SEISMIC DISPLACEMENTS OF RIGID RETAINING WALLS ON SUBMERGENCE

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SUMMARY

Rigid walls experience significant displacements during earthquakes. Eurocode (1994) recommends permissible displacements. Wu and Prakash (1997) used only some provisions of Eurocode-8 Ch7 (1994) to study performance of retaining walls during earthquake with dry or submerged conditions. A critical review of the behavior of the retaining walls during earthquakes, and comprehensive displacements of a typical wall for several backfills and foundation soils have been made by Wu and Prakash (1998). Wu and Prakash (1999) studied the effect of submergence on one typical wall. In this paper, the question of submergence of walls has been considered in detail for walls 4m-10m high.

INTRODUCTION

Conventional static design of rigid retaining walls requires estimating the earth pressure (Coulomb 1776, Rankine's 1857). Wall geometry is selected for safety against sliding, overturning and bearing capacity. Rigid walls experience significant sliding and rocking displacements during earthquakes. However the wall movement cannot be predicted by the conventional design method (Okabe 1926, Mononobe and Matsuo 1929). Prakash and Wu (1997) prepared a listing of damage of walls during Hokkaido-Nansi-Oki, Northridge and Kobe earthquakes, in which the walls failed by both sliding and rotation.

Rafnsson and Prakash (1994) and Prakash *et.al*. (1995 a, b) developed a solution to predict horizontal movement at the top of a retaining wall due to simultaneous sliding and rocking under a sinusoidal ground motion. Also design charts had been developed for permissible displacement of walls 4m to 10m high and for 21 dry/moist foundation soil and backfill combinations. By using this method, Prakash and Wu (1996), Wu and Prakash (1996) compared the performance of two rigid walls during earthquakes with their model and found good agreement. Later, Wu and Prakash (1997) used only some provisions of Eurocode-8 Ch7 (1994) to study performance of retaining walls during earthquake with dry or submerged conditions. A critical review of the behavior of the retaining walls under *sinusoidal* ground motion, available methods of analysis and design, and a comprehensive displacements of typical walls for several backfills and foundation soils have been made by Wu and Prakash (1998). Wu and Prakash (1999) studied the effect of submergence on a typical wall of 6m high.
In this paper, the effect of submergence of walls has been considered in detail for several walls.

FIELD CONDITIONS

The following field conditions (Table 1) may be considered in a comprehensive design of a rigid retaining wall.
For static design, the Coulomb's earth pressures are minimum in condition 3 and 4. Condition 5 and 6 will cause very large hydrostatic pressures; therefore, some sort of a drain is introduced as in condition 7. However, under earthquake conditions, the static plus dynamic earth pressures will follow a different sequence as explained further.

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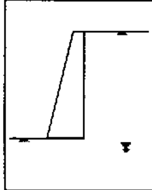
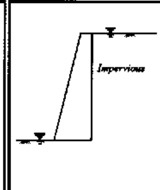
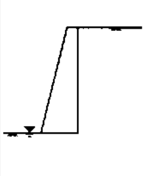
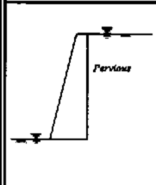
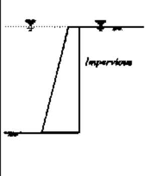
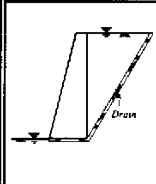
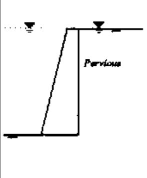
Also, the displacements of wall may be the largest in condition 3, 4, 5, and 6 above. We will examine behavior of a typical wall under all the above field conditions. Subsequently data is presented for walls 4m to 10m high subjected to 3-real ground motions. Provisions of Eurocode are described first which is the basis of this comparison. Non-linear soil properties have been considered throughout (Wu, 1999).

Table 1: Loading conditions and corresponding parameters for dynamic displacements

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

EUROCODE-8 CH7

Comprehensive provisions for seismic design of rigid retaining walls are included in codes of India, Japan (IAEE, 1992) and Eurocode-8(1994). However, only Eurocode-8 proposed limiting displacements smaller than 300*α (mm) for free gravity walls, where α is the maximum horizontal ground acceleration coefficient. Also non-linear soil properties for foundation soil and backfill in analysis of sliding and rocking displacements are recommended. The seismic coefficient of horizontal acceleration for design is α_h (= α/r) which is constant along the wall height and r is 2 for free gravity walls. A general expression for computing the lateral dynamic force due to soil skeleton and water is

$$P_{ae} = \tfrac{1}{2}\,\gamma^*\,(1\ \_\ \alpha_v)\,k_{ae}H^2 + P_{ws} + P_{wd}$$

Where k_{ae} is dynamic earth pressure coefficient (Okabe 1926, Mononobe and Matsuo 1929) and is given by

$$k_{ae} = \frac{\cos^2(\phi - \psi - \alpha)}{\cos\psi\ \cos^2\alpha\ \cos(\delta + \alpha + \psi)\left[1 + \sqrt{\frac{\sin(\phi + \delta)\ \sin(\phi\ \text{i}\ \psi)}{\cos(\alpha\ \text{i})\ \cos(\delta + \alpha + \psi)}}\right]^2}$$

where

H = height of wall
i = the slope of backfill surface
φ = the friction angle of backfill
ψ = the angle which is a function of coefficients of horizontal (α_h), vertical (α_v) accelerations and is defined differently for several field conditions (see Table 1)
δ = friction angle of the wall-backfill interface
α = angle of back of the wall to vertical
α_h and α_v= horizontal and vertical ground acceleration coefficients
P_{ws} = static water force
P_{wd} = hydrodynamic water force
γ^* = appropriate unit weight of soil in different field conditions

The point of application of the force due to the dynamic (soil skeleton) earth pressures is assumed at mid-height of the wall and the point of application of the hydrodynamic water pressure lies at a depth below the top of the saturated layer equal to 60% of the height of such layer.

Condition 1 and 2 :

Dry/moist backfill in Eq. 1,

$$P_{ws} = P_{wd} = 0 \quad and \quad \psi = \tan^{1} \left[\frac{\alpha_h}{1 \pm \alpha_v} \right]$$

Condition 3 :

Completely submerged condition with *impervious* backfill below the water table. For static condition, hydrostatic water force is acting at both sides of the wall and is balanced. Hence, the total hydrostatic water force acting on the wall is zero i.e., $P_{ws} = 0$. In *impervious* backfill, the internal water is not free to move with respect to the soil solids skeleton under seismic action (Eurocode, 1994). There is therefore no hydrodynamic pressure on the wall from the backfill. Therefore

$$P_{wd} = 0 \quad \text{and} \quad \psi = \tan^{1} \frac{\gamma_{sat}}{\gamma_{sat} - \gamma_w} \left[\frac{\alpha_h}{1 \pm \alpha_v} \right]$$

The hydrodynamic pressure at the outer face of the wall will induce *suction* pressure during earthquake, when the water tends to move away from the wall. The magnitude of the suction force is given by

$$q(z) = \frac{7}{8} \alpha_h \gamma_w \sqrt{h z}$$

Where

h = free water height above the base
z = vertical downward coordinate with the origin at the surface of water

For completely submerged condition, the free water height (h) is the same as the height of wall (H). By integrating Eq. (5) over the depth of water (z=H), the hydrodynamic suction at the outer face of the wall can be written as:

$$P_{wd} = \frac{7}{12} \alpha_h \gamma_w H^2$$

Submerged unit weight is used for computing effective earth pressure in this condition; ie

$\gamma^* = \gamma_b = \gamma_{sat} - \gamma_w$

Therefore, the total dynamic active force is then given by

$P_{ae} = ½ \gamma_b (1 \_ \alpha_v) k_{ae} H^2 + P_{wd}$

Condition 4 :

Completely submerged condition with *pervious* backfill below the water table. The static hydrostatic water force is the same as that in condition 3. Hence, the hydrostatic force (P_{ws}) equals zero. In *pervious* backfill, the internal water is free to move with respect to the soil skeleton under seismic action; therefore hydrodynamic force for water on the wall is given as in Eq. 6. In this case, there will be two hydrodynamic forces, one acting on the wall from the fill and the other hydrodynamic *suction* as in Condition 3 from the outer face of the wall. The unit weight of soil is the same as Eq. 7. The total dynamic active force is given by

$P_{ae} = ½ \gamma_b (1 \_ \alpha_v) k_{ae} H^2 + 2 P_{wd}$

and ψ as in Table 1.

Condition 5 :

Perched water table with *impervious* backfill below the water table. The water stands high in the backfill, but there is no water standing against the exposed face of the wall. This might happen after very heavy and prolonged rainfall. In the *impervious* backfill the hydrodynamic force is not applicable as in condition 3. The γ and ψ used for this condition are the same as the Condition 3 (Eqs. 7 and 4 respectively). The total force is given by

$$P_{ae} = ½ \gamma_b \ (1 - \alpha_v) k_{ae} H^2 + P_{ws}$$

Condition 6 :

Perched water table with *pervious* backfill below the water table. The γ and ψ used for this condition are the same as in Condition 4. Only the total force equation is different and is given by

$$P_{ae} = ½ \gamma_b (1 - \alpha_v) k_{ae} H^2 + P_{ws} + P_{wd}$$

Condition 7 :

Perched condition with sloping drain. This condition is designed to reduce the hydrostatic pressures and had been described by Lambe and Whitman (1979). However, the soil is still saturated, and the saturated unit weight of backfill is used for computing static and dynamic earth pressure.

$$P_{wd} = P_{ws} = 0$$

Also due to the sloping drain, no hydrodynamic force is generated during the earthquakes. Therefore, ψ is defined as Eq. 3. The total dynamic active force is given by

$$P_{ae} = ½ \gamma_{sat} (1 - \alpha_v) k_{ae} H^2$$

STUDY OF A TYPICAL WALL

A 6m height wall will be first designed for static conditions. Its displacements will then be analyzed according to seven field condition in Table 1 (Wu and Prakash 1999).

A typical wall (Figure 1) 6m high with the foundation and backfill properties shown in this figure is designed for FOS against sliding (≥ 1.5), overturning (≥ 1.5), bearing capacity failure (≥ 2.5) and Eccentricity (≤ B/6) under static condition. The displacements were computed on the assumption that the base width has been designed as for field condition 1 and displacements computed for Northridge earthquake, Jan. 17, 1994, for field conditions 1-7 (Table 1). The magnitude of this earthquake is M 6.7 and peak ground acceleration is 0.344g. Displacement computations and solution technique have been explained by Wu (1999) and Wu and Prakash (1998) and will not be repeated here for want of space. Table 2 lists the displacements in column 5. Figure 2 is plot of cumulative displacements with time.

Table 2. Displacements of wall for Field Condition 1 to 7.

Field Condition	Displacement				% of Height
	Sliding (cm)	Rocking		Total (cm)	
		degree	cm		
1	2	3	4	5	6
1	8.08	1.29	13.47	21.55	3.5
2	8.56	1.39	14.60	23.16	3.9
3	14.39	2.46	25.74	40.13	6.7
4	18.47	3.09	32.32	50.79	8.5
5	9.57	1.62	16.99	26.56	4.4
6	13.33	2.23	23.38	36.72	6.1
7	8.70	1.42	14.91	23.61	3.9

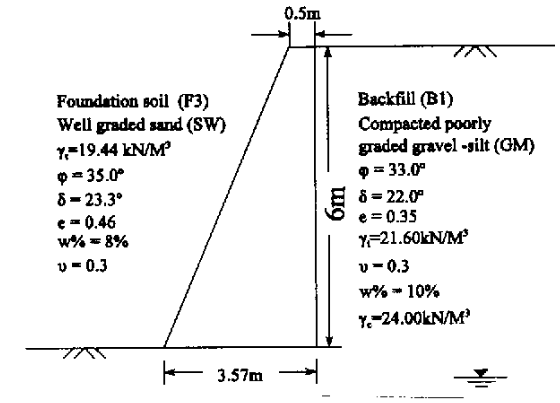


Figure 1. Dimensions of wall and soil properties in foundation (F3) and Backfill (B1)

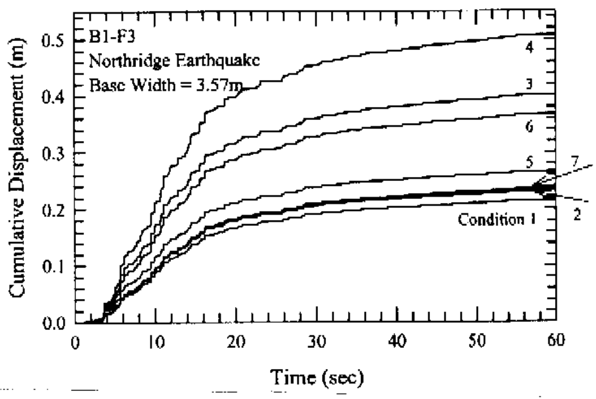


Figure 2. Computed displacements for 6m high wall (B1-F3) for conditions 1-7

Table 3. **Cumulative displacements for walls 4 to 10m high with B1-F1 and field conditions 1, 2 and 7 subjected to El-Centro, Northridge and Loma-Prieta earthquakes**.

H and B[1] (m)	Field Con.	Cumulative Displacement								
		El-Centro[2]			Northridge[2]			Loma-Prieta[2]		
		Sliding m	Rocking degree (m)	Total m	Sliding m	Rocking degree (m)	Total m	Sliding m	Rocking degree (m)	Total m
4 (2.08)	1	0.0895	2.52 (0.1760)	0.2655	0.0604	1.62 (0.1128)	0.1732	0.0052	0.11 (0.0074)	0.0126
	2	0.0940	2.71 (0.1889)	0.2829	0.0642	1.75 (0.1221)	0.1862	0.0057	0.12 (0.0083)	0.0140
	7	0.0960	2.76 (0.1928)	0.2887	0.0652	1.79 (0.1247)	0.1899	0.0058	0.12 (0.0085)	0.0143
5 (2.60)	1	0.1058	2.54 (0.2515)	0.3273	0.0722	1.65 (0.1439)	0.2160	0.0068	0.12 (0.0104)	0.0172
	2	0.1118	2.71 (0.2365)	0.3483	0.0766	1.77 (0.1546)	0.2311	0.0074	0.13 (0.0113)	0.0187
	7	0.1136	2.76 (0.2412)	0.3548	0.0779	1.81 (0.1578)	0.2357	0.0075	0.13 (0.0116)	0.191
6 (3.22)	1	0.1184	2.37 (0.2483)	0.3667	0.0809	1.54 (0.1615)	0.2424	0.0082	0.12 (0.0124)	0.0206
	2	0.1235	2.53 (0.2654)	0.3889	0.0849	1.66 (0.1740)	0.2589	0.0087	0.13 (0.0138)	0.0225
	7	0.1225	2.58 (0.2736)	0.3961	0.0863	1.70 (0.1776)	0.2639	0.0089	0.13 (0.0140)	0.0229
7 (3.84)	1	0.1281	2.25 (0.2745)	0.4026	0.0880	1.47 (0.1794)	0.2674	0.0094	0.12 (0.0147)	0.0241
	2	0.1335	2.39 (0.2923)	0.4258	0.0922	1.58 (0.1924)	0.2846	0.0101	0.13 (0.0163)	0.0264
	7	0.1357	2.44 (0.2979)	0.4336	0.0937	1.61 (0.1964)	0.2901	0.0103	0.14 (0.0167)	0.0270
8 (4.56)	1	0.1353	2.05 (0.2863)	0.4216	0.0931	1.34 (0.1871)	0.2802	0.0104	0.12 (0.0161)	0.0265
	2	0.1407	2.18 (0.3048)	0.4455	0.0970	1.44 (0.2011)	0.2981	0.0112	0.13 (0.0178)	0.0289
	7	0.1428	2.22 (0.3106)	0.4535	0.0985	1.47 (0.2052)	0.3037	0.0114	0.13 (0.0181)	0.0295
9 (5.08)	1	0.1442	2.05 (0.3213)	0.4655	0.0998	1.35 (0.2122)	0.3120	0.0117	0.12 (0.0192)	0.0309
	2	0.1498	2.17 (0.3405)	0.4903	0.1035	1.44 (0.2267)	0.3303	0.0127	0.13 (0.0211)	0.0339
	7	0.1521	2.21 (0.3470)	0.4991	0.1051	1.47 (0.2312)	0.3364	0.0130	0.14 (0.0216)	0.0345
10 (5.80)	1	0.1499	1.91 (0.3373)	0.4816	0.1034	1.26 (0.2195)	0.3229	0.0128	0.12 (0.0205)	0.0334
	2	0.1558	2.01 (0.3515)	0.5073	0.1073	1.34 (0.2342)	0.3415	0.0138	0.13 (0.0227)	0.0365
	7	0.1581	2.05 (0.3581)	0.5162	0.1089	1.37 (0.2388)	0.3477	0.0141	0.13 (0.0232)	0.0372

[1] H: height of wall,   B: base width
[2] Permissible displacements for three earthquakes according to Eurocode = $300\times\alpha_{max}$
El-Centro = 0.349*300 (mm) = 0.1047m
Northridge = 0.344*300 (mm) = 0.1032m
Loma-Prieta = 0.113*300 (mm) = 0.0339m

DISCUSSION

According to Eurocode, the permissible displacement is 300 times the peak ground acceleration, i.e., 300*0.344 = 10.32cm. Computed displacements (Col 5 Table 2) have exceeded the permissible values in all cases.

The displacement values for completely submerged conditions 3 and 4 are much higher than thoses in condition 1. However these condition may not exist for a sufficient length of time, since, an earthquake with submerged condition may be a remote possibility. In condition 5, the displacements are close to those in 1 and 2. However, in condition 6, the displacements are too high. It appears that when the backfill is likely to be saturated, a sloping drain (condition 7) is helpful in reducing seismic displacement. It will be seen that only for condition 1, 2, 5 and 7, only sliding displacements are within the permissible limits. The walls experience rotation of about 1.29° to 1.62°. The walls may, therefore, be built with initial tilt and designed only for sliding (Wu 1999).

Table 3 lists cumulative displacements for walls 4m to 10m high with a typical Backfill and Foundation Soil (B1-F1) (Wu 1999) for 3-earthquakes El-Centro, Northridge and Loma Prieta for field conditions 1, 2 and 7. It is seen that for Loma-Prieta and Northridge earthquakes, the sliding displacements are close to the permissible values listed at the bottom of Table 3. However, for El-Centro earthquake, the walls beyond 5m high experience larger sliding displacements. Similar tables have been prepared for 7 backfills (B1-B7) and 3-foundation soils (F1-F3) and are a helpful design tool for the practicing engineer (Wu 1999).

COMMENTS ON EUROCODE

The following comments are offered on Eurocode for practical applications;

1. Eurocode recommends different ψ and P_{wd} values based on the fill being impervious or pervious. Impervious fills will appear superior for seismic condition, because P_{wd} is recommended as zero. The logic of this recommendation needs further examination.
2. Permissible displacement is related to the maximum horizontal seismic coefficient (α_{max}). In the authors opinion, it may also be related to the height of the wall.
3. Eurocode may include recommendations on the initial tilt of the walls.

CONCLUSIONS

Based on this study the following conclusions may be drawn.

1. Completely submerged walls experience much larger displacements during earthquakes.

2. Sloping drains reduce the displacements considerably.

3. Walls may be designed for sliding displacements only and be constructed with an initial tilt towards that fill.

4. Some provisions of the Eurocode need re-examination.

ACKNOWLEDGMENT

The draft was typed with great care by Charlena Ousley.

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