Sensors in the Real World

Protecting Geotechnical Sensors and Cable from Lightning Damage

Dale Shoup, R&D Engineering Manager, Slope Indicator

Abstract

Lightning is a common, but generally unrecognized cause of damage to geotechnical sensors and cables. Sensor failures and erratic readings caused by lightning are often mistakenly attributed to poor installation techniques, failure of seals, or inadequacies in the design of the sensor or system.

This paper describes the interaction of lightning, ground faults, cables, and sensors. The author presents case studies which suggest that sensor damage and degraded readings are almost unavoidable unless protection measures have been implemented. Generalizing the lessons learned, the author presents recommendations for protective grounding systems and other measures that may significantly improve sensor longevity and system reliability.

Introduction

Lightning damage is sometimes obvious, especially when sensors and cable are accessible and can be examined, or when immediately after a lightning event, symptoms appear throughout the system. Other times, however, lightning damage has to be deduced from symptoms such as electrical leakage from conductors to ground, excessive electrical noise, and inconsistent readings. Such problems may become apparent long after the lightning storm itself, and then it is difficult to establish lightning as the cause.

There is an obvious lack of published information that correlates instrument failures with lightning activity, ground faults, and the layout of the instrumentation, yet this information will be required before standards for economical and effective protection measures can be established.

Papers addressing industrial applications are usually not concerned with buried cable or equipment. Even articles for communications applications are concerned only with shallow buried cable. Ungar [1] and others in the communications industry have noted tiny "pinhole" punctures in insulating jackets, a common result of lightning strikes, but do not suggest preventive measures.

Lightning Current in the Ground

Lightning current develops electric fields, or voltage gradients, in proportion to the resistivity of the soil. The formula below shows an electric field E developed in homogenous ground by a current J flowing in soil with resistivity ρ at a distance r from a lightning strike.

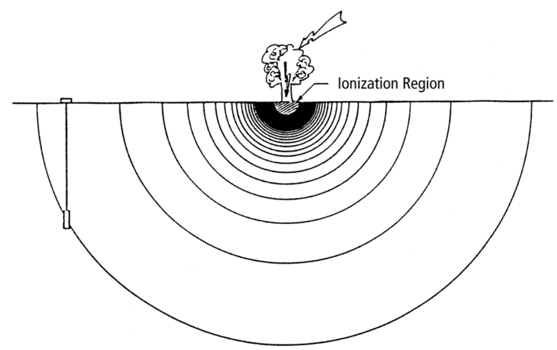
$$E = \frac{J \cdot \rho}{2\pi r^2}$$

This equation would seem to imply that higher electric fields occur in soils with higher resistivity. However, the highest currents and highest fields have been found to occur in soil with low resistivity. Chang [2] cites a formula developed by Mikhailov and Sokolov [3] for calculating current as a function of resistivity:

$$J_m = 16000 + \frac{2 \times 10^9}{\rho^2}$$

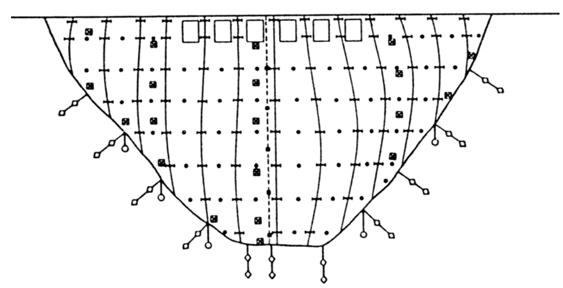
This equation, for a 1% probable event, fits measurement data from 150 to 1100 ohm-meters. However, typical values for soil resistivity may be as low as 100 ohm-meters. Substituting 100 ohm-meter for ρ (resistivity) in equation (2), the maximum current is 216,000 Amperes. The author's recommendations, presented later, are based on this value, which seems to be suitable even for higher resistivities, since buried electrical conductors may reduce effective resistance.

Buried Sensors



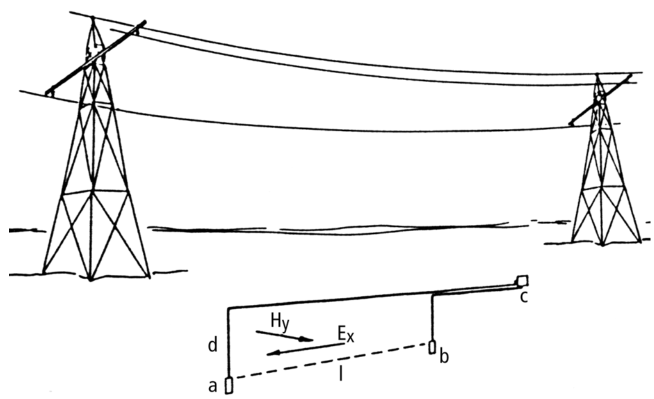
The drawing at right shows a buried sensor and a lightning strike to a nearby tree. The concentric lines are iso-voltage lines showing voltage levels at the instant of the strike. Each line represents a voltage difference of about 50 kV. The terminal box for the sensor signal cable is nearer to the strike, so it sees a higher voltage than the sensor itself, which is further from the strike and sees a lower voltage. The difference in voltage from the terminal box to the sensor can easily exceed 10 kV, even if the sensor is not very deep. Sensors, cables, and cable terminations cannot withstand such high voltage differences, and the typical result is arcing that damages or destroys the sensor and leaves pinhole punctures in the cable jacket. Even when the sensor is not destroyed, the punctures in the cable jacket allow the entry of water, causing all the symptoms of a seal failure and a significant increase in noise and interference.

When a sensor is not connected to a data acquisition system or a central terminal box, risk of damage from a lightning strike is limited to the immediate vicinity of the sensor and its cable. However, in a confined and densely instrumented area such as a dam, this does not provide much security.



The drawing at right shows sensors installed in a dam. In this case, nearly any strike to the dam will result in some damage. The risk of damage is increased dramatically by lateral cable runs. For example, a strike within 250 meters of a 1000 meter long cable will expose the cable to up to 10 kV. Routing cables into a common trench and terminal box can also dramatically increase vulnerability, since arcing can occur between adjacent cables as well as between ground and cables.

Ground Fault Voltages



Ground faults, whether caused by lightning or by other phenomena, are responsible for symptoms such as excessive noise and inconsistent readings. A ground fault, for the purposes of this paper, is defined as electrical leakage resulting in a resistance between any conductor or shield and earth ground of less than 1 MΩ as measured with a 500 Volt insulation tester.

Ground fault voltages are generated by the magnetic field within the included area or by the electric field acting on the distance between the faults. (This paper considers only nonpropagating fields, such as those created by nearby power lines and low frequency transmitters.)

The drawing above shows sensors *a* and *b* which are at depth *d* and separated by distance *l*. Suppose there is a ground fault affecting one or more conductors in each sensor cable. Assuming a uniform electric field *E*, a magnetic field *H*, a sinusoidal frequency *f*, and permeability *m*, the voltage between the faulted conductors at terminal box *c* is:

$$V_{ab} = E_x \cdot l + 2\pi f \cdot \mu H_y \cdot l \cdot d$$

While cable faults found in dam instrumentation typically generate voltages of 5 volts or less at 50/60 Hertz, unbalanced loads and switching transients on nearby power lines can generate hundreds of volts by those same faults. To protect data acquisition modules from such high voltage differences at sensor input connections, secondary voltage limiting devices are usually incorporated in the system. These devices, when activated by ground faults, allow currents to flow on cables. Such currents create electrical noise and degrade readings of sensors with faulted cables. Even readings of non-faulted sensors can be upset if the current developed between any two faulted sensors is greater than the system can accommodate.

Case History 1

The first site was a large dam with sensors installed over a 300 x 600 meter area. Cables were routed to a central monitoring location and no ground system was installed. Severe damage resulted from the first lightning storm in the area, and approximately 50 of the sensors failed almost immediately.

Many of the sensors employed a protection device to limit voltage between the sensor circuit and the sensor housing, which was in contact with local earth ground. Primary lightning protection devices at the other end of the cable also limited the voltage relative to earth ground. Since the two earth grounds were up to 1000 meters apart, it was possible for a large difference in local ground voltage levels to develop during a lightning storm. The voltage difference caused currents that overloaded the protection devices, and the majority of the sensors failed for this reason. While many of the sensors were replaced, it was not possible to replace all the cables. Multiple faults on sensor cables, probably caused by pinhole punctures of the cable jacket, made several of the new sensors unreadable. Cables with the worst faults had to be disconnected to improve the reading quality of other sensors.

Lessons to be learned from this installation include the following:

- Vulnerability to problems caused by lightning and ground faults increases dramatically with cable length.
- Internal overvoltage protection devices connected to the sensor housing are easily overloaded and destroyed by lightning.
- Sensor readings are adversely affected by ground faults.

Case History 2

Sensors at the second site were installed over a 200 x 15 meter area. Distributed data acquisition modules were used, but there was no protective ground system or any isolation from power mains. A UPS unit (Uninterruptible Power Supply), a computer, components of the data acquisition system, and approximately 20% of the sensors were damaged by a power line transient that was probably caused by lightning.

Damage to the data acquisition system occurred while an electrical storm was in the vicinity, but no evidence of any nearby lightning strikes was reported. A common mode voltage transient on the power mains was deduced to be the most likely cause of damage to UPS, computer interface, and several sensors.

Sensors at the deepest depths suffered the most damage. Grounding of the power mains at the site was found to be very shallow and inadequate compared to the depth of sensors. Repeated failures of the computer serial port and system interface also occurred due to unbalanced power mains circuits which resulted in differences of more than 50 volts between the local ground and the mains ground. This was corrected by installing a large ground conductor to the coffer dam and isolating the system from the power mains. After protective measures were implemented, no further damage occurred, despite a number of direct lightning strikes.

Lessons to be learned from this case include the following:

- Power mains ground must be isolated from the ground used for computer, the data acquisition equipment, and the protective ground system for sensors.
- The computer serial port, which is referenced to computer ground, should be isolated from the data acquisition system.
- The protective ground system should be at least as deep as the deepest sensor.
- A protective ground system, combined with isolation, can prevent damage to sensors and cables.

Case History 3

The third site provides an interesting example of the effect of ground faults on reading quality. Sensors were installed in a 300 x 15 meter area at a construction project near a waterway. Data acquisition modules were distributed along the length of the area, but no primary lightning protectors were used on sensor connections and no protective ground system was installed. Although lightning damage has never been proven, there was a serious deterioration of electrical insulation to ground of approximately 20% of the sensors or cables.

Sensors were read continuously so that an alarm could be sounded if movements occurred. False alarms were triggered repeatedly, not only by faulted sensors, but also by non-faulted sensors. Nearly all the alarms occurred while rafts of barges were broken apart for passage through the waterway. Possible causes were eliminated one by one until only interference from power mains transients and imbalances remained. The correlation with barge activity was troubling until it was realized that the barges acted as a magnetic lens, concentrating and redirecting the magnetic field. When a barge was positioned opposite a pair of faulted sensors or cables, it enhanced the magnetic field and thus increased the probability of interference for even non-faulted sensors.

Lessons to be learned from this case include the following:

- Faulted sensors and cables may cause serious degradation of the quality of readings of even non-faulted sensors.
- Data acquisition systems should be designed to minimize crosstalk between channels when secondary overvoltage protection is activated.

System Protection

Generalizing on experiences with these and other installations, the author has compiled a list of measures to protect instrumentation from lightning damage and ground fault problems.

1. A diversion system consisting of at least two lightning arresters should be installed at prominent locations outside the instrumented area. The purpose of the diversion system is to attract lightning and direct current away from the protective grounding system, which could otherwise be overcome by a maximum probable current of 216,000 Amperes. The diversion system should be at least 100 meters, but not more than 1000 meters from the nearest sensors, cable, data acquisition system, or protective ground system. The conductor connected to each lightning arrester must go straight down or be directed away from the protected instrument area. The conductor should reach a depth at least equal to that of the deepest sensor and have less than 1 ohm total resistance over its length.
2. A protective ground system for sensors and cables, installed separately from the diversion system above, is the single most critical measure that can be taken. Its purpose is to prevent the development of electric fields (voltage gradients) along the cable path. All sensors and cables should be protected by a bare, non-insulated copper ground conductor that runs parallel to each cable or group of cables from the proximity of each sensor to its termination at a terminal box or data acquisition module. The conductor should have a total resistance of less than 0.1 ohm. It should extend at least 1.8 meters deeper than the sensor and should be separated from sensor and cable by at least 10 centimeters, but no more than 3.6 meters. Without these protective conductors, currents emanating from a lightning strike would generate large and potentially damaging voltage differences along cable paths.
3. The conductors (including the cable shield) inside each sensor should have a factory-measured resistance to the sensor housing which is greater than 50 MΩ at 500 Volts. After installation and connection of additional cables to sensor, but prior to connection to the data acquisition system, each electrical conductor (including the cable shield) should be tested with an insulation tester. Resistance to earth ground from shield or any conductor should be greater than 10 MΩ at 500 Volts.
4. Primary lightning protection devices, such as gas discharge tubes, may be used to protect sensor connections to data acquisition modules, but only if an appropriate protective ground system is installed

first. If a protective ground system is not installed, such lightning protectors could actually increase the severity of damage to sensors and associated cables. Data acquisition modules are easily replaced, so the consequences of lightning damage are not so great as for sensors and cable.

5. Isolators for data bus cables are recommended at each data acquisition site, unless the resistance of the protective ground system, including the ground conductor parallel to the data bus, is less than 0.1 ohm. Isolation should be rated for at least 500 Volts minimum between the data bus and sensor connections.
6. Either an isolated UPS unit or an isolation transformer rated for 2500 VAC common mode is required for connection to power mains. Surge protection should meet ANSI/IEEE C62.41, category A and B standards as a minimum. Common mode rejection of 120 db minimum is recommended. Although it is not standard practice in the industry, the power mains (input) ground should be isolated from output ground. Output ground (and frame ground) should be connected to the protective ground system using AWG #8 or larger conductor. The power supply, data acquisition equipment, computer, and all related peripherals should be connected to the output of single isolated UPS or isolation transformer whenever possible.
7. A modem protector is required if the computer or data acquisition system is to be linked to a telephone system.
8. An optical isolator for RS-232 is highly recommended to further isolate the computer's serial port from the data acquisition system. Isolation should be rated 500 Volts minimum.
9. Faulted sensors and cables must be detected and disconnected from the system. Any sensor or cable that fails an insulation test with less than 1 MΩ at 500 Volts may have to be removed from the system to maintain the quality of readings for non-faulted sensors.
10. The design and manufacture of data acquisition systems should minimize crosstalk so that readings of good (non-faulted) sensors will not be upset by ground fault voltage or current between any two sensor input connections.
11. Secondary voltage limiting devices are required for the input connections of the data acquisition module, if the logger does not provide 500 volt minimum isolation between all input connections (including power and shield for every sensor). Secondary voltage limiting devices should be rated 1500 watts peak minimum for 10 microsecond rise x 1000 microsecond decay exponential pulse (REA PE-60).

Conclusion

Installations of geotechnical sensors in the real world are still fraught with difficulties. Electrical cables and sensors are vulnerable to damage from many causes. While engineers are aware of the most obvious causes, and take measures to control them, they often overlook lightning damage. However, the costs of replacing damaged components, loss of critical data, and degraded reading quality are too great to be ignored.

Of the measures proposed in this paper, the most important is the implementation of a protective ground system that eliminates large voltage difference only cable paths and thereby prevents pinhole punctures of cable jackets and arcing damage within sensors.

References

[1] S.G. Ungar: "Effects of Lightning Punctures on the Core-Shield Voltage of Buried Cable"; The Bell System Technical Journal, Val. 59, No. 3, March 1980.

[2] Hsi-Tien Chang; "Protection of Buried Cable from Direct Lightning Strike"; IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-22, No. 3, August 1980.

[3] M.I. Mikhailov and S.A. Sokolov; "Reducing the Cost of Protecting Cable Mains From Direct Lightning Action"; Telecommun., USSR, No. 6, pp. 50-53, 1965.