Assessment of Displacement Demand for Earth Retaining Structures

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Abstract

Earth retaining walls and bridge abutments are part of the key infrastructure in support of a modern transportation system. Assessment of the structural safety of a retaining wall in seismic conditions is considered in this paper. Present work deals with systematic review of analytical modelling of seismic actions on retaining walls. Experimental investigation for finding displacement demand of scaled down retaining wall models has been discussed. A detailed experimental investigation has been recommended for ensuring the accuracy of the analytical modelling approach.

Keywords: retaining wall, abutment, displacement, seismic, performance, similitude.

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1. Introduction

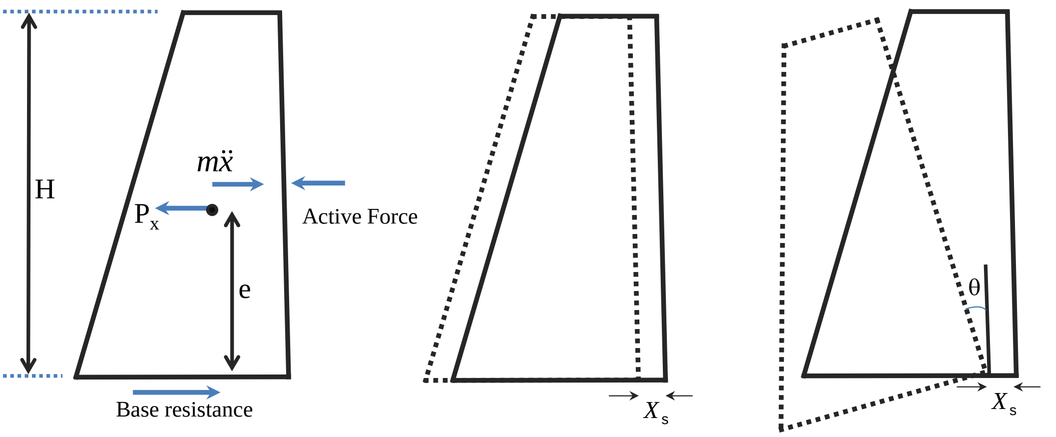
Earth retaining structures are extensively used in modern transportation system. Accurate and realistic seismic assessment of earth retaining structures is an important part of geotechnical seismic design. Seismic performance of earth retaining structure is evaluated based on its displacement behavior during an earthquake. Researchers have performed studies to understand the seismic performance behavior of retaining walls and bridge abutment. However, a schematic analytical and experimental investigation for modelling the seismic displacement behavior of earth retaining structures has not been reported in the literature. Present work deals with the review of analytical modelling of seismic actions on retaining walls. The ongoing shaking table experiment on scaled down retaining wall models is also presented. The shaking table experiment is currently in progress in The Department of Infrastructure Engineering, The University of Melbourne.

2. Literature Review

Several researchers have studied the performance of earth retaining structures against earthquake loading. Richards and Elms (1979) proposed a design procedure for the seismic design of gravity retaining wall based on the capacity design principles. Whitman and Liao (1985) studied the seismic displacement of gravity retaining walls. The study was based on investigations by Newmark (1965) and Richards and Elms (1979). Siddharthan et al. (1994) examined the seismic performance of seat type abutments. They studied the consequences of simple assumptions; considered in conventional force based design. Psarropoulos et al. (2005) performed numerical investigations into dynamic earth pressure developed in retaining walls, and compared the dynamic earth pressure with the pseudo static earth pressure calculated from the Mononobe-Okabe (MO) method. It was shown that passive pressure decreased with increment in wall flexibility and base rotation capacity. Choudhury and Chatterjee (2006) proposed a displacement based method for finding seismic active earth pressure, and observed a nonlinear dynamic pressure distribution behind the retaining wall. Yazdani et al. (2013) studied the MO method and its limitations. Modifications were recommended for increasing the accuracy of the MO method. Wilson and Elgamal (2015) studied the seismic behavior of rigid retaining walls. Shaking table tests on full scale walls have been conducted. Experimental results were compared with analytical solutions, and parabolic distribution of seismic pressure behind the wall has been observed. It was concluded based on a detailed literature review that displacement based design procedure for earth retaining structures has not been reported in the literature nor in design standards. In order to fill the knowledge gaps and develop a displacement based design procedure for earth retaining structures, a detailed experimental and analytical investigation has commenced at the Department of Infrastructure Engineering, The University of Melbourne. The present work forms part of displacement modelling of seismic actions on retaining walls.

3. Analytical modelling of seismic actions on retaining walls

The analytical modelling approach for estimating the displacement demand of retaining wall is based on investigations performed by Rafnsson (1991) and Wu (1999). Figure 1 shows the typical retaining wall considered in the analytical investigation and the various forces acting on it in seismic conditions. The retaining wall can slide and rotate under seismic loading. It was observed that very small amount of sliding is required for the formation of active failure plane in backfill (Choudhury and Chatterjee, 2006).



(a) Forces acting on retaining wall (b) Sliding (c) Sliding and Rotation

Figure 1 Forces acting on retaining wall, sliding and rotation of retaining wall.

Sliding (X_s) and rotation (θ) of the retaining wall when subject to sinusoidal force has been investigated. It was assumed that the force was acting at the center of gravity of the retaining wall. The amplitude of ground motion varied from 0.1g to 0.4g. It should be noted that the stiffness and damping of the base soil and backfill material has been evaluated for sliding and rotation (Rafnsson 1991). The stiffness and damping ratio of base soil and backfill has been evaluated based on the shear modulus and cyclic shear strain levels. Calculations have been performed at each time step. Figure 2 shows the degradation of the shear modulus in different soils with increasing cyclic shear strains. The earthquake response behavior of soils is highly influenced by the amount of cyclic shear strain (Kramer 1996). Figure 3 shows the relationship between the damping ratio and cyclic shear strain for different types of soils. For simplicity, sand has been chosen to model stiffness and damping of base soil and backfill. The shear strain amplitude in soil at rest state is 1e-6, for all soil type a maximum damping ratio was observed at 10% shear strain and minimum shear modulus was observed at 1% shear strain (Rafnsson 1991). Shear strain has been calculated for base soil and backfill at each time increment (0.01 sec) and compared with the previous shear strain amplitude. It was assumed that retaining wall would not move further away from the backfill whenever, the seismic action changes in direction from active to passive state.

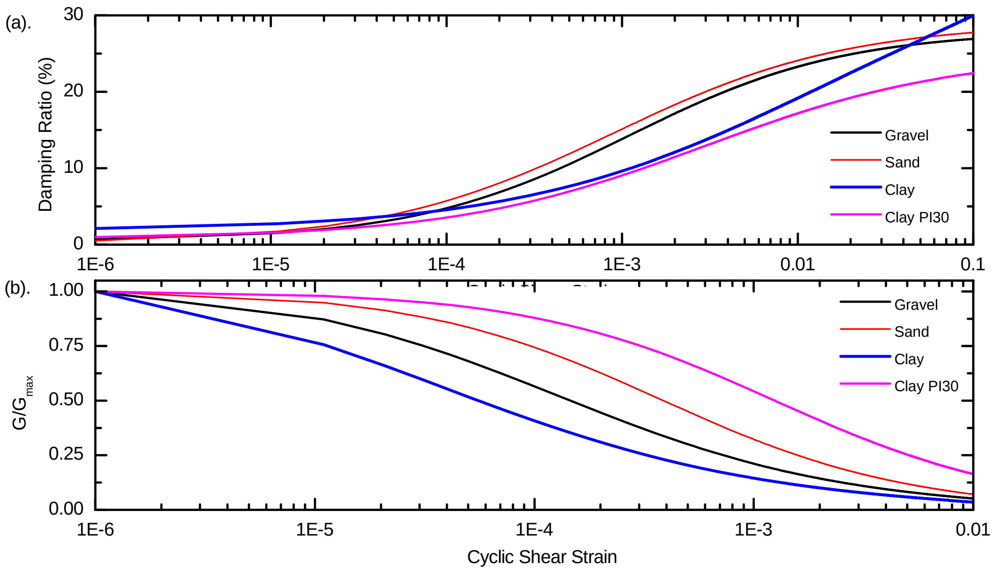


Figure 2 Effect of cyclic shear strain on damping ratio and shear modulus for different soil type (Rafnsson 1991).

The equation of motion considered for sliding and rotation is given by equation 1.

$$\begin{bmatrix} m & me \\ 0 & M_{mo} \end{bmatrix} \begin{bmatrix} \ddot{X}_s \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} C_{xt} - C_{at} & \dfrac{-C_{at}H}{2} \\ \dfrac{-C_{\phi at}H}{2} & C_{\phi t} - \dfrac{C_{\phi at}H^2}{4} \end{bmatrix} \begin{bmatrix} \dot{X}_s \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} k_x - k_a & \dfrac{-k_a H}{2} \\ \dfrac{-k_{a\phi}H}{2} & k_\phi - \dfrac{k_{a\phi}H^2}{4} \end{bmatrix} \begin{bmatrix} X_s \\ \theta \end{bmatrix} = \begin{bmatrix} P_x(t) \\ M_x(t) \end{bmatrix} \quad (1)$$

Notations:
m = Mass of the retaining wall.
e = Eccentricity (distance from base to the center of gravity of wall).
M_{mo} = Mass moment of area.
H= height of wall
C_{xt} , k_x = Damping and stiffness of base soil in sliding.
$C_{\phi t}$, k_ϕ = Damping and stiffness of base soil in rotation.
C_{at} , k_a = Damping and stiffness of backfill soil in sliding (active case).
$C_{\phi at}$, $k_{a\phi}$ = Damping and stiffness of backfill soil in rotation (active case).
$P_x(t)$, $M_x(t)$ = Excitation force and moment acting at the center of gravity of retaining wall.

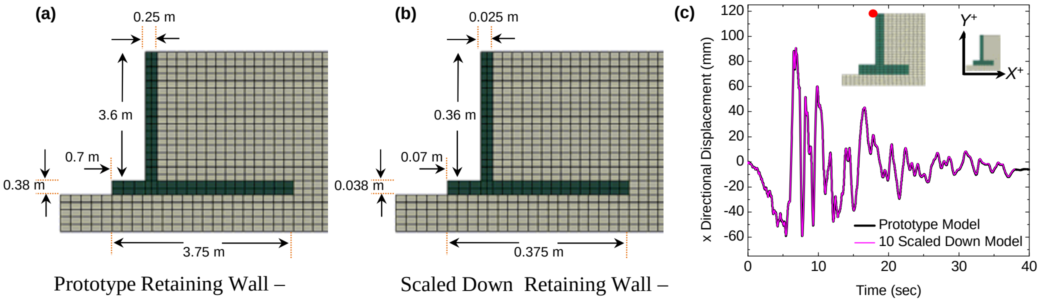
Newmark’s average acceleration method has been used for the time step integration. The cumulative displacement (sliding + rotation) has been measured at the top of retaining wall after each time step.

4. Seismic displacement of retaining walls under sinusoidal loading

Rafnsson (1991) observed that retaining walls shows a higher displacement at higher acceleration amplitudes. The cumulative displacement at the top of the wall increases in a nonlinear manner for the first few cycles. It was observed that due to the higher strain levels in base soil and backfill, the shear modulus degrade rapidly. Higher shear strain amplitudes have been observed at higher acceleration levels, which results in a linear cumulative displacement behavior at the top of the wall. A parametric investigation has also been performed by Rafnsson (1991) for varying angle of internal friction of the base soil and backfill soil. It was observed that the angle of internal friction of the backfill has only minor effects on the wall displacement. However, lesser cumulative displacement was observed in retaining walls with a higher base soil angle of friction.

5. Present experimental investigation at The University of Melbourne

To understand the earthquake induced displacement behavior of retaining walls, a schematic experimental and analytical investigation has commenced at the Department of Infrastructure Engineering, The University of Melbourne. Shaking table test of scaled down retaining wall models is in progress to investigate response behavior of the retaining wall to seismic actions. Similitude analyses have been performed for finding the dimensions and weight requirement of scaled down models in 1g environment. The capability of scaled down retaining wall models has also been evaluated (Tiwari et al. 2016). Figure 3 shows the comparison of horizontal displacement of prototype retaining wall (concrete) and the scaled down retaining walls (fabricated with polycarbonate sheets) (Tiwari et al.2017). Figure 4 shows the ongoing shaking table experimentation on scaled down retaining wall models.



Prototype Retaining Wall – Concrete

Scaled Down Retaining Wall – Polycarbonate

Figure 3 Comparison of horizontal displacement of prototype retaining wall model and scaled down retaining wall model.

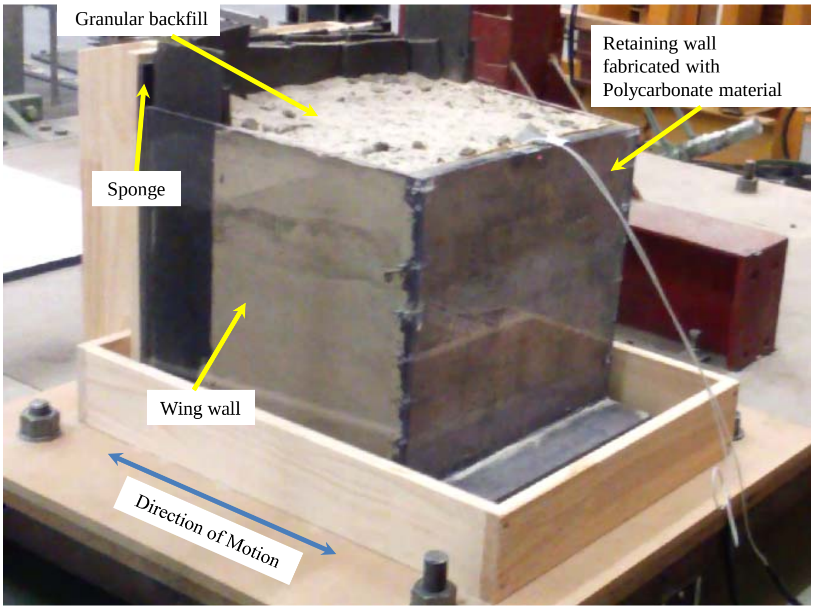


Figure 4 Ongoing shaking table experiment on scaled down retaining wall model.

6. Closing remarks

A review of seismic performance of retaining walls has been presented. The analytical approach for modeling the seismic actions on retaining wall has also been discussed. It was observed that retaining walls are highly vulnerable to earthquake-induced active displacement. The analytical approach is an effective and time efficient tool to evaluate the seismic displacement of retaining walls. However, the validity of analytical tool is still uncertain. Hence, a schematic experimental and analytical investigation is recommended for a better understanding of seismic performance of earth retaining structures.

Acknowledgement

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References

Choudhury, D. and Chatterjee, S. (2006) Displacement-based seismic active earth pressure on rigid retaining walls, Electronic Journal of Geotechnical Engineering,

Newmark, N. M. (1965) Effects of earthquake on dams and embankments, Geotechnique, Vol 15(2), pp. 139-160.

Kramer, S. L. (1996) Geotechnical earthquake engineering, Third Indian Reprint, Pearson Education, Singapore.

Psarropoulos, P. N., Klonaris, G. and Gazetas, G. (2005) Seismic earth pressures on rigid and flexible retaining walls, Soil Dynamics and Earthquake Engineering, Vol 25, pp 795-809.

Rafnsson, E. A. (1991) Displacement based design of rigid retaining walls subjected to dynamic loads considering soil nonlinearity, PhD thesis, University of Missouri-Rolla, USA.

Richards, R. J. and Elms, D. (1979) Seismic behavior of gravity retaining walls, Journal of the Geotechnical Engineering Division, ASCE, Vol 105(GT04), pp. 449-464.

Siddharthan, R., El-Gamal, M. and Maragakis, E. A. (1994) Investigation of performance of bridge abutments in seismic regions, Journal of Structural Engineering, ASCE, Vol 120, No 4, pp 1327-1346.

Tiwari, R., Lam, N. and Lumantarna, E. (2016) Displacement based design of bridge abutments, Australian Society of Earthquake Engineering Conference, Melbourne, Australia.

Tiwari, R., Lam, N., Lumantarna, E. and Au, T. K. F. (2017) A Drift and Displacement Based Seismic Assessment Method for Bridge Abutments, Australian Bridge Conference, Melbourne, Australia.

Whitman, R. V. and Liao, S. (1985) Seismic design of gravity retaining walls, US Army Corps of Engineers, Washington, USA.

Wilson, P. and Elgamal, A. (2015) Shake table lateral earth pressure testing with dense $c-\phi$ backfill, Soil Dynamics and Earthquake Engineering, Vol 71, pp 13-26.

Wu, Y. (1999) Displacement-based analysis and design of rigid retaining walls during earthquakes, PhD thesis, University of Missouri-Rolla, USA.

Yazdani, M., Azad, A., Farshi, A. H. and Talatahari, S. (2013) Extended Mononobe-Okabe method for seismic design of retaining walls, Hindwi Publishing Corporation, Journal of Applied Mechanics, Vol 2013, Article ID 136132, pp 1-10.