WASHINGTON MONUMENT
Seismic Assessment

National Mall, Washington DC

Final Report
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EXECUTIVE SUMMARY

On August 23, 2011, the Washington Monument (Monument) was subjected to ground shaking from the Magnitude 5.8 Mineral, Virginia earthquake (Mineral event), whose epicenter was roughly 82 miles (132 kilometers) from the National Mall. Swaying of the Monument in response to the shaking resulted in damage, primarily to the pyramidion. The Monument has been closed to the public since the earthquake event. A post-earthquake damage assessment project catalogued the damage to the Monument and that information was used to develop specifications and drawings for repair of the earthquake damage.

The Mineral event and the damage to the Monument that ensued raised questions about the seismic vulnerability of the Monument should stronger ground shaking occur in the future. The earthquake also raised questions about seismic strengthening measures that might be considered, if necessary, in order to protect the Monument during future earthquakes from damage more consequential than that which occurred on August 23. The purpose of this assessment is to address those questions, particularly as they pertain to an earthquake with a 2,475-year return period, which is commonly relied on as a basis for seismic assessments of existing structures and seismic design of new structures throughout the United States. In engineering parlance, a 2,475-year return period earthquake is called the Maximum Considered Earthquake (MCE). It is the maximum event required to be used by the building codes and other standards for seismic design of new structures and for seismic assessment of existing ones.

The seismic assessment of the vulnerability of the Monument to future earthquakes addressed the entire Monument but focused on three distinct components; the pyramidion, the shaft, and the foundation. The assessment involved multiple studies, including; studies of the type and distribution of physical damage documented subsequent to the August 23 Mineral event; conceptual studies of the general behavior of the Monument when subjected to lateral forces; and seismological studies that were used to develop a science-based understanding of the shaking intensity at the National Mall that actually occurred during the August 23 Mineral event and of the shaking that might someday occur during future 2,475-year earthquakes from various other sources. These latter studies produced synthetic mathematical representations of the shaking of the ground during the Mineral event as well as during postulated future earthquake events.

Earthquake engineering analysis studies of the Monument responding to the mathematical characterizations of ground shaking developed by the seismologists were also conducted. These analyses employed detailed computer models of the Monument that were developed as part of the assessment. The models were designed to capture the most important structural characteristics of the 555-foot tall unreinforced masonry tower, the soil beneath its base, as well as the intricacies of the pyramidion construction. In the analyses, simulations of the Monument responding to the Mineral event were run by subjecting the models to the synthetic representations of shaking during the Mineral event. The models were then validated by comparing damage predictions from the simulations with the physical damage that actually occurred during the August 23 earthquake. With the validated models, the effects of future potentially more damaging 2,475-year earthquake events were then determined by subjecting the models to mathematical representations of those earthquakes, and the significance of the predicted damage was evaluated and compared to what occurred on August 23. This general analytical approach was followed

by Wiss, Janney, Elstner Associates, Inc. (WJE), who conducted the primary detailed analyses and by Tipping Mar (TM) who conducted supplemental validation analyses using different analytical models and different analysis software. Although the analyses by WJE and TM were independent, the results revealed wide-ranging agreement between the two disparate modeling approaches. AMEC Environment and Infrastructure Inc. (AMEC) conducted the geotechnical and seismological studies utilized by the structural analyses. This report summarizes the results of these studies.

Findings

The items described below summarize the primary milestones and findings of the seismic assessment.

- When the Monument is subjected to ground shaking during an earthquake, like all other structures, it responds by swaying. That swaying causes deformation of the pyramidion, the shaft and/or the soils beneath the foundation to occur to varying degrees, depending on certain subtle characteristics of the shaking during different earthquake events. In other words, some earthquake events from some sources may excite the pyramidion relatively more than the shaft and base of the Monument, but other events may excite the shaft and base more than the pyramidion.
- The ground shaking at the National Mall during the August 23 Mineral event caused a substantial amount of deformation to the pyramidion and to the top of the shaft just below the pyramidion, but relatively little deformation to the lower portions of the shaft and to the soils beneath the foundation. The dynamic characteristics of the Mineral event caused the deformations to be concentrated in the pyramidion, which is what caused the damage to the Monument to be concentrated in the pyramidion.
- The type of damage experienced by the pyramidion and the top of the shaft during the August 23 Mineral event can be predicted reasonably well using the now understood characteristics of the shaking on the Mall on August 23 and the models developed during this seismic assessment.
- The pyramidion was found to be the most vulnerable portion of the Monument, in part because the particular motion to which it responds the most is amplified by the soil layers beneath the Monument. In engineering terms, the period of vibration of the pyramidion is very similar to the period of vibration of the soils supporting the Monument.
- The occurrence of another earthquake capable of causing more damage to the pyramidion than occurred on August 23 is judged to be extremely unlikely. This finding is based on the unusually high energy content of this earthquake in the period range of the supporting soils and the pyramidion. With respect to the particular shaking characteristics to which the pyramidion is most vulnerable, the shaking on the National Mall during the Mineral event was roughly 10 to 20% stronger than the predicted median 2,475-year event. To say it another way, a future 2,475-year event is more likely to have similar or less damage potential with respect to the pyramidion than the Mineral event. The pyramidion therefore appears to have just experienced its 2,475-year event, or similar.
- Damage to the pyramidion similar to that which occurred during the Mineral event should be expected during some 2,475-year events. That damage did not present a concern for collapse but did introduce some concern of potential falling hazards. Because of inherent randomness in earthquake generated shaking, the expected damage patterns will not be precisely the same as they were on August 23 and certain stone masonry units and joints in the pyramidion that were not damaged during the August 23 event are likely to be damaged in a future event. The severity of damage in a future 2,475-year event, however, is not predicted to be worse than what occurred during the Mineral event.
- Ground shaking from a 2,475-year earthquake that is likely to excite the shaft and base of the Monument more than the pyramidion -- and to cause substantially more deformation of the shaft and supporting soils than occurred on August 23 -- is likely to have a more distant source than the Central Virginia region that was the source of the Mineral event. A Magnitude 7.5 earthquake from the

Charleston, South Carolina source occurred in 1886. That earthquake is believed to have generated shaking intensity at the National Mall that is consistent with or exceeds the 2,475-year hazard. Charleston, South Carolina is a likely source of a future 2,475-year earthquake.

- The simulations run with the computer models being subjected to 2,475-year earthquake motions from a more distant source demonstrate that the shaft of the Monument and the soils that support are adequate to withstand a 2,475-earthquake, with some cracking of mortar joints and perhaps minor spreading of some masonry but essentially without damage to competent stone masonry units. It should be noted, however, that a number of stone masonry units in the shaft have deteriorated over the years since construction, and some have failing repairs. These locations are likely to be detrimentally affected by a future 2,475-year event.
- The finding that the structure of the shaft and soils supporting the base of the Monument are adequate to withstand a distant 2,475-year event is supported by the historical record; construction of the Monument was completed in 1884 and historical records accessed during this project do not mention that any damage occurred to the Monument during the 1886 Charleston earthquake.

Recommendations

- The pyramidion is potentially subject to being damaged again during a future 2,475-year event; careful consideration was therefore given to whether remediation of the potential for damage was necessary in order to achieve conformance with commonly invoked seismic safety expectations. These expectations, briefly described, are that the primary goal of seismic resistant design is to protect life safety that the occurrence of structural and nonstructural damage during a major earthquake is acceptable, and that such damage may or may not be repairable. While the pyramidion may well experience some damage in a future 2,475-year earthquake, the re-occurrence of damage even of the severity of what occurred during the August 23 Mineral event, with an estimated return period between 2,000 and 3,000 years, is relatively remote. Moreover, seismic safety standards employed nationally for new construction require structures to satisfy life safety criteria for a so-called “design earthquake” which is equivalent to only two-thirds of the predicted 2,475-year event. A “design earthquake” in accordance with this industry standard definition would cause substantially less damage to the pyramidion than what occurred on August 23. Seismic improvements to the pyramidion are therefore not needed to conform to the seismic safety standards that are applicable to other public and privately owned properties in the United States. However, the existing panel-to-rib connections that were not damaged during the August 23 Mineral event and will therefore not be positively attached with steel brackets during the upcoming repair phase are at some risk during future very strong but rare events and the possibility of some of these panels becoming dislodged cannot be discounted entirely. The degree of risk is difficult to characterize in part because different earthquakes have the potential to damage different panel-to-rib connections. Especially because repair work in the pyramidion is being scheduled, it would not be unreasonable to at the same time install additional earthquake-resistant panel-to-rib connections to the more vulnerable of the currently undamaged locations. The panel-to-rib connections at which two panels are supported were found to be more vulnerable, and exhibited a far greater damage rate after the Mineral event, than the panel-to-rib connections at which only a single panel is supported. In addition, the panel-to-rib connections in the course just below the tie-beams are considered to be more vulnerable. This assessment recommends that if improvements to the panel-to-rib connections are considered, these two categories of connections be considered. There are approximately 14 connections that fall into these categories.
- The shaft and the soils supporting the Monument are not vulnerable to safety-compromising damage from a 2,475-year event; seismic strengthening measures are therefore not needed to conform to the seismic safety standards that are applicable to other public and privately owned properties in the

United States. This assessment also finds that neither the shaft nor the soils is expected to experience permanent deformations more severe than minor cracking of mortar joints and minor but localized spreading of the masonry. We do, however, recommend that the deteriorated stone masonry units and damage documented on the exterior of the Monument be stabilized to limit the potential for falling hazards during a strong earthquake.