Geomechanics of Large Stone Structures: A Case History from the Washington National Cathedral

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ABSTRACT: The Washington National Cathedral is one of the largest masonry structures in the USA, and like many of its European Gothic counterparts, it required nearly a century to construct. The design was altered during this period, resulting in greater loadings than were originally anticipated on the soil beneath the foundation. When signs of continuing differential settlement were observed in the early 1990's, the Cathedral approached the US Bureau of Mines (now the National Institute for Occupational Safety and Health (NIOSH)) for assistance in monitoring the movements of the massive towers and walls. An array of dual-axis tiltmeters was installed about 40m above ground level to measure wall and tower inclination, with the data sent over a dedicated phone line to the NIOSH Pittsburgh Research Laboratory for processing. Mechanical gages and string-potentiometers are also being used to measure motion across cracks and joints, and differential pier settlement is being monitored with optical-level surveying. Data have now been collected for almost 7 years, and they show a long-term settlement trend masked by dramatic diurnal and seasonal thermal movements. The paper discusses the major findings of the study, implications for the future of the Cathedral, and conclusions regarding the use of geotechnical monitoring at major national monuments.

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2 INTRODUCTION: BUILDING HISTORY

Comparable to the campaigns for construction of the great cathedrals of the Middle Ages, it took some eight decades for the Washington National Cathedral to be completed. The period of its construction, spanning 1907 to 1990, witnessed two great wars, a world-wide economic depression, and other intervals of fiscal and political turmoil. Indeed, just as in the Middle Ages, the rate of cathedral construction varied greatly with time according to the availability of funds.

The original design for a Protestant Episcopal Cathedral in the District of Columbia (Washington, DC) was conceived by the English architect George Frederick Bodley. Henry Vaughan, who had apprenticed with Bodley before moving to Boston, became the second Cathedral architect following Bodley's death in 1907. The apse of the Cathedral (Fig. 1) was largely completed during his tenure which ended with his death in 1917. All remaining questions of design were subsequently resolved by the a third group of principal architects, the Boston firm of Frohman, Robb, and Little, with the firm of Cram and Ferguson acting as consulting architects. Frohman himself continued working at the Cathedral site until he retired in 1971.

The entire foundation, including that for the projected west front towers, 8 m in depth, was in place by 1924. The structure of the choir was completed in 1930. Work slowed during the depression and WWII, but the three eastern-most bays of the 31-meter tall (floor to vault keystone) nave and both transepts were standing by 1966, by which date the 92 meter high crossing tower was also complete. Before raising the western-most bays of the nave, the relatively diminutive western wings were constructed between 1963 and 1968 on spread footings isolated from the footing for the west front towers. The nave was completed in 1976, but little further work was carried out at the site until 1983 when the 72 m-high west towers (Fig. 2) were raised in an intensive six-year building campaign (Feller 1989).

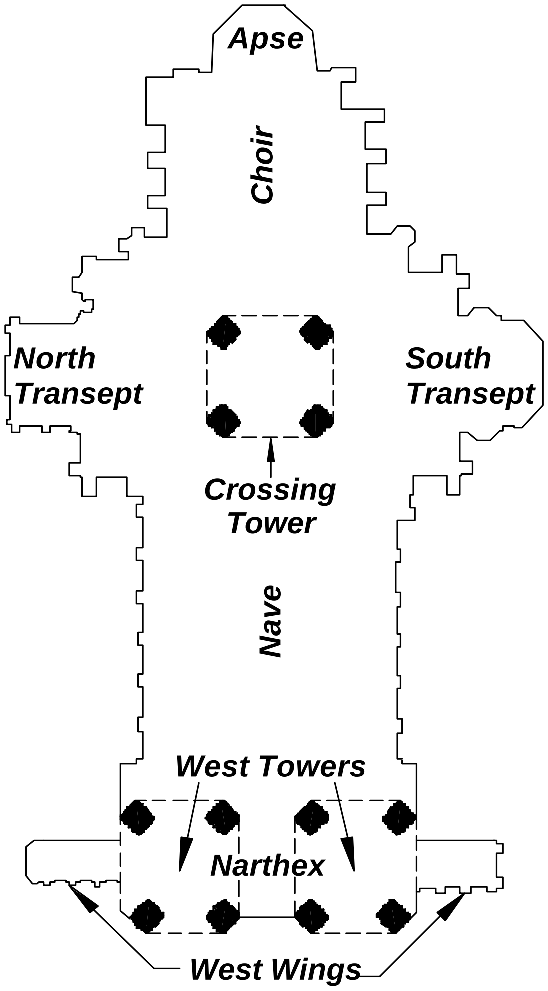

Figure 1. Ground-level plan of the Washington National Cathedral

Figure 2. View of the west front and west wings of Washington National Cathedral.

As the architects of this twentieth-century Cathedral sought to follow Gothic architectural precedent, they rejected modern construction employing stone veneer on a steel or reinforced concrete skeleton. The Cathedral is not built exclusively of stone block, however. Instead, the main vessel of load-bearing masonry, about 150 m in length, was constructed with exterior Indiana limestone walls. The walls, constructed without expansion joints, average about one-third of a meter thick, and encase brick cores reinforced by steel rods. The covering vaulting (Fig. 3) is entirely of stone.

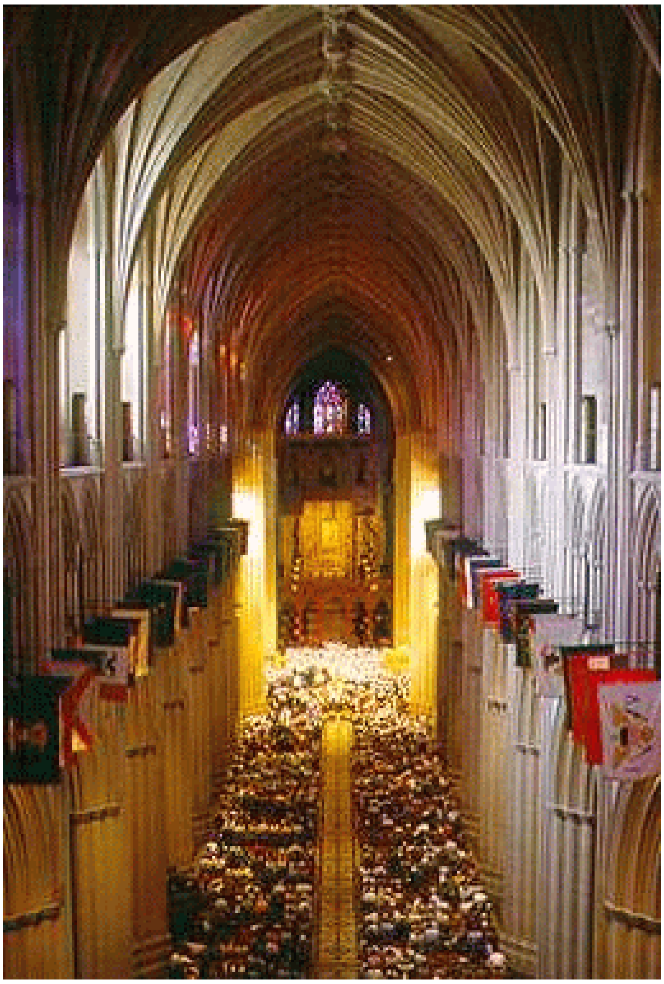

Figure 3. High vaults of the nave of the Washington National Cathedral

3 GEOTECHNICAL ISSUES

From the point of view of structural integrity, the design of the Cathedral has been generally successful. As with all monumental buildings, a few problems relating to local details of construction have came to light. One example is the damage experienced by a large pinnacle already in place for 30 years, which was caused by water infiltration into the brick core behind its thick outer stone facing (Bork et al. 1995).

One of the more critical problems is differential settlement of the foundation. Evidence of differential settlement is most pronounced in the vicinity of the west towers, and includes:

- Distortion and cracking of the stone tracery supporting the glass panels within the large windows beneath the high vaulting of the nave bay adjacent to the west towers;
- Transverse cracks across the nave floor and over the high vaulting in this same region;
- Shearing distortion of interior pillars supporting the west towers;
- Distortion and cracking of tracery in both of the diminutive western wings adjoining the west towers (e.g. in intricate, stone- mullioned cabinet doors of the Rare Books Library), and;
- The lowering of the narthex floor, beneath the west towers, which was presumably perfectly flat when it was placed in 1976, and is now six centimeters below the floor elevation at the outer walls of the western wings.

Elsewhere, transverse cracks have developed over the high vaulting adjacent to the crossing tower, and outward rotation of the south transept end wall is also indicated by cracking in the floor over the high vaulting adjacent to this wall. While none of these manifestations has as yet posed the necessity for structural intervention, they do indicate a need for carefully monitoring the building structure.

The differential settlement is largely a consequence of several crucial, early decisions made by the Cathedral architects. The first of these, a determination made around the time of the original design (1907), is linked to the positioning of the Cathedral on the building site. The south transept arm lies at the summit of a long, steep hill extending away from the end wall of the transept (Fig. 4) that was filled to furnish a more-or-less level building site. Secondly, no core samples were taken of the subsoil below the foundations during any stage of construction. Instead, the foundation was designed using information obtained from test pits. The Cathedral is sited on one of the highest elevations in the District of Columbia, and thus it might appear that bedrock would lay close to the surface. However, the test pits showed that the upper 10 m of ground consisted of layers of relatively competent silty sand and clayey sand. It was assumed that these soils continued down to bedrock. In fact, test borings taken by Schnabel Engineering Associates (1994) near the west towers found that the hard shale bedrock is 35 m deep, and that the lower 25 m of soil includes layers of "fat" (fine-particle high-plasticity) and "lean" clays. Laboratory testing indicated that the clay soils display primary and secondary consolidation behavior, and that they are overconsolidated. Figure 5 is an idealized soil section based on those borings, and Table 1 shows representative geotechnical properties.

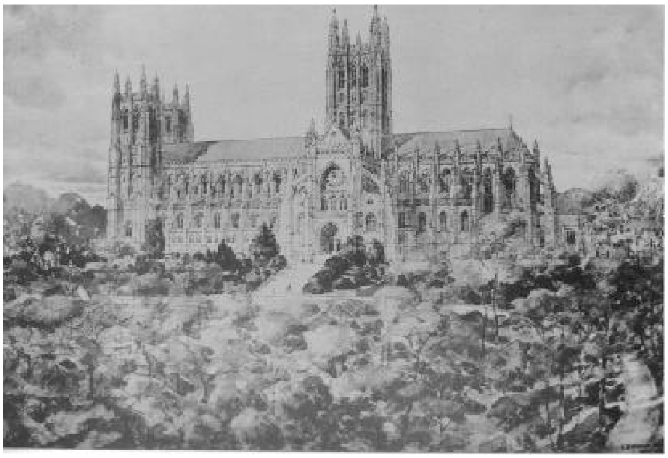

Figure 4. Prospective of the south flank of the Washington National Cathedral, by Donald Robb in 1934, indicating grade below the South transept outer wall.

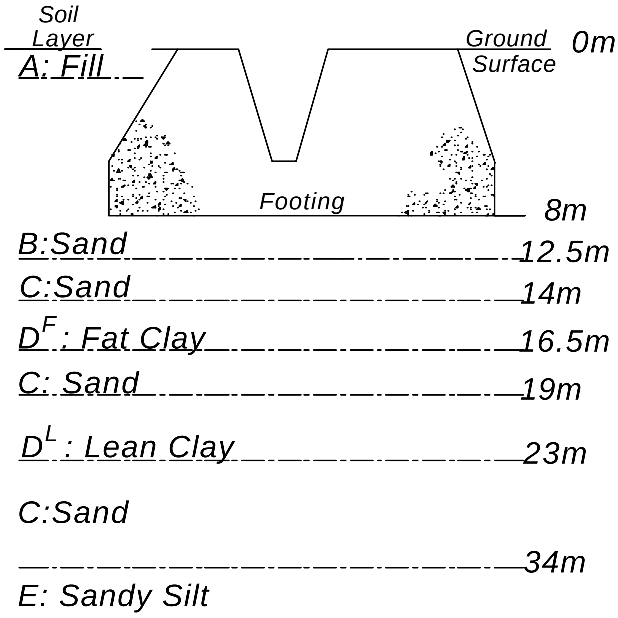

Figure 5. Soil section obtained from test boring near the west towers.

Table 1. Properties of soil layers beneath the west towers shown in Figure 5 (Schnabel Engineering Associates, 1994).

STRATUM	Soil Classification[1]	Penetration Resistance [2]	Plastic Limit	Liquid Limit
B (Sand)	SC + SP	10 to 30	-	-
C (Sand)	SM, SC+SP	8 to 100+	8 to 13	30 to36
D^F (Fat Clay)	CH	6 to 12	31 to 33	53 to 56
D^L (Lean Clay)	CL	15 to 42	-	-

[1] From ASTM D-2487-83, Definition of Soil Group Names.
[2] Minimum and maximum values in blows per ft, per ASTM D-1586.

Some light on the decision not to conduct test borings is shed by a surviving exchange of letters from 1922 between Scientific American editor J. Bernard Walker (who held a degree in Civil Engineering) and the then-Dean of the Cathedral, Dr. B.C.F. Bratenahl. Walker (1922) wrote that: "probably more trouble has been caused by uneven settlement of foundations than by all other causes combined.... In view of the size and weight of the Washington Cathedral it would be wise to ... determine the character of the sub-soil and its absolute bearing capacity." Walker then suggested that "it would be highly desirable" to have General William Barclay Parsons proceed with the work. Apparently Parsons had already submitted a proposal to the Cathedral to take what he considered to be an adequate number of borings for about $15,000, and Walker thought the estimate most reasonable.

Dean Bratenahl (1922) replied to Walker in a long, thoughtful letter that he: "would rather leave these matters to such Gothic architects as [the consultants] Cram and Fergusson, who have given their whole life to Gothic construction, than to leave the matter to engineers. Furthermore, the soil as we go down, is almost like cement; it is so hard and compact that we need no shorings for the sides nor do they need to be sloped.... We should take thought before we pay a sum almost equal to the entire fee to the architects [for all their work to date]."

Certainly the most significant decision influencing the settlement rate of the west towers was made after the footing had already been placed. Shortly after the appointment of the third group of principal architects, Philip Frohman (1921) argued that the size of the west towers should be dramatically increased on the basis of aesthetics: "The whole front has a narrow, constricted appearance... it seems lacking in that beauty and grandeur which should be possessed by the facade of a great cathedral." In a letter to Frohman from one of his partners written in 1925, Donald Robb supported Frohman's aesthetic view, but warned that: "There is the matter of the foundation mat already in place.... If the necessary extensions to this mat are poured within a short time, they will have ample time to come to their permanent level [of strength] before the superstructure is added."

Unfortunately, this advice was not followed. Ultimately, the upper portion of the great concrete footing was modified to accept the enlarged towers, but the lower portion of the footing (its critical 21 x 49 m "footprint" on the soil 8 m below the surface) remained unaltered. The west towers, which were finally completed in 1989, are close to 10 m taller and wider than the originally proposed facade (Fig. 6).

While the original design of the mat footings gave a uniform bearing pressure of 29 T/m^2 beneath the crossing tower, and presumably the same for both west towers, the bearing pressure of the revised west tower design (including the footing) is estimated to be 47 T/m^2. Computation of the predicted settlement of the west towers, using the laboratory soil strength values, indicates that a primary consolidation of approximately 75 mm would have been expected. The primary consolidation should have been essentially complete after six years. The long-term secondary consolidation is predicted to be about 10 mm over next 10 years, followed by a further 10 mm over the next 100 years.

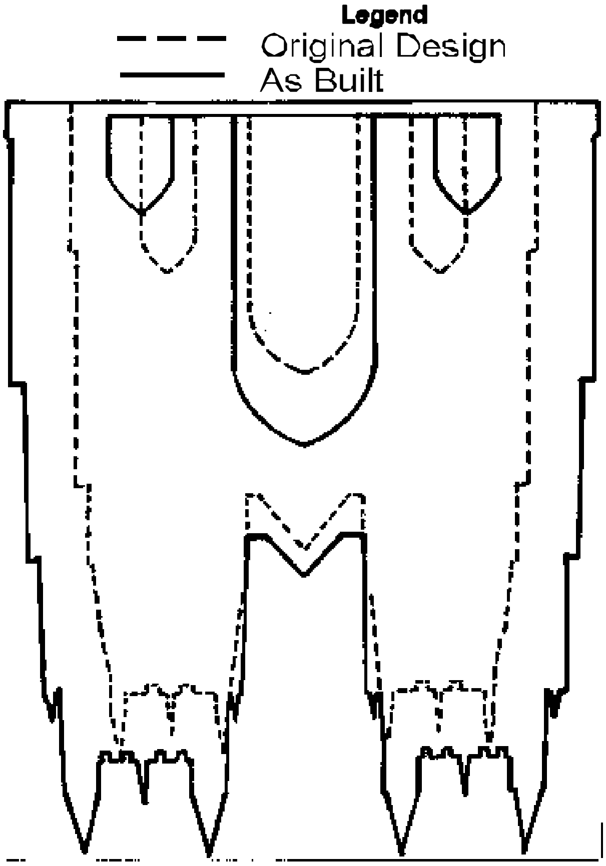

Figure 6. Comparative west-front facade profiles for Washington National Cathedral

4 OBSERVATION AND INSTRUMENTATION

Monitoring at the Cathedral is being carried out using four overlapping strategies. The first two, primarily within the province of the Cathedral staff under the direction of the mason foreman, comprise:

- **Mechanical crack measurements:** Quarterly recording of gap widths at 10 locations by means of (automotive) feeler gages set between pairs of rigid blocks fixed to both sides of existing cracks, and;
- **Level elevations:** Monthly recording of dumpy-level elevations of metal pins set into the eight west tower piers and the two western-most main arcade piers of the nave relative to datum pins set into the end walls of the west wings.

The other two are being carried out under contract by the Disaster Prevention and Response Branch of the

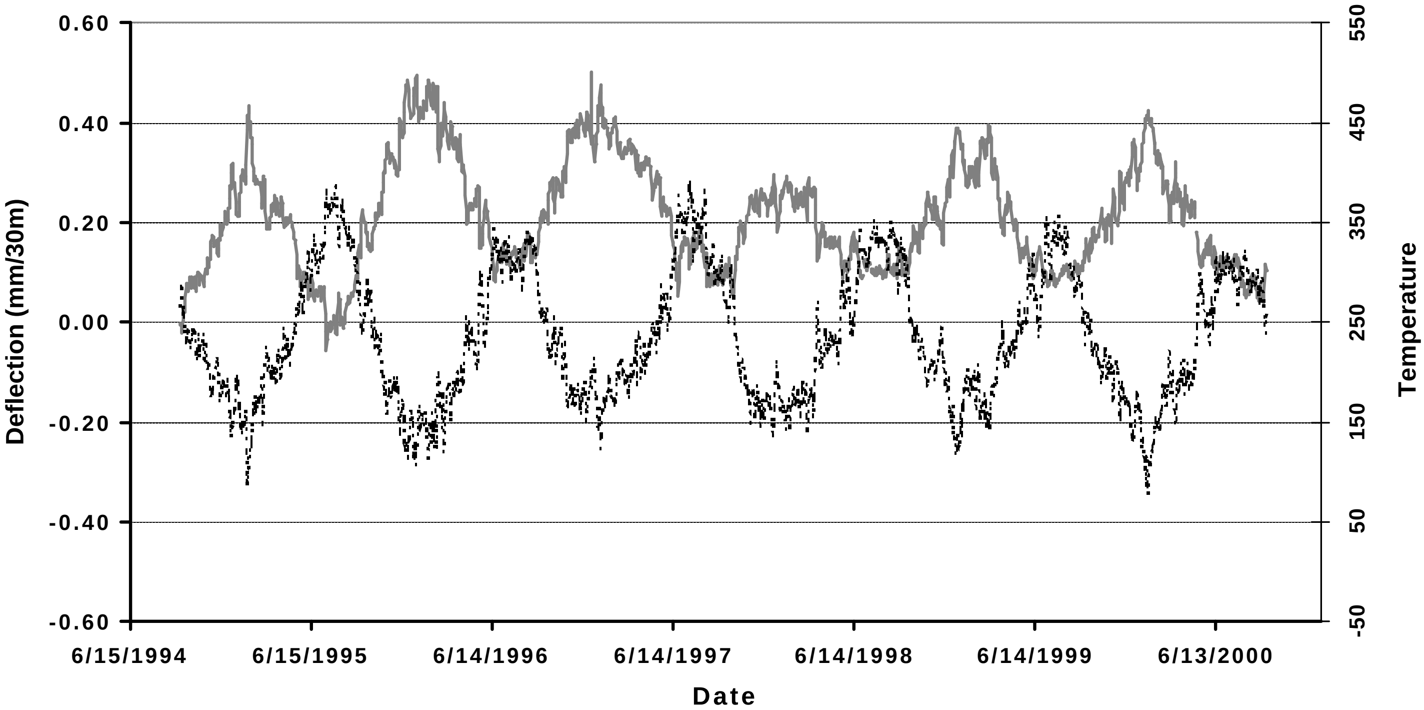

Figure 7. Inclination variation and instrument temperature (uncalibrated) vs. time from southwest tower tiltmeter. East/west inclination (west is positive) is indicated by the solid trace above the graph axis. Temperature variation is indicated by the broken trace.

National Institute for Occupational Safety and Health - Pittsburgh Research Laboratory (formerly, the US Bureau of Mines). These comprise:

- **String potentiometers:** Hourly recording of crack movement at four locations using Technovision model PT-10-A string potentiometers that incorporate a spring-loaded cable rotating a shaft coupled to a precision potentiometer, and;
- **Tiltmeters:** Hourly recording of tower and wall inclination from four Applied Geomechanics model 716 dual-axis tiltmeters that incorporate electrolytic sensors, one for each axis, together with temperature sensors.

The tiltmeters, fixed to interior walls of the western towers and the southern transept, are located about 40 m above ground level; the crossing tower tiltmeter is mounted at about 50 m elevation. A central 12-volt D.C. power supply, with battery backup, powers the instruments, and their signals, sent over a dedicated telephone line, are recorded in Pittsburgh (only midnight readings are used in data presentation). Monitoring of the Cathedral was initiated at the beginning of the summer of 1994. Results to date, therefore, are based on close to seven years of data.

5 RESULTS

One of the significant findings of the study was that daily and seasonal temperature fluctuations give rise to appreciable motion throughout the building structure, most notably cyclic opening (and closing) of joints and cracks in the walls, floors, and vaults adjacent to the central and west towers. The normal, yearly temperature range for the District of Columbia, according to the US National Weather Service, is 56 degrees C; and the maximum recorded yearly range is 67 degrees C. The large amplitude of the seasonal cyclic component of movement, combined with a small number of measurement points, makes it difficult to discern the relatively slight long-term movement from these data. Movements caused by annual seasonal variation can be an order of magnitude greater than those caused by the underlying settlement. The cyclic, seasonal, opening and closing of transverse cracks above the high vaults adjacent to the towers necessitates their periodic, careful examination, particularly to ensure that even small masonry fragments that may be produced by this type of movement do not fall to the floor below.

The tiltmeter data display the highest seasonal (and daily) variations of any of the instruments. The maximum yearly range of east/west inclination of the southwest tower is 4.2(10)-4 radians, which corresponds to 12 mm of lateral movement at an elevation of 30 m (Fig. 7). However, regression of the data obtained over the entire study period indicates that the net change in tilt has been negligible. The trace of north/south south-west tower inclination indicates less seasonal variation than along the east/west axis.

Level elevation measurements in the west towers also show non-linear seasonal effects, but they are

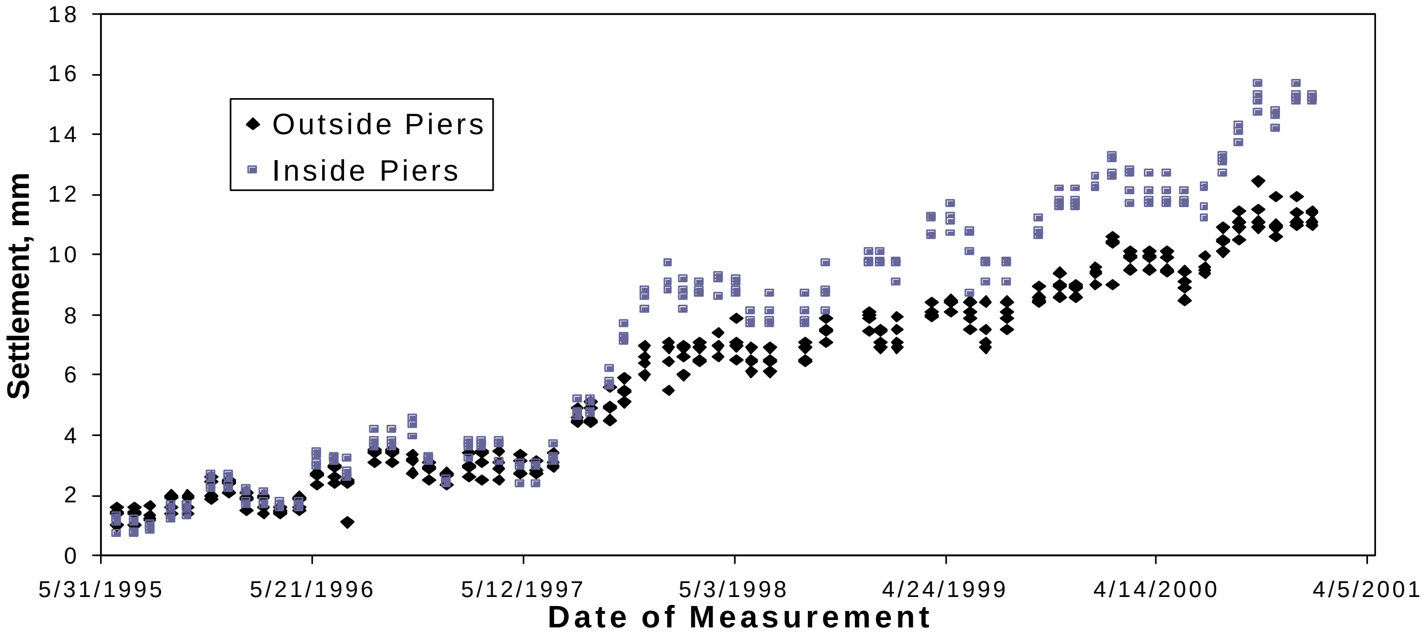

Figure 8. Level elevation measurements from the piers supporting the west towers. The “inside piers” are located closer to the longitudinal centerline of the Cathedral, the “outside piers” are located closer to the wings.

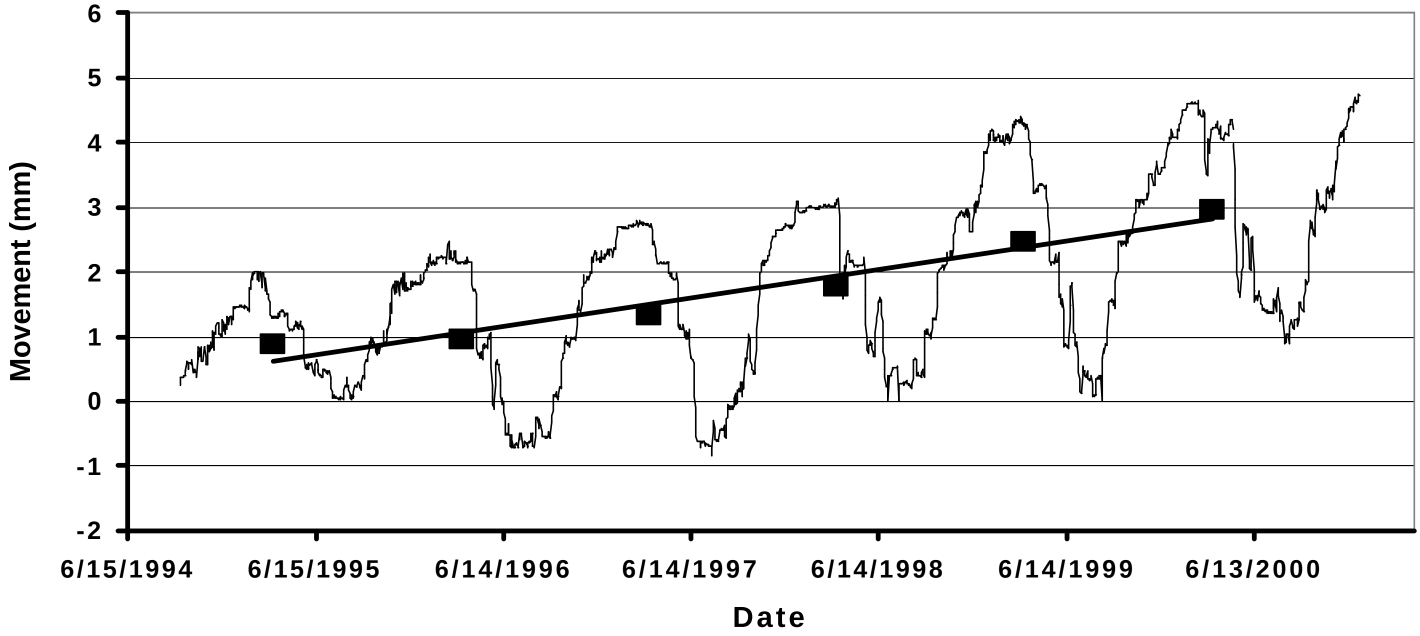

Figure 9. Gap movement (in mm) vs. time measured by a string potentiometer installed over the nave high vault adjacent to the south-west tower. Annual averages and the regression line through them are also shown.

much less pronounced. However, ongoing slow settlement is clearly evident in the data. Regression lines through the measurements on each of the eight supporting piers indicates that the average rate of differential settlement during the last six full years is approximately 1.4 mm/year (Fig. 8). The r-squared for these regressions averaged 0.8. The measured rate is slightly greater than the calculated value of 0.9 mm/year for secondary settlement during this period. While there is no evidence yet that the rate of secondary settlement is diminishing, the current rate is appreciably less than it was during the period of primary settlement (when it averaged about 8 mm/year).

The data also indicate that the eight piers are settling at slightly different rates. The average for the outer four piers ranged from 0.118 to 0.123 mm/year, while the inner four rates range from 0.153 to 0.156 mm/year. It appears that the concrete mat foundation, which is believed to be unreinforced, is bowing slightly in response to the soil pressure.

The automatic, effectively-continuous data recording from the string potentiometers has been effective in showing long-term crack opening trends. For example, regression of data from the string potentiometer located over the high vault adjacent to the south-west tower indicates a rate of 0.43 mm/year (r-squared = 0.95 based on yearly averages). The maximum yearly range, due to seasonal effects, is as much as 4.5 mm/yr (Fig. 9). The less frequent mechanical measurements broadly agree with the string potentiometers.

Instrumentation mounted on the crossing tower and the south transept wall display diurnal and seasonal movements that are similar in both form and magnitude to those measured on the west towers. There is no evidence of long-term trends at any of these locations, however.

6 CONCLUSIONS

Although the program of monitoring the Washington National Cathedral is ongoing, preliminary inferences may be drawn concerning both the state of the building fabric and the strategies for monitoring. Most importantly, the rate of west tower (differential) settlement, more than a decade after final completion of the towers, appears to have slowed, although it remains appreciable. While the ongoing settlement imposes the need for a program of more-or-less continuous mending of affected stonework, the towers themselves appear to be stable. Certainly, a catastrophic failure due to excessive settlement and rotation is highly unlikely. The same salutary prognosis for long-term stability of the crossing tower is implied by the tiltmeter data received from it.

The combination of mechanical and electronic devices, especially where there is an overlap of measurement points, has provided rubustness and credibility to the data. Furthermore, automatic, continuous data recording has facilitated discrimination of long-term trends. Even so, given the appreciable thermal movement, data from a great many cycles is required. Without several years of measurement, a single, unusual season (a particularly hot summer, for example) can skew the data enough to significantly effect regression projections. In fact, the lively thermal activity of the Cathedral has important implications for the long-term behavior of other large masonry structures.

The direct involvement of the Cathedral staff in the monitoring process has had a number of valuable benefits. For one, it has served to heighten everyone's understanding of possible structural problems within the building. Historical studies have shown that animportant factor contributing to the success of pre-scientific construction was the detailed observation by the designer/builder of the building fabric. This ensured that steps were taken to eliminate tensile cracking in the masonry and any other undesirable behavior (Mark 1990). Successful conservation of historic buildings can only be enhanced by similar perception on the part of the building staff.

The strategy described herein can be readily applied in any large masonry building to help determine sources of structural distress and to ascertain rates of crack motion. Indeed, National Parks Service engineers recently visited the Cathedral to observe the application of the remote sensing instrumentation. The result of the visit was a decision to employ similar instrumentation to monitor the tallest masonry structure ever constructed, the Washington Monument.

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