Final Report

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Project Title: Evaluation of Seismic Performance Factors and Pedestal Shear Strength in Elevated Water Storage Tanks

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A finite element approach was employed along with nonlinear static analysis in order to investigate the effect of axial compression on shear strength as well as the effect of wall opening on the seismic response characteristics of RC pedestals in elevated water tanks. The seismic performance factors were also evaluated in this study.

In the first part, the current ACI371R-08 equation for nominal shear strength of RC pedestals and the effect of axial compression in enhancing the shear strength of the RC pedestals was investigated. Twelve prototypes of elevated water tanks with four pedestal heights of 15, 25, 35 and 45 meters and tank sizes of 0.5, 1, 2 and 3Mgal were defined and designed based on the requirements of ACI371R-08, ASCE/SEI 7-2010 and ACI 350.3-06. Next, the pushover analysis was conducted in three stages of empty, half-full and full tank and graphs of base shear versus lateral deflection were generated.

In all of the prototypes, the maximum base shear prior to collapse of structure was highest in the full tank state. The ratio of V_n/V_{Full} was as low as 0.55 for the lightest tanks which indicates that the ACI 371R-08 estimation of nominal shear strength is nearly half of the FE model shear strength in full tank state. This ratio increased and reached to the maximum of 0.85 for heavy tanks. Moreover, in FE models with light and medium tank size, the nominal shear strength was equal or less than the maximum shear strength of the RC pedestal in empty, half-full and full tank states. In addition, the nominal shear strength was more consistent with the results of finite element analysis of prototypes with lower values of h/d_w.

It was also concluded that the shear strength calculated by finite element method for the full tank state was higher than the nominal shear strength by a factor of 1.7, 1.45 and 1.2 for light, medium and heavy tank sizes respectively. This difference is explained by the fact that the ACI371R-08 equation does not include the effect of axial compression in enhancing the shear strength of the pedestals. In addition, the contribution of axial compression was shown to be more significant in light and medium size tanks comparing to heavy tanks. The results of this section showed that the axial compression can at least increase the nominal shear strength by 20% for heavy tanks and this increase reaches up to 70% for light tank sizes.

In the second part, five FE models which were modified by adding the openings and pilaster were selected for inspecting the effect of wall opening on the nonlinear response behaviour of elevated water tanks. The width of the pilasters ranged between a minimum of 1.1m to 1.5m and additional vertical and horizontal reinforcement were provided around the opening based on requirements of ACI371R-08.

First, the critical direction of lateral loading was determined by conducting pushover analysis on the FE model of two prototypes in three directions. It was shown that the direction which is parallel to the plane of wall opening gives the lowest base shear. Next, Pushover analysis was conducted on the five FE models with openings and the resulting pushover curves were compared to the one developed for pedestals without openings. The cracking propagation pattern was studied as well and it was shown that the primary cracks were generated around the opening area for all models.

A comparison between the pushover graphs of FE models with and without opening revealed that when the openings were designed based on requirements of ACI371R-08, nearly identical nonlinear seismic response behaviour was observed. The effect of openings in the response of heavy tank size models is minor comparing to the light tank size models. This could be explained by the fact that less percentage of the cross-section area of the heavy tanks comparing to light tanks is deducted by openings. It was also shown that the difference between maximum base shear developed in models with and without openings is limited to less than 5.4%. However, no considerable change between the maximum lateral deformations was observed. The highest reduction of base shear capacity (less than 5.4%) is observed in light tank groups which were shown to have highest shear strength compared to nominal shear strength in first part and hence having insignificant effect on the response.

The results of the study also shows that for the same tank size, taller tanks demonstrate much lower maximum base shear (V_{max}) comparing to shorter tanks. Accordingly, two types of cracking propagation are observed during the pushover analysis. Elevated water tanks with a pedestal height to mean diameter ratio (h/d_w) of above 2 demonstrate flexure-shear cracking pattern which initiates at the opposite top and bottom corners of RC pedestal. However, if the h/d_w ratio is less than 2, then the cracking propagation will be in the category of web-shear cracking which starts near the base, parallel to the lateral load direction and gradually extends to the top of pedestal. These patterns could be employed for seismic rehabilitation and strengthening of existing elevated water tanks which are located in high seismicity regions and do not comply with current codes.

The overstrength factors of heavy, medium and light tank size groups are calculated to be 1.3, 1.6 and 2 respectively for elevated water tanks located in high seismicity region. As the seismicity level decreases, the overstrength factor increases. Consequently, for the lowest seismicity (level four) the overstrength factors of heavy, medium and light tank size groups increase to 4, 6 and 7 respectively. On the other hand, the range of variation of ductility factor is not wide and fluctuates between 1.5 (lightest tank in highest seismicity zone) to 3 (heaviest tank in lowest seismicity zone). The ductility factors for elevated water tanks located in high seismicity region are determined as 2, 1.8 and 1.5 for heavy, medium and light tank size groups respectively. Ductility factor is not significantly influenced by the seismicity level as it is mainly a function of geometry and material properties of the structure.

For elevated water tanks with the same height but various tank sizes which are located in the same seismicity zone, the heavier tank sizes undergo more lateral deformation and comparatively experience more damages. Furthermore, increasing the fundamental period and h/d_w ratio result in higher overstrength factor and lower ductility factor. On the other hand, as the tank size increases, the overstrength factor decreases and ductility factor increases. However, the effect of tank size on ductility factor is not significant. In the current codes and guidelines, all elevated water tanks, regardless of the tank size and pedestal dimensions are considered in the same category for seismic design. This study shows that variation of the tank size and pedestal height can significantly affect the seismic response behaviour of RC pedestals in elevated water tanks and consequently result in different seismic response factors. It is suggested that for seismic design purposes, the elevated water tanks must be divided into three groups of light, medium and heavy based on their tank sizes.

It should be mentioned that, in this study, the base of the pedestal was assumed to be rigid; other restraining conditions at the base level could be investigated and the effect of soil-structure interaction may be taken into account as well. This study does not evaluate and verify the response modification factor of elevated water tanks which may be the subject of future research studies.

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