Seismic Behavior of Concrete Retaining Wall with Shear Key, Considering Soil-Structure Interaction

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SUMMARY:
Seismic behavior of concrete retaining walls is very important because of their widespread usage and also many reported seismic damages to them.
Shear key is sometimes used in the footing of retaining walls to reduce sliding. This research is about the seismic behavior of concrete retaining walls with shear key in footing.
The shear key was considered below the wall's stem with vertical sides that continue all along the wall.
The soil mass behind the wall is cohesionless, dry and with a horizontal surface.
The effect of nonlinear behavior of soil has been considered using Drucker-Prager failure criterion.
Soil-structure interaction was considered while modeling.
The problem was analyzed as a plane strain one using finite element method and seismic behavior of walls with and without shear key was studied. The effect of shear key on design moment at the stem's bottom, wall's sliding and rotation of the stem was investigated.

Keywords: concrete retaining wall, shear key, seismic behavior, soil-structure interaction

1. INTRODUCTION

Retaining walls are widely-used structures which there have been many reports about seismic damages to them in different earthquakes (Gursoy and Durmus 2009). So it is important to pay enough attention to wall's seismic behavior during design process in order to prevent seismic damages. Designing of retaining walls include following steps:
a) choosing initial dimensions for the wall
b) determining the loads acting on the wall
c) controlling overturning of the wall
d) controlling sliding of the wall
e) controlling the wall's foundation bearing capacity
f) designing of structural elements

Shear key is a structural element which is sometimes used in the footing of retaining walls to reduce wall's sliding. There has not been much study about the effect of shear key in the footing of retaining wall on its seismic behavior. In one research Horvath investigated the effect of footing shape on cantilever retaining wall's static behavior. He examined footings with different shapes, including flat bottom, sloped bottom and footings with shear key in different locations. He concluded that retaining wall with sloped bottom has the best static behavior (Horvath 1991).

In this research seismic behavior of concrete retaining wall was studied in two conditions: walls with and without shear key in footing. Shear key location is below the wall's stem. In other words the wall would have a T-shaped footing in the presence of shear key. The shear key sides are vertical which continue all along the wall. The soil mass behind and below the wall is dry and cohesionless. No other structures are supported by the wall and it is only under the effect of earthquake. Because of the wall's length the problem was analyzed as a plane strain one using finite element method and design moment of the wall’s stem and wall’s stability were compared in these conditions and positive and negative consequences of shear key were determined.

2. THE PROCESS OF MODELING

2.1. Wall Model

It is important to consider walls with common and practical dimensions; so three different heights were selected for the analyzed walls which are 3 m, 6 m and 10 m. The proportions between each wall’s dimensions are shown in Fig. 1 and dimensions for each wall are shown in Table 1.

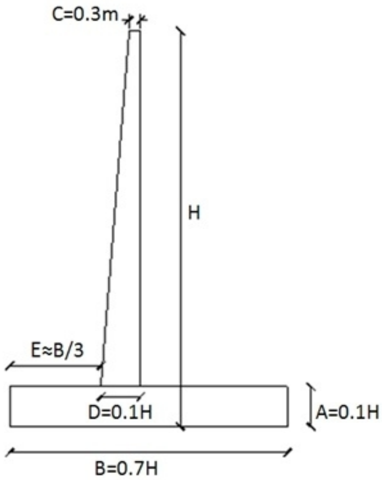

Figure 1. General dimensions selected for the analyzed walls

Table 1. Walls’ dimensions (according to Fig. 1.)

wall	H (m)	A (m)	B (m)	C (m)	D (m)	E (m)
3-m wall	3	0.3	2.1	0.3	0.3	0.7
6-m wall	6	0.6	4.2	0.3	0.6	1.4
10-m wall	10	1	7	0.3	1	2.3

The shear key was modeled with three different depths below the wall’s stem. The depths are 0.05H, 0.10H and 0.15H which H is the wall’s height. In other words nine walls with shear key in footing and three walls with flat bottom were analyzed in this research. The sides of the shear key are vertical and its thickness is 0.3 m in all cases as shown in Fig. 2. The used depths for shear key in the footing of different walls are shown in Table 2.

Concrete properties which were used in modeling are ρ_c=2400 kg/m^3, E_c=25.278 GPa and ν_c=0.2.

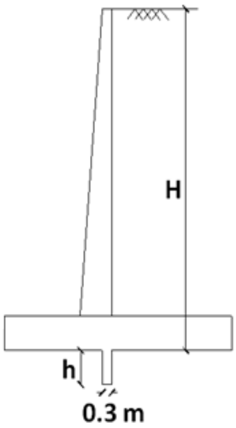

Figure 2. Shape and location of shear key

Table 2. Shear key depths in different walls (according to Fig. 2)

wall	h_1=0.05H	h_2=0.10H	h_3=0.15H
3-m wall	0.15 m	0.3 m	0.45 m
6-m wall	0.3 m	0.6 m	0.9 m
10-m wall	0.5 m	1 m	1.5 m

2.2. Soil Model

Selected dimensions for the soil mass behind and below the wall are shown in Fig. 3. The wall's behavior is only affected by this limited area (Gursoy and Durmus 2009). It should be mentioned that dashpot elements were used in the model boundaries to model soil's radiation damping.

The soil was considered cohesionless with φ=33º. Soil properties needed for modeling were considered as ρ_s=1700 kg/m^3, E_s=50 MPa and ν_s=0.35. The inelastic behavior of soil was modeled by Drucker-Prager failure criterion.

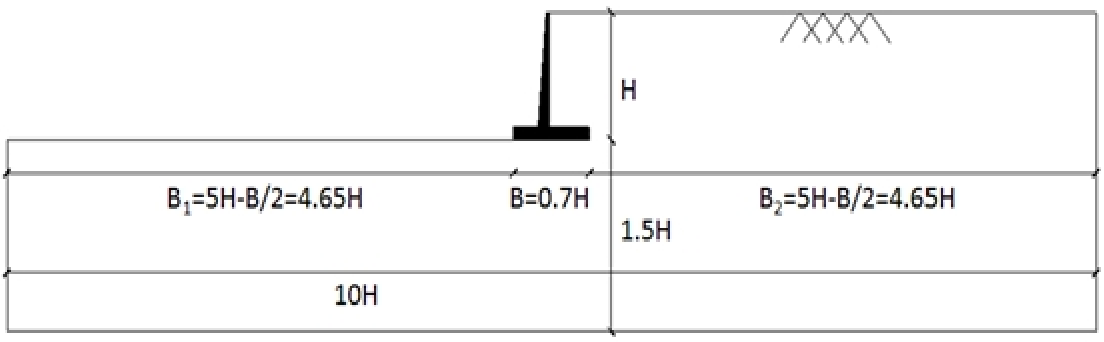

Figure 3. General selected dimensions for the soil mass in different models

Tabas and Loma Prieta earthquake accelerations were used in this research. Tabas earthquake has a PGA of 0.85*g* which happens at 11.06 second and Loma Prieta earthquake's PGA which is about 0.6*g* happens at 10.35 second. According to these earthquakes and soil mass properties, Rayleigh damping factors in different models were calculated, assuming that soil damping is 5% (ξ=0.05). These factors are shown in Table 3.

2.3. Other Properties of Model

Fig. 4 shows the model of retaining wall with the soil mass behind and below it. Earthquake accelerations were imposed at the bottom of the soil mass. Horizontal movements at vertical boundaries and vertical movements at the bottom boundary were fixed.

As shown in the figure, the problem was modeled as a 2D one. That’s because the wall is so long that the problem could be modeled as a plane strain one. The elements used for meshing are plane strain 4-node elements. Only in some regions with special shapes, plane strain 3-node elements were used.

The problem has its own complications due to the soil presence; so the soil-structure interaction was considered in modeling. The problem was modeled by the means of Abaqus (a finite element software) and it was analyzed by an explicit method.

Table 3. Rayleigh damping factors in different models

model	3-m walls models	6-m walls models	10-m walls models
Tabas earthquake	α=0.0211 β=0.0192	α=0.0202 β=0.0368	α=0.0192 β=0.0581
Loma Prieta earthquake	α=0.1231 β=0.0151	α=0.0989 β=0.0242	α=0.0783 β=0.0319

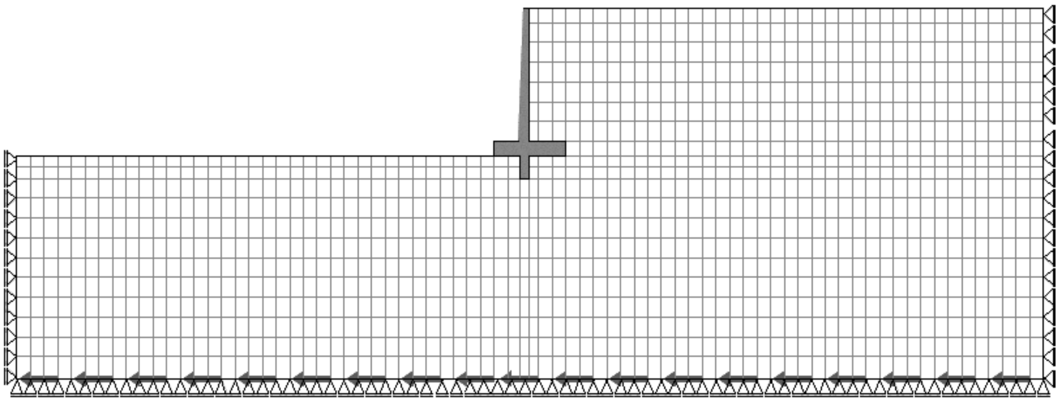

Figure 4. The model of retaining wall and soil mass behind and below it

3. RESULTS AND COMPARISONS

3.1. Design Moment at the Stem’s Bottom

The maximum moment at the stem’s bottom during each earthquake in different models was determined. Table 4 shows this parameter for walls with flat bottom and also the average design moment for walls with shear key in footing. As Table 4 shows the design moment in walls with shear key is much greater than the same parameter in walls with flat bottom. That’s because walls without shear key under seismic active soil pressure can move away from the soil easily; but in walls with shear key, this element prevents the wall from that. So in walls with shear key the seismic active pressure acting on the wall increases and as a result of that, the design moment increases too.

Table 4. Design moment at the stem's bottom of wall in different models

model	3-m wall with flat bottom	average results of 3-m walls with shear key in footing	6-m wall with flat bottom	average results of 6-m walls with shear key in footing	10-m wall with flat bottom	average results of 10-m walls with shear key in footing
Tabas earthquake	131.2 kN.m	146.6 kN.m	657.5 kN.m	1377.5 kN.m	1357.5 kN.m	4052 kN.m
Loma Prieta earthquake	41.3 kN.m	92.8 kN.m	321.1 kN.m	573.2 kN.m	368.9 kN.m	1870 kN.m

3.2. Walls' Sliding

Sliding results at the end of the earthquakes are shown in Table 5. Results show that using shear key in the footing of retaining wall, reduces wall's sliding considerably. The reason is that in wall with flat bottom, the friction under footing resists wall's sliding; but in wall with shear key, passive pressure acting on the key reduces sliding. The passive pressure acting on the key is greater than the friction under the wall's footing; so walls with shear key experience less sliding.

Table 5. Sliding results at the end of the earthquakes in different models

model	3-m wall with flat bottom	average sliding of 3-m walls with shear key in footing	6-m wall with flat bottom	average sliding of 6-m walls with shear key in footing	10-m wall with flat bottom	average sliding of 10-m walls with shear key in footing
Tabas earthquake	1.22 m	0.021 m	1.23 m	0.035 m	2.22 m	0.019 m
Loma Prieta earthquake	0.146 m	0.001 m	0.048 m	0.002 m	0.126 m	0.002 m

3.3. Walls' Stem Rotation

Table 6 shows the walls' stems rotation at the end of each earthquake. The results show that using shear key increases wall's stem rotation. As it was mentioned before the walls with shear key experience larger seismic active pressure; so these walls would have larger deformations as well.

Table 6. Results of walls' stems rotation at the end of the earthquakes in different models

model	3-m wall with flat bottom	average result of 3-m walls with shear key in footing	6-m wall with flat bottom	average result of 6-m walls with shear key in footing	10-m wall with flat bottom	average result of 10-m walls with shear key in footing
Tabas earthquake	0.27º	18.2º	1.35º	10.9º	0.94º	5.3º
Loma Prieta earthquake	0.10º	5.1º	0.02º	0.12º	0.06º	0.52º

4. CONCLUSION

In this research concrete retaining walls with common and practical dimensions and the soil mass behind and below them were modeled. Under Tabas and Loma Prieta earthquakes walls' seismic behavior was investigated in two conditions: with and without shear key in footing. Results show that using shear key has positive and negative consequences. Although shear key reduces wall's sliding considerably, it increases design moment and rotation in the wall's stem. The reason is that the wall can not move away from the soil under seismic active pressure in the presence of shear key. So wall with shear key in footing has to resist larger forces and deformations. So designers should pay attention to the seismic behavior of retaining wall with shear in the process of design and choose whether to use this element or not.

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