

ON SEISMIC DESIGN OF RETAINING WALLS

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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 soil stiffness of soil and geometric case and material damping and coupling effects is now available (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) Soil stiffness in sliding and rocking 2) Geometrical and material damping in sliding and rocking, and 3) non-linear coupling effects for stiffness and damping.

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

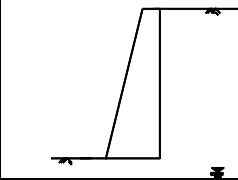
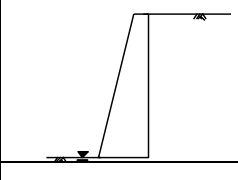
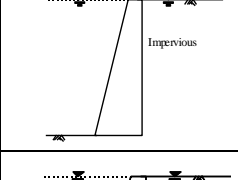
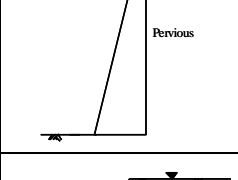
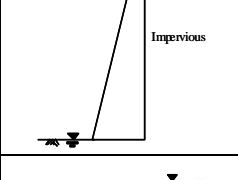
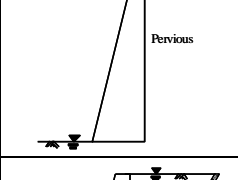
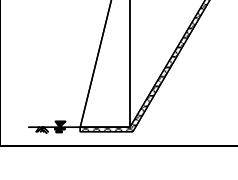
2. TYPICAL RESULTS

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 query as all and are outside the scope of present work.

Conditions 5 and 6 refer to free saturation backfill of earth pressure need to reduce by an appropriate drainage as in correctly. These conditions 1, 2 and 3 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.

Table 1: Loading conditions and corresponding parameters for dynamic displacements

| | Field Condition | Parameters for | |
|---|--|---|--|
| | | Static Condition | Dynamic Condition |
|  | Condition 1 moist backfill moist foundation soil | $\gamma^* = \gamma_t$ $P_{ws} = 0$ | $\gamma^* = \gamma_t$ ————— $P_{wd}(t) = 0$ |
|  | Condition 2 moist backfill saturated foundation soil | $\gamma^* = \gamma_t$ $P_{ws} = 0$ | $\gamma^* = \gamma_t$ ————— $P_{wd}(t) = 0$ |
|  | Condition 3 submerged with impervious backfill | $\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$ | $\gamma^* = \gamma_{sat} - \gamma_w$ ————— $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$ |
|  | Condition 4 submerged with pervious backfill | $\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 0$ | $\gamma^* = \gamma_{sat} - \gamma_w$ ————— $P_{wd}(t) = 2 \times 7/12 \times \alpha_h \times \gamma_w \times H'$ |
|  | Condition 5 perched with impervious backfill | $\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$ | $\gamma^* = \gamma_{sat} - \gamma_w$ ————— $P_{wd}(t) = 0$ |
|  | Condition 6 perched with pervious backfill | $\gamma^* = \gamma_{sat} - \gamma_w$ $P_{ws} = 1/2 \times \gamma_w \times H^2$ | $\gamma^* = \gamma_{sat} - \gamma_w$ ————— $P_{wd}(t) = 7/12 \times \alpha_h \times \gamma_w \times H'$ |
|  | Condition 7 perched with sloping drain | $\gamma^* = \gamma_{sat}$ $P_{ws} = 0$ | $\gamma^* = \gamma_{sat}$ ————— $P_{wd}(t) = 0$ |

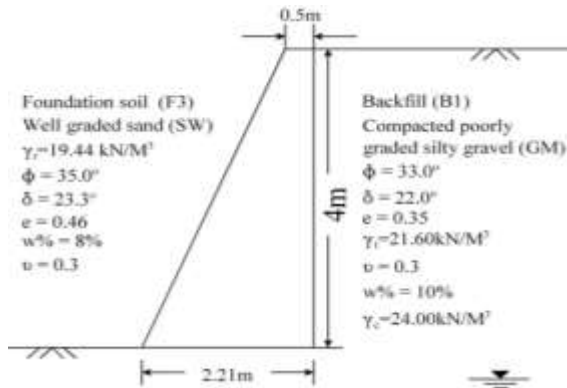


Figure 1a: Dimension of 4m high wall and soil properties used

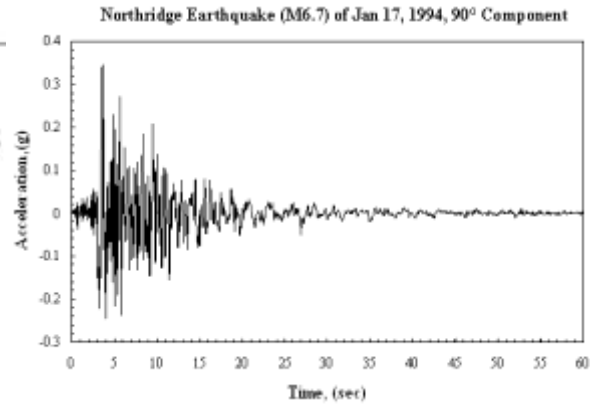


Figure 1b: Accelerogram of Northridge earthquake of Jan. 17, 1994, 90° Component

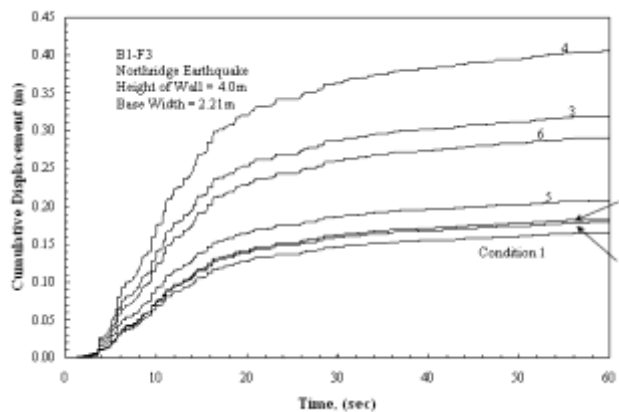


Figure 2: Computed displacement for 4m high wall and conditions 1 through 7 of Table 1

An examination of Table 2 indicated that sliding displacements (column 2) are close to 30 - 40 percent of the total displacement (Column 5). Maximum total displacements occur in field condition 4 i.e., submerged wall with pervious backfill. According to Eurocode, the permissible displacements is 10.32 cm ($300 \times \alpha_{\text{max}}$, where α_{max} is 0.344 in Northridge earthquake). Sliding displacement in conditions 3 and 4 exceed this value. For practical design field conditions 1 and 2 even 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 4 lists cumulative displacements for B3-F4.

Table 2. Engineering properties for both foundation soil and backfill (Wu, 1986)**FOUNDATION SOIL (F)**

| | Soil Type | kN/M ³ | deg | deg | void ratio | v | c kN/M ² | 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)

| | Soil Type | kN/M ³ | deg | deg | void ratio | v | c kN/M ² | 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".

Table 3: Displacement of 4m high wall for Field Condition 1 to 7

| Field Condition | Displacement | | | | %of Height |
|-----------------|--------------|----------|----------|----------|------------|
| | Sliding | Rocking | | Total | |
| | m | degree | m | m | |
| Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | Column 6 |
| 1 | 0.0622 | 1.48 | 0.1034 | 0.1656 | 4.1 |
| 2 | 0.0667 | 1.61 | 0.1126 | 0.1793 | 4.5 |
| 3 | 0.1168 | 2.90 | 0.2023 | 0.3191 | 8.0 |
| 4 | 0.1492 | 3.67 | 0.2564 | 0.4055 | 10.1 |
| 5 | 0.0759 | 1.89 | 0.1319 | 0.2078 | 5.2 |
| 6 | 0.1076 | 2.62 | 0.1830 | 0.2905 | 7.3 |
| 7 | 0.0682 | 1.64 | 0.1148 | 0.1830 | 4.6 |

4. VERTICAL VS INCLINED WALLS

In order to economies 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 ' α ' (0° , 1.25° , 2.5° , 3.75° , $+5^\circ$, -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° 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 ' α ' result in somewhat smaller cumulative displacements compared to the case of vertical wall face ($\alpha = 0$) or for positive value of α within the range considered

Another typical plot of cumulative displacement of a rigid retaining wall of 6.0 m height and having a base width of 4.61m and subjected to North Ridge earthquake motion is shown in Fig. 4. The foundation and backfill soils in this case were silt of low compressibility and silty gravel respectively. The trend of the results in Fig. 4 is similar that in Fig: 3. similar results were observed for other cases. It, therefore, appears that retaining walls be designed for permissible displacement for sliding only and then be built resting by a few degrees on the backfill. In this case this tilt is about 4° (3.67° maximum).

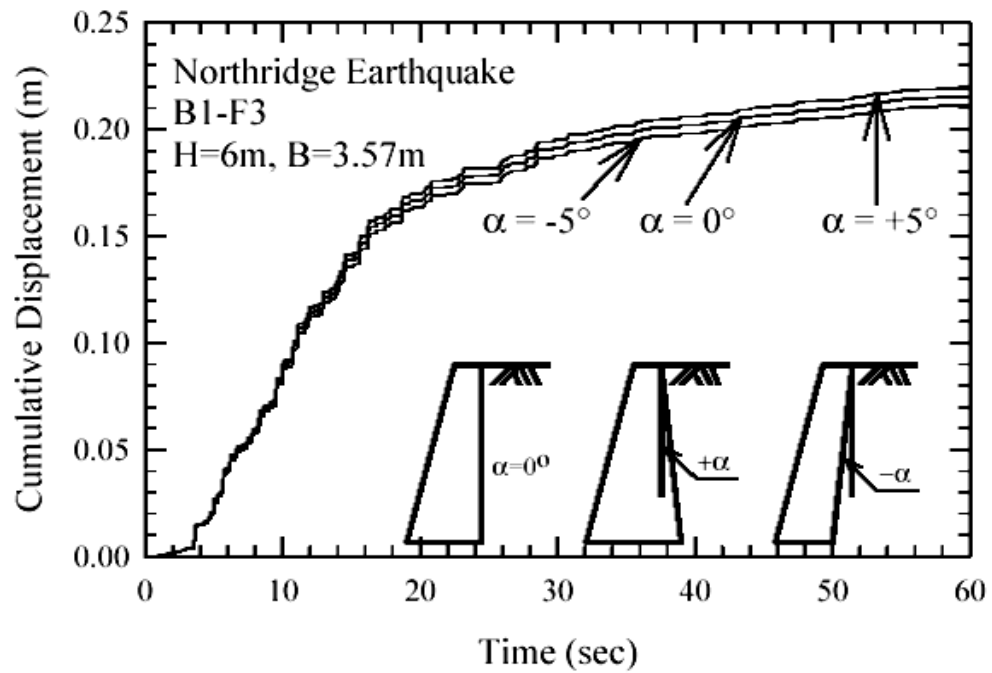


Fig: 3. Cumulative displacements of walls (B1-F3) with different inclinations with the vertical

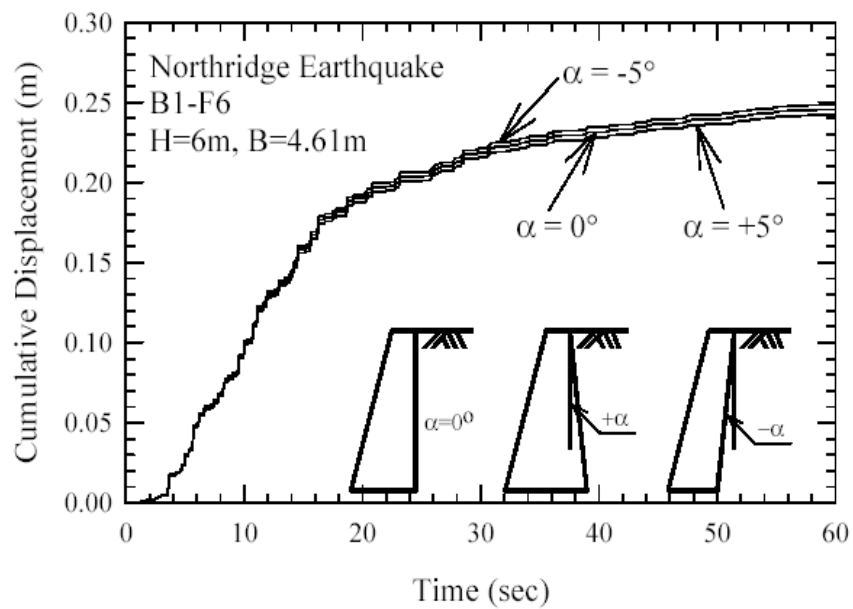


Fig: 4. Cumulative displacements of walls (B1-F6) with different inclinations with the vertical

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

| Inclination- on angle (degree) | Base width-h (m) | Cumulative Displacement by Fixed Base Width (3.57m) | | | |
|---|---------------------|--|---------------------|-------------|--------------|
| | | Sliding (m) | Rocking (degree) | Rocking (m) | Total (m) |
| +5.00° | 3.81 | 0.0820 | 1.31 | 0.1374 | 0.2194 |
| +3.75° | 3.76 | 0.0820 | 1.30 | 0.1366 | 0.2186 |
| +2.50° | 3.70 | 0.0815 | 1.30 | 0.1361 | 0.2176 |
| +1.25° | 3.63 | 0.0808 | 1.29 | 0.1355 | 0.2163 |
| 0.00° | 3.57 | 0.0808 | 1.29 | 0.1347 | 0.2155 |
| -1.25° | 3.50 | 0.0806 | 1.28 | 0.1338 | 0.2144 |
| -2.50° | 3.43 | 0.0805 | 1.27 | 0.1329 | 0.2134 |
| -3.75° | 3.35 | 0.0803 | 1.26 | 0.1320 | 0.2123 |
| -5.00° | 3.38 | 0.0801 | 1.25 | 0.1311 | 0.2112 |

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° to -5°, 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° ($\alpha=0$) to 1.25° ($\alpha=-5^\circ$), 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 -5° lying on the backfill, the wall experienced a rocking movement of 1.25° 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°. At this time, the wall may become vertical.

Further analysis was conducted for 21 backfill and foundations 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

α from 0° to -5° . 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 head.
2. Estimate the sliding displacement from Wu's (1999). Design charts for comparable, backfill and foundation soils, and comparable ground motion.
3. Compare these displacements with permissible displacements as per Euro Code ($300 \times a_{\max}$).
4. If displacement in 2 is less than that in 3, then design is OK, or else revise the sections of the wall for lower FOS in (1).

6. TYPICAL DESIGN CHARTS

Table 4 lists the sliding and total displacement and rotation of walls 4m-10m high and subjected to 3-good motions of 1) EL contour (1946) 2) North ridge (19) and 3) Lome Pride (1979).

Table 5: Cumulative Displacements for Walls 4 to 10m High with Granular Backfill and Foundation Soil and Field Conditions 1, 2 and 7 (Table 2) 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 (1.82) | 1 | 0.0882 | 2.91 (0.2031) | 0.2913 | 0.0605 | 1.91 (0.1332) | 0.1937 | 0.0051 | 0.13 (0.0089) | 0.0140 |
| | 2 | 0.0925 | 3.07 (0.2140) | 0.3065 | 0.0637 | 2.02 (0.1413) | 0.2050 | 0.0052 | 0.13 (0.0093) | 0.0145 |
| | 7 | 0.1012 | 3.40 (0.2375) | 0.3387 | 0.0698 | 2.26 (0.1580) | 0.2277 | 0.0057 | 0.15 (0.0105) | 0.0162 |
| 5 (2.22) | 1 | 0.1049 | 3.00 (0.2615) | 0.3665 | 0.0726 | 1.99 (0.1740) | 0.2467 | 0.0065 | 0.14 (0.0123) | 0.0189 |
| | 2 | 0.1088 | 3.15 (0.2745) | 0.3833 | 0.0753 | 2.11 (0.1837) | 0.2591 | 0.0070 | 0.15 (0.0135) | 0.0205 |
| | 7 | 0.1189 | 3.49 (0.3049) | 0.4238 | 0.0830 | 2.35 (0.2050) | 0.2881 | 0.0078 | 0.17 (0.0152) | 0.0230 |
| 6 (2.63) | 1 | 0.1181 | 3.00 (0.3143) | 0.4324 | 0.0822 | 2.02 (0.2118) | 0.2940 | 0.0081 | 0.16 (0.0167) | 0.0248 |
| | 2 | 0.1218 | 3.13 (0.3282) | 0.4500 | 0.0850 | 2.12 (0.2221) | 0.3071 | 0.0086 | 0.17 (0.0181) | 0.0267 |
| | 7 | 0.1330 | 3.48 (0.3645) | 0.4975 | 0.0929 | 2.37 (0.2477) | 0.3406 | 0.0096 | 0.20 (0.0206) | 0.0302 |
| 7 (3.03) | 1 | 0.1290 | 2.96 (0.3615) | 0.4905 | 0.0899 | 2.01 (0.2456) | 0.3355 | 0.0096 | 0.17 (0.0212) | 0.0309 |
| | 2 | 0.1327 | 3.08 (0.3759) | 0.5086 | 0.0927 | 2.10 (0.2566) | 0.3493 | 0.0103 | 0.19 (0.0230) | 0.0332 |
| | 7 | 0.1448 | 3.42 (0.4175) | 0.5622 | 0.1025 | 2.34 (0.2856) | 0.3880 | 0.0115 | 0.21 (0.0259) | 0.0374 |
| 8 (3.54) | 1 | 0.1370 | 2.76 (0.3857) | 0.5227 | 0.0963 | 1.88 (0.2625) | 0.3588 | 0.0110 | 0.17 (0.0240) | 0.0350 |
| | 2 | 0.1408 | 2.87 (0.4005) | 0.5413 | 0.0994 | 1.96 (0.2739) | 0.3732 | 0.0115 | 0.19 (0.0259) | 0.0374 |
| | 7 | 0.1536 | 3.19 (0.4449) | 0.5985 | 0.1084 | 2.19 (0.3053) | 0.4137 | 0.0129 | 0.21 (0.0291) | 0.0421 |
| 9 (4.04) | 1 | 0.1443 | 2.60 (0.4084) | 0.5527 | 0.1015 | 1.77 (0.2786) | 0.3801 | 0.0122 | 0.17 (0.0268) | 0.0390 |
| | 2 | 0.1482 | 2.70 (0.4236) | 0.5718 | 0.1041 | 1.85 (0.2906) | 0.3946 | 0.0129 | 0.18 (0.0289) | 0.0418 |
| | 7 | 0.1616 | 2.99 (0.4704) | 0.6321 | 0.1133 | 2.06 (0.3235) | 0.4368 | 0.0143 | 0.21 (0.0326) | 0.0469 |
| 10 (4.54) | 1 | 0.1510 | 2.46 (0.4298) | 0.5808 | 0.1056 | 1.68 (0.2939) | 0.3995 | 0.0133 | 0.17 (0.0296) | 0.0429 |
| | 2 | 0.1550 | 2.55 (0.4453) | 0.6003 | 0.1085 | 1.75 (0.3057) | 0.4142 | 0.0142 | 0.18 (0.0319) | 0.0461 |
| | 7 | 0.1685 | 2.83 (0.4939) | 0.6624 | 0.1180 | 1.95 (0.3401) | 0.4581 | 0.0156 | 0.21 (0.0359) | 0.0515 |

¹ H: height of wall, B: base width

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

El-Centro = 300×0.349 (mm) = 0.1047m

Northridge = 300×0.344 (mm) = 0.1032m

Loma-Prieta = 300×0.113 (mm) = 0.0339m

7. ILLUSTRATIVE EXAMPLES

7-1. A rigid retaining wall is 4.5 m high. The soil conditions are as in Table 4. Estimate the displacement of the wall.

7-2. A rigid retaining wall is 6.5m high. The soil conditions are as in Table 3 (B1 F1). Estimate the displacement of the wall.

7-3. A rigid retaining wall is 5m high (B1 F1). It is subjected to a seismic event similar to Northridge but the peak ground accelerates to 0.5g. Estimate the sliding displacement.

8. 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 (Wu 1999) non-linear soil properties and any water condition behind the wall.
Design charts for wall heights 4m-10m and 21m backfill at too soil have been developed for use in preliminary design.

9. REFERENCES

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