Monitoring Bridge Compaction Grouting

- **Objectives:** Detect deflection during compaction grouting
- **Solution:** Jewell **C801** and **C700** Tuff-Tilt Sensor
- **Benefits:** High-precision and near-instantaneous updates
- **Results:** Accurate grouting-induced movement readings

Introduction

In June of 1999, Jewell Instruments was retained by Hayward Baker to monitor the Laurel Street Bridge in Santa Cruz during compaction grouting of the ground beneath the bridge footings. This work was performed as part of an extensive program of seismic upgrades to many of California's bridges after the 1989 Loma Prieta earthquake. The project specifications for the compaction grouting put stringent requirements on the allowable amount of bridge movement during the grouting process. Hayward Baker recognized that tiltmeters were one of the few instruments that could measure movements small enough to satisfy the specifications. The tiltmeters used for this application are capable of detecting 0.001 inch (0.0254 mm) deflections over a 100 foot (30.48 m) span. Continuous monitoring of the tiltmeters was implemented to provide instant notification of vertical deflections greater than 0.1 inch (0.254 mm). However, the threshold alarming was complicated by the fact that the normal diurnal movement of the bridge due to thermal expansion and contraction is of the same order of magnitude. Therefore, the normal daily movement of the bridge was modeled with a sine wave, and the alarm thresholds were based on the difference between the model and the recorded data. This model is relatively easy to program within a datalogger and results in alarms that respond to grout-induced movement rather than thermoelastic bridge deformation.

Instrumentation

The project specifications limited vertical bridge deck movement to 0.1 inch during any grouting episode. This equates to an angular displacement of 0.007 degrees (~25 arc seconds) over the 70 feet (21.3 m) between the abutment and pier. A good rule of thumb is to use an instrument with at least 20 times higher resolution than the minimum specified movement. High resolution tiltmeters are one of the few instruments that can reliably measure angles smaller than 1 arc second. The tiltmeters used were Model 800 and Model 711, manufactured by Jewell Instruments. The tiltmeters have a published resolution of between 0.25 and 0.5 arc seconds – or 50 to 100 smaller than the maximum allowable movement. These simple yet precise instruments work on the concept of a trapped air bubble inside a glass or ceramic vile (Figure 2). The vile also contains electrodes and conductive fluids. As the sensor tilts, the bubble moves and changes the fluid-electrode contact area, therefore changing the resistance to the flow of current between the electrodes. By measuring this change with an electrical resistance bridge, the change in angular movement can be determined with unparalleled sensitivity and precision

A total of one biaxial (A711) and six uniaxial (A801) tiltmeters were installed inside the box girders beneath the deck to measure longitudinal and transverse movement of the bridge. All of the tiltmeters were monitored continuously using a Campbell Scientific CR10X datalogger. Alarm thresholds were used to activate a strobe light in the event of excessive movements. Four of the six tiltmeters were installed near the joining of the support columns and bridge deck to provide a first indication of movement transferred through the footing to the deck. Two of the tiltmeters were installed along the span midway between the footing and abutment to measure changes in deck elevation (Figure 3).

Jewell Instruments C801 Tuff-Tilt sensor

Jewell Instruments C711 Tuff-Tilt sensor

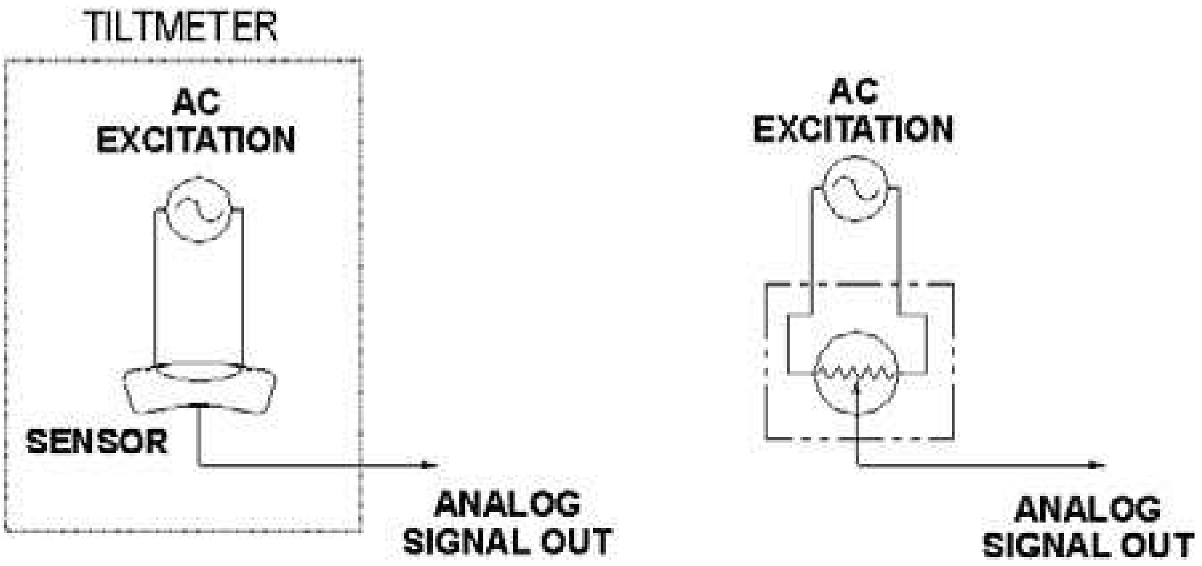

Figure 2 – Sensor in electrolytic tiltmeter behaves as a variable resistor

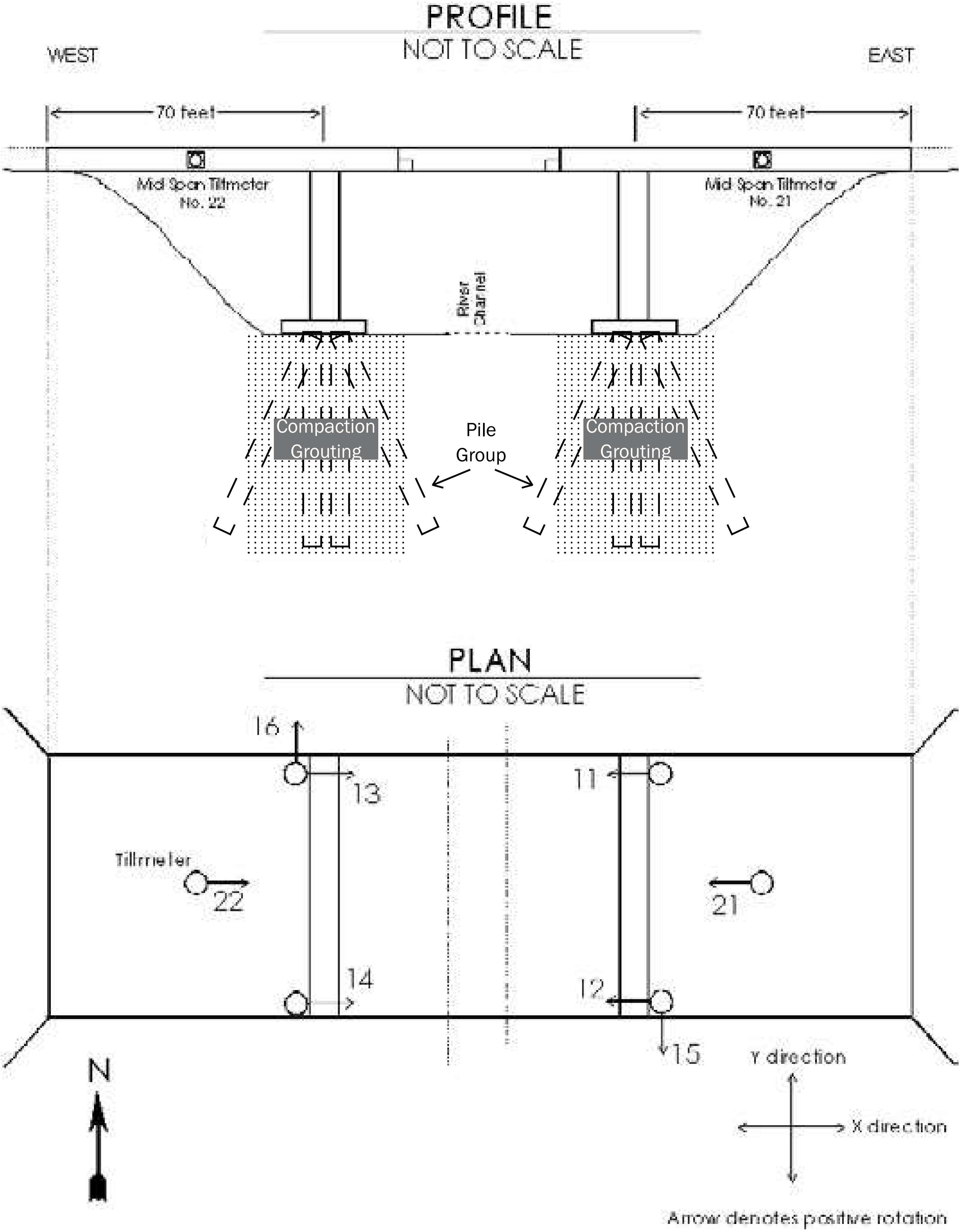

Figure 3 – Schematic plan and profile of Laurel Street Bridge showing location of tiltmeters and positive (+) rotation directions

Assumptions

A tiltmeter is an instrument that measures rotation of the structural element to which it is attached. The specifications for this project was to limit the relative vertical bridge deck movement to 0.1 inch (2.54 mm) or less during any one grouting episode. To convert rotation measured by the tiltmeters to displacement requires integration of the angular measurements over some finite length. The rigidity of the structure allows for a fairly simple model for calculating displacements (Figure 4). The tiltmeters measuring rotation parallel to the bridge axis were used to measure vertical movement of the bridge deck between the abutment and support piers. For this purpose the abutment is assumed to be a fixed point, and the bridge deck is assumed to be rigid. Vertical displacement (heave) is then calculated by assuming the rotation, θ, measured by the tiltmeter is occurring over the entire span. Heave *(h)* is therefore calculated as $h=(70ft)(\sin\theta)$, where θ is the angle measured with the mid-span tiltmeter. The tiltmeters have a published resolution of 1.75 microradians, or 1.75 millimeters in a kilometer. This equates to 0.0015 inch (0.04mm) over the 70 foot (21 m) span between the bridge pier and abutment.

Bridge deck movements transverse to the bridge axis were likewise determined using the tiltmeters aligned in this direction. In this case, the integration is performed over the width of the bridge.

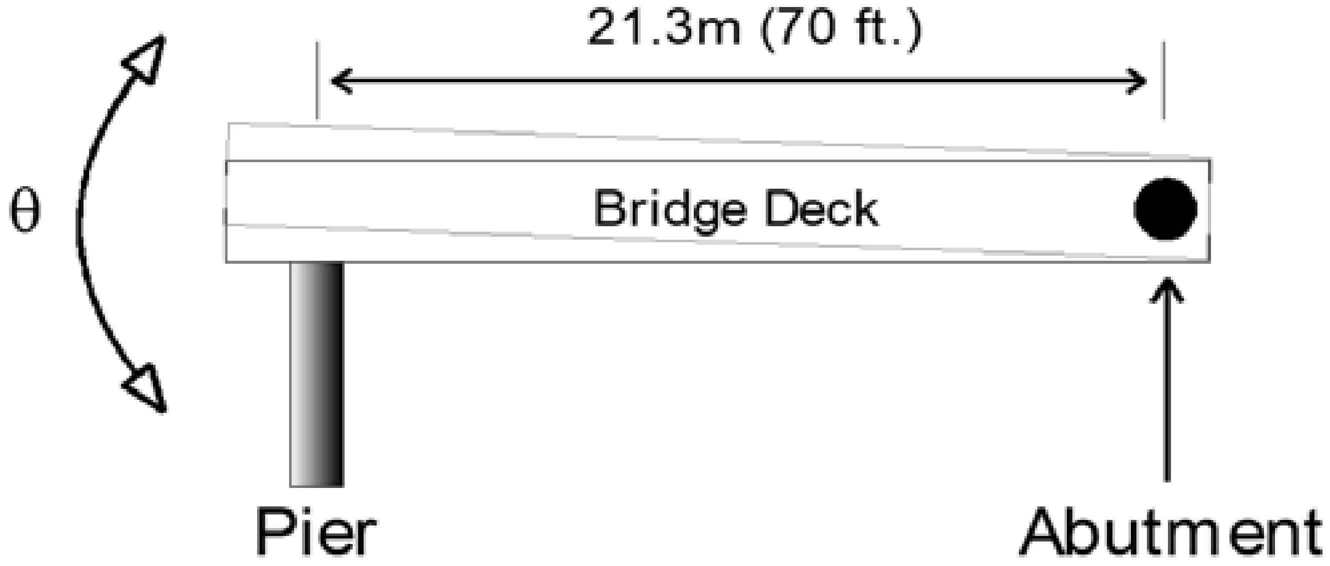

Figure 4 – Model used to calculate heave using tiltmeter measurements

Results: Longitudinal Displacement

Tiltmeters 21 and 22 (Figure 3) were installed at mid-span with their measurement axis aligned along the bridge axis to measure vertical displacement of the bridge deck on the east and west side of the bridge respectively. For this purpose, the point where the bridge deck meets the abutment is assumed to be fixed. Figures 5 and 6 show the results obtained from tiltmeter 21, mounted on the eastern span during grouting beneath the east footing. The mid-span tiltmeters show excellent correlation to the average of four vertical survey points on the bridge deck throughout the 60+ day period of monitoring. However, the tiltmeter is able to accurately measure displacements less than 0.02 inch (0.5mm). This is approximately 10 times better precision than that available using conventional surveying. But the real benefit to this approach is the ability to measure and respond to bridge movement in real time.

The sinusoidal nature of the data obtained from the tiltmeters is the thermoelastic expansion and contraction of the bridge due to diurnal temperature changes (Figure 6). All structures exhibit some degree of thermoelastic movement. High resolution tiltmeters are sensitive enough to measure the rotation associated with this behavior. This is why a continuous record from most above-ground tiltmeters exhibits a characteristic sine wave form. Many people have mistakenly assigned this behavior to the tiltmeter's own sensor or circuitry. But it is most often the structure itself, or even the mounting that is moving. Distinguishing the normal daily movements of the bridge from those caused by the compaction grouting turned out to be the most challenging aspect of the job.

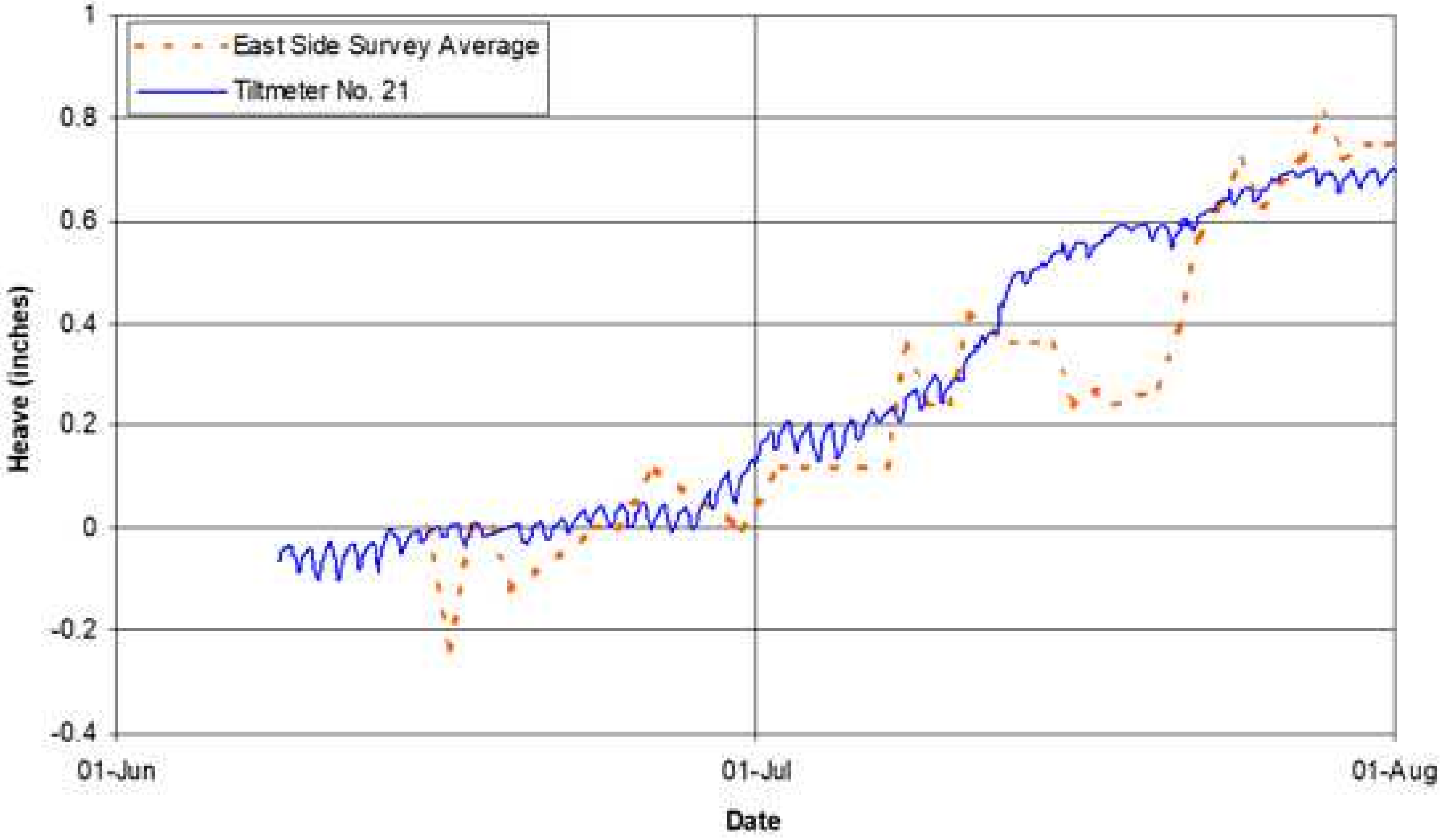

Figure 5 – East-side bridge deck heave measured using high-resolution tiltmeter and conventional surveying.

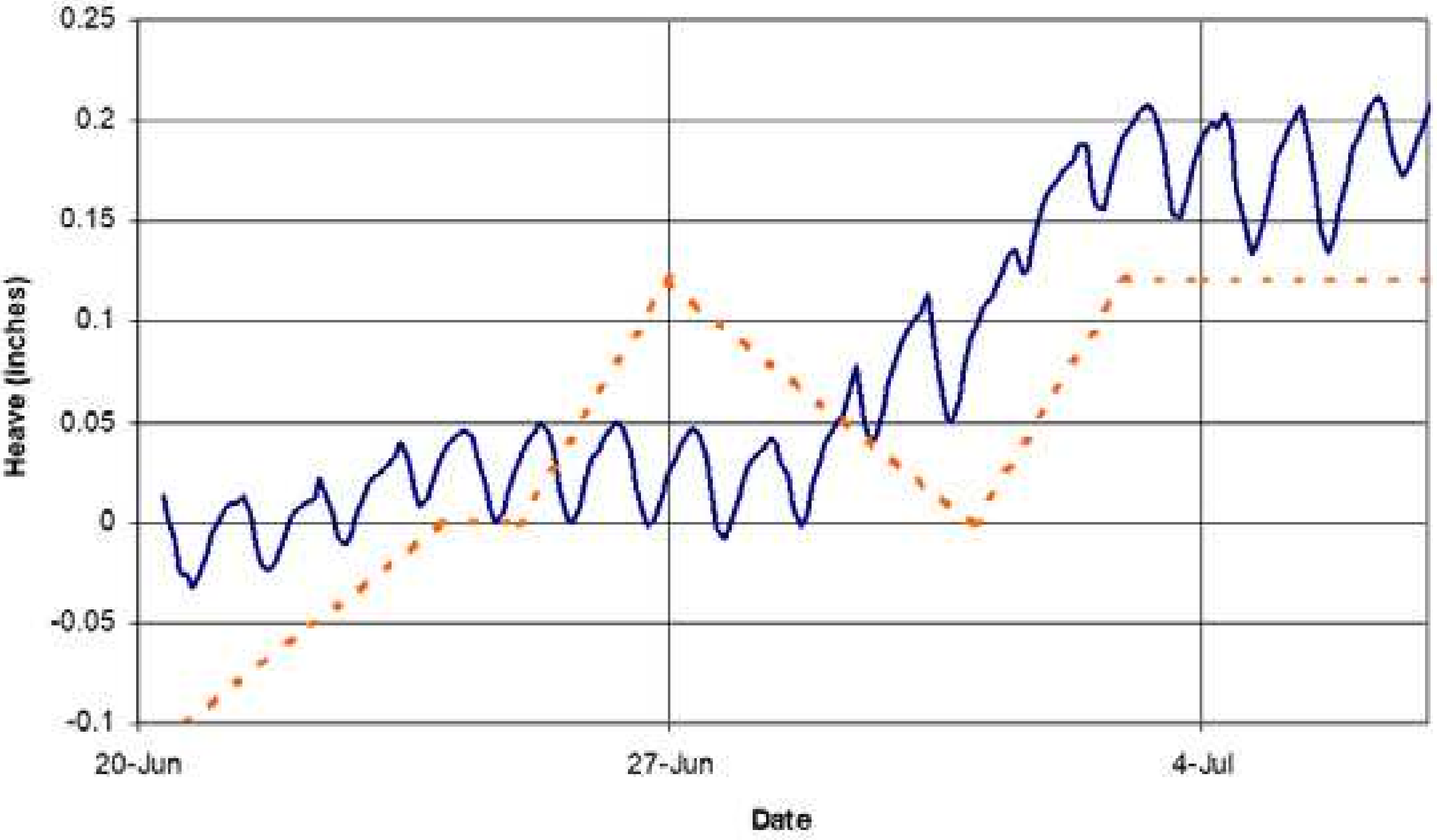

Figure 6 – Close-up of tiltmeter measured heave showing diurnal expansion and contraction of bridge.

Results: Transverse Displacement

Tiltmeters mounted with their axes oriented across the bridge deck measure transverse displacement. In this case, there clearly is no fixed point of rotation, and integration of the angular measurements produces relative displacement. The measurements are not useful for limiting grout induced displacements in real time. But they do provide critical information about the effect of the process on the ultimate levelness of the deck.

Figure 7 shows one tiltmeter measuring transverse displacement on the east side of the bridge during the grouting. The record clearly shows the bridge deck tilting one way and then the other as the grouting proceeds along the footing from south to north. The uniformity of the grouting process is reflected in the fact that the ultimate displacement is essentially zero.

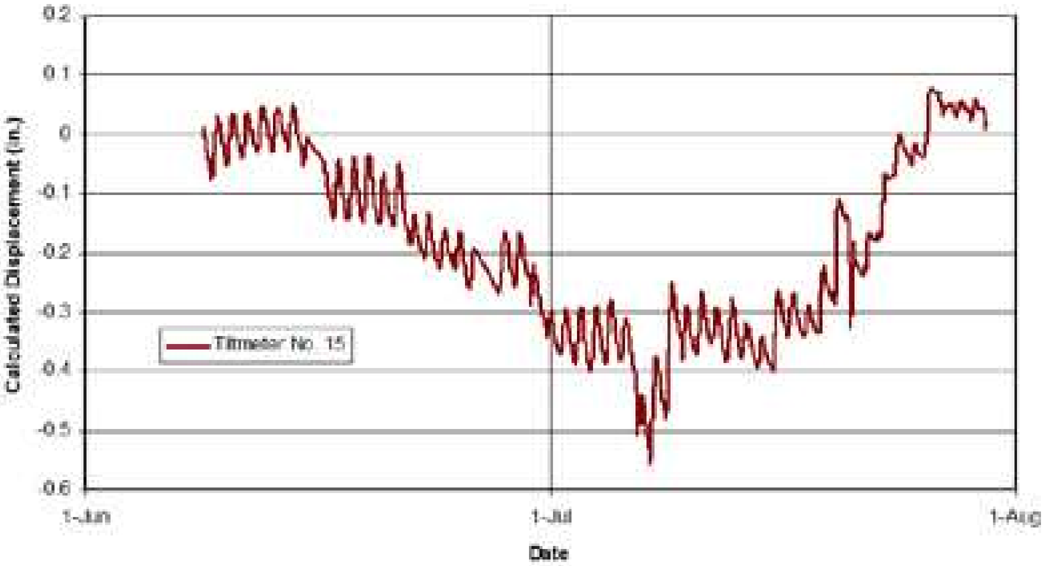

Figure 7 – Transverse displacement on the east side of the bridge during grouting beneath the east footing.

Modeling DIurnial Behavior

One of the project responsibilities for the instrumentation was to immediately notify the grouting crew when vertical displacement (heave) of the bridge deck exceeded 0.1 inch (2.54 mm). This presented a challenge since the normal diurnal expansion and contraction of the bridge was about the same order of magnitude (Figure 8). The problem with simple threshold alarming in this scenario is that the grouting-induced movement required to reach the threshold is different depending on what time of day it is.

The regular periodic nature of thermoelastic expansion and contraction can easily be filtered out of a time series, but filtering is too complex for a real-time method that requires that the processing be done in the datalogger. Another possible approach is to model the diurnal expansion and contraction as a function of temperature, which is measured by each tiltmeter and the datalogger. The difficulty with this approach is that the relationship between bridge movement and instrument temperature is not straightforward. The tiltmeters themselves were installed inside the hollow bridge deck, so their temperature record is attenuated and lags that experienced by the bridge. Temperature sensors mounted on an external surface of the bridge are influenced by direct sunlight. There is really no practical way to measure the “global” bridge temperature for use in a correlative expression.

In the end it was decided to model the diurnal bridge motion with the simple sine wave function shown in equation (1) that includes parameters to adjust the amplitude, phase, and symmetry (skewness) of the waveform.

$$X = \text{Amplitude}_1 * \text{SIN}\left[\left(\frac{360\ \text{degrees}}{1440\ \text{minutes}}\text{Time}\right) + \text{Phase}_1\right] - \text{Amplitude}_2 * \text{SIN}\left[\left(\frac{360\ \text{degrees}}{1440\ \text{minutes}}\text{Time}\right) + \text{Phase}_2\right] \tag{1}$$

This is relatively easy to program within the datalogger and results in alarms that are responsive to grout-induced movement (Figure 9). Periodic adjustment of these parameters was necessary to account for variations in the diurnal behavior – caused for instance by the increased firmness of the foundation as the grouting proceeded. The program was written to activate a flashing light when the difference between the model and the measured values exceeded 0.1 inch. The flashing light was a signal to the grouting operators to cease pumping within the current stage and move up to the next stage. After five minutes, the program turned off the light and “re-zeroed” the alarm threshold by bringing it in conformance with the current tiltmeter reading.

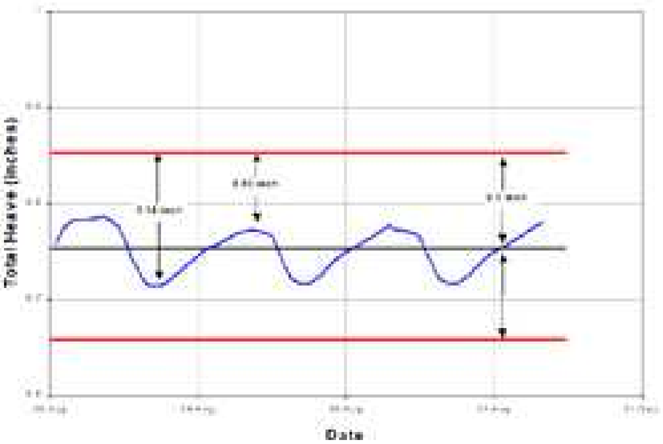

Figure 8 – Movement required to trigger alarm varies throughout day when linear threshold is used.

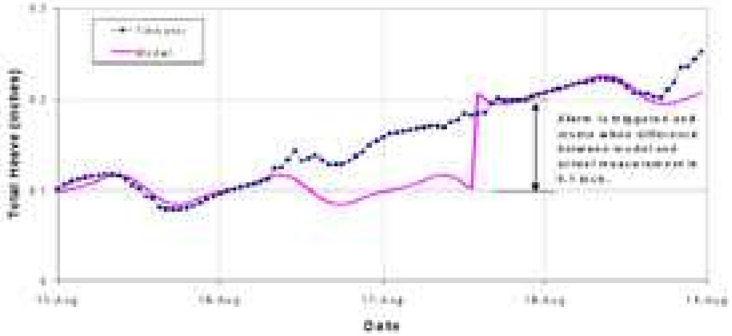

Figure 9 – Difference between modeled behavior and measured behavior used to trigger alarms.

Conclusion

High-resolution tiltmeters from Jewell Instruments were successfully used to monitor bridge response to compaction grouting around the bridge foundation. The tiltmeters are easy to install and connect to an automated data acquisition system for real-time monitoring and alarming of bridge movements. However, the sensitivity of the instruments requires that baseline monitoring prior to the onset of grouting be performed to establish the normal movement of the bridge. In this case, a sine function was used to model the diurnal expansion and contraction of the bridge to distinguish grout induced movement from normal movement. This is relatively easy to program into a datalogger. Alarming the difference between modeled behavior and measured behavior resulted in almost instantaneous notification of excessive vertical movements, which streamlined the grouting process (Figure 10).

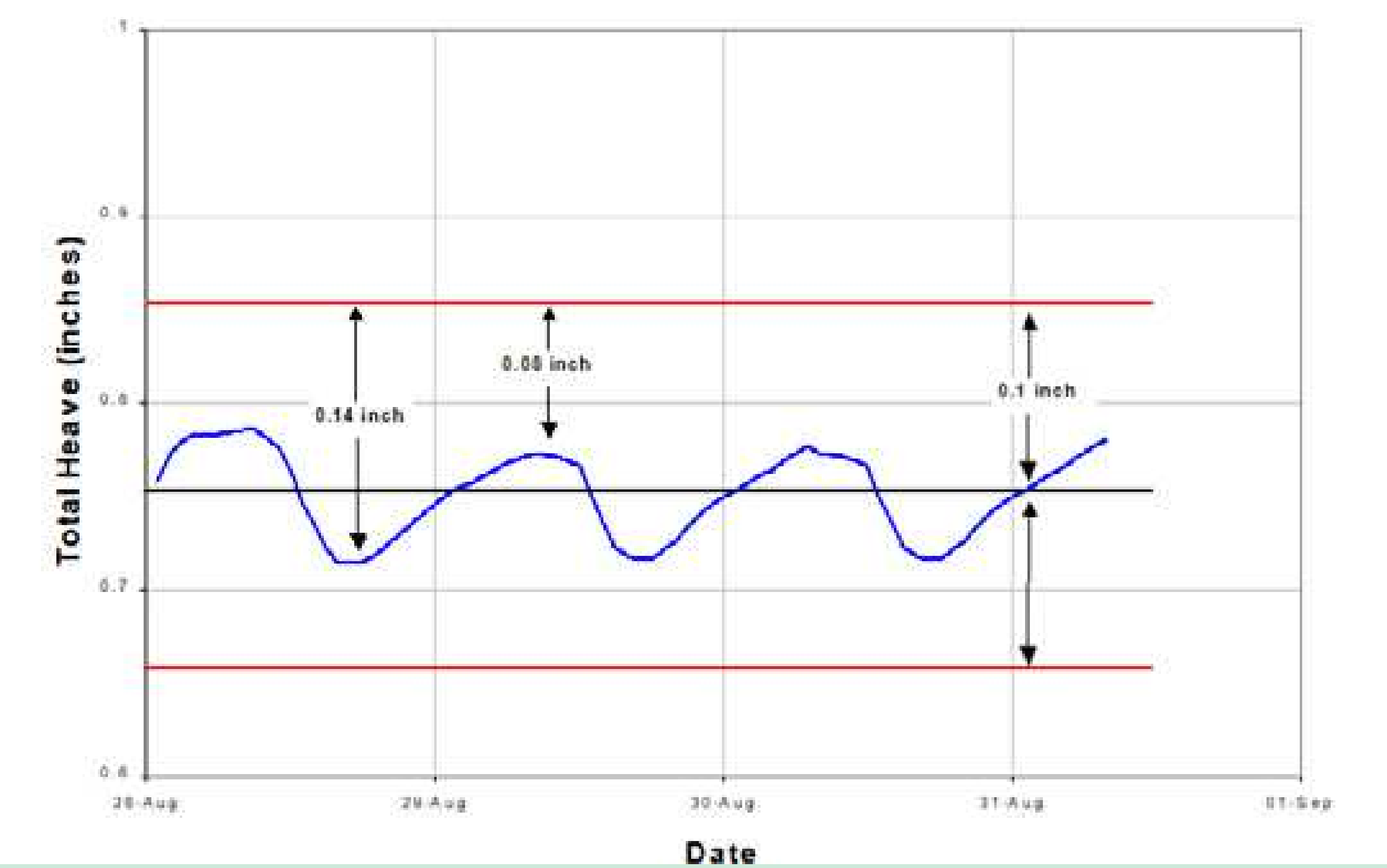

Figure 10 – Tiltmeter readings compared to alarm baseline model for entire grouting sequence beneath west footing