Avoiding moat wall pounding of base-isolated buildings using D3 viscous dampers

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ABSTRACT

Base-isolated buildings are typically important facilities that are expected to remain functional after a major earthquake. Seismically isolated buildings can experience large displacements at the isolation level during strong earthquake excitations, which can exceed the rattle space clearance and potentially cause pounding against the moat wall. The impact can transfer large accelerations to the superstructure, which can damage both structural and nonstructural components. To accommodate such large displacements, a sufficiently wide clearance must be provided around the building and the surrounding moat wall. However, the width of the seismic gap is limited by practical and architectural constraints, as well as associated costs. Additionally, for existing buildings, the available clearance may not be sufficient given the evolution of the seismic hazard characterization.

One solution to reduce the isolation system lateral displacement with a focus on its velocity is to place viscous dampers at the isolation interface. However, providing constant damping through viscous dampers may increase the force of the superstructure, especially for ULS earthquakes where displacement reduction is not necessary.

A D3 viscous damper can provide damping in any desirable quadrants, and therefore, this type of damper can be tailored to improve the performance of the isolated building by providing force only at critical displacement and recentering the isolation system.

This paper explores the seismic performance enhancement of a base-isolated building provided with D3 viscous dampers. The results show that using D3 viscous dampers could reduce the instances of moat wall contact and residual displacement for large earthquakes without reducing the performance of the base isolation during moderate earthquakes.

1 INTRODUCTION

Base isolation is an effective earthquake mitigation strategy, and it has been implemented in over 3000 buildings in Japan, over 200 buildings in the USA, and several more in New Zealand, China, Taiwan, Italy, Russia, and Turkey. The New Zealand base isolation guideline, published in 2019 by Whittaker, outlines three critical design checks for isolated buildings:

1. The isolator and rattle space displacement need to be checked for Collapse Avoidance Limits State (CALS).
2. The superstructure forces and isolator stability structure need to be checked at the Ultimate Limit State (ULS).
3. The superstructure displacement needs to be checked at the ULS.

The first design check ensures that the base isolation parameters are set to prevent the isolated building from reaching the moat walls during a Collapse Avoidance Limits State (CALS) event. If the clearance between the building and the walls is exceeded, moatwall pounding can occur, which transfers large forces into the building and affects critical Engineering Demand Parameters (EDPs) of the superstructure, such as story shears, floor accelerations, and inter-storey drifts [Bustamante 2022]. According to Bustamante et al. (2022), moat wall pounding can increase floor accelerations by up to three times, depending on the impact velocity.

There are several buildings that were designed before the publication of the New Zealand base isolation guideline. Additionally, the updated seismic hazard demand in New Zealand has increased by 1.5-3 times, which means that the required rattle space needs to be increased by the same amount. As a result, there are several isolated buildings that are vulnerable to moat wall pounding effects and do not meet the design criteria outlined in the guideline.

A common alternative solution to moat wall pounding is to install fluid viscous dampers, which provide additional damping to the base isolation system. However, several studies have shown that the addition of dampers generally increases drifts and story shear forces, while reducing isolation displacement. This effect is more pronounced when nonlinear dampers are used [Kelly 1999, Wolff 2015, Fatahi 2015, Providakis 2009, Providakis 2008].

Providakis's study (2008-2009) indicates the effect of increasing shear force, acceleration, and drift is the result of 'too much damping' in the weaker far-field motions, particularly when the damping is nonlinear. This is consistent with the observations of Hall and Ryan (2000) and Politopoulos (2008) who concluded that too much of linear viscous damping may be detrimental. The increase in these parameters can affect the critical design checks No. 2 and 3 mentioned earlier, requiring a redesign or retrofit of the superstructure.

On one hand, damping force is needed to prevent moat wall pounding, which can cause shock accelerations two to three times greater than the original earthquake. On the other hand, we do not want to increase shear force and acceleration at the ULS limit state. Additionally, base isolations often have residual displacement after large earthquakes, which can affect their performance during aftershocks or their overall lifespan.

Therefore, we need a damper that does not work in the small shake (ULS limit state) and just provides damping in the big shake (CALS limit state) in the direction of hitting the moat wall, not returning way to prevent hitting the moat wall and provide recentring, respectively.

Hazaveh et al. (2014-2021) introduced a new generation of viscous dampers called Direction Displacement Dependent (D3) viscous dampers. These passive devices can provide viscous damping in any desirable individual or multiple quadrants of the force-displacement response. The D3 viscous damper can be configured to meet the engineer's specific needs, making it a suitable device for retrofitting different kinds of structures. By providing selective damping forces during different phases of response, the D3 viscous damper could prevent moat wall pounding in large earthquakes while avoiding the increase of shear force and acceleration at ULS limit state. Furthermore, the D3 viscous damper has the potential to improve the aftershock or lifetime performance of base isolators by reducing their residual displacement.

This research demonstrates the effectiveness of passive D3 viscous dampers in improving the response of base-isolated buildings. The performance of an isolated building, an isolated building with a typical viscous damper, and an isolated building with a D3 viscous damper are compared numerically. The results show that moat wall pounding can significantly increase the shear force and acceleration and adding a typical viscous damper can prevent it at CALS limit state but at the cost of increasing shear force at ULS limit state displacement. However, adding a D3 viscous damper not only prevents moat wall pounding but also keeps the floor acceleration and shear force unchanged before ULS limit state. Therefore, the D3 viscous damper can be added to isolated buildings to improve all three critical design checks without affecting the superstructure design.

2 ANALYTICAL MODEL

2.1 Base-isolated building

The base-isolated building in this study represents an existing 8-story reinforced concrete building in New Zealand. The fundamental period of the superstructure is one second, with a total weight (W) of 5000 tons. The effective period of the isolated building is 2.75 seconds, and the characteristic strength is 9.4% of the total weight. A 20% torsion effect is considered. Therefore, the expected displacement of the centre of mass is 583mm (max=700mm) at the CALS limit state and 275mm (max=300mm) at the ULS limit state, as shown in Figure 2.1. The existing moat wall clearance is 700mm.

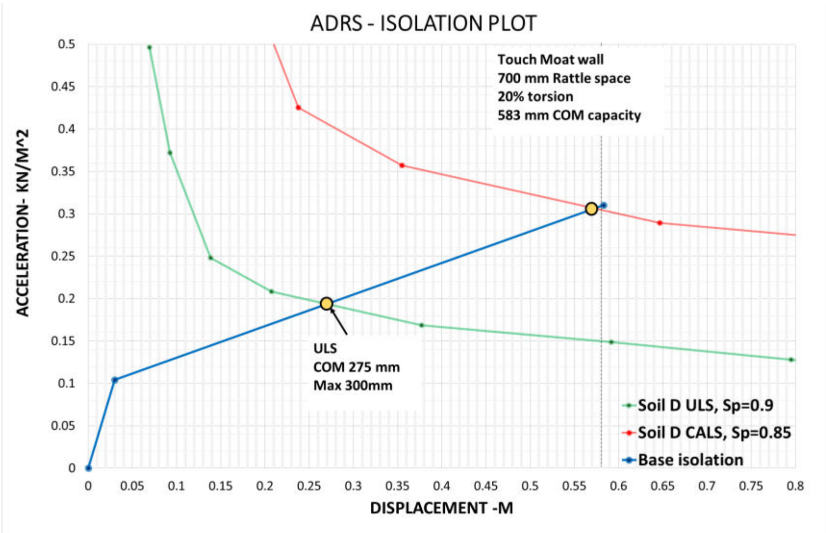

Figure 2.1. ADRS curve of the base isolation

2.2 D3 Viscous Damper model

The desired device to improve the base-isolated building needs to have three characteristics:

1. It should not provide damping before X to avoid increasing the shear force and acceleration of the superstructure that affects design criteria 2 and 3.

2. It should provide damping after X to prevent the moat wall pounding effect, which is the first design criteria.
3. After X, it should provide damping in a forward direction to assist in re-centring the base isolation in the strong ground motion.

X: the displacement demand at ULS limit state

Therefore, the D3 viscous damper has provided the following hysteresis loop to meet all of the top requests., as shown in Figure 2.2.

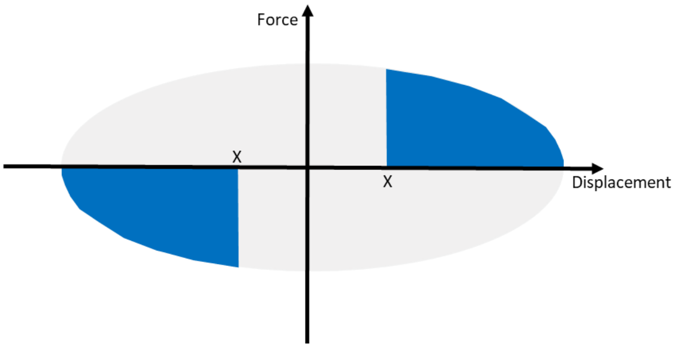

Figure 2.2. the D3 Viscous damper hysteresis loop to improve the base isolated structure

2.3 Ground motion set

Seven ground motions are used for nonlinear time history analysis, as shown in Table 2.1 . The earthquakes were scaled to match the response spectrum of soil type D at the CALS limit state. Figure 2.3 shows that the average of 7 earthquakes nearly matches the target response spectrum.

*Table 2.1. Record selected for CALS (1.5*ULS)*

Record	Name	MW	Mechanism and directivity
1	Denali (Alaska) 2002	-	-
2	Michoacan (Mexico) 1985	8.1	subduction interface
3	La Union (Mexico)1985	8.1	subduction interface
4	Duzce (Turkey) 1999	7.2	Strike-Slip
5	Tabas (Iran) 1978	7.4	Strike-Slip, Forward Directivity
6	Luceme Landers (California) 1992	7.3	Strike-Slip, Forward Directivity
7	Hokkaido (Japan) 2003	8.3	subduction interface

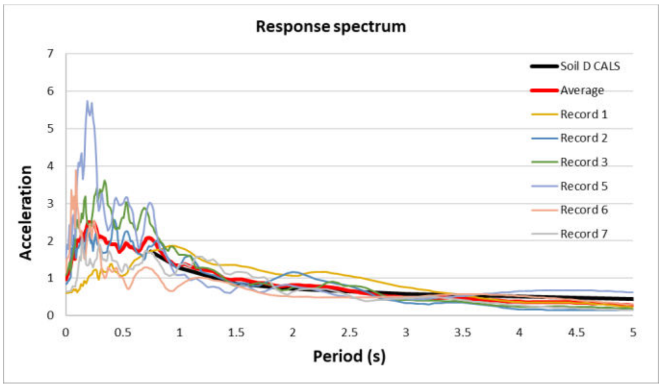

Figure 2.3: Response Spectrum under 7 earthquakes, average of them

2.4 Analysis cases

To understand the effect of the moat wall and find the solution for that, four analysis cases are considered.

Case 1: The base-isolated system without modelling the moat wall (No limitation for BI displacement)

Case 2: Adding the viscous dampers with a 15% effective damping and α=1.

Case 3: Adding the D3 viscous damper with a 15% effective damping, α=1 and an activation gap equal to 275mm, equivalent to the ULS displacement limit.

3 RESULTS

Table 3.1 shows the maximum displacement of the base isolation under seven ground motions. The results indicate that the average base isolation displacement is less than 700mm and moat wall pounding does not occur. However, in three out of seven earthquakes, the moat wall is hit. Hence, there is a 42% possibility of moat wall pounding occurring, resulting in the building experiencing a shock that causes floor acceleration to increase 2-3 times.

Table 3.1: maximum displacement of base isolation under 7 earthquake.

Name	Displacement (mm)	moat wall Pounding
Denali (Alaska) 2002	631	No
Michoacan (Mexico) 1985	561	No
La Union (Mexico)1985	431	No
Duzce (Turkey) 1999	782	Yes
Tabas (Iran) 1978	1058	Yes
Luceme Landers 1992	667	No
Hokkaido (Japan) 2003	737	Yes
Average	695	No

To avoid moat wall pounding, both typical and D3 viscous dampers were added to the base isolation system. The performance comparison was expressed in terms of the base shear coefficient and the isolation lateral displacement. Adding both the conventional and D3 viscous dampers prevented the moat wall pounding, satisfying the first design criterion.

Figure 3.1.a. compares the shear force-isolation displacement of three cases under the Tabas earthquake. The results show that the shear force of BI at 300mm is about 18%W and it increases to 35%W by adding the conventional viscous damper. However, by adding the D3 viscous damper, not only does the shear force not change under 300mm, but the base isolation also does not hit the moat wall. Figure 3.1.b. compares the force-displacement response of the typical and D3 viscous dampers. It indicates that by controlling the force of the damper, it is possible to satisfy all three design criteria.

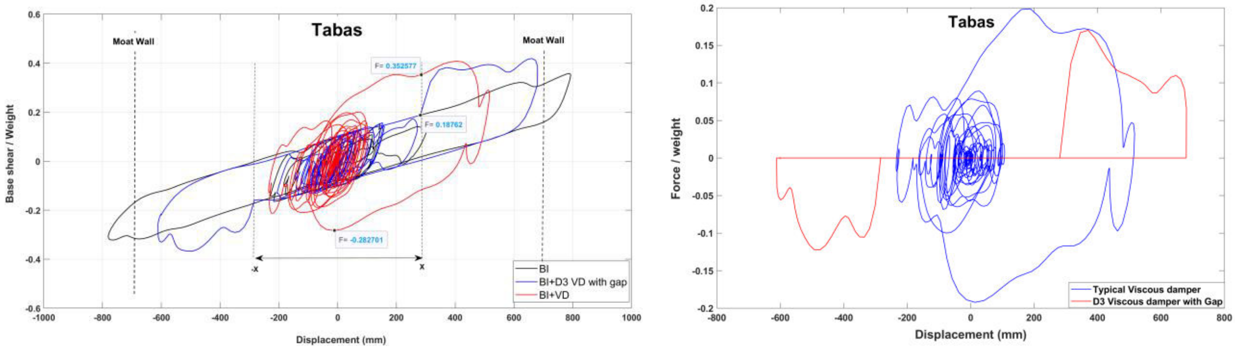

Figure 3.1. a. base shear Force-displacement of case 1 (BI), Case 2(BI+VD), Case 3(BI+D3 VD). b) the force displacement of typical and D3 VD under Tabs earthquake

The second and third critical design checks involve checking the superstructure for forces and displacement at the ULS limit state. Table 3.2 compares the shear force of Case 2 (BI+ VD) with Case 1 (BI) at the ULS limit state displacement. The results indicate that adding a typical viscous damper increases shear force by about 48% to 88%. Therefore, the superstructure should be designed for about an average of 64% more base shear at the ULS limit state. However, adding D3 viscous damper doesn't change the shear force.

Table 3.2. Maximum force/ weight, without and with typical viscous damper at Displacement=300mm

Earthquake	Case 1 (BI)	case2 (BI+VD)	Case 1/Case2
Duzce (Turkey)	0.206	0.305	148%
Tabas (Iran)	0.187	0.352	188%
Hokkaido (Japan)	0.185	0.287	155%

4 DISCUSSION

The evolution of seismic hazard characterization has led to larger intensities. When analysing the consequences of larger than expected seismic demands on existing buildings, particularly base-isolated buildings, the inability to provide additional rattle space constrains the solution realm. The critical design check for designing a base-isolated building is to ensure that there is enough rattle space at the CALS limit state, and the superstructure needs to be designed to withstand the shear force and displacement under the ULS limit state.

The addition of a conventional viscous damper to the base isolation is one solution to prevent the pounding effect. Previous studies have shown that this approach can reduce displacement, but at the cost of increasing shear force, acceleration, and drift during far field earthquake and ULS limit state events.

A Displacement and Direction Dependent (D3) viscous device can provide viscous damping force at any desirable hysteresis loop, making it possible to configure the D3 viscous damper to provide damping in only the forward direction after the ULS displacement. This could be a solution to meet all of the design criteria for the isolated building.

This paper first evaluates the base-isolated building under seven earthquakes, then the viscous damper and D3 viscous damper added to the BI to avoid moat wall pounding.

This paper evaluates the behaviour of a base-isolated building under seven earthquakes and explores the use of viscous damper and D3 viscous damper to avoid moat wall pounding. The results indicate that although the average maximum displacement is less than the rattle space, there is a 43% chance that the base isolation may hit the moat wall. To prevent this, viscous dampers are added to the building, and the results show that both typical viscous dampers and D3 viscous dampers avoid hitting the moat wall. However, the viscous damper reduces more displacement than D3 VD, which provides damping force only in the forward direction after the ULS limit state is engaged.

The benefit of adding D3 VD is that the base shear remains unchanged before the ULS limit state, whereas adding VD exhibits a 64% increase in average at ULS displacement. Thus, the superstructure needs to design/retrofit for about 1.6 times more shear force. Avoiding the base shear increase for frequent earthquakes allows the system to perform as is without the need to retrofit the superstructure to handle additional base shear, which it may not be able to handle.

However, the proposed configuration of the D3 viscous damper does not increase the shear force at the ULS limit state, providing a unique passive solution. Therefore, the superstructure does not require strengthening to handle additional base shear provided by the dampers for frequent earthquakes. For less frequent earthquakes that demand lateral displacement over the ULS limit, the proposed system is engaged, limiting the maximum displacement to avoid moat wall pounding.

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