ABSTRACT

Dam engineering practice has traditionally relied on two-dimensional numerical simulations performed under plane strain conditions to estimate the seismic performance of dams. Such a decision is based on the assumption that the dam has an infinite axial length relative to its cross-section dimensions. While this approach may be applicable to certain dam configurations, it may not adequately capture the dynamic response of earth dams with complex geometries, non-uniform foundation conditions, or where significant topographic changes occur along their length.

This dissertation investigates the two- and three-dimensional seismic response of earth dams beyond the conventional canyon-bound settings, which has been the primary focus of limited three-dimensional studies. Specific emphasis is given to Gatun Dam, an iconic component of the Panama Canal system and a uniquely complex case. Gatun Dam consists of two major embankments (East and West) comprised primarily of potentially liquefiable hydraulic fill dredged and pumped from nearby borrow sites. Both embankments rest on highly irregular foundation conditions that include soft sedimentary rock, thick heterogeneous soft soil deposits, and two deep paleochannels carved by the Chagres River, reaching depths of up to 100 m beneath the dam. The combination of these features presents challenges to traditional two-dimensional modeling assumptions.

Comprehensive three-dimensional finite element models were developed for both embankments based on extensive and detailed historical, geological, and geotechnical data. The dynamic evaluation was conducted in six stages: (1) Development of a geotechnical model of the dam based on the extensive information available from multiple series of exploration campaigns, spanning from design and construction to the current time; (2) Identification of seismic liquefiable volumes of materials in the dam and in its foundations; (3) Assessment of the harmonic response

under different directional loading scenarios; (4) Seismic response analysis using two representative seismic events, the Loma Prieta and the Michoacan earthquakes, selected based on the primary sources of seismic activity at the dam site; (5) Seismic-induced cracking evaluation based on a dual criterion involving principal stress and strains fields; and (6) Post-earthquake performance analysis considering residual shear strength conditions and consolidation of liquefied zones.

The harmonic loading, although an idealized excitation, proved instrumental in identifying deformation mechanisms, liquefaction onset, and differences between the two earthquake responses. The trends and observations made under harmonic loading were consistent with the more complex seismic simulations. The results show that two-dimensional models systematically overpredict deformations and the extent of liquefaction, particularly in the central embankment zones that overlie the paleochannels. The overestimation is due to the two-dimensional restricted deformation mechanisms and the inability to capture out-of-plane stress redistribution. In contrast, three-dimensional simulations revealed spatially variable deformation patterns governed by bedrock geometry and soil stratigraphy, with liquefaction initiating at the outer edges of the paleochannels and progressing inward —a behavior absent in two-dimensional representations.

The geometry of the paleochannels and the overlying stratigraphy were found to control the deformation patterns. The West Embankment, located on top of a narrow rock channel with liquefiable foundation soils, exhibited a relatively uniform deformation profile. In contrast, the East Embankment, seated in a wider channel without liquefiable foundation layers, showed a more spatially variable deformation response with displacements concentrated at the shoulders of the channel. A comparison of transversal-only and bidirectional loading confirmed that the longitudinal component plays a secondary role in the seismic response of the dam, with the response mainly controlled by the transversal shear direction, which dictated strain accumulation and liquefaction patterns.

The simulations also highlighted the influence of the input motion characteristics on the dam's deformation response. The shorter duration and steep energy release of the Loma Prieta earthquake produced more widespread deformation, particularly on the West Embankment. In contrast, the Michoacan event—longer in duration and with gradual energy release—induced more localized deformation near the shoulders of the dam.

Seismic-induced longitudinal cracking was predicted near the crest and downstream slope, primarily controlled by the transversal component of motion. While potentially identified tensile zones generally would not intersect the piezometric level inside the dam, localized regions along the downstream slope could closely approach it, raising the concern for internal erosion under high reservoir levels. Post-earthquake deformations, frequently matching or exceeding those experienced during seismic shaking, were found concentrated on the upper and mid-portions of the downstream slope, suggesting relatively stable post-liquefaction behavior.

The outcomes of this research demonstrate the limitations of conventional plane strain analysis while also highlighting the more effective and broader applicability of three-dimensional modeling in capturing the dynamic response of earth dams under complex foundation conditions.