (1-3 mm ± 2ppm)
RTK DGPS	Dx, Dy, Dh	Variable	± (5 mm ± 2 ppm)
Continuous operating GPS	Dx, Dy, Dh	Variable	± 2 – 3 mm

4 Conclusions

Earth observation satellites and remote sensing are able to provide significant information for mapping the extent and properties of landslides. Some of the techniques, for example the use of the new very high resolution optical satellite data for landslide inventory monitoring and hazard assessment, need to be further developed. The powerful In SAR tools, which provide accurate topography and motion maps and thus can make significant contributions to the assessment and mitigation of landslide hazards, are ready for transfer to operations. Terrestrial laser scanning technology offers a rapid means of collecting dense sets of three-dimensional point sets. For structural monitoring applications, laser scanning can be considered advantageous over geodetic methods (e.g., surveying, GPS), which can only sense deformation at a limited number of points, whereas a scanner can measure a deformation surface. Future work will concentrate on these aspects and integration of laser scanner data with measurements from other sensors (e.g., GPS, digital cameras). Only a few of the many monitoring techniques provide a true 3D indication of the displacement vectors of control points on the surface of the sliding area. GPS is an emerging technology that can be used to provide a dense 3D time series to map the position and velocity of the deforming mass. Regional scale continuous operating GPS networks, such as those used for monitoring of tectonic motion can provide a temporally dense and precise time-series of 3D deformation data at high installation and maintenance costs. Episodic GPS monitoring techniques may be a cheaper alternative but they result in poorer accuracy and reduced temporal density of the coordinate time series. Multi-antenna GPS monitoring systems can offer a high level of accuracy at a reduced implementation cost but this technique has still to be developed for larger scale landslide monitoring. Geotechnical measurements can also contribute to the study of a landslide phenomenon, alone or in combination with other monitoring techniques. In any case, the variability of spatial and temporal scales means that useful deformation monitoring must rely not just on one measurement technique, but on a suitable combination of monitoring tools. In particular, advances in GPS technology mean that it is possible to deploy arrays of low-cost receivers or multi antenna GPS systems to monitor ground movements with very high temporal resolution and moderate to low spatial resolution, while satellite-based InSAR systems are capable of very high spatial resolution but moderate to low temporal resolution. The investigation on combining such datasets, most likely with additional techniques such as robotic total stations, laser scanning, and geotechnical instruments for the efficient and reliable monitoring of real deformational hazards is still in progress.

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