

PIPELINE ROUTES - GROUND MOTION MONITORING USING OTDR

OTDR (optical time domain reflectometry) appears to be particularly applicable to monitoring ground motion along pipeline routes.

Pipelines are a very economic method of transporting liquid products. They are routed from the origin of a liquid product to the point of distribution. This routing may, or may not, be along existing road or rail right-of-ways. Pipelines often cross relatively untamed terrain and can be difficult to access on a routine basis.

Pipelines are generally buried. This serves to protect the pipeline somewhat from environmental surficial effects and sabotage, while obscuring the pipeline from the public vision.

Burial **DOES NOT** preclude damage by geologic events. Any shift in the earth encasing the buried pipeline transmits strain to the pipeline itself. If sufficient strain is suffered by the pipeline, it will rupture.

PIPELINE MONITORING

Two types of deformational monitoring are available for pipelines:

- Strain monitoring of the pipeline proper, and;
- External monitoring of the surrounding geologic medium

Pipeline strain monitoring

This heading is not the main topic of discussion within this article. Let it be said only that strain monitoring of the pipeline can be conducted utilizing a variety of methods. These may be either point-wise or continuous in nature along the pipeline. Both may be read both manually or automatically. Real time monitoring is available for most methods, with data being capable of being transmitted by any number of means to a data collection/analysis station.

It must be realized that pipeline strain monitoring is measuring primary deformation only if the pipeline is deforming as a function of internal or thermodynamic stress. In other words, if the pipeline is experiencing over-pressure, or extreme heat or cold, then monitoring will directly measure the strain imparted by these effects.

If deformation is a result of motion in the surrounding geologic medium, then all strain measured is secondary, i.e. ground motion displaces the pipeline, resulting in (measurable) strain in the pipeline walls. In this instance, monitoring the of the surrounding rock/soil provides more pertinent data, and an earlier warning, as compared to monitoring strain in the pipeline wall.

Geotechnical monitoring

Geotechnical monitoring measures displacement of the rock/soil surrounding the pipeline. As such it is primary monitoring.

Many types and variations of geotechnical monitoring exist. These will be listed here with a brief description and discussed elsewhere in this document in more detail. All can be either manual or fully automated (real time data collection):

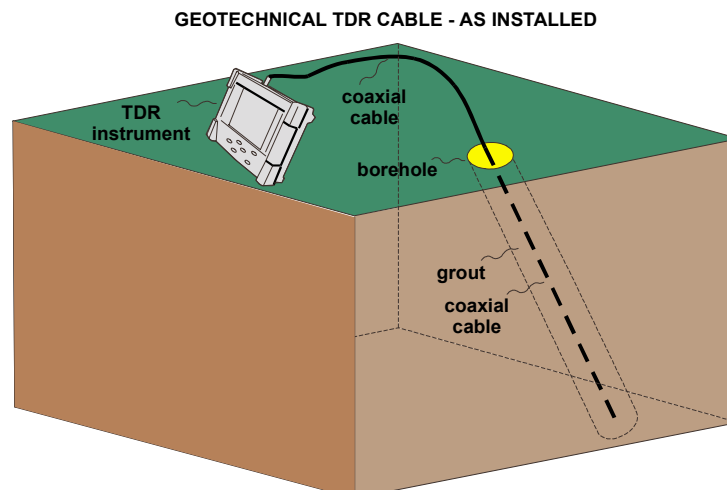
- **Survey prism systems** - Utilize survey prisms mounted on monuments within areas that may suffer surface displacement. They may be manual read or automatic (real time).
- **Inclinometers** - utilize a rigid casing installed in drillholes into the rock/soil. Any displacement in the geologic mass imparts displacement to the inclinometer casing. Sensitive probes indicate a change in the inclination of segments of the casing down hole.
- **Extensometers** - measures the length difference between two anchor points installed in a drill hole through a suspected failure plane in the rock/soil. While these are primarily constructed of cable, a variety of variations exist. They function best in tension sub-parallel to the plane of motion.
- **TDR/OTDR cables** - coaxial or fiber optic cables installed in drillholes through the rock mass or on surface. Detect shear and/or tension as a function of geotechnical cable displacement. Installed primarily at high angles (right angle) to suspected failure plane.

TDR/OTDR BASICS

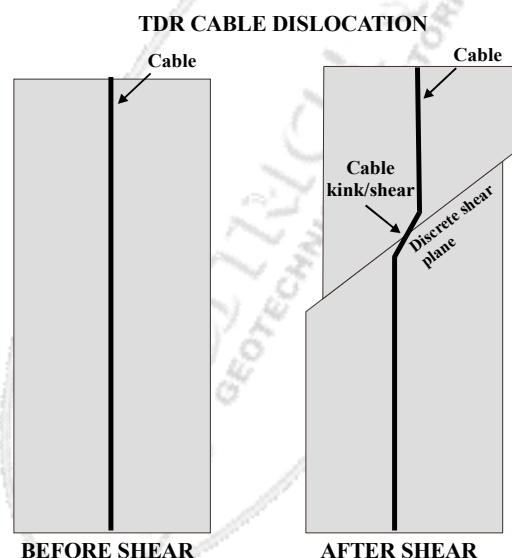
TDR (**T**ime **D**omain **R**eflectometry) is based on transmitting a pulse of energy as a waveform within a medium and watching for reflections of this transmission. As the velocity of propagation is known within a medium, the distance to the disturbance can be calculated.

The most familiar form of TDR is that of radar. Radio waves are transmitted in a predetermined direction at a specific frequency. Any object that interferes with this signal will cause reflections, with all, or part of the energy being reflected to the source. The arrival time and characteristics of these reflections are measured by sensitive detectors, allowing determination of the distance to the object.

Geotechnical TDR is generally applied to coaxial cables inserted, and grouted, into a drillhole. Similarly OTDR (**O**ptical **T**ime **D**omain **R**eflectometry) is based on measuring reflected light on fiber optic cable inserted, and grouted, into a drillhole. The properties of the grout, and cable, are determined by geotechnical conditions, expected failure modes, and required results.



As the ground displaces, the installed cable is sheared or displaced. This causes a change in the material properties of the cable. This change in properties is detectable, as noted above, and allows us to locate the actual area of dislocation.



Multiple shears and/or strains are locatable along the length of the hole. Each point of deflection causes a disruption, and thus degradation, of the imparted signal. However, as the goal of the system is to **INDICATE** that ground displacement is occurring and **LOCATE** the actual point of dislocation, this is relatively unimportant for most applications.

TDR and OTDR **ARE NOT** designed to quantify the actual magnitudes of displacement. While some sense of total displacement can be had by examining the signal trace in conjunction with cable type and diameter, it is not designed to measure such motion. Other instruments are much better suited for this application - for example, an inclinometer. However, for initial detection of motion and location of the point of shear, TDR/OTDR is superb.

GEOLOGIC SETTING

In order to compare geotechnical monitoring systems, with their inherent advantages and disadvantages, it is best to create a geologic setting. For our purposes, let's envision a zone which has experienced a landslide at some time in the prehistoric past (Figure 1a).

Prior to failure, the area to be examined is composed of a steep slope with a flatter lying toe or apron. Due to some mechanism (faults, bedding, creep, increase in local water pressure, etc.) the upper slope fails, creating a landslide. This, in turn, creates a debris apron at the toe of the slope (Figure 1b).

Over time, vegetation returns to the slope, covering both the landslide scar and the debris apron. What remains to be seen is the geomorphological traces, i.e, the lobes in the contour below a steep slope, small ponds above such lobes, hummocky terrain on the failure apron, etc.

This geologic setting was chosen as it:

- Is relatively common, especially in the Pacific Northwest (USA);
- Allows examination of a variety of failure modes (slumping, plane shear failure, circular failure, creep, reactivation of pre-historic failure, etc.)

Now, let us assume that a pipeline is routed through this area (Figure 1b). A few years later, some astute individual recognizes the features in the area for what they indicate of the past and recommends geotechnical monitoring in order to detect any ground motion in the area.

First, the area would be geologically mapped and material property testing conducted. Back analysis of the failure in an attempt to understand the original conditions of failure would likely be undertaken. The area would be examined for evidence of post-slide movement. Drilling would likely be conducted and the holes geotechnically logged. Piezometers would likely be installed in these drillholes to measure both the present water table and pressures, as well as seasonal variations.

Once the area has been geotechnically characterized, failure modes can be determined. In this case, a variety of modes exist (Figure 2a):

- New failure of the upper scarp (original source of landslide material).
- Reactivation of the lower landslide apron (basal motion, piezometric pressure driven or creep);
- Sloughing of the face of the landslide apron (piezometric pressure driven, rock/soil degradation, or both);
- Sloughing of the face of the landslide apron and the lower slope (as above);

Given the location of the pipeline (Figure 2a), it appears as if only two of the proposed failure modes will impact on the pipeline. Thus, monitoring must be located to determine if such failure planes are present and active.

TDR/OTDR cable monitoring

As this paper covers the application of TDR/OTDR as an early warning system for ground motion, this will be covered first. In Figure 2b, the potential locations of four drillholes are shown. These are positioned such as to cross any potential failure planes, of the type determined above, at high angles. Fiber optic riser cable is positioned, and grouted, in each of the holes. These cables, in turn, are connected to a main, armored, trunkline and routed to the remote test unit (RTU) for continuous monitoring. The trunk line can be surface laid or (preferably) trenched in coaxially¹ with the pipeline. Any localized shear motion across the monitoring cables will occasion detectable shear. An operator will be alarmed. Ground examination and examination of the OTDR cable trace data can be conducted. If required, and if it is believed that the failure/displacement mode is well understood, immediate remedial action may be taken. If not, further monitoring can be conducted by targeting the exact failure plane as indicated by OTDR cable motion. This would likely involve the installation of inclinometers and surface prisms.

What other systems could be utilized? As mentioned in the paragraph above, both inclinometers and surface prisms are viable methods. Why not utilize them?

The answer is that they could be utilized. However, as for any method, there are advantages and disadvantages to each system.

Survey prism monitoring

Survey monitoring of ground motion is a secondary monitoring system. It measures ground surface motion in an attempt to determine what is occurring at depth with the rock/soil.

Surface prisms are placed on monuments throughout the zone of proposed active failure (Figure 3a). It is assumed that any ground motion at depth will eventually be reflected at surface. In most cases, however, motion will initiate at depth along a plane. This motion may, or may not, be seen quickly at surface as the geologic mass distributes such motion, rendering it smaller the greater from the source it is detected. In addition, rotational and surface components come into play, rendering it difficult at times to determine exactly what is occurring at depth.

Another component of this system renders it untrustworthy in certain conditions. The survey instrument is situated such that it can "see" all the survey monuments. This is almost always a compromise in terms of location and angular relationships to the prisms. A laser measures the distance to the prisms. The laser must pass through the atmosphere to measure the distance and angular relationship to the base survey station. Atmospheric conditions affect the transmission of this signal. Distance relationships can be compensated for somewhat by temperature corrections and reference bases. However, traversing an inversion boundary will almost invariably introduce survey distance errors. In addition, weather conditions may make it impossible to see the prism target, allowing no reading.

¹ laying the fiber optic cable coaxial to, an above, the pipeline allows the trunkline to act as a rough security system. Digging above the pipeline by an excavator will break the fibers, occasioning an alarm on the OTDR system. If higher security (intrusion detection) is desired, more sensitive fibers can be utilized.

Thus, survey prism systems, while providing good secondary coverage of an area are not recommended for initial motion detection. The requirement of an expensive robotic survey system for localized area coverage and the inherent inaccuracies caused by weather and the secondary nature of the monitoring system render it incompatible, in most circumstances, for a ground motion detection system involving sensitive structures.

Inclinometer monitoring

Inclinometers are the electronic equivalent of a tiltmeter installed in rock or soil. They are highly sensitive and can locate areas of displacement with very good accuracy. Their installation is quite similar to that of TDR/OTDR cable - at high angles to the inferred failure plane (Figure 3b).

An inclinometer generally consists of a plastic tubular casing installed in a drillhole in the area to be monitored. This casing is grouted in place. Any motion of the surrounding geology causes deflection of the casing. A sensitive probe is lowered down the hole, following a set of rails in the casing. This probe records the depth down hole as well as the inclination at any specific point. Displacement will cause a point-wise change of the casing inclination. When this is compared to the original, undeformed trace, the depth and magnitude of the displacement can be determined and plotted. Fixed point and remote read inclinometers are available. All function on the same principle.

Inclinometers are not well adapted to remote, and thus real time monitoring. While they are capable of performing this task, the technology is quite expensive. In addition, the reliability may be suspect if frequent readings are required. Their primary purpose should be as monitoring devices for gradual, deformational change within rock/soil and/or confirmation of suspected failure planes and failure modes. Even if remote read and reliability were not an issue, cost would be. The precision casing and read instruments are far from inexpensive.

Extensometer monitoring

The word extensometer is based on the word "extension". The instrument has historically existed of cables or rods passing through a read head at the collar of a drillhole in the rock/soil. Each rod is anchored at varying depths down the drillhole with the rod/cable being decoupled from the grout filling the hole with some form of (plastic) sheath.

Deformation of the rock/soil results in a differential distance between the anchor and the drillhole collar. This is recorded at the read head as the cable moves in, or out, of the drillhole.

Extensometers can be equipped to be real time read capable. They are also very durable and extremely accurate. Extensometers are occasionally utilized in slope stability work. Their two biggest drawbacks are:

- They must be oriented sub-parallel to the plane of motion to provide "extensional" data on the deformation;

- They are point wise anchored. Deformation can be differentially calculated between anchor locations. However, the actual location of deformation is unknown.

Extensometers will function well as ground motion indicators in specific instances, especially when equipped with a remote read head. In addition, they can be relatively inexpensive. They are not recommended when they can only be installed at high angles to a shear plane. In the geologic setting shown here, they have no practical application. It would be difficult, if not impossible, to install an extensometer here such that reliable data would be obtained, even in a failure confirmation since. Inclinometers would be a better choice.

TDR/OTDR DETAILS

The dual advantage of TDR/OTDR is that it can provide real time detection of motion, and its exact location, in rock or soil. The cables are continually interrogated for faults on a user-determined schedule. Thus, even in the dead of night in a full scale blizzard, monitoring will take place. No one needs travel to the data collection site except for periodic inspections and repair.

In addition, the systems are relatively inexpensive and robust. The sensor portion of the device is a cable, encased in a grout, within the ground. Little affects the sensor in most cases, with the exception of water leakage (intrusion) and ground displacement. Cable cost is relatively low, with the cost being less than \$2.00/ft (US) for most coaxial and fiber cables. Instrument cost can be relatively high for OTDR units. However, when these costs are distributed over the number of points to be monitored, the potential increase in reliability, the real time, continuous nature of the monitoring, reduced personnel requirements, and increased monitoring density, the cost becomes much more manageable.

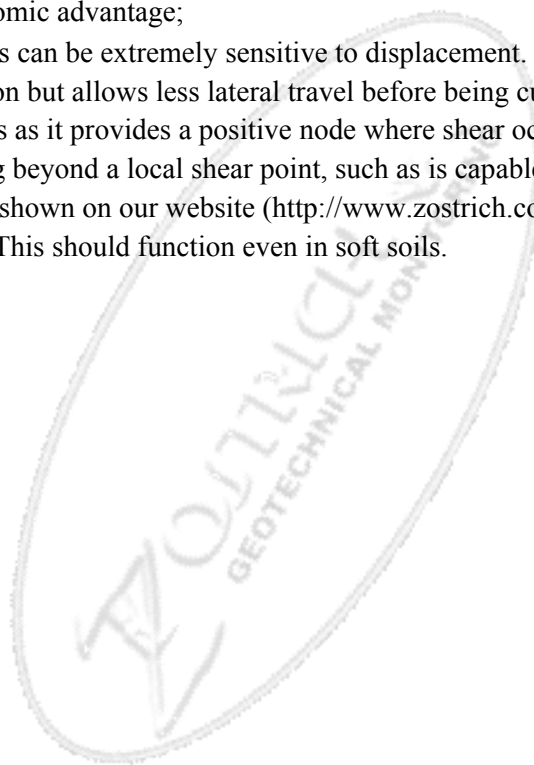
No other technique available provides real time detection of ground motion, with associated warning and remediation potential, as does TDR/OTDR.

For rock/soil deflection multiple bends or kinks can be detected within cables installed in drillholes, allowing precise location of dislocation zones or planes. Disadvantages are that relatively minor shear may cause the cable to fail and that only a limited estimate is obtained of the magnitude of displacement. However, the area above the failure within the drillhole continues to function as a monitor, allowing continuous monitoring as the failure progresses towards surface.

The major differences between optical and coaxial TDR are:

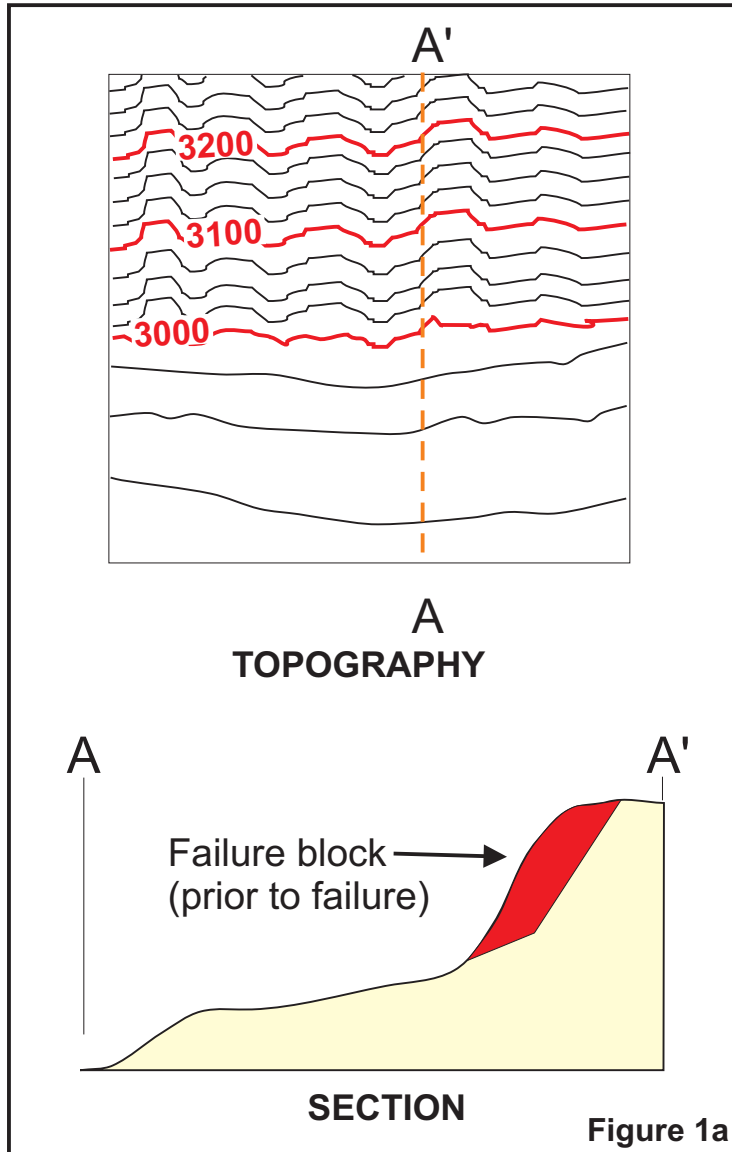
- Range - coaxial TDR, while potentially practical up to 20000 ft, is limited in accuracy at this distance. Distances of about 2000 ft/600m appear to be the maximum practical monitoring limit due to cable effects. This includes trunk lines on surface as well as the downhole monitoring probe. Longer cables can be utilized, however, by increasing the pulse voltage. Changes in the pulse shape and duration upon transmission downline, especially after encountering any kinks or bends will reduce accuracy. Optical TDR can theoretically be utilized at distances up to 25 miles/40km and beyond. As for coaxial cable, accuracy decreases as a function of cable length. However, indicator crimps or bends in the line can be utilized as reference markers, increasing local system accuracy;

- Redundancy - multiple fiber cables can be installed in a single hole at little extra cost. This is not true for coaxial cable, where one cable is generally the limit;
- Flexibility - fiber optic cable is very flexible and has potentially greater use in softer materials, especially with our patented anchor system as described under innovations on our website (<http://www.zostrich.com>);
- Survivability - armored fiber optic cable is extremely durable and will survive severe impact and abrasion. Once again, coaxial is less resistant to such damage and, for large diameter cable, is much more difficult to lay. Water leakage/pressure is also a problem with coaxial systems. If a foam dielectric is utilized, the buried end of the cable must be sealed against water intrusion. Upon cable shear, this seal is lost and water can intrude upon the dielectric space;
- Cost – coaxial cable TDR is cheaper for short range monitoring and a limited number of points. For long range monitoring, a large number of points, or a centralized monitoring system, optical TDR appears to have the economic advantage;
- Sensitivity – both systems can be extremely sensitive to displacement. Straight glass fiber is less sensitive to kink deflection but allows less lateral travel before being cut by shear displacement. This is both a plus and a minus as it provides a positive node where shear occurred but does not allow as much flexibility of seeing beyond a local shear point, such as is capable with coaxial cable. The solid rod fiber optic system as shown on our website (<http://www.zostrich.com>) will fail at around 1-2mm of lateral displacement. This should function even in soft soils.

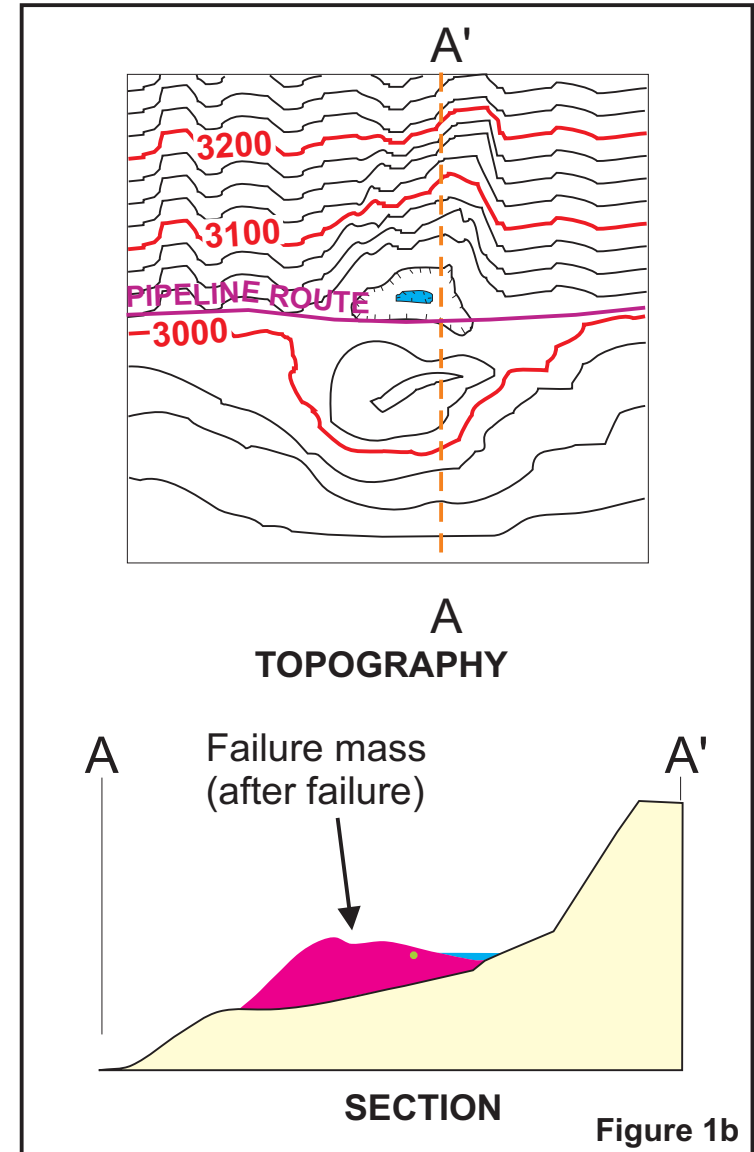


DEVELOPMENT OF LANDSLIDE TOPOGRAPHY

PRIOR TO LANDSLIDE



PRESENT TOPOGRAPHY (POST LANDSLIDE)



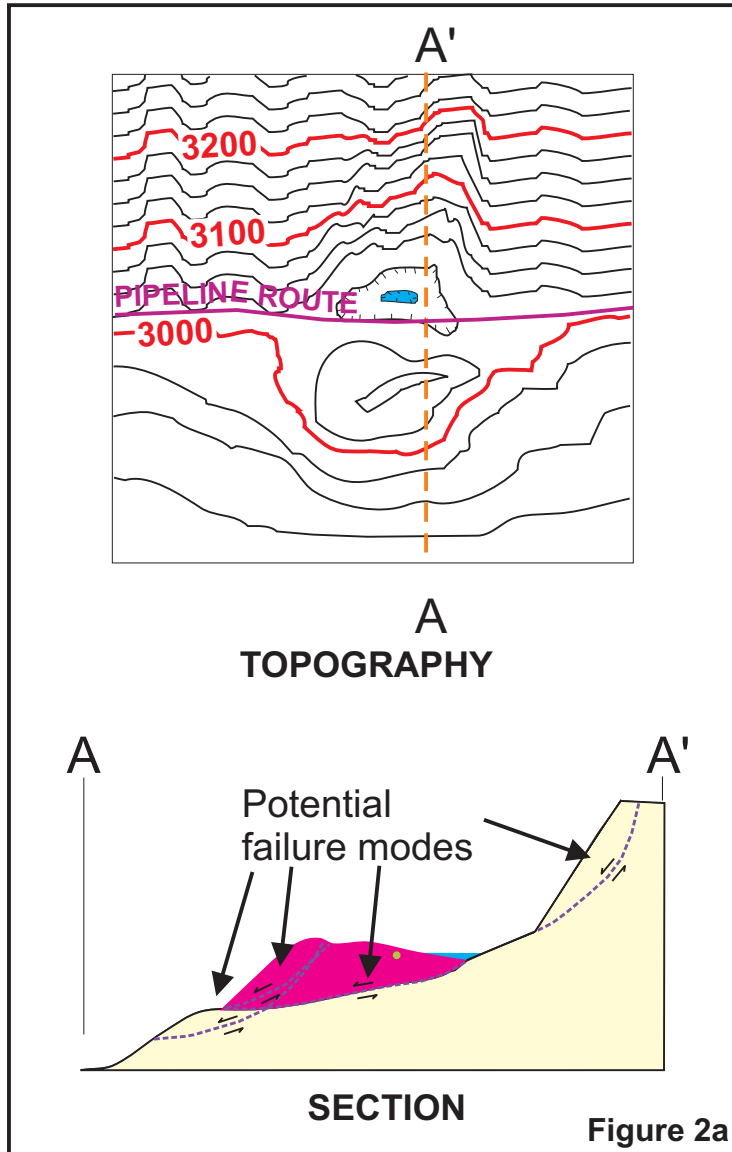
Note: Topography and sections are strictly conceptual illustrations. They are neither to scale nor intended for design use.



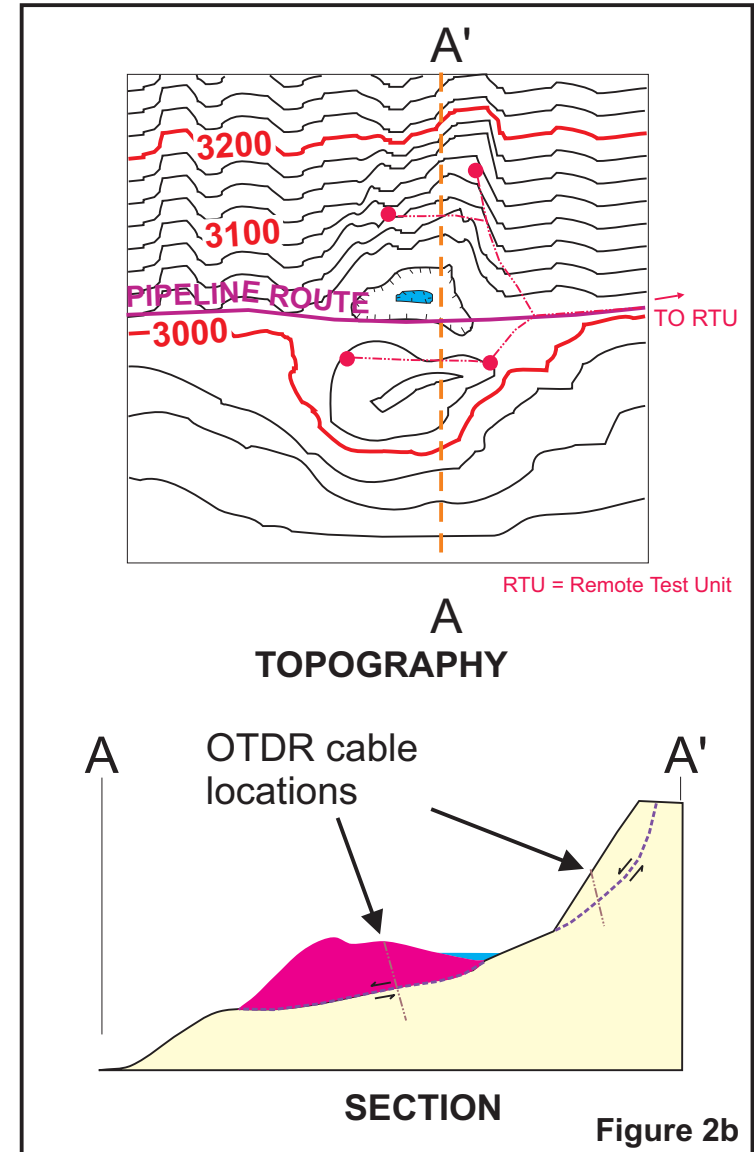
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FAILURE MODE IDENTIFICATION/MONITORING

POTENTIAL FAILURE MODES



POTENTIAL MONITORING LOCATIONS



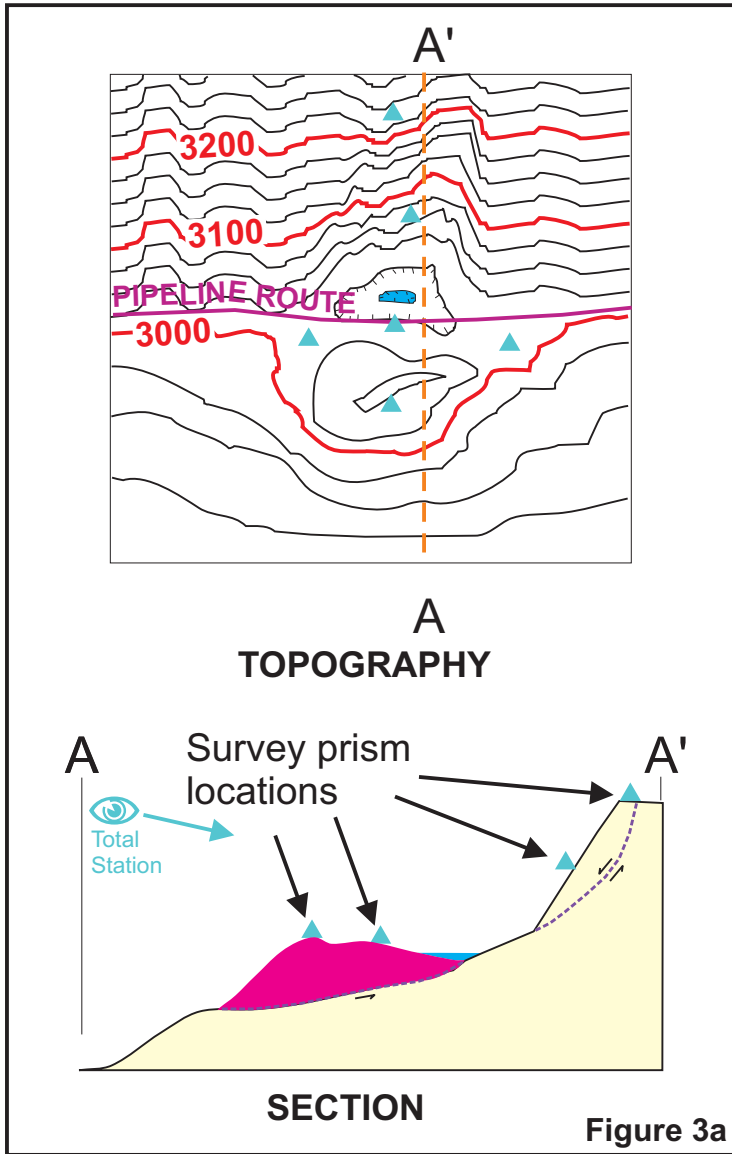
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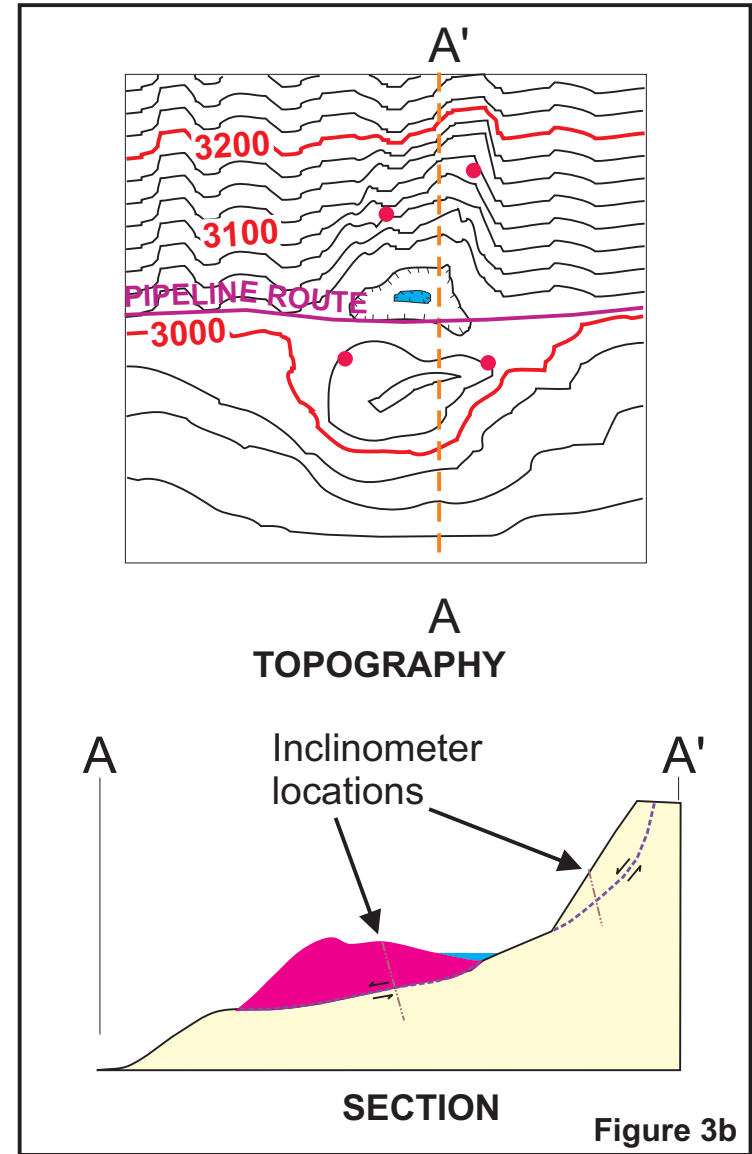
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ALTERNATIVE GEOTECHNICAL MONITORING

SURVEY PRISM



INCLINOMETER



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