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Instrumentation and Data Acquisition Needs for Slope Monitoring

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Abstract

Slope monitoring frequently involves in-ground transducers of varying types that can supply information on piezometric levels and on ground movement.

Much of this information is useful in analysing a slope and its failure mechanism but is not required in real time. However in the event of a potential catastrophic failure of a slope, there is a need for information to be available and acted upon with some urgency.

Real time monitoring at a central station means that the data has to get there, be processed and results passed back for action to be taken at the site. The alternative is to place a monitoring system with intelligence on the site so that it can take action, such as close a road, and relay that information to those who need to know.

This paper outlines the types of slope instability, their form and state, the instrumentation that might be used, how data may be gathered and processed, and finally how distributed real time models may be used to make decisions as to whether to take action and to raise an alarm.

What are Slope Failures?

Slope failures are a result of change of physical dimensions or properties of the ground. The changes essentially fall into four categories:

1) Changes in groundwater pressures that reduce the effective stress within the material.
2) Changing geometry of the slope which can be either natural changes brought about by erosion or man made changes caused by excavation or filling.
3) Changes in the strength of the material in the slope caused by:
    a. The natural process of weathering
    b. Some degree of movement which has caused the ground to pass peak strength
    c. Chemical changes in groundwater that alter the cohesion of clays
    d. Changes in the total strength of clays which are associated with the dissipation of negative pore pressures.
4) Changes in the acceleration to which the slope is subject, caused by natural seismic events or occasionally by blasting.

Forms of Slope Failures

All slope failures are caused by a loss of stability. This loss of stability is usually manifested in the sums of the shear stress on the potential failure surface becoming less than the resisting frictional force on that surface. As such these cases are functions of geometry and material properties. Failures may also take the form of toppling failures of jointed material or rolling failures of boulders. Both of these failure modes are principally functions of geometry rather than material properties.

Slope failures take many physical forms governed by the geology and the natural and artificially altered morphology of an area. These include:

1) Deep seated failures of soils or rock. These usually take place along preferential planes of weakness. They are frequently activated and reactivated by changes in groundwater pressures.
2) Failures brought about by the relief of stress fields through natural or man made excavation.
3) Shallow failures that are principally caused by the presence of locally high water or air pressures in soil. These typically occur in the high rainfall events of tropical areas.
4) Toppling or rolling caused by slight changes in geometry such as bearing capacity failure or water pressure that trigger the failed mass from the stable to unstable state.

It is important to realise that the time scales of slope failures differ vastly. A heavy tropical downpour on decomposed granite may lead to a failure in half an hour, while a failure in a clay may be spread over decades, with varying degrees of movement prior to a catastrophic failure.

The acceleration of a slope failure is a function of the net force acting divided by the mass of the moving block. Failures that proceed at an even rate are by definition in a state of zero acceleration and therefore the net forces are in balance. There are many large slow moving failures that are essentially in a state of force equilibrium and theoretically very little is needed to bring about deceleration and a cessation of movement. This is however very dependent on the nature of the shear resistance of the failed material. What is the shear rate versus shear resistance of the failure surface? While not generally taken into account by the geotechnical community, the rheology and essentially viscous shearing behaviour of the material in the failure zone may play an important limiting factor to the rate of movement of some failures through clays.

The question is often whether the continuing movement is disruptive and whether the movement will accelerate. Typically acceleration is brought about by changing pore pressure. It may also be caused by the peak shear strength of the material being exceeded followed by its rapid reduction. A classic instance of the latter is the shearing of filled joints in rock that then lose all of the non-frictional component of shear strength.

A downpour on a slope may saturate the surface and prevent the escape of air. In this case the water and air pressure may rise. The effect is one of multiple perched water tables without there being any change in the physical properties of the soil. In reality the ground is never homogeneous and such perched water tables are a function of the inhomogeneity of the ground and multiphase flow effects. Frequently such failures may proceed quite rapidly depending on the soil type.

Cases of geometric instability start slowly but tend to rapidly increase as toppling or rolling takes place.

The State of the Slope

In the natural environment slope failures take place most frequently in areas subject to high erosion rates. Slope failure is after all one of the mechanisms of erosion. This means that in areas which are steep, have high rainfall and have a means to remove the failed material by gravity and flowing water, failures continue to occur. This only becomes a problem when the failure interferes with humans.

Throughout history as man has colonised the world he has had to deal with such naturally occurring failures. Man's interaction with the natural environment has however meant that he seeks to stabilise such failures while frequently making matters more complex by creating roads, level areas for buildings, mines and other cultural features.

Where developments affect a new land, the job of the developer is to evaluate the area in terms of pre-existing signs of instability and to conduct adequate measurement and analysis so as to determine whether the proposed work will cause instability. The measurements would normally comprise assessments of soil or rock strength, the orientation and nature of jointing and of groundwater. Determining the latter often requires monitoring over a period so that the variations in groundwater may be determined.

While this investigation and design stage may appear to be relatively well defined, conducting investigations and design to an adequate level to ensure that slope movement does not occur can be difficult. The prime reasons for this are that conditions are encountered that could not reasonably have been predicted or because the limits are being tested because of a need to create an open pit mine or a road across a slope. Indeed roadways in mountainous terrain are frequently built with the expectation that slope failure will be an ongoing feature of their life and that remedial works will have to continue. In many cases these problems are simply historically acquired and have to be coped with.

The Role of Instrumentation in Slope Monitoring

The role of instrumentation in slope stability is quite different depending on the nature of the slope failure that is anticipated or is occurring. It also depends on what outcome is expected from the instrumentation.

Instrumentation may be used:

1) As part of analysis and design
2) As part of a system to provide a warning that failure is imminent
3) As a system to warn that failure is taking place
4) As a diagnostic tool to determine the nature of failure that is taking or has taken place

The types of instrumentation that may be used are:

1) Systems that measure surface movement remotely
    a. Surveying – manual or automated theodolite, laser systems
    b. Photogrammetric derivatives

The direct systems that measure something in or on the ground. These include:

2) Rain gauges
3) Piezometers to measure fluid pressure
4) Movement sensors
    a. Extensiometers
    b. Inclinometers
        i. Mobile
        ii. Fixed
    c. Accelerometers
    d. Tiltmeters
    e. Geophones
    f. Shear strips
    g. Time domain reflectometry
5) Load sensors

Surface Measurement Systems by their nature are slow but they do provide broad area coverage. If these are precision survey systems they will be able to detect small movements and are particularly useful for monitoring slow movements. The photogrammetric type scanning systems have less precision and are more suitable for determining if a block has moved on a slope. A good deal of human interaction is desirable with the latter system.

Rain Gauges are extremely important as rainfall is a key cause of slope failure. The measurement of rainfall can sometimes be the most important indicator that slope failures will occur. Because major rainfall events are frequently quite localised, the use of a number of automatic rain gauges to cover the terrain that may be affected by slope stability issues is important.

Piezometers to measure fluid pressure are probably the most useful single sensor to be used in all aspects of landslides – prediction, warning and diagnostic. Generally the pressure sensing element of a piezometer is a pressure transducer that is connected to some form of data acquisition system. Care needs to be taken in their correct installation as in some it is relatively easy to install the transducer incorrectly so that it fails to correctly record the fluid pressure in the ground. For example the position of a transducer in a filter pack within a borehole will affect its reading under dynamic groundwater events. This occurs if the transducer is placed near the bottom of the filter pack in what is normally an unsaturated soil. When it rains water flows downward in the soil and will drain into the filter zone partially filling it and giving a false reading, which indicates the presence of a perched water table. The grouting of transducers directly into a hole is also a way to risk problems with inadequate connection between the sensor and the ground. Where these are used tests should be used to ensure that they are working.

Movement Sensors can be very useful in determining the nature of landslides provided that they are located correctly.

Extensiometers can be used to determine relative movement between points to great levels of accuracy, typically down to 0.01 mm. In their simplest form they are simply a taut wire hung over the edge of a pit with a weight on the end which rests on a bench. In this form they are subject to all sorts of disturbance. If installed in boreholes they can monitor the dilation of a soil or rock mass with great precision as the effects of temperature change and outside interference are minimised.

Extensiometers are generally inadequately used to monitor the movement within and across failure planes. The reason for this is that in most cases people are prepared to drill vertical holes because they are used to doing so and they are frequently the shortest hole that can be created to detect a failure plane. Having drilled a hole which is essentially perpendicular to the failure plane the movement in these is best detected by the use of inclinometers or shear strips. If holes were drilled to cross the expected failure plane at an acute angle then extensiometers can be installed in these, and because of the precision of monitoring that can be achieved, changes in length with time can be reliably calculated to yield information on the rate and acceleration of movement.

Where holes cannot be drilled wire extensiometers can sometimes be advantageously installed in conduits on surface. Doing this exposes them to risk of damage but avoids the problem of an extensiometer being lost as movement on the failure surface displaces sections of a borehole with respect to each other.

Inclinometers are generally manually operated devices which are run down a slotted casing which is cemented into a borehole. The first limitation of this is the frequency of measurement that can be achieved. This is governed by how fast the tool can be got up and down a hole and the results processed and understood. These devices can be highly accurate and have considerable use in determining how the hole is deforming so as to enable the location of the shear surface. The second main limitation is that once sufficient deformation has taken place the inclinometer will no longer pass through the casing. Fixed inclinometers that are located in a plastic grout within the borehole do not provide the continuous measurement along the entire length of the hole but do permit high monitoring rates. They also suffer from failure when the cable connecting the inclinometer element to surface is damaged by movement.

Accelerometers are also useful in the detection of seismic events which may trigger a landslide. The measurement of a seismic event is essentially notice to go and look for a landslide. Major fast landslides can be accompanied by some local ground vibration that may be picked up by the accelerometer. It is once again an indicator to look for the effects rather than as a predictive tool.

Tiltmeters are a form of accelerometer that measure the change in the direction of gravitational acceleration. They are highly accurate and under used in dealing with slope movements. The advantage they have is that they can be readily mounted on the surface of a slope or in a shallow hole and unlike extensiometers have a small footprint. The disadvantage of a tiltmeter is that it will only detect rotational rather than translational movement.

Geophones have the potential to listen for failure occurring in rock masses. However their placement near surface has the problem that other sources of noise such as traffic or blasting may lead to problems in interpretation. As with all such geophysical techniques they require a vast amount of data to be acquired and a lot of effort to be expended on interpretation. They may well be good in providing in hindsight an indication of the failure progression but are unlikely to be a useful predictive tool.

Shear Strips are an old fashioned and very simple means to determine the approximate location of a shear surface. They comprise a series of looped cables which are cemented into a borehole. Shearing breaks the conductivity of the cable so that the approximate position of a shear surface can be detected. Shear strips can be read using a manual or automated ohmmeter.

Time Domain Reflectometry is the modern version of the shear strip only in this case a single coaxial or fibre optic cable is cemented into a hole and the location of breakage can be determined by the reflection of a pulse down the cable. It can give the exact location of the break but requires a lot more sophisticated equipment than an ohmmeter to determine this.

Load Sensors can be used wherever a soil nail, rock bolt or cable anchor can be installed. Indeed it may simply be beneficial to install such a restraining device so that a load sensor can be fitted to it and used to detect changes. Increases in load are an obvious indication that the restraining device is working harder. Reductions in load may indicate that it has pulled out or broken. Typical load measuring applications include rock bolts that are installed to restrain blocks of rock that may potentially slide, topple or roll.

Monitoring the Sensors

Any form of sensor needs to be monitored. The frequency of monitoring needs to be tailored to its purpose and the speed with which changes in the slope may take place and failure occur.

The item of instrumentation that is likely to be installed on slopes that are not thought to be moving, but which need to have their stability checked without further works taking place is the piezometer. To make real sense of the piezometric readings a rain gauge should be installed nearby. This then provides a basis for determining how groundwater may behave in different storm conditions. The response time of fluid pressures on slopes varies hugely. The fastest changing water pressures tend to be found in cracks in rock or near the surface in soils during downpours. In such cases piezometers may need to be monitored every minute so that a full picture of groundwater pressure variation is obtained. The water pressures in deeper seated landslides may change much more slowly and need measurement only every few hours.

Landslides may have quite different hydrogeological regimes that exist over the same slope and that affect the failure surface. Groundwater characteristics can sometimes change in a quite unexpected manner. The development of soil pipes is a classic example of such a change. A natural soil pipe may remove water from an area and deliver it to another. They can sometimes become blocked with quite disastrous consequences. Such blockage is likely to be inadvertently caused by construction works. Given the amount of water that can be conveyed in a 100 or 300 mm soil pipe this is a serious consideration.

Because of the importance of groundwater in slope failure the rain gauge and piezometer are likely to be the single most important sensors used in design, prediction of stability, the warning of a potential failure and as a diagnostic tool to determine why a slope failed.

Movement sensors are unlikely to be installed unless a slope failure has been detected or is considered to be a significant risk. The location of such sensors requires a knowledge of where the movement may be. The simplest of the devices to use are those which occupy a small footprint such as tiltmeters and shear strips. If, however, extensiometers are installed they can be extremely valuable because of the ready ability to differentiate their movement with respect to time.

The amount of movement and the rate of movement that is significant can vary vastly between landslides. This once again calls for hugely varying monitoring rates. The same would be expected to apply to load sensor based devices. Where such devices are pre-tensioned anchors, the amount of change in load that is significant may be small in relation to the total anchor load.

Such devices as accelerometers and geophones require a totally different rate of monitoring to be of any use. The approach can be in three forms. The first and most comprehensive is that all data acquired is transmitted. This is however quite impractical in terms of the volume of data. The other end of the scale is some device which records when a peak value is reached and transmits that this is the case. A variant of this is where the moving average of the absolute value of acceleration is taken and used as a threshold. Some seismographs offer the option of continuously processing information but only holding, and then transmitting information, once a significant event has been determined to have occurred.

The more usual geotechnical sensors from which data is acquired at much lower rates can adopt much the same approach. The way in which this is logically accomplished is by the data acquisition device reading the sensors at an adequate fixed rate so that no significant information is lost. Over the vast bulk of time however the sensors will not show any change and there is no need to record this lack of information. If however a reading does change from the previous one by a pre-set threshold then that value is recorded. By this means the data that has to be stored, and more particularly transmitted, is minimised. The function of the recording device can be verified by ensuring that it records data at a defined minimum interval.

Getting The Data

It is inconvenient, expensive and sometimes dangerous to have to walk around a landslide site to gather data. The use of cables to convey information from a site is also undesirable because of the likelihood of damage occurring to them. Fortunately the increasing use of wireless communication makes this unnecessary, provided that there is adequate power available to power each data acquisition device. Because radio frequency transmission in any form requires a significant amount of electrical power, purely battery powered communication is impractical. This means that another source of power must be available. In sunny climates the practical source of power are solar cells which charge a battery. In cold climates with inadequate solar radiation the only way to power communication may be by cable from a substantial power source. In this case it might still be considered desirable to use radio rather than cable based communication. The reason for this is because charged batteries can transmit for a period even after a slope movement has caused the loss of the power cable. Of course in the colder climates the power source may also be required to heat the battery so that it may function.

Wireless mesh networking systems form a robust system by which data can be collected from a number of nodes which are typically the data acquisition devices themselves. These wireless mesh networking systems permit the transmission of data through a number of routes. If a node fails they have enough intelligence that they can find an alternative wireless pathway to transmit information. This is ideally suited to landslide conditions where a node may be lost. The use of such wireless networks protects the instrumentation network against lightning damage. Essentially nothing will protect a data acquisition node against a direct strike but the lack of interconnecting cables means that the damage is likely to be limited rather than spread and the mesh has the capability to re-establish communication.

The information is typically brought to a base node which has the ability to transmit it from the site using land line telephone, cellular phone network or more powerful radio modems. The base node may also have the computing power to make decisions as to what to do with the data. Ideally more than one base station exists so that if one goes out of service another will continue to transmit.

In the case of landslides with higher rates of piezometric change or potential movement rate, it is not considered desirable to use a typical process control system that connects to each data acquisition node at a fixed interval and requests data sampling at that time. Rather it is better to provide some means by which the data acquisition system can initiate the data transfer process. With this it may be necessary for the system to initiate some level of action, either as data transmission or direct on site action or warnings.

It should always be borne in mind that no matter what marvels of modern communication exist there will be failures in data transmission. These are most likely to occur when electrical storms or heavy rainfall occur. These events are also often the trigger to a landslide. The process then by which all data must be transferred back to a central office, processed and a decision made there has real limitations. So does the fact that those decisions need to be transferred back to the slope for some action to be taken.

Processing the Information

The level of processing that should be applied to information gathered from instrumentation on a slope is highly variable, depending on its purpose. This will range from groundwater information that will be incorporated into a slope design with information from a site investigation.

In the case of a large and complex landslide that is continuing, the information will extend to a far greater level, incorporating such information as may be provided by virtually all the types of instrumentation. The process of dealing with it is essentially the same however, namely that the engineers and geologists involved analyse that information to arrive at the failure mechanism. This will then permit them to design remedial works to stabilise the slope. In this case the speed with which data is delivered from slope instrumentation is generally not critical.

The next stage in the process of managing a landslide follows the implementation of remedial works. In this case instrumentation serves to confirm that the slope is behaving as expected.

The real difference comes when the information gathered indicates that the slope is not necessarily stable or that movement is continuing. The body responsible for the slope usually then wants information as frequently as it can be provided, to enable them to make a decision on what to do about it. This decision process may involve re-evaluating the design or making a decision to limit access to the area. The basis of decision making will typically be based on critical rainfall or groundwater levels being reached or a level of movement occurring that is considered unacceptable.

One of the techniques that can be used to great advantage in this situation is one of real time simulation. In this a numerical model of the slope is created which accepts direct inputs of parameters being measured on site. These changing parameters are most likely groundwater levels that may be directly input into the slope stability model or may be processed first by a hydrogeological model and then input into a stability model. For such numerical models to be useful they must be able to be computed relatively quickly. As such, limit equilibrium models, whether in two or three dimensions, are likely to be of the greatest value because of the quick computational times required.

Even in this age of instant communication it is the relaying of such information for a decision to be made that may not be adequately reliable. The question is then what to do with information that is available at the site? This in turn depends on the sophistication of measurement that exists.

Let us consider a simple case where a water level in a standpipe piezometer is measured and operates a flashing light or a red stop sign on a road if it becomes too high.

Another simple version is a movement indicator that either raises an alarm if movement exceeds a threshold, threshold rate or threshold acceleration. Possibly a combination of either the threshold movement or threshold acceleration are the most needed measurements. In either case the warning should be conveyed to some hopefully intelligent human being who can take action to verify what has happened and can initiate whatever further measures are required. Such a warning could be conveyed through the telecommunications system, possibly by SMS. This simply requires a pre-programmed modem to send the warning.

The next stage comes when there are multiple instruments monitoring the slope. Is every one of the data acquisition nodes on the slope then capable of raising an alarm in its own right? Alternatively should all the information be transferred to a base station node that is connected to some form of computer programmed to make a decision based on direct numerical values or a statistical determination as to whether these are significant or not ?

Finally it is quite possible with the low power computational power that exists now to conduct the real time simulation on site and for the equipment to be programmed to raise alarms and send warnings. The outcome of such a simulation may simply be based on a computed factor of safety. All that is required here is for the model of the slope to be adequately accurate so that the model is correct. Also it is prudent to override whatever the model may predict if sufficient movement is taking place for there to be cause for concern.

Conclusion

Landslides are of widely differing types and the instrumentation to monitor slopes needs to be varied in type and frequency of monitoring to gain suitable information for design, predictive and warning purposes. Given the importance of groundwater, the rainfall and piezometric monitoring is of greatest value followed by the direct measurement of movement.

The potential now exists to not only relay this information to a remote site where it can be processed but also to process it on site using real slope models that can be used as part of a decision making and warning process. The key to the use of this is the validity of the model and the continuity and veracity of the information being gathered.