MONITORING OF EMBANKMENT STABILITY USING EMBEDDED COAXIAL CABLES

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ABSTRACT

The use of time domain reflectometry (TDR) to monitor movement in embankments and slopes is an emerging technology. TDR was originally developed for the telecommunication industry to locate breaks in cables. TDR is a time dependant pulsing electronic signal that detects changes in the impedance of a coaxial cable. Deformations, such as crimping or shearing of the cable, can be located quickly and accurately. By installing either vertical or horizontal cables in embankments or slopes, movement of slip planes, shear zones, or tension cracks can be easily detected. This paper reports on the use of TDR to monitor 20 to 30 feet high embankment levees in the Sacramento/San Joaquin Delta region of Northern California. Vertical cables were installed to monitor movement. In one installation, an adjacent inclinometer was installed and used for comparative data. The results show that a relationship exists between the inclinometer and TDR data. The location of the TDR cable signature spikes correlate with the zone of movement as shown by the inclinometer. In addition, the rate of spike growth correlates with the rate of levee slope movement. As a result, TDR appears to be an effective and economical method for embankment monitoring.

INTRODUCTION

Project Location

California's best-known delta lies inland, where the Sacramento and San Joaquin Rivers merge to enter the chain of waters that eventually lead to the San Francisco Bay and the Pacific Ocean, Figure 1. "The Delta", as it is referred to locally, is approximately 1250 square miles and consists of many islands by the channels and sloughs of the two rivers. The Delta is a major collection point for water that serves over 20 million people, two-thirds of California's population. The rich soils of the Delta are excellent for agriculture, and provide habitat for hundreds of species of fish, birds, mammals, and plants. The Delta also is a

Figure 1. Location of California Delta and Locations Where Time Domain Reflectometry (TDR) Instrumentation Has Been Used.

source of a variety of recreational opportunities for the public, including fishing, camping, and boating.

The Delta is located in the Sacramento Basin of Northern California and is underlain by substantial deposits of river channel and alluvial fan material placed during the Pleistocene period. At the end of the Pleistocene, rising sea level caused a large inland marsh to form. The creation of the marsh led to accumulation of substantial peat and organic sediments. The peat and organic sediments are interbedded with additional river, channel, and flood deposits. This created a complex soil stratigraphy throughout the Delta. Peat deposits in the Delta vary from several feet to 60 feet thick.

Starting in the late 1800's and continuing into the early 1900's, reclamation projects were begun to reclaim valuable farm land and prevent the periodic flooding of rapidly growing settlements. The existing channels and sloughs were either dredged or rerouted with a vast network of levees constructed from the dredged material to contain them. This created a series of 70 reclaimed islands surrounded by approximately 700 miles of levees.

Levee Stability

The Delta levees were not engineered. The material was placed and spread for the levees as it was dredged out of the channels. This resulted in variable levee cross-sections with generally weaker soils toward the bottom of the levees. The levees themselves were often founded on peat. Once the islands were reclaimed and farmed, subsidence of the islands began and continues to the present day. The main contributors to subsidence of the islands are consolidation of the soft soil strata and oxidation of the drying peat due to artificially lowering the ground water. Most of the islands are presently 10 to 20 feet below Mean Sea Level with some islands over 30 feet below sea level. Subsidence of the central Delta islands is ongoing with an average of two to three inches per year.

The weak foundation soils and the ongoing subsidence create a condition where levee stability is a constant concern. This situation requires ongoing levee monitoring and maintenance. Generally the monitoring consists of periodic visual inspections and surveying. However, in areas of serious concern, geotechnical instrumentation is employed in the form of inclinometers and piezometers. To improve the economics of monitoring the levees, a new, but effective, technique known as time domain reflectometry (TDR) was used.

LEVEE MONITORING

Two different monitoring methods were employed to measure movement in the levees. The first, an inclinometer, is relatively well-known. The second method used was TDR.

Inclinometers

When a specially cased borehole is drilled into a slope, an inclinometer can be used to monitor the movement. An inclinometer probe is manually lowered into the casing and accelerometers detect the orientation of the probe as it moves down the hole. Any changes over time in orientation indicate that slope movement has occurred. If the changes are rapid with respect to time, it may indicate that failure is imminent.

Time Domain Reflectometry

TDR was originally developed by the power and communications industries to find breaks in cables. In TDR, a voltage pulse waveform is sent down a cable. If the pulse encounters a change in the characteristic impedance of the cable, it is reflected. This can take the form of a crimp, a kink, a foreign substance such as water, or a break in the cable. The returned pulse is compared with the emitted pulse and the reflection coefficient (in rho's or millirho's) is determined. If the reflected voltage equals the transmitted voltage, the reflection coefficient is +1 and the cable is broken. If the opposite occurs, and the cable is shorted, all of the energy will be returned by way of the ground and the reflection coefficient will be -1. Should the cable have a change of impedance, the reflection coefficient will be between -1 and +1.

Electrical energy travels at the speed of light in a vacuum. The speed at which it travels in a cable is less, depending on the impedance of the cable. This speed is known as the velocity of propagation and is a property of each cable. When the cable propagation velocity and the time delay between transmitted and measured pulses are known, the distance to any impedance change (cable deformation) can be determined accurately.

Coaxial cables are composed of a center metallic conductor surrounded by an insulating material, a metallic outer conductor surrounding the insulation, and a protective jacket, Figure 2. The cables have a characteristic impedance determined by the thickness and type of insulating material between the cables. This insulating material is called the "dielectric" and may be made of almost any non-conducting material. Common dielectric materials are PVC-foam, Teflon, and air. If the cable is deformed, the distance between the inner and outer conductors changes as does the impedance at that point. The TDR cable tester can then determine the location of the deformation.

Data consist of a series of TDR signatures. Different wave reflections are received for different cable deformations. The length and amplitude of the reflection indicate the severity of the damage to the cable. The use of TDR for determining ground movement requires embedding a cable in a vertical or horizontal borehole or trench, and reading the cable signature at various times. Ground movement, such as shearing along a failure zone, will deform the cable and result in a change in cable impedance, Figure 3. This change can be monitored to find the position of failure and its rate will correspond to the rate of ground movement.

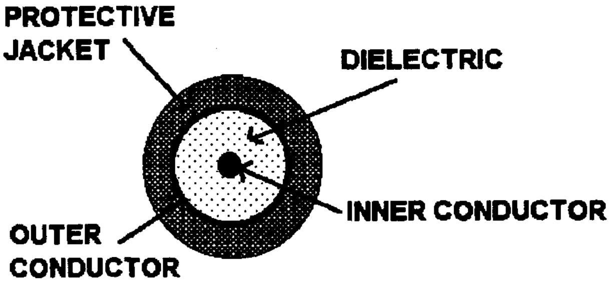

Figure 2. Cross-section of a Coaxial Cable

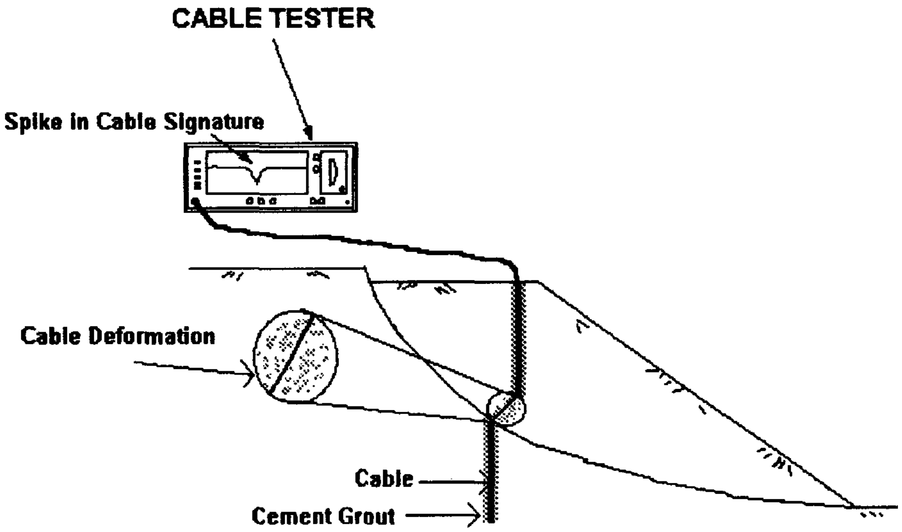

Figure 3. Deformation of Coaxial Cable Causes "Spike" in Cable Signature

CASE STUDIES

Venice Island

Venice Island is an agricultural, central Delta island that is experiencing subsidence with subsequent levee instability, Figure 1. The island has a mean elevation of 25 feet below sea level with 33 foot high levees surrounding it. Movement of a 300 foot section of the levee was toward the interior of the island, and a 1.5 foot high head scarp was visible on the levee crest. The head scarp daylighted in the roadway on top of the levee.

Borehole data indicated that the levee profile at this location consisted of 10 feet of stiff clayey silt underlain by 5 feet of soft clayey silt followed by 15 feet of soft elastic silt. Foundation soils consisted of 15 feet of soft peat underlain by a medium elastic silt.

To monitor the levee, an inclinometer and three vertical coaxial cables were installed in two separate boreholes located on the island side shoulder of the levee roadway. The purpose of the inclinometer installation was to provide comparative data for the TDR cables. Three coaxial cables were installed in a single borehole. The first was a jacketed, 0.25 inch diameter, flexible, braided cable (RG59/U). The second was identical except that the outside jacket was removed. Laboratory tests indicated that removing the outer jacket might make the cable more sensitve to shear displacement. The third cable was a 0.5 inch diameter corrugated copper cable with a plastic jacket. The cables were separated by spacers and grouted with a cement grout into a 40 foot borehole. An inclinometer casing was installed about 25 feet away from the cables.

Tyler Island

Tyler Island, Figure 1, is a second Delta island experiencing similar levee instability. Movement of a 500 foot section of the levee was observed along the eastern side of the island. The elevation of the toe of the levee at this location was 10 feet below Mean Sea Level with a 20 foot high levee. Movement was toward the island side with numerous tension cracks running parallel to the levee roadway. Settlement of the roadway was as much as eight inches.

Borehole data indicated that the levee profile at this location consisted of 15 feet of medium silty clay. Foundation soils were composed of 10 feet of peat underlain by 7 feet of soft clay followed by a very stiff clay.

Six RG59/U coaxial cables were installed in two locations as shown in Figures 4 and 5. Cable lengths ranged from approximately 40 feet at the levee crown to 20 feet on the inboard toe. All cables were grouted in a weak cement grout.

RESULTS AND DISCUSSION

Figure 6 shows the the cumulative inclinometer movement for Venice Island. The data indicate that the soil mass is rotating about a point located at a depth of approximately 20 feet. The inclinometer initially showed a slight movement toward the levee side of the embankment and then a steady increase in movement inland. The final reading for the

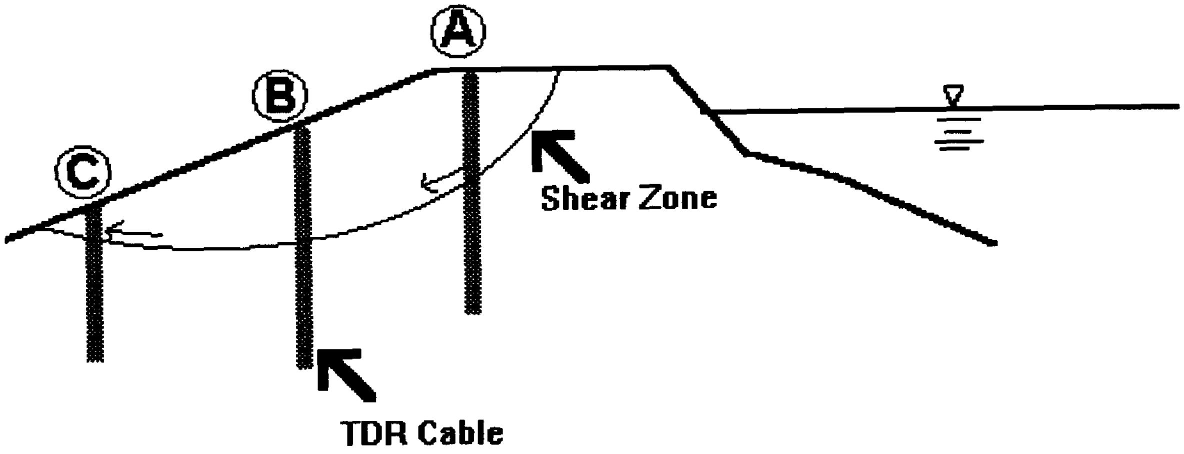

Figure 4. Cable Installation to Determine Location of Shear Plane

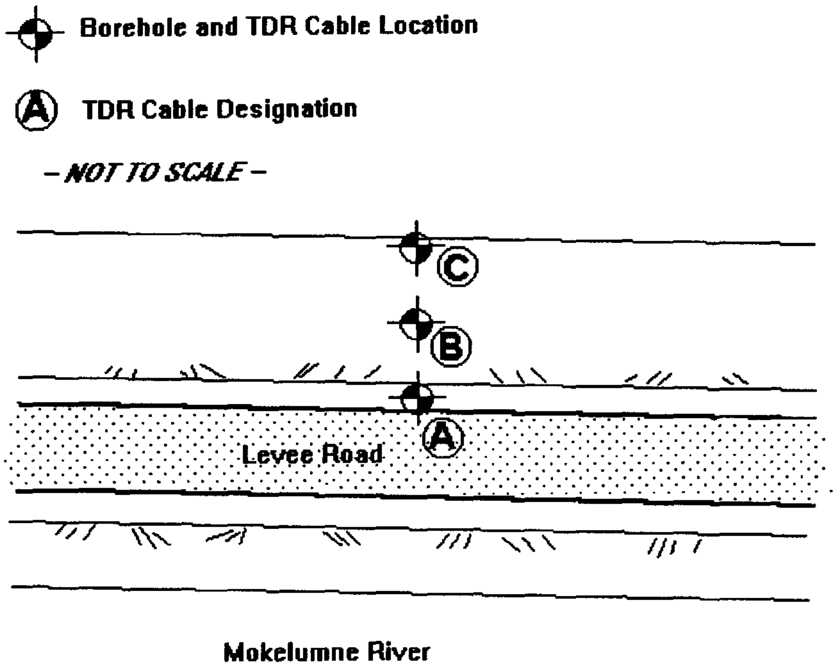

Figure 5. Relative Locations of TDR Cables on Levee (Plan View)

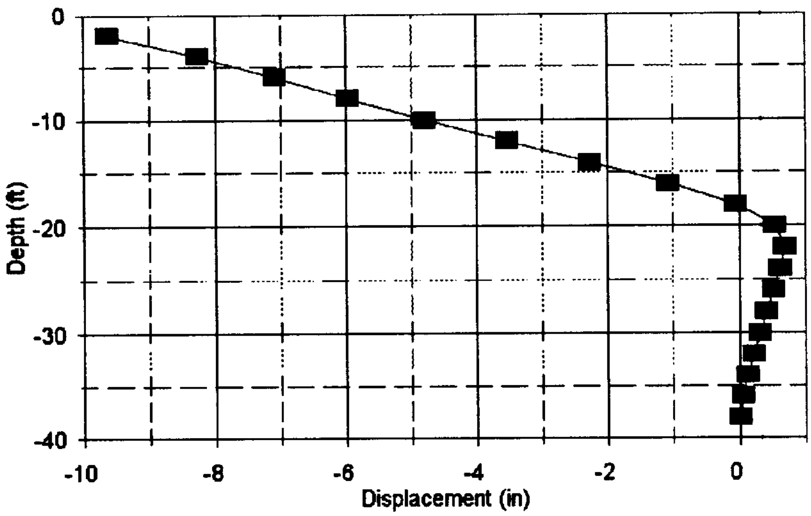

Figure 6. Cumulative Inclinometer Displacement for Venice Island

inclinometer showed a displacement inland of about 9 inches.

The inclinometer results are verified by the growth in the TDR cable signature spike, Figure 7. Figure 8 is the signature from the jacketed RG59/U cable and provides a good time-history of the slide movement. The TDR signature for June 1995 shows that the cable is approximately a straight line. The cable did not indicate any slope movement until August 1995. This spike remained at approximately the same depth as the inclinometer data showed. The other cables showed similar changes.

The signature spikes continued to grow with slope displacement. Figures 8 and 9 show the changes in spike magnitude versus time. Also shown in each figure is the change in surface displacement as indicated by the inclinometer. The jacketed and copper cables show an excellent correlation with the surface movement. Correlation of unjacketed cable with surface movement was not as good.

Figure 10 shows the TDR signature for a cable located on Tyler Island. Because the cables were installed in the dry season, not much slope movement was expected. However, this cable shows a region of possible shearing, as evidenced by the slight trough in the signature at a depth of 11 feet. Although it is too early to determine if there is actually movement at this depth, this is a location for concern. Additional data will be acquired, especially in the rainy winter months to monitor stability.

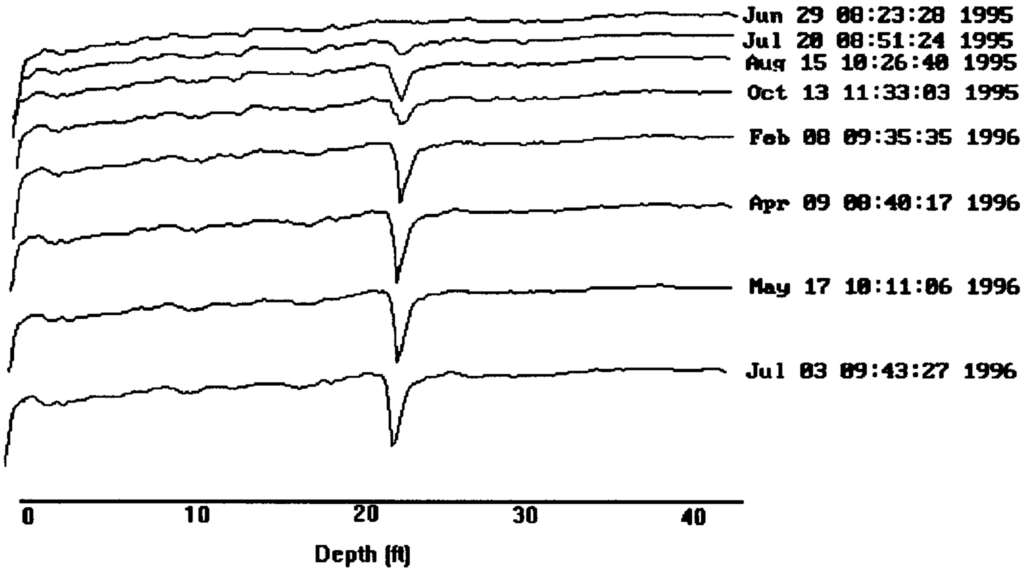

Figure 7. Growth in Cable Signature Spike with Time

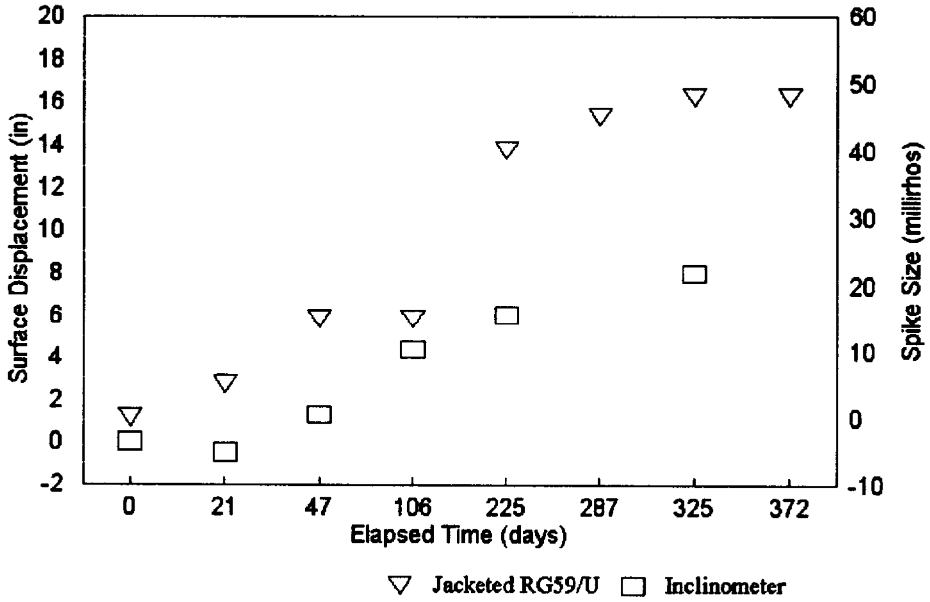

Figure 8. Comparison of Jacketed Cable Spike Growth and Inclinometer Reading

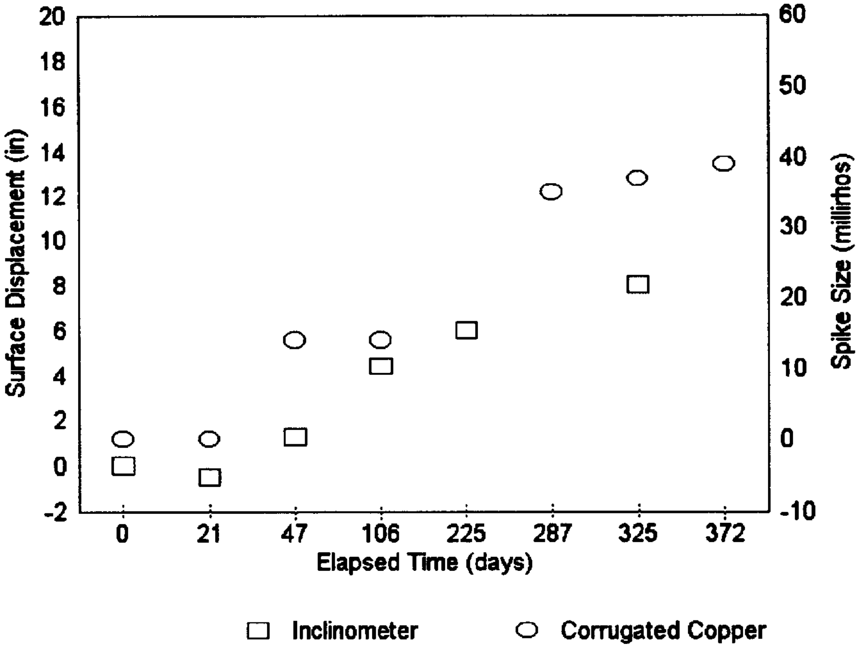

Figure 9. Comparison of Copper Cable Spike Growth and Inclinometer Reading

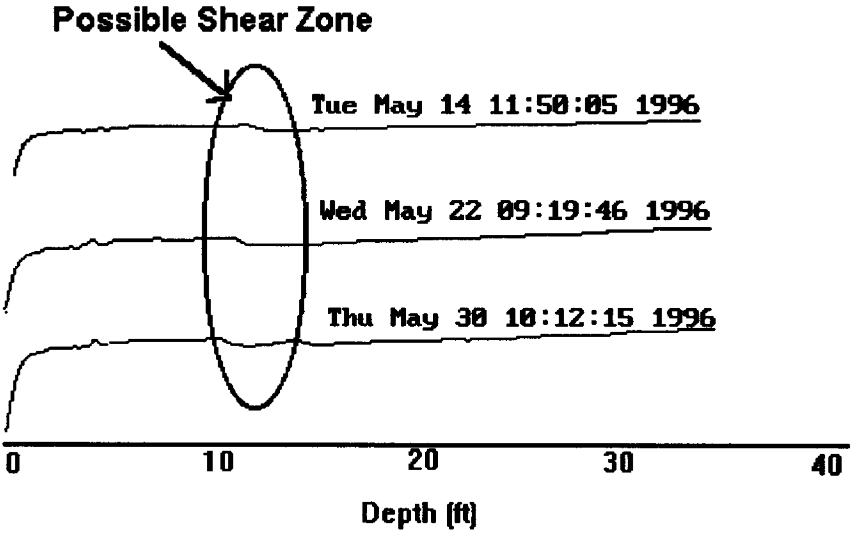

Figure 10. Development of a Trough in Cable Signature at Tyler Island

CONCLUSIONS

Several conclusions can be made with respect to using TDR in soil embankments such as levees and dams.

1. **TDR can be used as an economical alternative to inclinometers as a means of embankment slope monitoring.** It is less expensive to install and data collection is more rapid. The technology exists to use a datalogger and mobile phone to acquire cable signatures making routine site visits unnecessary.
2. **TDR will locate the depth of movement and allow determination of a slip surface location.** At present it will not provide the magnitude of movement However, in the future, laboratory testing of cables may make this possible.
3. **The change in the rate of movement can be determined by plotting the size of the signature spike with time.**

TDR as a technology is seeing increased use throughout the world. In California alone the number of sites using cables has increased from one in 1994 to twelve at the time of this writing, Figure 1, with more planned. Many of these sites use multiple cables.

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