

# ON SEISMIC DESIGN OF RETAINING WALLS

Yingwei Wu

*Geotechnical Engineer, HNTB Corporation, Kansas City, Missouri, USA*

Shamsher Prakash

*Emeritus Professor, Civil Engineering Missouri S&T, Rolla, Missouri, USA*

Vijay K. Puri

*Professor, Civil and Environmental Engineering, Southern Illinois University, Carbondale, USA*

## ABSTRACT

Retaining walls have failed either by sliding away from the backfill or due to combined action of sliding and rocking displacements, during earthquakes. Performance based design of the retaining walls in seismic areas must account for these displacements, in addition to the usual factors of safety against failure in bearing, sliding and overturning. A realistic model for estimating dynamic displacement, which accounts for the combined action of sliding and rocking and takes into consideration, non-linear stiffness of soil and geometric and material damping and coupling effects is now available, Wu and Prakash (2009). This model has been used to calculate the displacement for several combinations of backfill and foundation soil conditions. Based on this study, typical design charts for preliminary design have been proposed.

## 1. INTRODUCTION

Retaining walls have failed during earthquakes by sliding away from the backfill or due to combined action of sliding and rocking displacements. Performance based design of the retaining walls in seismic areas must account for the likely displacements, the retaining wall may experience during an earthquake, in addition to calculating the usual factors of safety against failure in bearing capacity, sliding and overturning. A realistic model for estimating the dynamic displacement must account for the combined action of sliding and rocking vibrations and considering 1) non-linear soil stiffness 2) non-linear geometrical and material damping and 3) non-linear coupling effects.

This model has been developed by Wu (1999) and Design charts have been developed for performance based design. For further details see Wu and Prakash (2001, 2009 and 2010).

## 2. TYPICAL RESULTS

A wall 4m high (Figure 1) with granular backfill and foundation soil is used for illustration of typical results subjected to Northridge earthquake of January 17, 1994 (Figure 1). The displacements were computed on the assumption that the base width has been designed as for field condition 1 (Table 1) and displacements computed for Northridge earthquake for field conditions 1 through 7. Nonlinear soil modulus and strain-dependant dampings are used in this solution.

Field conditions 1 through 4 have been specified in Eurocode 8 (1994). Field Conditions 3 and 4 refer primarily to quay walls and are outside the scope of present work. Conditions 5 and 6 refer to full saturation of backfill and earth pressure must be reduced by an appropriate drainage as a necessary design condition. Thus conditions 1, 2 and 7 are only important for these studies. The magnitude of this earthquake is M 6.7 and peak ground acceleration is 0.344g. Figure 3 shows displacements of the 4m high wall under 7 field conditions. Table 2 lists these displacements, for conditions for 1, 2 and 7 only.

**Table 1: Loading conditions and corresponding parameters for dynamic displacements**  
 ( $\gamma$  - Unit Weight,  $\alpha_h$  and  $\alpha_v$  - Horizontal and Vertical Seismic coefficients,  $P_{wd}$  - Hydrodynamic Pressure)

	Field Condition	Parameters for	
		Static Condition	Dynamic Condition
	<b>Condition 1</b> moist backfill moist foundation soil	$\gamma^* = \gamma_t$ $P_{ws} = 0$	$\gamma^* = \gamma_t$ $\psi = \tan^{-1} \left( \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	<b>Condition 2</b> moist backfill saturated foundation soil	$\gamma^* = \gamma_t$ $P_{ws} = 0$	$\gamma^* = \gamma_t$ $\psi = \tan^{-1} \left( \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	<b>Condition 3</b> submerged with impervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\psi = \tan^{-1} \left( \frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$
	<b>Condition 4</b> submerged with pervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\psi = \tan^{-1} \left( \frac{\gamma_d}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 2 \times 7/12 \times \alpha_h \times \gamma_w \times H'$
	<b>Condition 5</b> perched with impervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\psi = \tan^{-1} \left( \frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$
	<b>Condition 6</b> perched with pervious backfill	$\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$	$\gamma^* = \gamma_{sat} - \gamma_w$ $\psi = \tan^{-1} \left( \frac{\gamma_d}{\gamma_{sat} - \gamma_w} \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$
	<b>Condition 7</b> perched with sloping drain	$\gamma^* = \gamma_{sat}$ $P_{ws} = 0$	$\gamma^* = \gamma_{sat}$ $\psi = \tan^{-1} \left( \frac{\alpha_h}{1 \mp \alpha_v} \right)$ $P_{wd}(t) = 0$

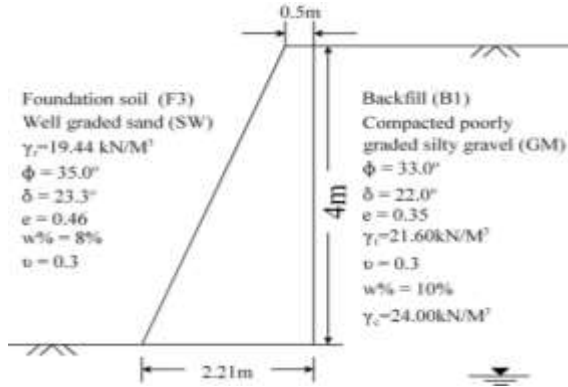


Figure 1a: Dimension of 4m high wall and soil properties used ( $\gamma_c$  – unit weight of concrete)

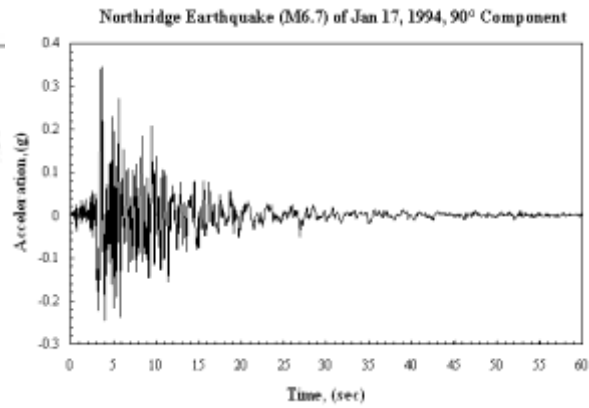


Figure 1b: Accelerogram of Northridge earthquake of Jan. 17, 1994, 90° Component

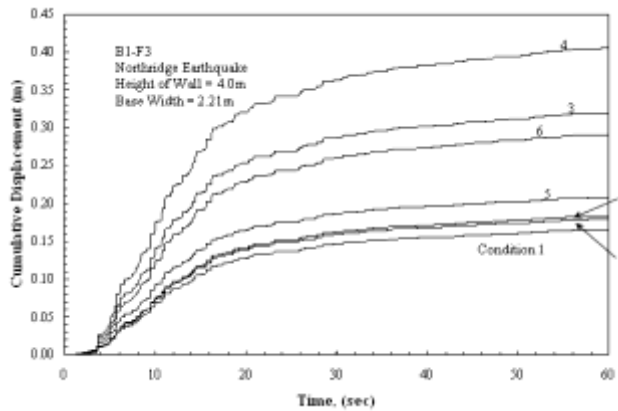


Figure 2: Computed displacement for 4m high wall and conditions 1 through 7 of Table 1

Table 2: Displacement of 4m high wall for Field Condition 1 to 7

Field Condition	Displacement				%of Height
	Sliding	Rocking		Total (top)	
		Rotation	Translation		
m	Heel, degree	m	m		
1	0.0622	1.48	0.1034	0.1656	4.1
2	0.0667	1.61	0.1126	0.1793	4.5
7	0.0682	1.64	0.1148	0.1830	4.6

An examination of Table 2 indicates that sliding displacements are close to 30 - 40 percent of the total displacement. According to Eurocode, the permissible displacement is 10.32cm ( $300 \times \alpha_{\max}$ , where  $\alpha_{\max}$  is 0.344 in Northridge earthquake). For practical design field conditions 1 and 2 and for saturated soils but with a sloping drain in condition 7 are appropriate.

### 3. SOIL AND WALL HEIGHTS USED TO DEVELOP DESIGN CHARTS

Wu (1999) has studied seven soil conditions for foundation soil F1-F7 and three soils for backfill B1-B3. Thus 21 combinations for foundation and backfills soils were investigated (Table 3). Rigid walls heights investigated are 4m, 5m, 6m, 7m, 8m, 9m, and 10m. Table 5 lists cumulative displacements for B3-F4.

**Table 3. Engineering properties for both foundation soil and backfill (Wu, 1999)**

#### FOUNDATION SOIL (F)

F	Soil Type	$\gamma_d$ kN/M <sup>3</sup>	$\phi$ deg	$\delta$ deg	void ratio	v	c kN/M <sup>2</sup>	PI	W%
F-1	GW	21.07	37.5	25.0	0.25	0.3	-	-	6
F-2	GP	19.18	36.0	24.0	0.36	0.3	-	-	6
F-3	SW	18.00	35.0	23.3	0.46	0.3	-	-	8
F-4	SP	16.82	34.0	22.7	0.56	0.3	-	-	10
F-5	SM	15.70	33.0	22.0	0.68	0.3	-	4	15
F-6	SC	14.00	30.0	20.0	0.88	0.3	-	13	25
F-7	ML	14.15	32.0	21.3	0.85	0.3	9.57	4	14

#### BACKFILL (B)

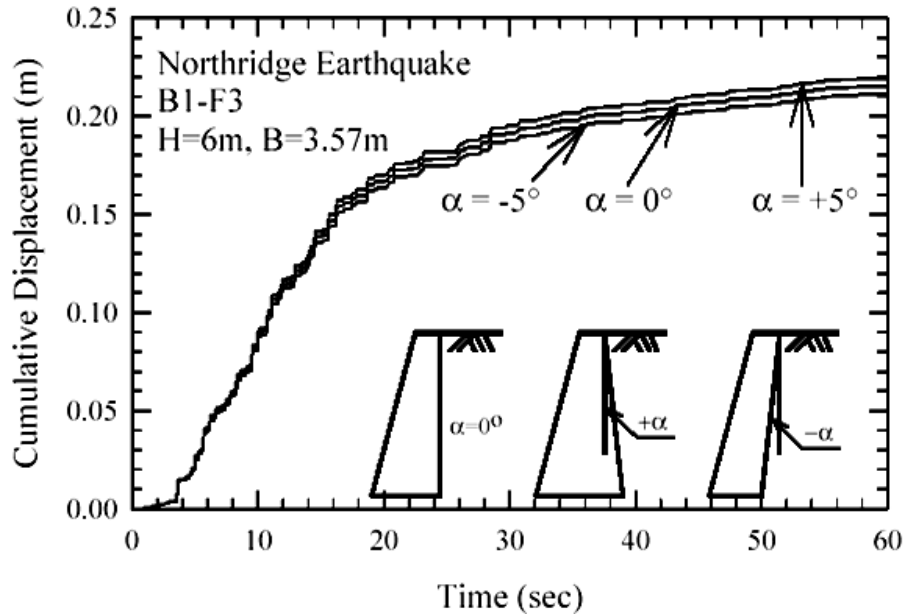
B	Soil Type	$\gamma_d$ kN/M <sup>3</sup>	$\phi$ deg	$\delta$ deg	void ratio	v	c kN/M <sup>2</sup>	PI	W%
B-1	GM	19.6	33.0	22.0	0.35	0.3	-	-	10
B-2	GP	18.9	34.0	22.7	0.40	0.3	-	-	8
B-3	SP	15.6	34.0	22.7	0.69	0.3	-	-	8

\*All properties of backfill are for the condition of 90 percent of the "Standard Proctor".

### 4. VERTICAL VS INCLINED WALLS

In order to economize on design of walls, several cases of 6.0 m high retaining walls were analyzed for typical cases of foundation soil condition varying from well graded gravel (GW) to silt (ML) and the backfill soil varying from silty gravel (GM) to poorly graded sand (SP). Ground motions corresponding to El Centro, Loma Prieta and North Ridge earthquakes were used in the analysis. Typical case of a reference retaining wall 6.0 m high with nine different inclination angles of the wall face in contact with the backfill ' $\alpha$ ' (0°, 1.25°, 2.5°, 3.75°, +5°, -1.25°, -2.5°, -3.75°, and -5°) subjected to Northridge earthquake is used for illustration. The negative angle at the back of the wall is the case of the wall resting on the backfill. Figure 3 shows cumulative displacement of the retaining wall away from the backfill due to combined sliding and rocking effects for  $\alpha = -5^\circ, 0^\circ$  and  $+5^\circ$  for a base width of 3.57 m. The foundation soil for this case was well graded sand (SW) and the backfill consisted of submerged silt gravel (GM). It can be observed from this figure that the negative values of ' $\alpha$ ' result in somewhat smaller cumulative displacements compared to the case of vertical wall face ( $\alpha = 0$ ) or for positive value of  $\alpha$  within the range considered. Similar results were observed for other cases also. It, therefore, appears that retaining walls may be designed for permissible

displacement for sliding only and then be built resting by a few degrees on the backfill as explained below. In this case this tilt is about  $1.31^\circ$  (Table 4).



**Fig. 3. Cumulative displacements of walls (B1-F3) with different inclinations with the vertical**

**Table 4. Cumulative displacement for several angles of inclination of the back of the wall subjected to Northridge earthquake condition (B=3.57m).**

$\alpha$ angle (degree)	Base width (m)	Cumulative Displacement by Fixed Base Width (3.57m)			
		Sliding (m)	Rocking (degree)	Rocking (m)	Total (m)
+5.00°	3.81	0.08	1.31	0.13	0.21
+3.75°	3.76	0.08	1.30	0.13	0.21
+2.50°	3.70	0.08	1.30	0.13	0.21
+1.25°	3.63	0.08	1.29	0.13	0.21
0.00°	3.57	0.08	1.29	0.13	0.21
-1.25°	3.50	0.08	1.28	0.13	0.21
-2.50°	3.43	0.08	1.27	0.13	0.21
-3.75°	3.35	0.08	1.26	0.13	0.21
-5.00°	3.38	0.08	1.25	0.13	0.21

Table 4 shows a summary of new base widths and computed displacement for various inclinations. The computed cumulative sliding, rocking and total displacements are also shown in this table. The base widths decreased from 3.57m to 3.38m as the inclination changed from  $0^\circ$  to  $-5^\circ$ , since the active earth forces decrease with negative inclination. Therefore, the base width was somewhat smaller for a wall with a negative

inclination. The angular rotation in rocking (Table 4) decreased from  $1.29^\circ$  ( $\alpha=0$ ) to  $1.25^\circ$  ( $\alpha=-5^\circ$ ), and the total displacements decreased slightly from 0.2155m to 0.2112m. The cumulative displacements for these walls will not be significantly altered by changing the inclination at the back of the wall.

For the wall built as a leaning-type rigid retaining wall with  $\alpha = -5^\circ$  lying on the backfill, the wall experienced a rocking movement of  $1.25^\circ$  during the Northridge earthquake. Therefore, when the wall was subjected to the same earthquake event up to 3 or 4 times, the wall experienced a total rocking close to  $5^\circ$ . At this time, the wall may become vertical.

Further analysis was conducted for 21 backfill and foundation soil combinations for a typical reference wall 6m high, subjected to three earthquakes. The backfill soil was varied from silty gravel to poorly graded sand, and the foundation soil varied from well graded gravel to silt of low compressibility.

The results generally indicated that the design widths of foundations for 21 cases of backfill – foundation soil combinations used in analysis generally reduced with values of  $\alpha$  from  $0^\circ$  to  $-5^\circ$ . This may result in saving of 8 -10 % in the material cost. It is, therefore recommended that rigid walls be constructed with the negative batter in the walls resting on the backfill. In this situation, these can be designed only for sliding displacements.

## 5. RECOMMENDED DESIGN PROCEDURE

1. Determine the section for static loading condition with FOS=2.5 in bearing, and FOS= 1.5 for sliding and tilting as a rigid body and no tension on the heel.
2. Estimate the sliding displacement from Wu (1999) design charts for comparable backfill and foundation soils and comparable ground motion.
3. Compare these displacements with permissible displacements as per Euro Code ( $300 \times \alpha_{\max}$ ).
4. If displacement in step 2 is less than that in step 3, then designs is OK, otherwise revise the sections of the wall for lower FOS in step 1.

## 6. TYPICAL DESIGN CHARTS

Table 5 lists the sliding and total displacement and rotation of walls 4m-10m high and subjected to 3-good motions of 1) El-Centro1946, 2) Northridge 1994, and 3) Loma Prieta 1979. Similar design charts for all 21 cases of table 3 have been prepared by Wu (1999)

**Table 5: Cumulative Displacements for Walls 4 to 10m High with B3-F4 and Field Conditions 1, 2 and 7 (Table 2) subjected to El-Centro, Northridge and Loma-Prieta earthquakes**

H and B <sup>1</sup> (m)	Field Con.	Cumulative Displacement								
		El-Centro <sup>2</sup>			Northridge <sup>2</sup>			Loma-Prieta <sup>2</sup>		
		Sliding m	Rocking degree (m)	Total m	Sliding m	Rocking degree (m)	Total m	Sliding m	Rocking degree (m)	Total m
4 (2.09)	1	0.0943	2.59 (0.1808)	0.2751	0.0642	1.67 (0.1164)	0.1806	0.0055	0.11 (0.0077)	0.0132
	2	0.0987	2.75 (0.1922)	0.2909	0.0673	1.79 (0.1248)	0.1922	0.0059	0.12 (0.0083)	0.0142
	7	0.1076	3.04 (0.2124)	0.3200	0.0739	1.99 (0.1386)	0.2125	0.0065	0.13 (0.0093)	0.0157
5 (2.51)	1	0.1113	2.74 (0.2395)	0.3509	0.0769	1.81 (0.1576)	0.2343	0.0073	0.13 (0.0116)	0.0189
	2	0.1156	2.89 (0.2526)	0.3681	0.0802	1.92 (0.1673)	0.2475	0.0078	0.15 (0.0127)	0.0205
	7	0.1256	3.20 (0.2760)	0.4046	0.0872	2.13 (0.1859)	0.2731	0.0086	0.16 (0.0142)	0.0228
6 (2.92)	1	0.1247	2.79 (0.2926)	0.4173	0.0868	1.87 (0.1955)	0.2823	0.0089	0.15 (0.0160)	0.0249
	2	0.1289	2.92 (0.3063)	0.4352	0.0896	1.97 (0.2060)	0.2956	0.0096	0.17 (0.0173)	0.0269
	7	0.1400	3.23 (0.3384)	0.4784	0.0977	2.18 (0.2283)	0.3260	0.0106	0.19 (0.0195)	0.0301
7 (3.35)	1	0.1359	2.78 (0.3398)	0.4757	0.0948	1.88 (0.2299)	0.3247	0.0106	0.17 (0.0205)	0.0311
	2	0.1399	2.90 (0.3540)	0.4939	0.0987	1.97 (0.2403)	0.3390	0.0114	0.18 (0.0221)	0.0335
	7	0.1519	3.20 (0.3911)	0.5430	0.1073	2.18 (0.2668)	0.3741	0.0215	0.20 (0.0248)	0.0373
8 (3.77)	1	0.1457	2.74 (0.3823)	0.5280	0.1025	1.87 (0.2606)	0.3631	0.0124	0.18 (0.0250)	0.0374
	2	0.1500	2.84 (0.3970)	0.5471	0.1051	1.95 (0.2720)	0.3771	0.0131	0.19 (0.0270)	0.0401
	7	0.1628	3.14 (0.4390)	0.6018	0.1144	2.16 (0.3015)	0.4159	0.0147	0.22 (0.0303)	0.0449
9 (4.19)	1	0.1544	2.68 (0.4209)	0.5754	0.1083	1.84 (0.2886)	0.3969	0.0140	0.19 (0.0296)	0.0436
	2	0.1584	2.77 (0.4356)	0.5941	0.1108	1.91 (0.3001)	0.4109	0.0147	0.20 (0.0319)	0.0466
	7	0.1718	3.07 (0.4817)	0.6536	0.1203	2.12 (0.3327)	0.4259	0.0160	0.23 (0.0358)	0.0519
10 (4.72)	1	0.1608	2.53 (0.4411)	0.6017	0.1123	1.74 (0.3033)	0.4156	0.0151	0.19 (0.0326)	0.0477
	2	0.1648	2.61 (0.4559)	0.6207	0.1153	1.80 (0.3144)	0.4297	0.0157	0.20 (0.0350)	0.0507
	7	0.1785	2.89 (0.5039)	0.6825	0.1250	2.00 (0.3484)	0.4734	0.0172	0.22 (0.0392)	0.0564

<sup>1</sup> H: height of wall, B: base width

<sup>2</sup> Permissible displacements for three earthquakes according to Eurocode =  $300 \times \alpha_{\max}$

El-Centro =  $300 \times 0.349$  (mm) = 0.1047m

Northridge =  $300 \times 0.344$  (mm) = 0.1032m

Loma-Prieta =  $300 \times 0.113$  (mm) = 0.0339m

## **7. CONCLUSIONS**

The following conclusions are drawn:

1. A realistic displacement model for rigid retaining walls under earthquake condition has been developed.
2. This model considers non-linear soil properties and any water condition behind the wall (Wu 1999).
3. Design charts for wall heights 4m-10m and 21 backfill foundation soils have been developed for use in preliminary design.

## **8. ACKNOWLEDGEMENT**

The manuscript was typed by Khushboo Lall and Reformatted by Raghu Mutnuri, with great care.

## **9. REFERENCES**

EUROCODE 8 (EUROPEAN PRESTANDARD 1994). "Design Provisions for Earthquake Resistance of Structures- Part 5: Foundations, Retaining Structures and Geotechnical Aspects", The Commission of the European Communities.

Wu, Y. (1999). "Displacement-Based Analysis and Design of Rigid Retaining Walls during Earthquakes", Ph.D. Dissertation, Univ. of Missouri-Rolla.

Wu, Y. and Prakash, S. (2001). "Seismic Displacements of Rigid Retaining Walls-state of the art" paper number 705, Proceedings Fourth Intrn Conf Recent Adv in Geot Eq Eng and Soil Dynamics CD ROM, San Diego, March

Wu, Y. and Prakash, S. (2009). "Design of Retaining walls in Seismic Areas "IS Tokyo 2009". Paper No 149, International conference on Performance based Design in Geo Earthquake Engineering (CD-ROM).

Wu, Y. and Prakash, S. (2010). "Design Charts for Retaining Walls in Seismic Areas". Paper No 178 , ASCE Conference . Geo-FL. (CD, ROM).