REMR Technical Note GT-RE-1.7

Improving the Assessment of Applied Forces on Gravity Structures Using Instrumentation: A Case History

Older gravity structures sometimes fail to meet the current Corps of Engineers (CE) criteria for sliding and overturning, yet these structures are presently performing satisfactorily. The current methods of analysis (limit equilibrium method and summing of moments) assume simplifications in the geometry of the failure surfaces, boundary stresses, material strength, and kinematics of failure. These assumptions may be a source of inaccuracy within the analysis, which would explain the satisfactory performance of structures not meeting stability criteria after reevaluation. The accuracy of stability analyses can be increased by either improving the assessment of material strengths or improving the accuracy of evaluating the applied stress loads (Meade 1993). Instrumentation of structures can provide measurement of actual deformation and stresses, which allows inference to the stresses applied by loads.

This technical note describes the installation of such instrumentation and a brief comparison of the observed measurements with the assumptions made during design of the structure.

Background

A landside lock wall (Monolith 13, Winfield Lock and Dam, Kanawha River, West Virginia) was instrumented with pressure cells and deformeters to measure applied stresses and deformations at the foundation/structure interface and at the landside wall. The monolith was instrumented with a total of 26 instruments: 10 total pressure cells (TPCs), 2 earth pressure cells (EPCs), 5 piezometers, 5 thermistors, 2 deformeters, and 2 joint meters. Basically, the instruments (except for the two EPCs) were hand placed onto or into the rock foundation before placement of the first lift (base lift) of concrete. The remaining two instruments (EPCs) were hand placed vertically within the backfill of the monolith, adjacent to but not touching the wall.

The 24 base instruments were installed in clusters (4 to 6 instruments per cluster) on 3 May 1995. They were read before, during, and after installation. On 4 May 1995, approximately 457 mm (18 in.) of mortar was carefully placed over each instrument cluster, topping off the cluster box forms. The

base lift was placed over the instrument clusters on 8 May 1995, and the instruments were read immediately after the placement. The instruments were monitored closely at first (sometimes more than once daily) and weekly thereafter. The date "8 May 1995," when the base lift was placed, is referred to as "Day D" for data management purposes. Therefore, the base instruments were installed on Day 5 (five days *before* 8 May 1995). The EPCs were installed separately at elevations 530 and 540 msl, on 26 April 1996 and 6 June 1996 (Days 354 and 395), respectively. Readings were taken daily, directly after installation of the EPCs, and weekly thereafter.

Description of Instruments

Each instrument was calibrated at ambient pressure and temperature before installation. Each instrument reading was plotted in appropriate units versus time in days to distinguish changes in pressures and deformations with time during the construction phase. All instruments are sensitive to temperature and pressure changes; therefore, thermistors were installed in each instrument cluster to permit accurate temperature corrections (Taylor 1995). All instruments were purchased from ROCTEST, Inc., Plattsburgh, NY. A complete description of each instrument is available in the ROCTEST instrument manuals (ROCTEST 1995).

Total pressure and earth pressure cells

The TPCs and the EPCs, called Gloetzl Cells, are identical hydraulic instruments. The names are different only to distinguish the placement of the cells. The TPCs were installed at the base of the monolith, while the EPCs were installed within the backfill of the monolith (Taylor 1995). Each pressure cell is basically a round steel flat jack, approximately 229 mm (9 in.) in diameter by 19 mm (0.75 in.) in thickness and filled with oil. The pressure exerted by the surrounding material (concrete or backfill) onto the cell is transferred through the steel cover and onto the oil. The change in oil pressure is then measured by a transducer connected to the flat jack. The transducer transforms the pressure change to an electronic signal that is read from the readout panel (ROCTEST 1995).

Thermistors and piezometers

The thermistors are simply rugged electronic thermometers that give readings in degrees Fahrenheit and Celsius at a desired point (ROCTEST 1995). The thermistors are in a protective stainless steel case and are approximately 63.5 mm (2.5 in.) long and 12.7 mm (0.5 in.) in diameter. The piezometers are vibrating wire instruments that are about 152 mm (6 in.) long by 25 mm (1.0 in.) in diameter. They have a very small sensitive diaphragm (accuracy of 3.4 Pa (0.5 psi)) that measures the change in fluid or air pressure

at a desired point in the atmosphere. These piezometers were designed to be installed within concrete or earth fill (ROCTEST 1995).

Deformeters and joint meters

The deformeters and joint meters are also vibrating wire instruments, but they measure very small changes in length along a defined interval. Their precision and accuracy are dependent upon the range being measured (ROCTEST 1995). Both of these instruments have thermistors installed within their housings to read temperature at the instrument. The joint meters measure the change in length of 25.4 mm (1 in.), which spans the foundation/structure interface. They have an accuracy of 0.0254 mm (0.001 in.) and are anchored approximately 102 mm (4 in.) below the rock/structure interface. The interval measured by the deformeters includes the interval measured by the joint meters and extends approximately 8 m (25 ft) below the interface. The deformeters have an accuracy down to 0.254 mm (0.01 in.). Both intervals described above are measured perpendicular to the foundation/structure interface.

Both instruments are approximately 63.5 mm (2.5 in.) in diameter and have a stickup of approximately 305 mm (12 in.) above the foundation, into the protective mortar that covers each instrument cluster. If a crack should open or close a bedding plane or fracture located below the depth of the joint meter, the deformeter will record the displacement, and the joint meter will not.

Installation of Instruments

Placement of the clusters

The 24 base instruments were placed in five clusters, each 914 by 914 mm^2 (36 by 36 $in.^2$). The clusters were evenly spaced on a line perpendicular to the long axis of the lock and at the center of the monolith. The line of instruments, Clusters 1 through 5, extended from the landside to the lockside of the monolith. Hence, Cluster 1 was closest to the landside, and Cluster 5 was closest to the riverside. Placement of the clusters is illustrated in Figure 1.

Clusters 1 and 5 were identical with respect to the number and type of instruments they contained. Each cluster contained six instruments: two TPCs, one piezometer, one foundation deformeter, one joint meter, and one thermistor. Layout details and dimensions of Clusters 1 and 5 are shown in Figure 2.

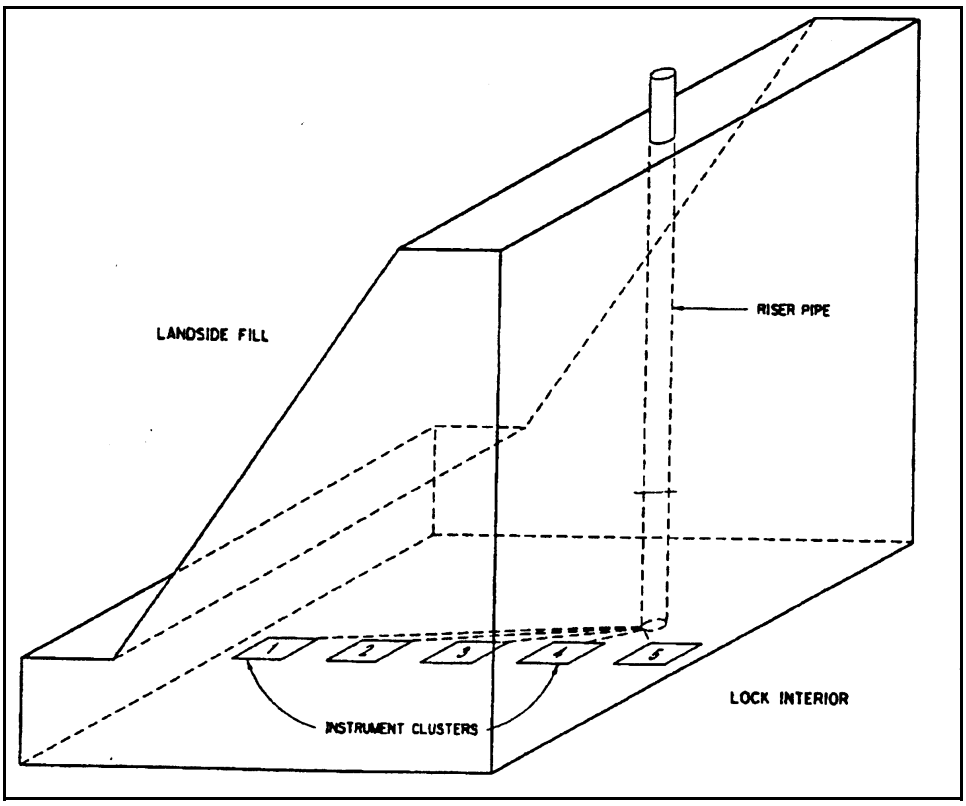

Figure 1. Placement of clusters along structure/foundation interface

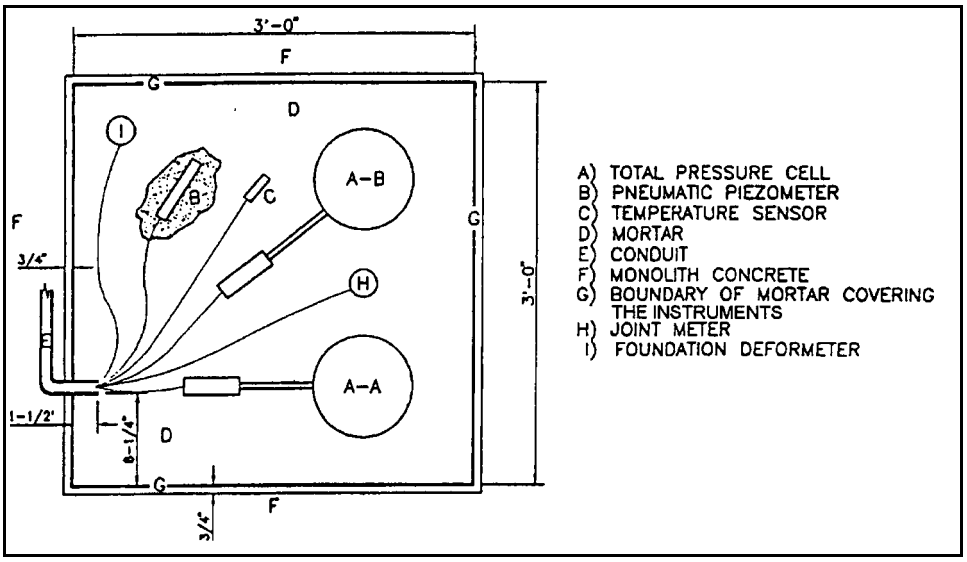

Figure 2. Detailed layout of Clusters 1 and 5

Clusters 2, 3, and 4 were also identical and contained four instruments each: two TPCs, one piezometer, and one thermistor. The layout for Clusters 2, 3, and 4 is illustrated in Figure 3. A brief description of the installation process is provided below. A complete description of the installation of these instruments is given in the "Specifications for Additional Lock and Gate Bay—Phase IIB, Winfield Lock and Dam, Section C; Description/Specs/Work Statement" (U.S. Army Corps of Engineers (USACE) 1993b).

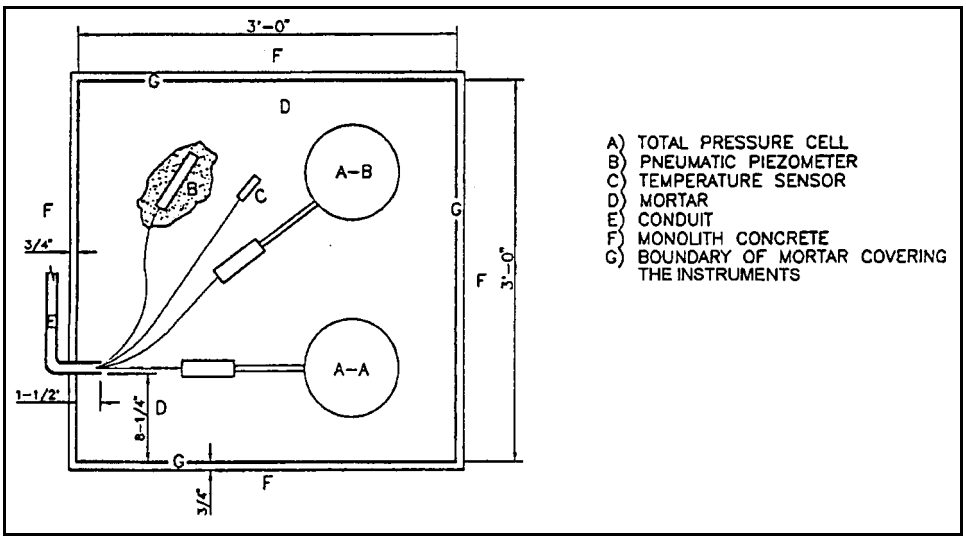

Figure 3. Detailed layout of Clusters 2, 3, and 4

Individual placement of instruments

The TPCs and thermistors were hand pressed horizontally onto a thin wet mortar pad that was just thick enough to create a smooth surface on the rock foundation. The piezometers were encompassed by a protective cover of saturated sand and placed horizontally onto the bedrock surface. The deformeters and joint meters were installed vertically in predrilled holes in the rock foundation and grouted at depths of 7.62 m (25 ft) and 101.6 mm (4 in.) below bedrock surface, respectively. These instruments were covered with 457 mm (18 in.) of mortar in a 914- by 914-mm (36- by 36-in.) form to protect them while the first concrete lift was placed. The deformeters and joint meters were completely covered by the mortar. The EPCs were installed after the backfill reached elevations 533 and 543 msl. The excess 0.9 m (3 ft) of backfill was removed to the specified elevations (530 and 540 msl), and the EPCs were installed vertically within the small excavation. The small holes were backfilled by hand with the original backfill, excluding particle sizes greater than 6.35 mm (0.25 in.).

The electric leads from each instrument were gathered into one conduit and raised above the placement of the backfill on the landside of the monolith. The single conduit connected eventually to a protective enclosure or terminal readout box at the top of the completed monolith. The conduit was originally designed to extend through the monolith as shown in Figure 1, but was changed for convenience.

Intended Purpose for Each Instrument

The overturning analysis used by the CE involves satisfying static equilibrium conditions for vertical forces and moments. By making an assumption regarding the uplift pressure, summing the vertical forces, and summing the moments about the base, the magnitude and the location of the foundation reaction can be found. The base pressure distribution is then calculated, and the assumption regarding uplift pressure is checked. If the base pressure distribution indicates that a "noncompression" zone (crack) is present at the heel of the structure, the uplift pressure diagram is modified to include full hydrostatic pressure along the "noncompression" zone. The analysis is then iterated until the assumed and calculated locations of the "noncompression" zone agree. The present criteria for overturning stability require defining the location of the foundation reaction and a linear pressure distribution at the base of the structure (Shannon and Wilson 1993). In addition, the criteria for sliding stability assume linear uplift pressures and full hydrostatic pressure at noncompression zones. The sliding analysis also assumes in this case that the base of the structure is horizontal and is coincident with the plane of potential failure.

In an attempt to validate the assumptions described above, an instrumentation plan was designed to measure the actual stress distributions and deformations along the structure/foundation interface, deformations within the foundation, and horizontal pressure acting on the landside of the monolith. Ten TPCs were installed at the structure/foundation interface to measure the total stress distribution. Since pressure has not been directly measured successfully in any known case histories, two TPCs were installed in each cluster for redundancy of measurements. Similarly, piezometers were installed to validate the assumed linear distribution of uplift pressure, in addition to the assumption of full uplift pressure applied at noncompression areas. Two joint meters were installed to validate the assumption made that a noncompression area will develop, as predicted for this monolith during normal operating conditions. The deformeters will measure any extension or compression of the foundation beneath the structure/foundation interface that is assumed to be negligible or nonexistent. Finally, the thermistors were installed in each cluster for correcting each instrument reading.

Summary of Instrument Readings

Results from the instruments are plotted in Figures 4-8. The plots show a distribution of measurements (uplift, total pressure, and deformation) for specific days across the 15 m (48 ft) of the base of the structure. The measurements are plotted for Days 300, 401, 504, 602, and 658. The construction of the monolith began on Day 0 and was completed near Day 240.

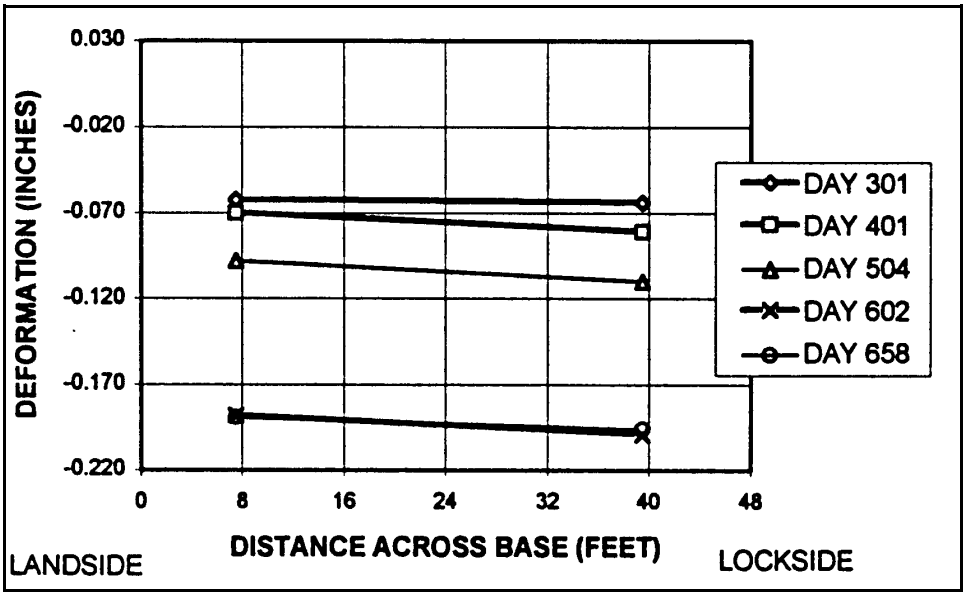

Figure 4. Foundation deformation distribution

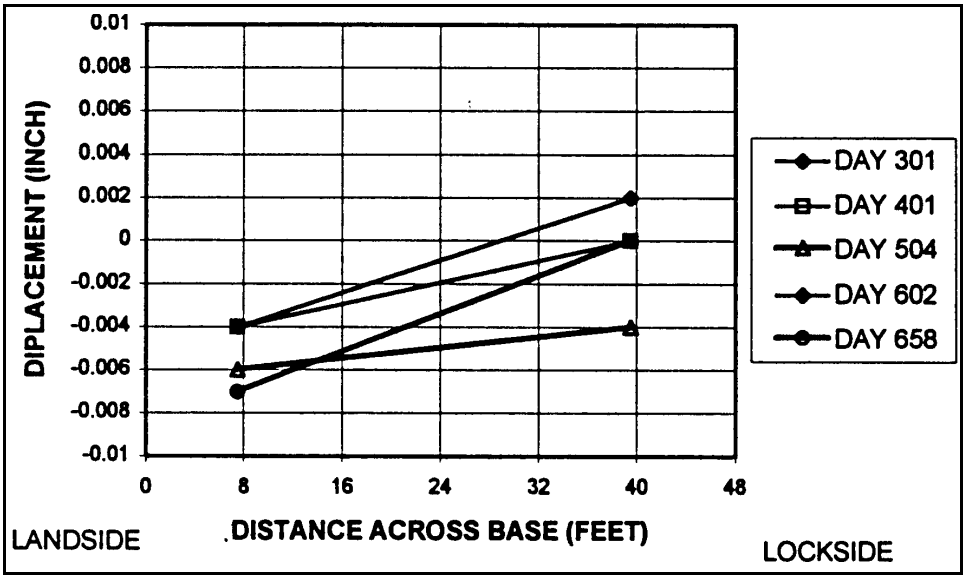

Figure 5. Joint meters

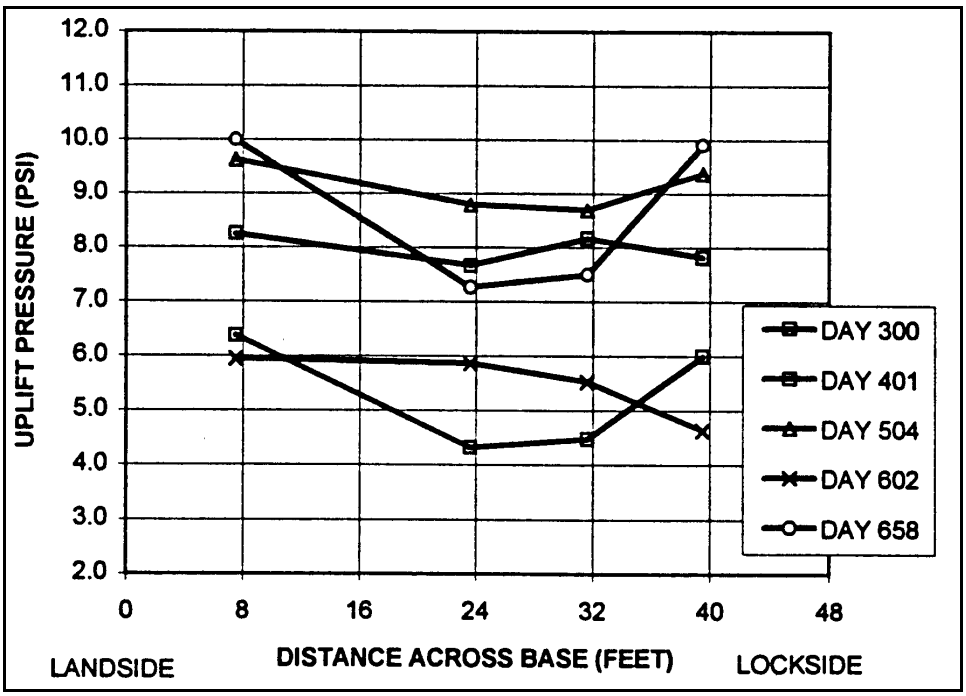

Figure 6. Piezometer readings

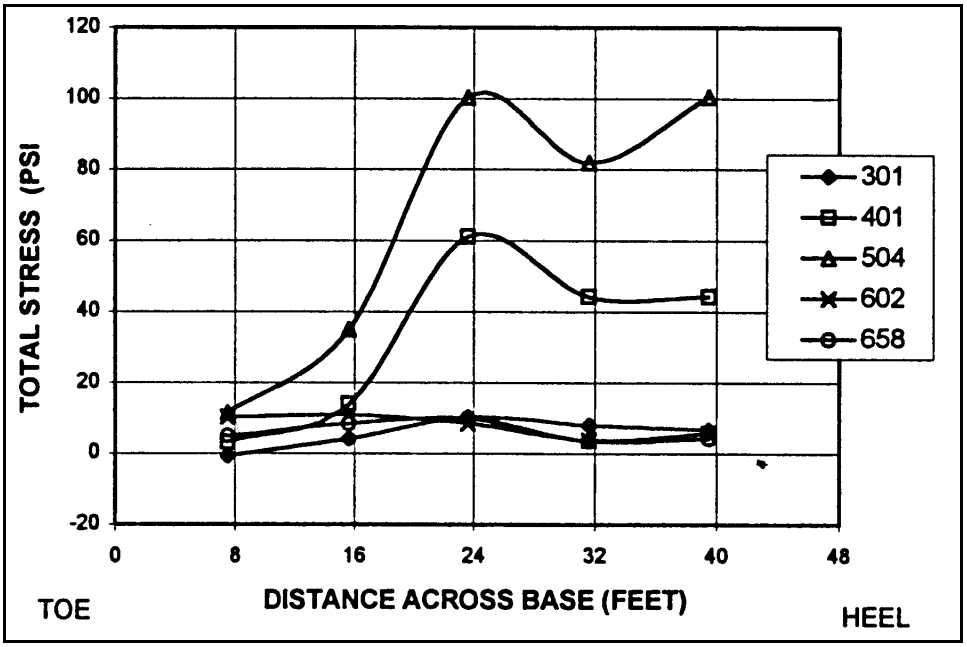

Figure 7. Total pressure distribution

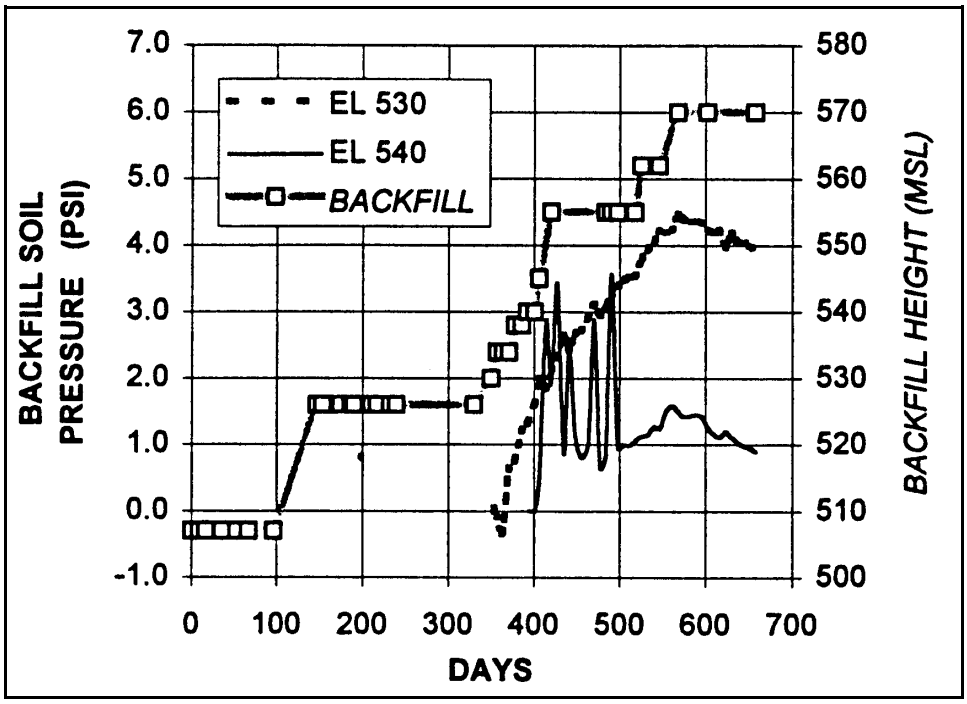

Figure 8. Backfill horizontal pressure

The majority of the backfill was placed between Days 160 and 630. The instrument readings reflect changes in pressure, uplift, and deformation during the construction process. For example, the deformeters (Figure 4) show a gradual compression of the foundation with the increase in height of the monolith and time after construction. The average compression of the foundation was approximately 5.08 mm (0.20 in.). Also, the deformeters show the landside and lockside of the monolith settling at almost the same rate. The foundation deformation rate leveled off to approximately zero from Day 600 to Day 658, or approximately 360 days after completion of the monolith. Looking at this chart, it is impossible to isolate the effect on the foundation (deformation) caused by the addition of the backfill during Days 160 through 630. However, looking at the deformation plotted continuously with time (not shown), there is a noticeable compression of the foundation with the addition of the backfill.

The two joint meters (Figure 5) also showed compression of the structure/ foundation interface as a result of the construction process. Although the deformations are extremely small (-0.178 mm (-0.007 in.) for joint meter (JM) 1; 0.05 to -0.102 mm (0.002 to -0.004 in.) for JM 2), it is interesting to note that the interface near the landside of the structure is practically static during placement of the backfill, while the lockside is moving both up and down. However, the data from Day 602 and Day 658 are directly on top of each other, suggesting an equilibrium was reached since construction ceased at this monolith.

In summary, the data from the joint meters infer mostly elastic compression at the structure/foundation interface, with more movement on the riverside probably due to the presence of wall friction through the addition of backfill through Day 630. A comparison of the joint meters and the deformeters indicates that about 98 percent of the foundation compression occurred below the rock/concrete interface. Note that the average compression of the deformeters on Day 658 was 5 mm (0.20 in.), while the average compression of the joint meters was 0.101 mm (0.004 in.). This means that 4.978 mm (0.196 in.) of deformation occurred below the rock/structure interface.

One of the piezometers failed to give any readings; therefore, results have been plotted from the other four. The piezometer readings (Figure 6) reflected the construction sequence and some saturation of the backfill. Specifically, there was an increase in piezometric pressure during construction of the monolith (Day 0 through Day 240). However, after the monolith was completed, the uplift pressures leveled off to an average across the base of approximately 37.9 Pa (5.5 psi) (see distribution plotted for Day 301). Then, as the backfill was being placed, the pressure began to rise again, up to 65.5 Pa (9.5 psi). After completion of the backfill, the uplift pressures decreased to an almost even distribution across the base of approximately 41 Pa (6 psi) (see distribution for Day 600). The piezometers reacted to the applied loads appropriately; pressures increased with applied loads and dissipated with time, as expected. The distributions ranged from relatively uniform to a nonuniform U-shape. The latest distribution shown is for Day 658, where the distribution is U-shaped and pressures are up to 69 Pa (10 psi), or approximately 7 m (23 ft) of head is on the foundation/structure interface.

Similar to the piezometers, the TPCs measured an increase in pressure with an increase in applied load, as expected. However, the instruments did not sustain the pressure, as expected, but eventually lost all pressure with time. A brief discussion of the TPC behavior follows.

The TPCs measured a gradual increase in pressure of up to 552 Pa (80 psi), as construction of the monolith progressed. Although the applied load was still increasing around Day 120, all the instruments sharply declined in pressure and approached 0 psi near Day 200. Later, near Day 340 (Figure 7), the pressures began to rise again, in conjunction with placement of the backfill. However, near Day 500 the pressures began to decline, even though the applied load was still increasing, and near Day 600 the pressures again approached 0 psi.

The reason for the decline in the pressure readings could be twofold. Either the stresses were redistributed around the TPCs with time after an increase in applied load, or the TPCs were not in contact with any material during the winter months. Because of the difference in elastic moduli between the TPC and the mortar (the TPC having a smaller modulus than the mortar), the applied stresses will arch around the TPC; therefore, the pressure will not be felt by the instrument.

In addition, the decline in TPC readings could be caused by contraction of the cells due to the onset of winter. The temperatures at the cells are approximately 50 °F in the winter months, or 20 °F lower than the initial temperature during installation. Although the readings are corrected for temperature changes, this cannot correct for the instruments contracting away from the mortar surface. It is not known to the author where pressure cells have ever been successfully used, and there are apparently many reasons for this. Consequently, because of the reasons stated above, the TPC readings were not considered valid.

The EPCs were installed vertically at elevations 530 and 540 above msl within the structural backfill. As stated earlier, hese instruments are identical to the TPCs and, unfortunately, the readings are not much better. The EPC installed at 530 msl was under 12 m (40 ft) of overburden and showed a reading for horizontal pressure of 27.6 Pa (4 psi). The density of the backfill was 1,620 kcm (100 pcf); therefore, the vertical pressure at 12 m (40 ft) should be approximately 19,530 ksm (4,000 psf) or 191 Pa (27.7 psi). The horizontal-to-vertical stress ratio (k at rest, not saturated) for a clean gravelly sand is 0.5 (Peck, Hanson, and Thornburn 1973) and is the k_o value used in the design stability analysis (USACE 1993a). Using this k_o value, the horizontal stress at 12 m (40 ft) should be approximately 97 Pa (14 psi). The EPC reading was 3.5 times smaller than expected, or approximately 28 Pa (4 psi) (Figure 8). The EPC installed at elevation 540 also read a very small horizontal pressure of 6.89 Pa (1.0 psi), even though there was 9 m (30 ft) of overburden above it.

The author believes that the in situ state of stress was destroyed during the excavation of the backfill to install these instruments and was never reinstated at the instrument. The backfill that was hand placed around the instruments must have been too loose. These instruments may have yielded better results if they could have been buried simultaneously with the placement of the backfill. Consequently, the data from the EPCs are considered invalid.

Conclusions

The instruments provided important information regarding assumptions made during construction of a gravity structure. For example, the construction phase assumptions include full contact of the base and uplift pressures near zero. The deformation recorded by the deformeters shows that the displacement beneath the structure was uniform and compressive. Full contact of the base is evident. The piezometers indicated a distribution of uplift pressure that ranged from relatively uniform on Days 401, 504, and 602 to a distribution that was 50 percent lower in the center of the base than the outside edges on Day 300 and 30 percent lower on Day 658. The uplift pressures were not close to zero, as assumed in the stability analysis for this monolith. The results are significant such that operational phase assumptions can also be

evaluated. Specifically, uplift pressures can be measured, noncompression of the base can be detected, and deformations can be monitored.

It remains to be seen when the structure is in full operation if the deformations and stresses within the structure will match those inferred by the design calculations. If funding continues, the instruments will be monitored for the next year, and another examination of the measurements will be conducted.

It is believed that the piezometers, joint meters, deformeters, and thermistors will all continue providing useful data. From these data, a more comprehensive evaluation of the actual boundary conditions can be compared with the design conditions expected. Conclusions from this study may improve confidence in some parameters used during risk assessments of existing structures by giving the design engineer an example of measured versus assumed boundary conditions.

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