Seismic Evaluation and Retrofit of Existing Distribution Reservoirs in Taipei City

Chen-Hsiang Lu[1], Ching-Yang Huang[2], Ing-Sen Yuan[3], and Chuan-Chiang Fan[4]

ABSTRACT

This paper presents the main results of the seismic safety assessment for the Nangang distribution reservoir in Taipei city. The distribution reservoir is an underground rectangular RC tank with maximum storage of 5000 m^3. In a recent on-site inspection, it was found that some of the support columns suffered severe damage, where significant cracking occurs at the top of the columns accompanied by buckling of the reinforcing bars inside. It was inferred that the damage was due to the so called “short column effect” resulted from the connection of the guide walls to the columns in partial height. To further exploit the cause of the damage as well as to assess the impact of the damage to the distribution reservoir, a 3D finite element model was developed using analysis package SAP2000 and was then employed to conduct seismic analysis of the distribution reservoir. The inference that the damage was mainly due to the short column effect was confirmed by the analysis results. In addition, the earthquake-resistant capability of the distribution reservoir was assessed using a draft code for seismic design of tank structures newly prepared by NCREE. In this code, the Housner’s approach (Housner, 1963) is adopted instead of the conventionally used simplified Westergaard formula for calculation of the hydrodynamic forces acting on the distribution reservoir. To realize the difference between the forces calculated using the two approaches, a comparative study was carried out for tanks of different sizes with varying water depths. It was indicated that the simplified Westergaard formula produces higher hydrodynamic force than the Housner’s approach does when the ratio of the tank length to the water depth is relatively small. Therefore, for larger tanks in Taipei city designed during 1980s~1990s like the Nangang distribution reservoir, the hydrodynamic force calculated by using the simplified Westergaard formula in design was probably under-estimated, which may fail to meet the requirements of the new design code. Finally, some retrofit measures were proposed to prevent the distribution reservoir from further development of the damage.

Keywords: Water facilities, Seismic evaluation, Distribution reservoir

INTRODUCTION

Water distribution system is the vital part of a city’s potable water supply system. It ensures that water is delivered to the citizens with proper quality, quantity and enough pressure. Once the water distribution system was not able to operate as required, the water supply service will be severely impaired. Moreover, if the distribution system was damaged during an earthquake, the secondary disaster such as fire or plaque in the city will be hard to

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control because the water could not be properly delivered. Distribution reservoirs are one of the key parts of the water distribution system, the purpose of which is to store the treated water for delivery and to maintain constant pressure within the distribution pipes. The distribution reservoirs can also provide with water in case of emergent situations.

There are many distribution reservoirs in the Taipei city. Because of their importance, the authority, i.e., the Taipei Water Department has commissioned projects in the past years to assess the safety and operation function of the distribution reservoirs during earthquakes and to propose suitable retrofit measures if necessary. This paper presents the main results of the safety assessment for the Nangang distribution reservoir, which is an underground rectangular RC tank with maximum storage of 5000 m^3. The distribution reservoir was built and started operating in 1988 and has been in service over almost 30 years.

In the analysis of the tank-like structures, the hydrodynamic pressure induced by the fluid contained inside the tank during earthquakes is an important loading to be considered. For the distribution structures in Taipei city designed over 20 years ago, the earthquake-induced hydrodynamic force was almost calculated using the simplified Westergaard (1931) [1] formula assuming infinite fluid domain. It is obvious that the assumption of infinite fluid domain is not appropriate for the case of tank structures where the water domain is finite. As a result, the Housner's approach (Housner, 1963) [3] that is capable of calculating the hydrodynamic force for the case of finite fluid domain was employed in the new code "Seismic Design of Potable Water Tank Structure" [2] drafted by the National Center for Research on Earthquake Engineering (NCREE) of Taiwan in 2016. The Housner's approach employed in the new code is the same as that suggested in ACI 350.3-06 (Seismic Design of Liquid-Containing Concrete Structures and Commentary)[4]. The above-mentioned new code was adopted for the safety assessment of the Nangang Distribution Reservoir. As a part of the safety assessment, a case study was conducted to exploit the difference of the hydrodynamic forces calculated by using the two approaches, which will be presented in the paper.

ON-SITE INSPECTION

The dimension of the Nangang distribution reservoir is 34.02m long, 27m wide and 5.8m high(Fig. 1). There are 30 circular columns with 45cm in diameter placed equally in the reservoir base. Interim walls connecting the columns are provided to guide the water flow. These guide walls are 15cm in thickness with one layer of reinforcing steel bars (Fig. 2). The compressive strength of the concrete of the walls and columns f_c'is 280 kgf/cm^2 and the yielding strength of the steel bars f_y is 2,800 kgf/cm^2.

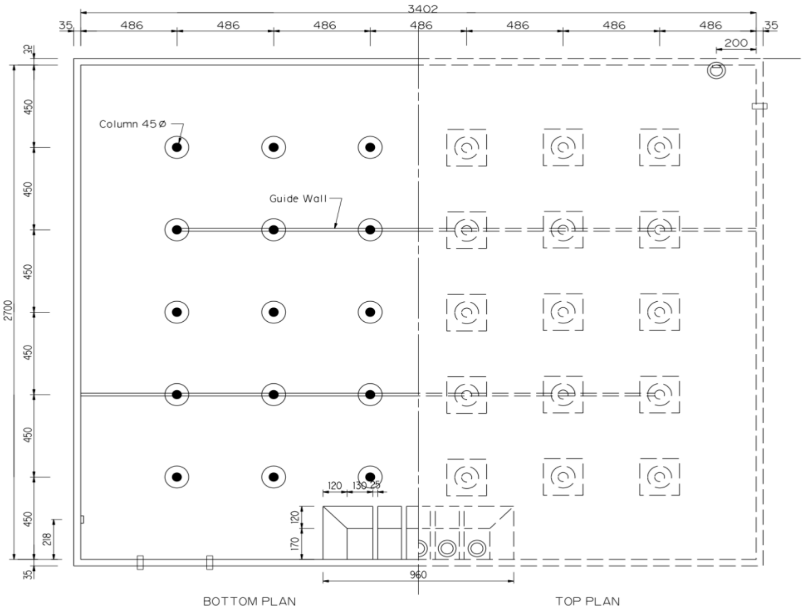


Figure 1. Plan View of Nangang Distribution Reservoir

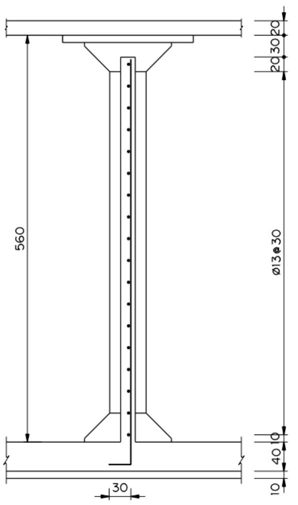


Figure 2. Section of Guide Walls of Nangang Distribution Reservoir

The on-site inspection reveals that the reservoir has suffered from some damages (Fig. 3). Visible cracks were found appearing on the columns, guide walls and bottom slab. Among these cracks, those occurring at the top of the columns (Fig. 4) are relatively sever. In addition to cracking, some of the reinforcing bars within the columns were exposed and buckled (Fig. 4).

Figure 3. Damages of Nangang Distribution Reservoir by On-Site Inspection

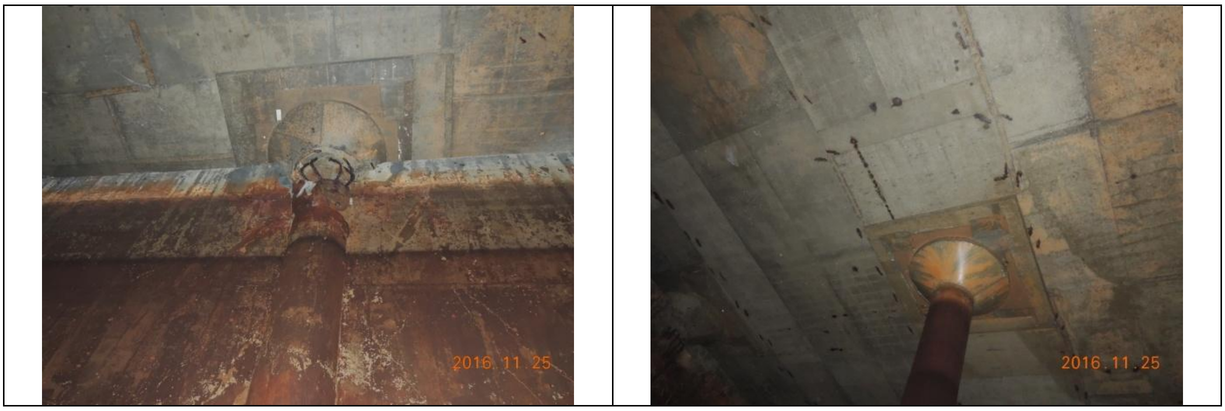


Figure 4. Exposure of Reinforcing Bars Within Columns of Nangang Distribution Reservoir

It was also found that only columns connecting to the guide walls were damaged and the others, i.e., not connecting to the guide walls are nearly intact. Based on the fact, it was inferred that the damage was mainly due to the so called “short column effect” resulted from the connection of the guide walls to the columns in partial height. This “short column” effect is often seen in school buildings with window openings. The guide walls connecting to the column were also damaged, where several 45-degree cracks can be observed on the wall panel.

STRUCTURAL ANALYSIS AND SEISMIC ASSESSMENT

The structural analysis of the distribution reservoir was carried out using finite element package SAP2000. A 3D finite element model of the distribution reservoir was developed, in which the slab and the walls were modeled using SHELL element, while the columns were modeled using BEAM element (Fig. 5).

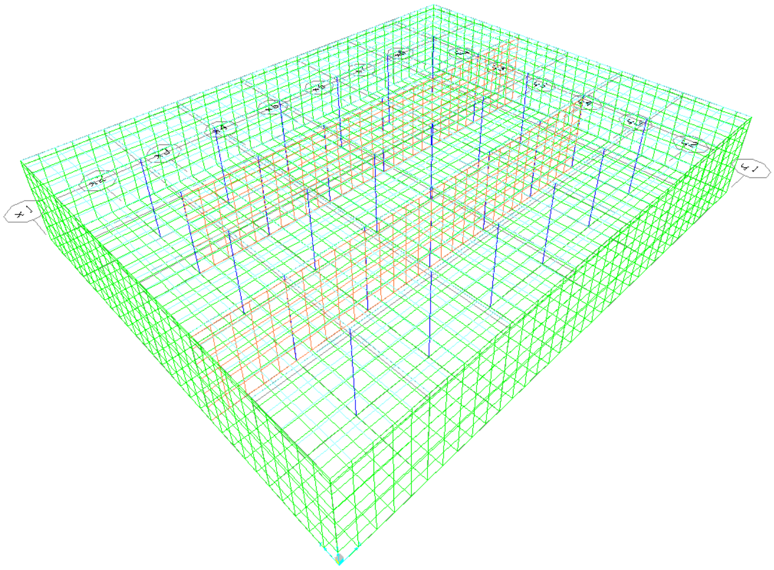
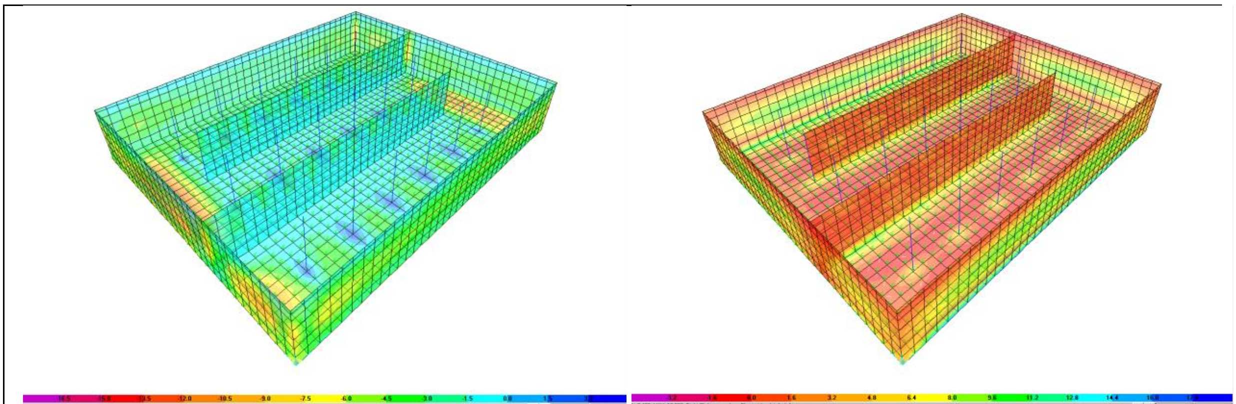


Figure 5. A 3D Finite Element Model for Nangang Distribution Reservoir

Loadings considered in the analysis include self weight, static and dynamic soil pressures and hydrostatic and hydrodynamic pressures of the liquid inside the reservoir, the calculation of which followed the approaches specified in the draft code. The results of the analysis are presented in what follows.

The contour of the moments of the reservoir along the two principle directions, i.e., M11 and M22 are shown in Figure 6.



M11	M22

Figure 6. Moment Contours of Nangang Distribution Reservoir (roof slab removed for clarity)

The flexural and shear capacities of the slab and of the walls are both enough. However, some of the columns connecting to the guide walls fail to the shear capacity check (Fig. 7). The shear capacity of the columns is 0.056cm^2, which is far less than the demand obtained by the analysis. The inference that the damage was mainly due to the short column effect posed by on-site inspection results was confirmed by the analysis result. The results of the structural analysis agree generally well with those by the on-site inspection (Fig. 8).

In general, the Nangang distribution reservoir satisfies the requirements for seismic case suggested by the newly proposed code.

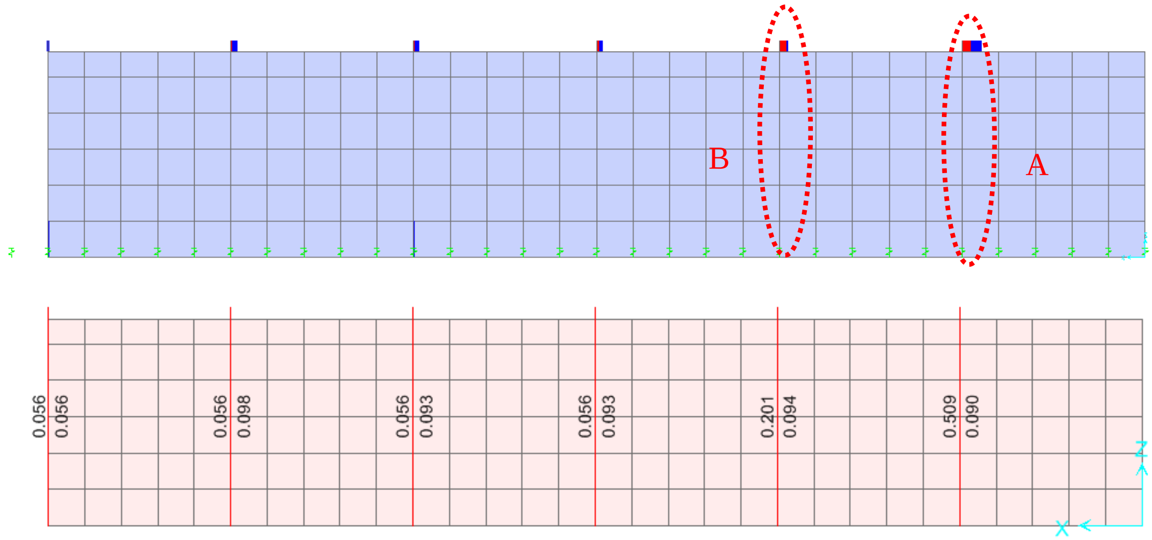


Figure 7. Shear Demand and Capacity of Columns

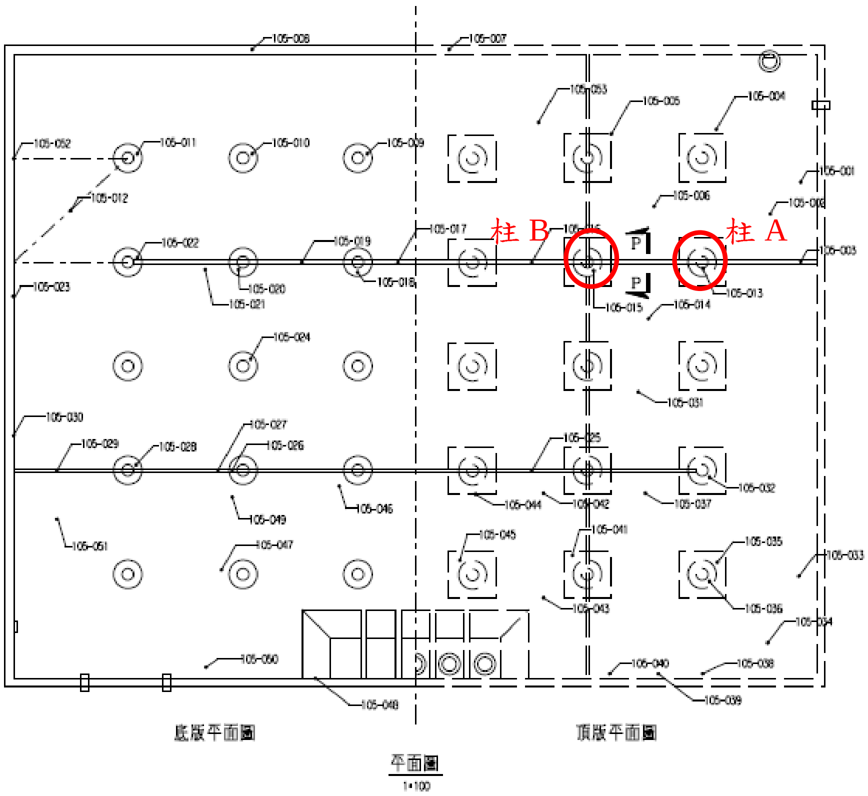


Figure 8. Damage Distribution of Nangan Distribution Reservoir

Due to the constraint of the guide walls, the non-constrained length of the columns is drastically reduced, which produces the short column effect. As a result, the columns closer to the side walls (denoted as A and B in Fig. 8) are constrained more largely than the others, resulting in more damages.

COMPARISON OF WESTERGAARD ANG HOUSNER APPROACHES

The simplified Westergaard's formula has long been widely used for calculating the hydrodynamic force induced by earthquakes in hydraulic and dam engineering. It was also used for tank design [5] in Taiwan during 1980s~1990s. The simplified Westergaard formula assuming infinite fluid domain can be written as follows,

$$P = \frac{7}{12} k_h \gamma_w {H_L}^2$$

where *P*= total hydrodynamic force, k_h =0.4S_{DS} and H_L=water depth.

The Housner's approach considers the sloshing effect of the water containing in the tank during earthquakes. In the approach, the hydrodynamic force is divided into convective (Pc) and impulsive (Pi) parts, as depicted in Fig. 12.

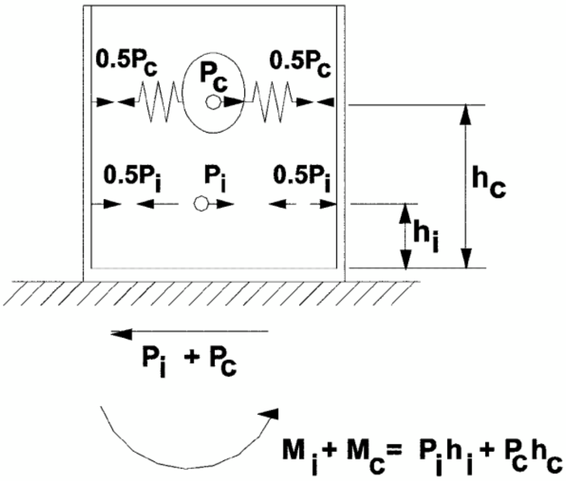


Figure 12. Dynamic Model of Liquid-Containing Tank [Fig. R9.1 ACI 350.3]

The simplified Westergaard formula only involves the height of the water, but the Housner's approach takes into account the size of the tank in addition. To realize the difference of the two approaches, various L/H_L ratios were considered, where L and H_L are respectively the depth of the water and the length of the tank. Impulsive and convective forces were both calculated and the moments at the base of the tank wall were then obtained. Since the maximum value of the impulsive force and that of the convective force do not occur simultaneously, the combined moment M_{comb} was used, which is determined as

$$M_{comb} = \sqrt{M_{imp}^2 + M_{conv}^2}$$

The forces calculated for different L/H_L ratios by the Housner's approach are listed in Table 1. In addition, the moments for different cases are plotted in Figure 13 to better display the differences.

TABLE I. Forces for Different L/H_L Ratios Calculated by Housner's Approach

L (m)	H_L (m)	L/H_L	P_i (tf/m)	P_c (tf/m)	M_{imp}(tf-m/m)	M_{conv}(tf-m/m)	M_{comb} (tf-m/m)
1.25	5.0	0.25	2.46	0.49	0.49	0.49	0.49
2.5	5.0	0.5	4.94	0.98	0.98	0.98	0.98

5.0	5.0	1.0	8.64	1.94	1.94	1.94	1.94
10.0	5.0	2.0	11.59	3.31	3.31	3.31	3.31
15.0	5.0	3.0	12.31	3.60	3.60	3.60	3.60
20.0	5.0	4.0	12.44	3.40	3.40	3.40	3.40
25.0	5.0	5.0	12.46	3.06	3.06	3.06	3.06
30.0	5.0	6.0	12.47	2.74	2.74	2.74	2.74
35.0	5.0	7.0	12.47	2.45	2.45	2.45	2.45
40.0	5.0	8.0	12.47	2.21	2.21	2.21	2.21
45.0	5.0	9.0	12.47	2.01	2.01	2.01	2.01

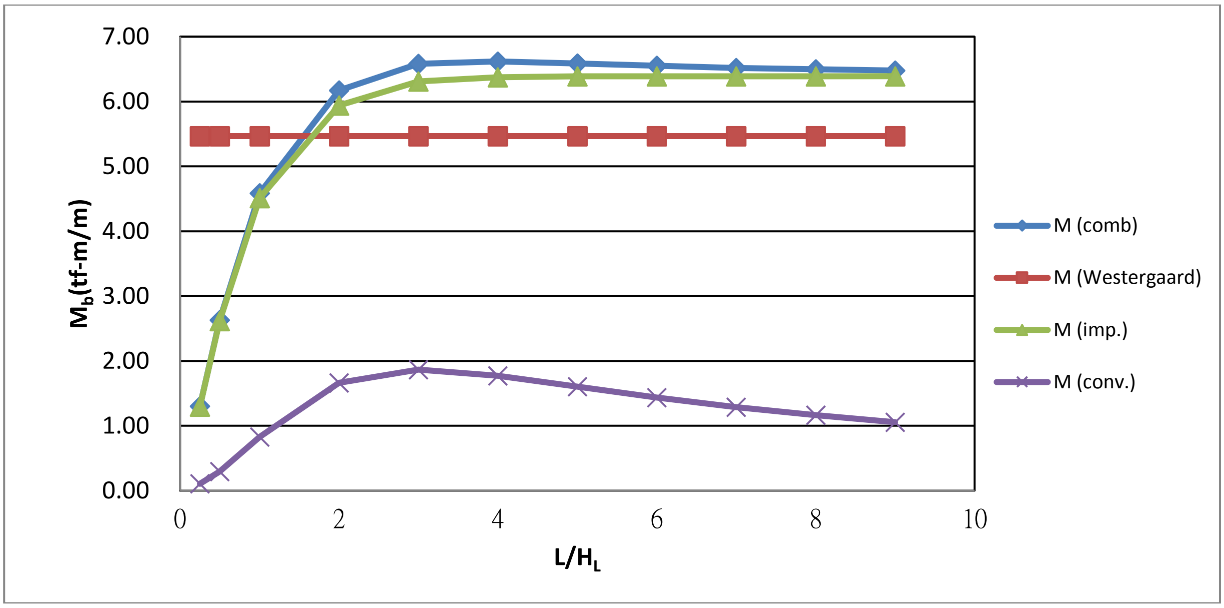


Figure 13. Moments at the Base of Wall by Two Approaches

Because the simplified Westergaard formula only takes into account the water depth H_L, the moment at the base of the wall does not vary with the tank length. When the L/H_L ratio is smaller than 2.0, which stands for "taller" tanks, the Westergaard formula produces larger moments than the Housner's approach does. While as the L/H_L ratio gets larger, the Housner's approach produces larger moments.

It can be concluded from the comparison that for smaller tanks, which usually have lower L/H_L ratios, the hydrodynamic force was probably over-estimated if the simplified Westergaard formula was used, while on the contrary for larger tanks such as distribution reservoirs the hydrodynamic force may be under-estimated.

RETROFIT MEASURES

The following measures were proposed to retrofit the columns of the distribution reservoir to prevent the columns from appearing the short column effect.

1. Column Retrofitting

The direct way is to increase the column strength. The columns were designed to be retrofitted with 20cm thickness jacket of concrete. Additional longitudinal and transversal reinforcement would be placed in the concrete jacket. To achieve a proper bond for the RC jacket, the longitudinal rebars should be fixed in top and bottom slabs using chemical anchors.

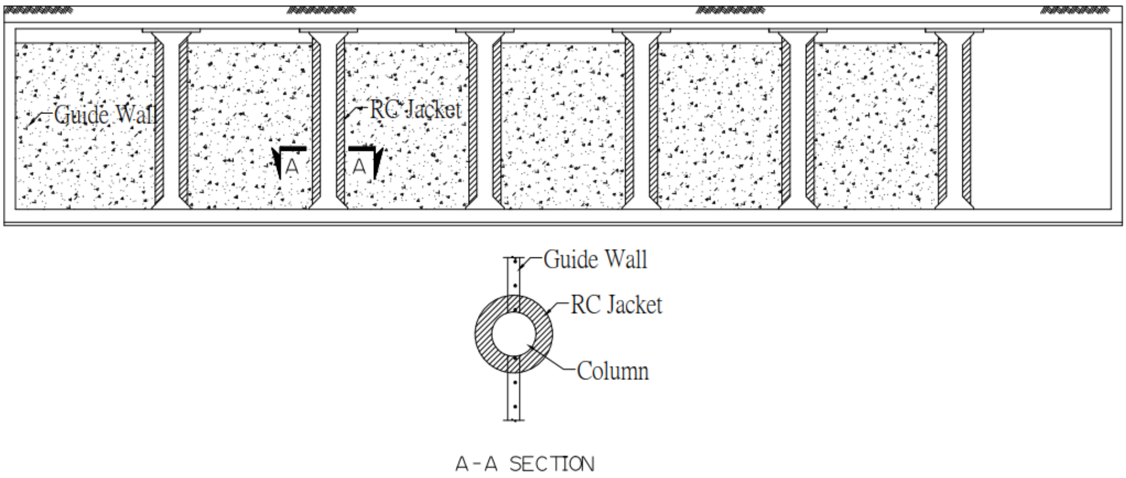


Figure 9. Retrofit with RC Jacket

2. Guide Wall Retrofitting

Since the “short column” effect is due to the partial height wall adjacent to columns, one simply way to eliminate the effect is to increase the wall height to its full height. Partial top wall should be demolished first and rebuilt to full height. Additional reinforcements should be provided to splice existing reinforcement and fixed at top slab by chemical anchor.

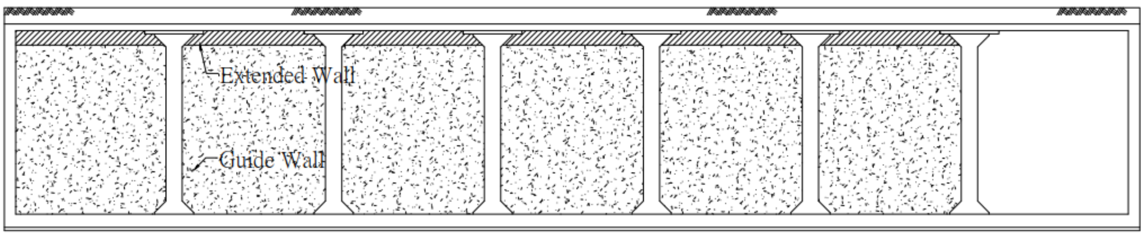


Figure 10. Retrofit the Wall to Full Height

3. Lower the Height of Guide Wall

Different from the second retrofit measure, part of the guide walls is demolished to increase the effective length of the columns. If the height of the wall is decreased by half, the strength of the column will be enough to resist lateral force. This is the most easy and economical way to cut down the short column effect. However, function of the guide wall will be compromised and the flow efficiency may be impaired.

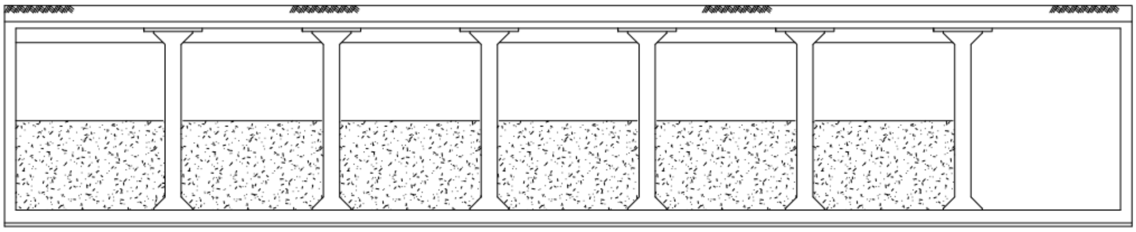


Figure 11. Guide Wall Reduced to 50% Height

CONCLUSIONS

Seismic assessment of the Nangang reservoir was carried out by employing the draft code "Seismic Design of Potable Water Tank Structure " prepared by NCREE in 2016. Overall, the earthquake-resistant capacity of the distribution reservoir is still sufficient according to the code. However, some of the support columns do not have enough capacity to sustain the shear load amplified by unfavorable "short column" effect. Measures that retrofit the columns with 20 cm thickness RC jackets or increase the height of the guide walls to its full height are advised to eliminate the short column effect. For design of distribution reservoirs with interior walls in the future, the "short column" effect should be carefully avoided or properly resisted.

From the results of comparison study, it was indicated that the simplified Westergaard formula produces higher hydrodynamic force than the Housner's approach does when the ratio of the tank length to the water depth is relatively small (<2.0). Therefore, larger tanks in Taipei city designed during 1980s~1990s like the Nangang distribution reservoir, the hydrodynamic force calculated by using the simplified Westergaard formula in design was probably under-estimated, which may fail to meet the requirements of the new design code.

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