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The nonlinear analysis of an innovative slit reinforced concrete water tower in seismic regions

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ABSTRACT

Water towers are widely used in our society as one of water distribution facilities within water network systems. In the event of a severe earthquake, however, a single plastic hinge that occurs in a water tower could cause its total collapse before nonlinear resources of the rest of the tower remains fully utilised. This research presents an innovative technique for the assembly of a water tower using the slits in its reinforced concrete shaft for the purpose of mitigating the seismic response. Slit shafts were designed to have four slits at 90° intervals along the full height of the shafts. The shaft parts were connected to each other at the bottom, top and every five meters with coupling beams. The slit width was used as a variable in this study which varied between 50 mm and 2000 mm. The nonlinear seismic performance of the proposed slit towers was analysed by means of a finite element approach with respect to soil types defined in Eurocode 8 and seismic behaviour were compared to the solid water tower. A detailed observation of the compression and tension stress distributions with respect to the slit width was performed.

The obtained analytical results revealed that slit width in the reinforced concrete tower affect the failure mode and stiffness of a water tower significantly. With an appropriate design, the conversion of a solid water tower into a slit tower can significantly increase its ductility under seismic action without significantly compromising its bearing capacity. The results showed that contours of tension and compression stress intensity in shafts, which could lead to a failure of water towers, highly depended on the slit width. In the solid water tower, the stress concentration dominated at the base of the shaft, however in the narrow slit water towers the stresses were equally distributed along the height of the shafts. Also, the stresses were mostly concentrated at the top of the shafts in the wide slit water towers. Conclusively, the results provided useful information regarding the compression stress distribution along the slit shafts in the water towers which can be used in obtaining an optimum slit shaft design for different soil types.

1. Introduction

There are a large number of water towers around the world which play an imperative role in municipal water supply and firefighting systems. Particularly, in the event of an earthquake, a water tower would become a vital lifeline and is expected to remain functional to serve, as a provider of portable water and for firefighting operations. The failure or malfunction of this essential infrastructure would disrupt the emergency response and recovery operation after an earthquake.

There have been numerous studies carried out on water tower regarding its fluid-structure interaction and seismic performance [1–3]. However, limited study has been conducted on RC shaft performance [4]. Unlike commonly constructed building structures whose actions do not vary too much during their lifetime, the actions on a water tower varies significantly whilst working in the water system. The overall weight of an empty water tower may drop to 20% of the full tank state. Such variation of the gravity load makes the seismic design of a water tower become more complicated. Furthermore, water towers do not have redundant members and therefore do not have any load redistribution path. During a strong seismic event, even if the water tank can survive, damages in the water tower itself could result in a total collapse, because of its low redundancy and poor ductility.

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The poor performance of water towers in many earthquakes have been documented in literature such as; Jabalpur 1997 [5], Bhuj 2001 [6], Chile 1960 [7], and Manjil Roudbar 1990 [8]. The extent of the damages ranges from minor cracks in the tower shaft to complete collapse of the entire towers.

Monolithic reinforced concrete (RC) water tower have relatively high load-bearing resistance and flexural stiffness. However, it does not show significant ductile behaviour. Ductile behaviour in RC water towers occurs by yielding of the flexural reinforcement in the tower shafts and development of a plastic hinge [9].

There are a number of seismic strategies to mitigate the damages on tower shaft and to prevent collapses of water towers. One is to increase the load-bearing resistance and flexural stiffness by increasing the thickness and reinforcements of a tower. However, it also increases seismic effect of the water tower due to the increase of the tower stiffness. Another is to decrease the seismic effects through energy dissipation system.

Numerous investigations have been conducted to improve the ductility of shear walls subjected to seismic loads and some practical solutions were proposed. The research aim was to reduce the energy concentration from the base of the wall and distribute it along whole height of the wall. In the early 1970s, an improved type of the shear wall called the slit shear wall was proposed by Mutoh [10] to improve the shear wall performance against lateral forces. The slit wall showed an increase of the ductility and seismic energy dissipation due to slits and connectors between parts of the wall. Further studies by other researches revealed an increase in the ductility within the slit shear walls in comparison to normal shear walls without undermining of load-bearing resistance [11,12]. Although this technique has been used in shear wall, no report has been found on its use in water tower.

This paper presents an innovative system of assembling water tower using a slit wall technique for the purpose of reducing seismic effects more uniformly distributed across the shaft height, which may lead to a decreased ductility demand at the base without decline of load-bearing resistance. The proposed silt water tower is analysed using finite element method to verify its nonlinear performance in an earthquake. The relevant results can be refereed to for the design of water towers in seismic zone.

2. Solid and slit water tower

The particular water tower configuration considered as solid model in this study is that of an actual Anjar Nagar Palika water tower which was damaged in the Bhuj earthquake that occurred on January 26th 2001 which reached a magnitude of 7.7 [13]. The tension-flexure cracks in the tower shaft were observed up to one third the height of the shaft. These cracks were parallel to the ground and covered the entire perimeter of the shaft. The cracks passed through the thin section of the shaft and were clearly visible from outside and inside. This damage to the staging seriously reduced its lateral load carrying capacity, increased its susceptibility to a greater damage or collapse in a repeat occurrence of such an event. Some simplifications have been done for the water tower model, however the effects of such simplification was found to have little effect on the total response. The simplified model of the Anjar Nagar Palika water tower shown in Fig. 1 and other properties of the water tower are given in Table 1.

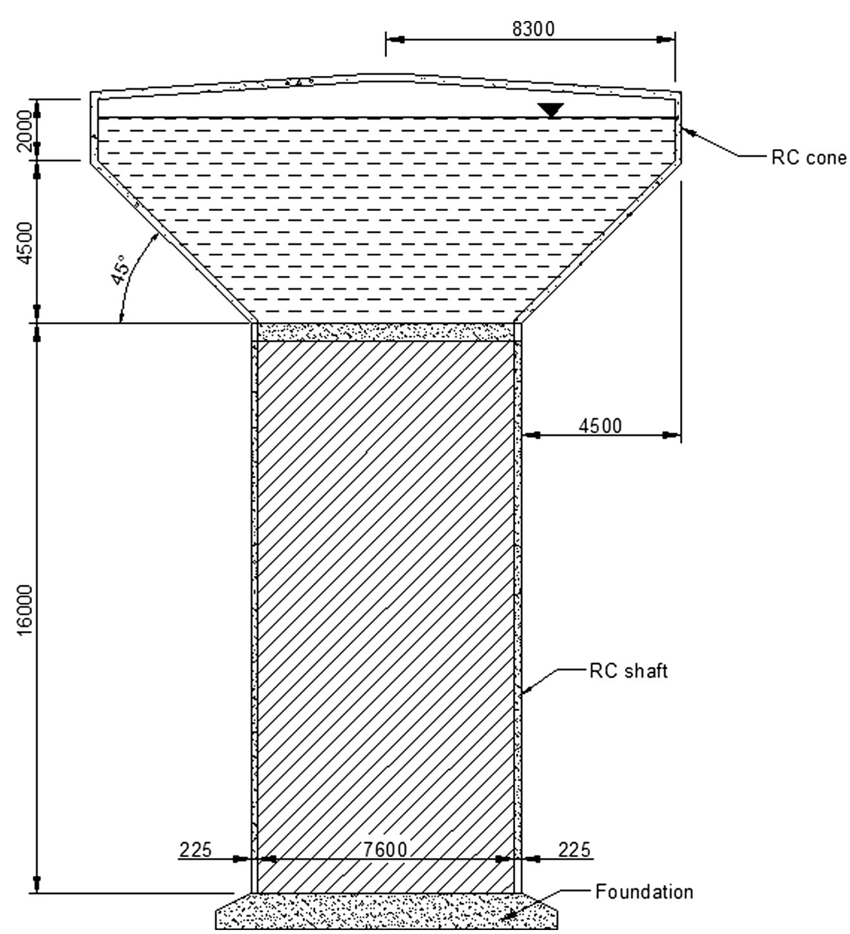

Fig. 1. Simplified model of the Anjar Nagar Palika water tower.