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Seismic design of concrete water retaining structures

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ABSTRACT

This paper presents simplified approach for seismic design of concrete water retaining structures using the provisions of the National Building Code of Canada (NBCC). The proposed approach is based on serviceability criteria and the level of performance for concrete structures. Four levels of damage are identified and discussed. The application of the proposed design method is illustrated with the aid of an example. Results are then compared with two other widely acceptable design methods.

INTRODUCTION

Concrete water retaining structures are considered as essential facilities that require special care and accuracy in their design. In these structures, crack and leakage control are of prime design considerations. For this reason, serviceability becomes the major factor in the design.

The objectives of building codes such as CAN3-A23.3-M84 (1984) and ACI 318 (1989) are that reinforced concrete structures should be designed in a ductile manner to allow these structures absorb energy in the inelastic range during a major earthquake without major loss in strength. However, in the case of water retaining structures, these structures should be designed to remain safe during a major earthquake and maintain the required serviceability after a major earthquake. Therefore, the concept of serviceability in terms of performance criteria becomes an important parameter for the design of these types of structures.

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It is the objective of this paper to make recommendation for seismic design of concrete water retaining structures based on serviceability requirements. Four different levels of damage for concrete tanks are identified based on the importance and expected performance of the structure. In this fashion, substantial savings in construction cost can be achieved if some degree of damage can be tolerated in the structure without loss of life.

BEHAVIOUR OF LIQUID RETAINING STRUCTURES

The most traditional approach that considers hydrodynamic effects for water retaining structures has been developed by Housner (1957). This approach which applies to flat bottomed tanks of rectangular, circular or uniform sections separates the liquid inside the tank into two parts. As shown in figure 1, the lower portion of the liquid acts as a rigid mass of weight W_o when accelerated by horizontal and/or vertical ground motion. This is defined as an impulsive force. The upper portion of the liquid is affected by the slosh motion which acts as a flexible mass of weight W_1. This is defined as a convective force. Although Housner's approach is based on simplifications and assumptions, it has proved to be sufficiently accurate for design purposes and is widely used by engineering profession. However, other researchers have made certain modifications to Housner's model. Some of these improvements have been made by Veletsos and Yang (1977), and Balendra (1982) for determining impulsive forces.

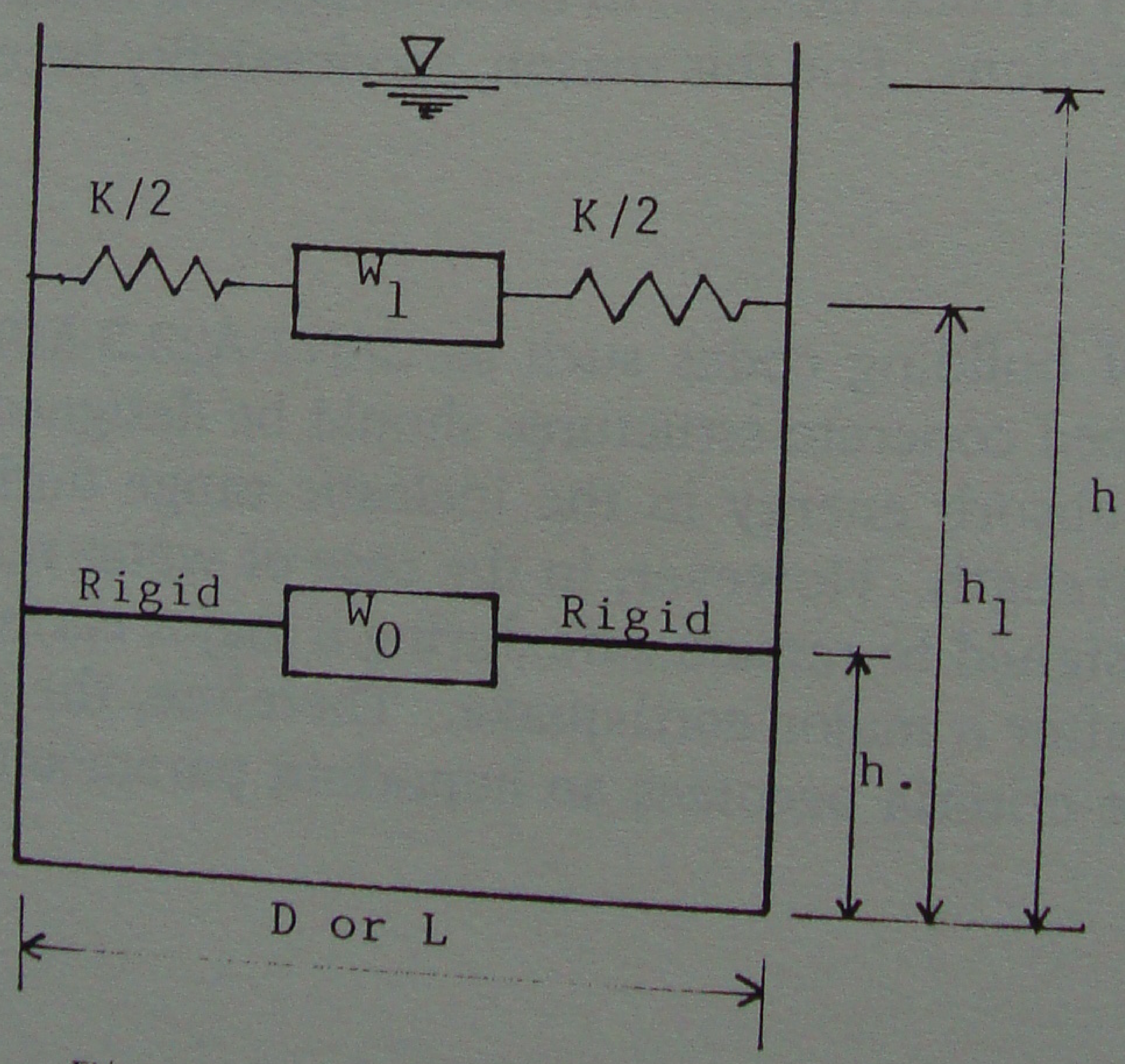

Figure 1. Tank model

Currently, there is a wide range of information available in the literature for the seismic analysis and design of water retaining structures. There are very few provisions in the North American building codes for their seismic design. The Uniform Building Code (1988) is the only recognized code that directly addresses seismic provisions for liquid holding tanks, and it does so only in a very general manner.

There are other standards that address seismic design for water retaining structures. These include the NSF report (1980), and the TID-7024 report (1963). These two methods are widely used in practice. The ANSI/AWWA standards (1986) and the Appendix E of the Petroleum Institute API-650 (1980) also address seismic design for tanks. In all of these standards, there are no specific statements related to concrete tanks. The performance criteria which is a crucial parameter for the design of water retaining structures is not clearly addressed in these standards.

The concept of performance criteria has been discussed by Priestley et al (1986) and recommendations have been made to the New Zealand National Society for Earthquake Engineering for inclusion in a code form for use by the design profession. A similar concept has also been discussed by Ikeda (1989) and has been adopted by the Committee on concrete in the Japan Society of Civil Engineering.

PROPOSED DESIGN CRITERIA

Based on the concept of performance criteria, an initial step in design of concrete water retaining structures is to categorize these structures in accordance with the type and importance of the structure. In categorizing water retaining structures, consequent disaster such as gas explosion and fires should be considered. In general, concrete water retaining structures can be divided into four different categories as follows:

Category 1 - Non-critical structures
For structures in this category, significant damage is not important. The entire system may be shut down after a major earthquake. These structures may undergo significant damage without collapse. Strengthening and/or repair of the structure will be necessary after a major earthquake.

Category 2 - Semi-critical structures
These structures are allowed to undergo limited damage without any required strengthening after a major earthquake. Major cracks and major leakage is acceptable. It should be possible to repair damages after a major earthquake.

Category 3 - Critical structures
In these structures, minor cracks and limited leakage in some local areas due to overstressing due to a major earthquake is acceptable.

Category 4 - Highly-critical structures
Structures in this category must remain fully functional and all components should retain their structural integrity. No cracks and no leakage is acceptable under the design loads.

Application of the proposed design method using NBCC

Based on the concept of the proposed design method using the performance criteria described above, it is possible to estimate the design forces for concrete water retaining structures using the NBCC (1990).
In the NBCC, the minimum lateral seismic force at the base of the structure is given by:

$$V = (V_e/R)U$$

where $U = 0.6$
V_e denotes the equivalent lateral seismic force
R denotes the force modification factor that reflects the capability of a structure to dissipate energy through inelastic behaviour.

In this formula, the R value can be assigned different values depending on the level of damage that can be tolerated. The suggested values for R are as follows:

Category 1 - Non-critical structures, $R = 2.5$
Category 2 - Semi-critical structures, $R = 1.8$
Category 3 - Critical structures, $R = 1.4$
Category 4 - Highly-critical structures, $R = 1.0$

Design example

The application of the proposed design method is illustrated here with the aid of an example. Results are then compared with two other well known design techniques that are commonly used by engineering profession. These are the TID-7024 (1963) method and the NSF (1980) method.

The TID-7024 approach is based on Housner's method. Using this approach, response spectrum data is necessary. In the NSF approach, information regarding the acceleration coefficients, the response modification factor and the period of vibration for the structure and sloshing water is necessary.

Details and dimensions of an above ground cylindrical tank used as an example are shown in figure 2. This example was taken from page VII-78 of the NSF report (1980). The seismic design forces are computed based on the following assumptions:

- The structure rests on a rigid foundation
- The structure is located in a high seismic risk zone. The acceleration coefficient is 0.40 and the zonal velocity ratio (v) is 0.4.
- The damping factor for structure and sloshing action is 5% and 0.5% of critical respectively.
- To determine the base moments, the point of application of impulsive force act at a distance of 3/8 h above the base of the tank. This is consistent with the assumption of parabolic distribution of lateral seismic hydrostatic loads.
- The working strength method is used in design.

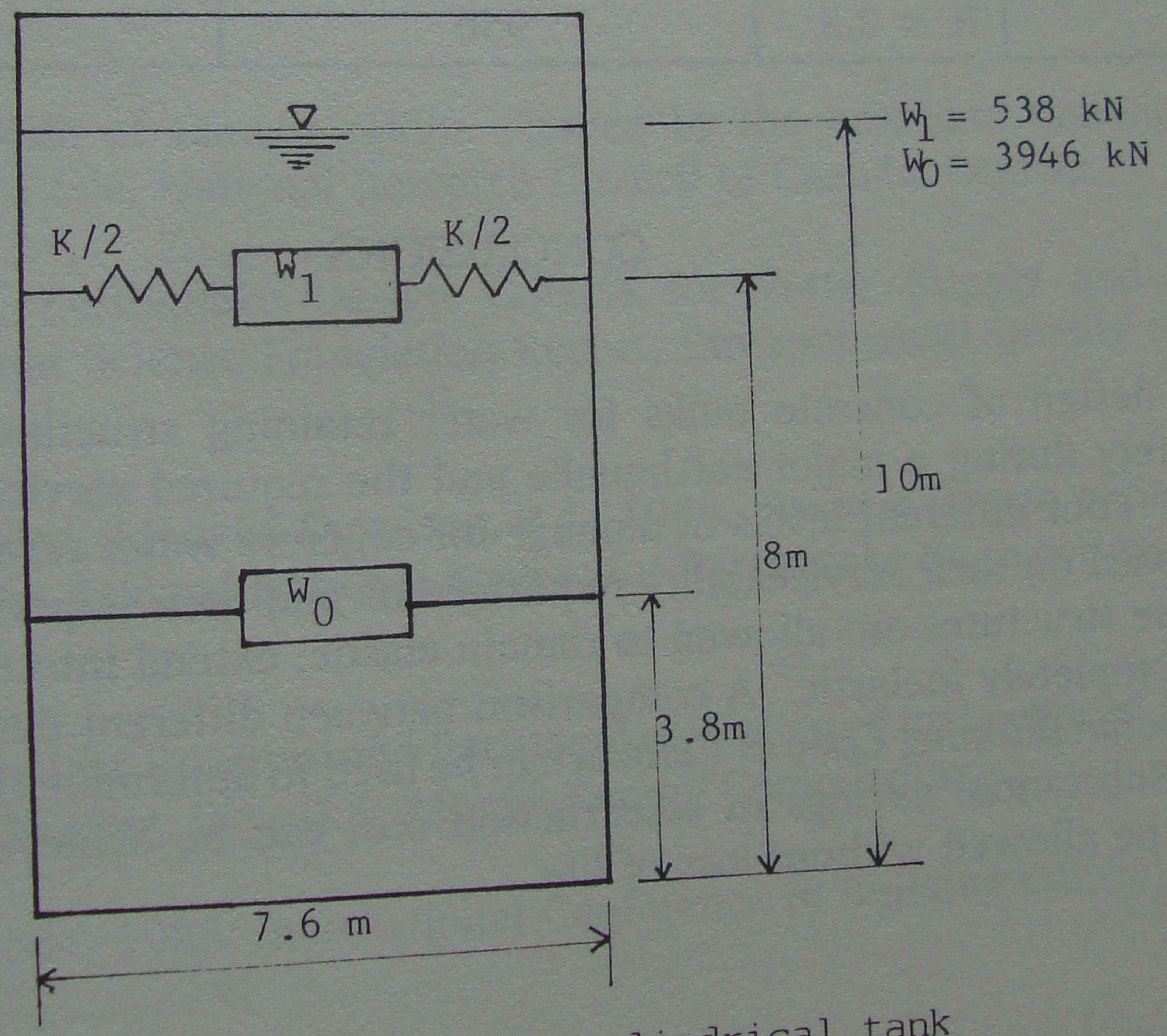

Figure 2. Details of cylindrical tank selected for design example

Table 1 shows a comparison in base shears and base moments using the three different approaches. These results show that the NBCC values for R=1.4 are very similar to the values obtained from the two other methods. This is because for values of R=1.4 or less, the behaviour of the tank approaches elastic response. The NSF approach and the TID-7024 approach are also based on elastic response. For values of R=1.8 and 2.5, the NBCC values are considerably less than the other two methods. This is clearly an indication that the response has been extended into the inelastic range.

Table 1 - Comparison of base shears and base moments for different design methods

Method		Base Shear (kN)	Base Moment (kNm)
TID-7024		1784	7137
NSF		1659	7945
Proposed NBCC	R = 1.0	2393	9309
	R = 1.4	1708	6649
	R = 1.8	1329	5172
	R = 2.5	956	3726

CONCLUSIONS

The design of concrete tanks for water retaining structures should ensure the required safety during a major earthquake and the required serviceability after a major earthquake. Four different levels of damage for concrete water retaining structures were identified based on their serviceability requirements and their importance. Based on such criteria, these structures are allowed to remain elastic; extend into elastic/inelastic range or behave completely inelastic. A comparison between different design methods showed that the National Building Code of Canada can be used to determine the design forces fairly accurately. Substantial savings in construction cost can be achieved if some degree of damage can be allowed without loss of life.

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