

29 May 2010, 8:00 am - 9:30 am

Dynamic Earth Pressures and Earth Pressure Cell Measurements

Yasir Ramzan Khokher
Arup, London, U.K.

Gopal Madabhushi
University of Cambridge, U.K.

Follow this and additional works at: <https://scholarsmine.mst.edu/icrageesd>



Part of the [Geotechnical Engineering Commons](#)

Recommended Citation

Khokher, Yasir Ramzan and Madabhushi, Gopal, "Dynamic Earth Pressures and Earth Pressure Cell Measurements" (2010). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 3.

<https://scholarsmine.mst.edu/icrageesd/05icrageesd/session08/3>



This work is licensed under a [Creative Commons Attribution-Noncommercial-No Derivative Works 4.0 License](#).

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.



Fifth International Conference on

Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics and Symposium in Honor of Professor I.M. Idriss

May 24-29, 2010 • San Diego, California

DYNAMIC EARTH PRESSURES AND EARTH PRESSURE CELL MEASUREMENTS

Yasir Ramzan Khokher

Arup
London, UK

Gopal Madabhushi

University of Cambridge
Cambridge, UK

ABSTRACT

Retaining Wall failures have frequently occurred during seismic events and have therefore been the subject of much research. The pseudo-static force designs, based on the Mononobe-Okabe earth pressure coefficient equations, have been adopted by most current design codes due to its simplicity and ease of use. However, it is clear that there are limitations attached with this approach and more research is required into how the earth pressures develop during seismic events. This paper investigates the seismic behaviour of sheet pile retaining walls using centrifuge testing facilities. In addition to using bending moment strain gauges on the wall, new generation earth pressure cells have also been used to investigate the generation of active and passive earth pressures. The results indicate that Mononobe-Okabe equations give relatively good estimates of active earth pressures but may be over-predicting passive earth pressures at certain peak ground acceleration levels. It was also found that earth pressure cells are successful in providing good qualitative data but are unable to produce quantitative results. Based on these results, it is suggested that pseudo-static force design may not be appropriate in all cases and better solutions, which are equally easy to implement, should be explored.

INTRODUCTION

The behaviour of retaining walls for seismic conditions has been the focus of a considerable amount of research. Although, research in this particular area has led to fewer collapses, the limitation of existing pseudo-static force theories has been exposed periodically. Even in recent times, there have been a number of failures of retaining walls during earthquakes. This paper investigates the seismic response of embedded retaining walls in dry cohesion-less soils using centrifuge testing facilities at Schofield Centre, Cambridge. Although, there are not many reports of complete failure of retaining walls in dry cohesion-less soils, the structures have been reported to suffer a loss of serviceability due to large deformations.

A number of codes currently advise the use of simple pseudo-static methods for the design of retaining walls in areas of seismicity. However, these methods are based on a number of key assumptions (Kramer, 1996), which are routinely overlooked for different types of retaining walls and soil conditions. This investigation aims to compare the analytically calculated earth pressures using pseudo-static methods and the measured earth pressures during centrifuge testing of sheet pile embedded retaining walls in dry cohesion-less soils. Although, a number of researchers have carried out similar investigations in the past (Steedman and Zeng, 1990), most

have opted to measure the bending moment on the retaining wall using strain gauges, which limited the research to flexible retaining walls. This has generally been the case because the use of Earth Pressure Cells (EPC) is generally avoided due to a number of issues (Egan and Merrifield, 1998) associated with the instrumentation. However, recently, a number of new EPC have been developed which have provided fairly promising results in other centrifuge tests (Dewoolkar et al, 2001). This study will use one of these EPC to investigate the generation of earth pressure on either side of an embedded retaining wall in dry cohesion-less soil during centrifuge testing.

EARTH PRESSURE CELLS

There has been very little research carried out to determine the actual magnitude and distribution of lateral seismic or static earth pressures acting on a retaining wall. Most researchers have been reluctant to make direct measurements of the soil pressures due to the lack of faith in the earth pressure transducers available in the past. Egan & Merrifield (1998) produced a list of factors that may affect the accuracy of soil pressure measurements during an experiment.

- a) Inclusion effects related to the disturbance of the stress field arising from the presence of a cell;
- b) Cell/soil interaction is a function of the relative stiffness of the cell with respect to the soil;
- c) Placement effects; and
- d) Environmental influences and dynamic response.

Indeed, most researchers have tended to back-calculate earth pressure indirectly from other instruments. Bolton & Steedman (1985) and Steedman & Zeng (1991) opted to measure bending moments using strain gauges and compare it with bending moment calculated using Mononobe-Okabe analysis. Oritiz et al (1983) also measured bending moment on a cantilever retaining wall during a centrifuge test and tried to differentiate it twice to acquire earth pressure. This was unsuccessful due to the propagation of errors inherent in differentiation.

However, Dewoolker et al (2000) carried out tests on a cantilever wall in saturated sand using Entran EPL miniature cells and the results were extremely encouraging. The researchers were able to carry out modeling of models and repeatability of the experiments was also proved. Dewoolker et al (2000) were also able to show the internal consistency between the earth pressures, accelerations, bending strains and deflections. It was hence decided to use similar pressure cells during this research to study the seismic behaviour of embedded sheet pile retaining walls and investigate further the reliability of these particular earth pressure transducers.

The earth pressure transducers used during this study were manufactured by Entran, model number EPL-200-100S and are miniature surface mount stainless steel diaphragm pressure sensors. The earth pressure cells are 3mm in diameter, 7mm in length and 1mm thick. The pressure cells consist of semiconductor strain gauges bonded to a circular, stainless steel sensing membrane. They have a resonant frequency of about 65 kHz and are capable of detecting a change in pressure of 6900kPa. The technical specifications for the EPC are shown in Table 1.

The above pressure sensors were calibrated in a shear box. This was done by taping the earth pressure sensors to a plate and placing them inside the shear box apparatus. The shear box was then filled with Leighton Buzzard Sand used during centrifuge tests. The shear box was subjected to repeated cycles of incremental normal loading and unloading using standard weights. The calibration factors were established after plotting the stress inside the shear box and the voltage reading from each earth pressure sensor.

In addition to EPC, strain gauges were used to measure bending moments on the sheet pile retaining wall, accelerometers were used to measure accelerations at different points in the soil mass, Linear Variable Differential Transformers (LVDT) were used to measure wall displacements at the top of the wall and at excavation level and, vertical and horizontal acceleration of the aluminum

model retaining wall was measured using Micro-electromechanical system (MEMS).

Table 1. Characteristics of the Entran EPL pressure transducers (Chua, 2003)

Factors affecting earth pressure measurements	Correction method / requisite	Entran EPL pressure transducers
Aspect ratio	T/D < 1/5	T/D < 1/5
Diaphragm deflection (arching)	d/Δ > 2000 – 5000	d/Δ = (7 bar FSO) d/Δ = (35 bar FSO)
Stress concentrations at cell corners	Use inactive outer rims d ² /D ² < 0.25 – 0.45	d ² /D ² = 0.35 approximately
Eccentric, non-uniform and point loads	Increase stress cell active diameter, d/D ₅₀ ≥ 10	d/D ₅₀ = 35
Soil-cell stiffness ratio, S	S < 0.5	S=0.26, S < 0.5

MODELING DETAILS

During the course of this study, three centrifuge experiments were carried out. Details of the centrifuge and dynamic testing facilities at Cambridge University Engineering Department (CUED) have been provided by Schofield (1980) and Madabhushi et al. (1998) respectively. The retaining wall models were tested in the deep equivalent shear beam model container (ESB). The design of the model container was described by Brennan & Madabhushi (2002a). The model container was built from stacked hollow aluminum rectangular rings with rubber between them to allow the box to deform. The internal dimensions of the model container are 673mm in length, 253mm in width and 427mm in height. Hence a soil bed of more than 25m at prototype scale can be modeled at 80g. The boundary effects resulting from this type of model container in dynamic centrifuge testing were outlined by Teymur & Madabhushi (2003).

All three tests were carried out at 80g, which acted at the excavation level in the front of the retaining wall. The data from the three tests was compared with the theoretical analyses based on previous research. The testing program carried out during this study is summarized in Table 2.

During all the centrifuge tests described above, Leighton Buzzard 100/70, fraction E, fine silica sand was used. The relative density of the sand was maintained at 50-55% during the three tests to carry out tests in light to medium dense sand. Additional tests with a similar test set-up, which focused on the influence of relative density, were carried out under the RELUIS project by Ricardo Conti, who has kindly agreed to share data with the authors of this paper. The RELUIS tests used flexible walls (488mm), embedment depth ratio of 1 and

strain gauges to measure bending moments as the relative density was varied from 30 to 75%.

Table 2. Centrifuge Testing Program

	Wall thickness	
D/H ratio	264 mm	488 mm
0.8	RW-3	RW-2
1	RW-1	

The retaining wall was modeled using an aluminum section of 3.3mm which retained the same flexural stiffness and thickness of a 264mm sheet pile at prototype scale. It must be noted here that all results and figures (unless where clearly stated) refer to the prototype scales.

RESULTS:

Performance of EPCs in Dynamic Conditions

Fig. 1 shows the time histories of the data collected from earth pressure cells during EQ1 in test YRK-1. These results are fairly typical throughout the three centrifuge tests when the first earthquake has been applied to the model. This earthquake’s input motion had an average amplitude of 0.11g. The starting earth pressure is the static earth pressure developed during the swing up phase of the centrifuge test and the flat line after the earthquake indicates the residual pressures. The oscillations in between followed the base horizontal input motion of the earthquake. As can be seen in the following figure, the EPCs were able to successfully capture the dynamic changes in the earth pressure during the earthquake. The readings were taken at 0.00025 seconds (model scale), and earthquake frequencies of up to 0.75Hz were applied to the package.

Retained Side

Excavation Side

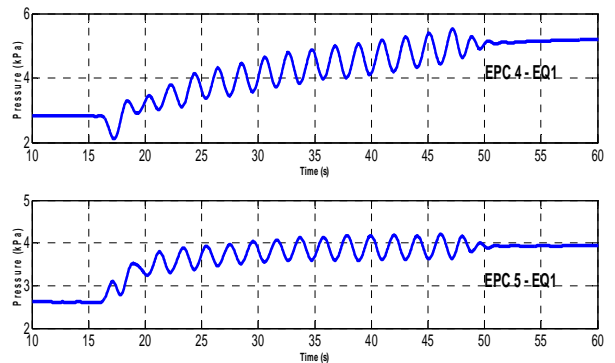
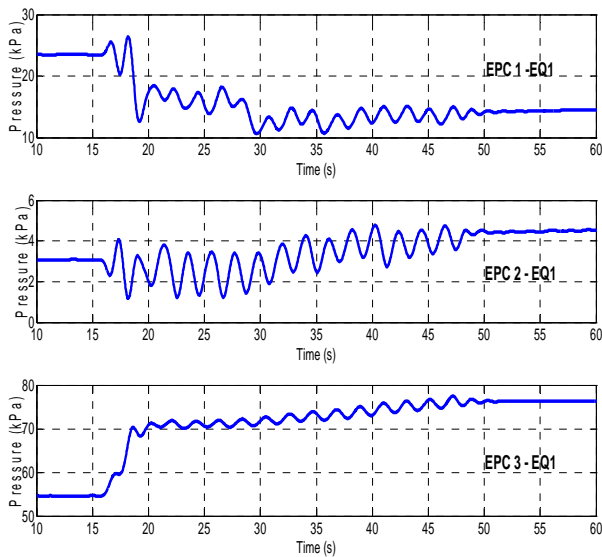


Fig. 1. EPC Data from EQ1: 0.11g earthquake during Test RW-1

The top EPC on the retained side experiences a drop in earth pressure with the beginning of the earthquake input motion. This is because as the wall experiences accumulated outward displacement due to accelerations, greater soil strains are induced near the crest reducing local earth pressures. This has been noted before for static conditions by Sherif et al (1984).

EPC2 is also able to detect the dynamic behaviour of the soil, but very small earth pressure measurements are registered due to proximity to pivot point location. However, EPC3 experiences a big rise in earth pressure because the passive

earth pressure is mobilised under the pivot point of the wall as wall experiences outward rotation.

The EPCs on the excavation side also experience a rise in earth pressure during dynamic conditions. The top EPC on this side also experiences an initial drop in pressure but passive earth pressure instantly starts to mobilise during the earthquake. There is only a small change in active earth pressure below the pivot point of the wall as the wall rotates.

After the conclusion of the earthquake, there is clearly an additional residual dynamic earth pressure that remains. The existence of earthquake residual earth pressures has been noted by other researches Whitman & Ting (1993) and Dewoolkar et al (2000). These increases are associated with the tendency of sand to densify with an increase in the minor principle stress when shaken or vibrated.

Fig. 2 shows typical earth pressure data from one of the latter earthquakes. The residual earth pressures after the last earthquake are indicated by the flat line at the start of this

earthquake. There are clear differences between the earth pressure behaviour between the early and the latter earthquakes. The earth pressures oscillate uniformly during these earthquakes and very little residual earth pressure is registered at the end of the earthquake. This behaviour suggests that the soil has started to behave as a rigid body which is similar to one of the assumptions underlying Mononobe-Okabe analysis. It was found that only an earthquake of significantly bigger intensity would cause an increase in residual pressures.

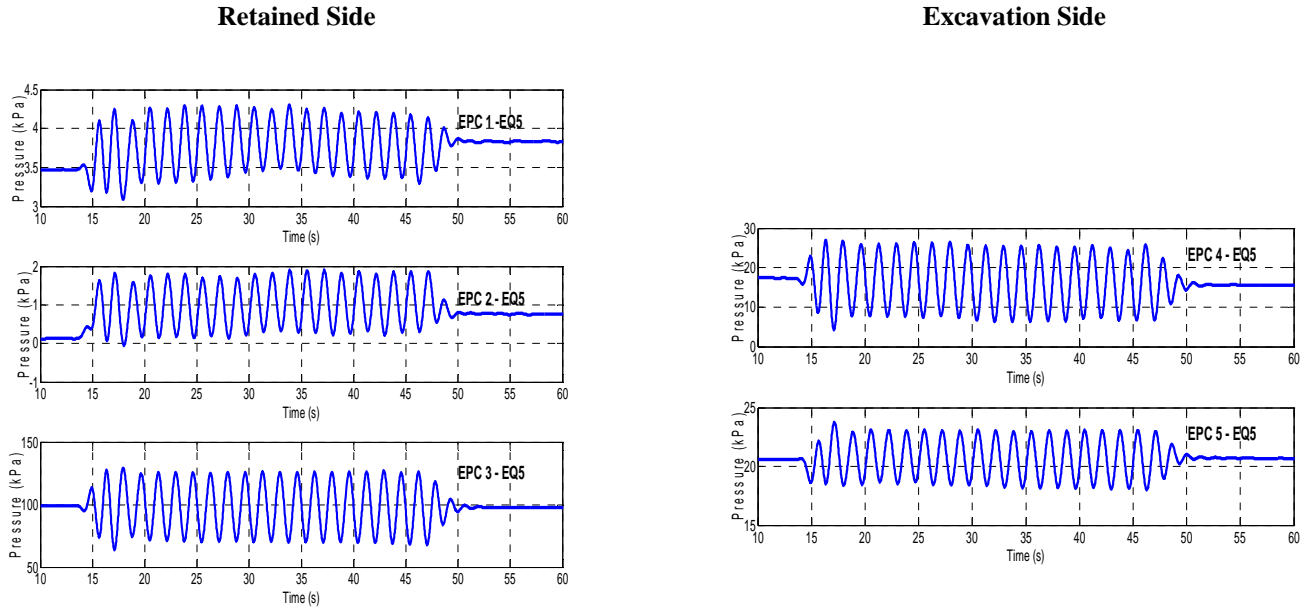


Fig. 2. EPC Data from EQ5: 0.22g earthquake during RW-2

Modes of displacement:

Fig. 3 shows the time history record from the two LVDTs measuring lateral displacements and the calculated rotation in test YRK-2 during EQ4. The displacements that developed during swing up to 80g and the accumulated residual displacements after each of the previous EQ are indicated by the flat line to the left of the figure.

The tip displacement accumulates gradually during the earthquake and a residual displacement is registered at the end of the earthquake. The displacement of wall is directly linked with the generation of earth pressures and is hence an important part of understanding the embedded retaining wall problem.

An important part of this study revolves around studying the modes of displacement of an embedded sheet pile retaining wall during static and seismic conditions. The lateral displacement of the wall was measured at the tip and near the excavation level as shown earlier. For a relatively stiff retaining wall of 500mm thickness in prototype scale, which is unlikely to bend and as modeled in RW-2, it is possible to investigate the modes of displacement. From Fig. 3, it is apparent that the wall has indeed rotated about some point at the bottom of the wall. Using the residual displacements and simple trigonometry, it is possible to ascertain the rotation after each earthquake. Table 3 and Table 4 show the total displacement and rotation results. Fig. 4 shows the displacements in a graphical form. It can be seen from the following data that greater residual displacements occur for higher acceleration earthquake motions.

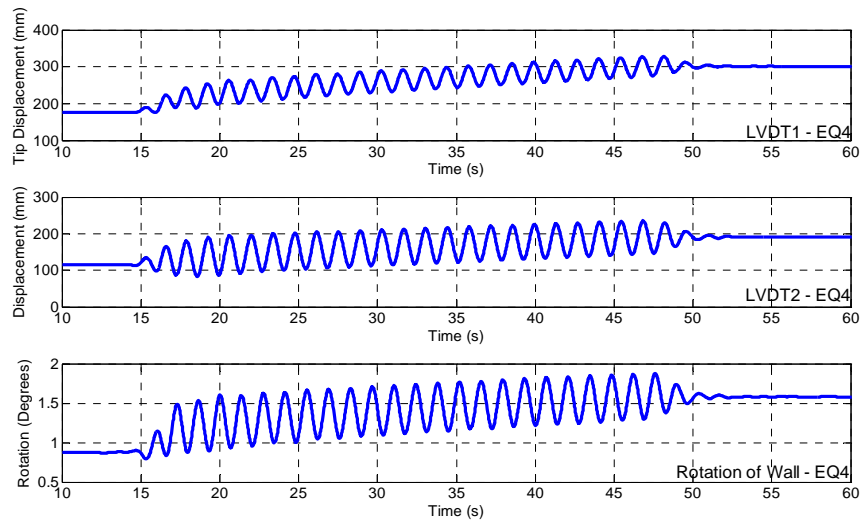


Fig. 3. LVDT data from EQ4: 0.28g earthquake during test RW-2

Table 3. Total displacement measured during RW-2

Depth (m)	Swg (mm)	Eq1 (mm)	Eq2 (mm)	Eq3 (mm)	Eq4 (mm)	Eq5 (mm)
LVDT - Top of Wall Level (0)	39.6	57.3	168.3	184.5	308.7	336.4
LVDT2- Excavation level (4)	11.5	21.9	113.4	123.4	198.5	216.0

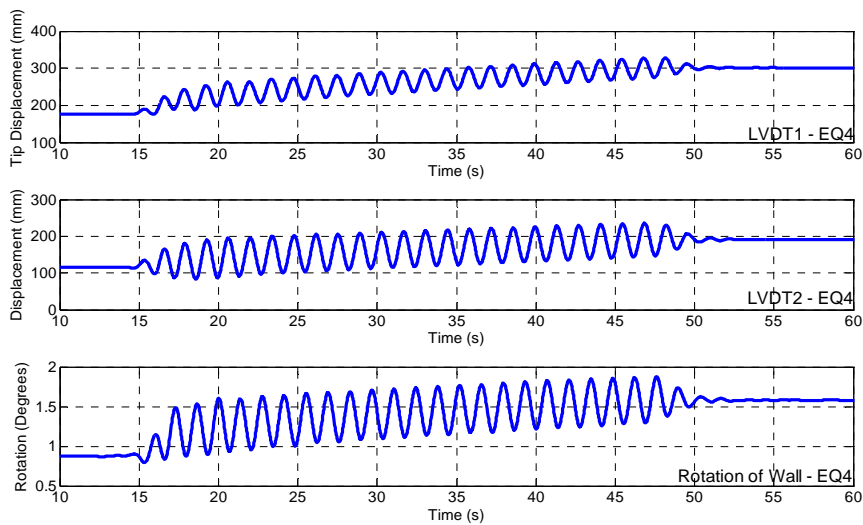


Fig. 3. LVDT data from EQ4: 0.28g earthquake during test RW-2

Table 4. Rotation of sheet pile wall during Test RW-2

	Swg 80g (degrees)	Eq – 11% of g (degrees)	Eq – 24% of g (degrees)	Eq – 18% of g (degrees)	Eq – 28% of g (degrees)	Eq – 22% of g (degrees)
Rotation between LVDT1- LVDT2	0.4024	0.5072	0.7873	0.8755	1.5798	1.7255

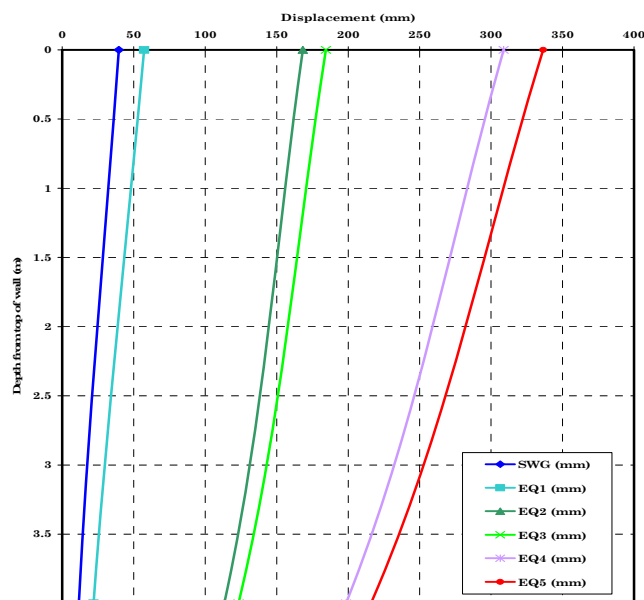


Fig. 4. Displacements recorded by LVDT at top of wall and at excavation level during test RW-2

Table 5. Lateral Translation of Retaining wall during test RW-2

Swg (mm)	Eq1 (mm)	Eq2 (mm)	Eq3 (mm)	Eq4 (mm)	Eq5 (mm)
1	5	59.8	63.8	90.9	98.6

These findings have been observed before by other researchers, including Nadim and Whitman (1984) and Siddharthan et al (1992), who have reported that walls can move by translation and/or rotation. They have shown that the relative amount of movement depends on the design of the wall and both modes may dominate or happen simultaneously in different retaining walls.

Comparison with Mononobe-Okabe: Active Conditions:

Mononobe-Okabe is an extension of the Coulomb analysis which is intended to provide an evaluation of the total force acting on the wall and not necessarily the distribution of lateral earth pressures with depth. It was hence decided to evaluate the total lateral thrust on the wall experimentally and compare it with the M-O force. The vertical centroidal location of the lateral earth pressure profile was also calculated at each time step to obtain the time history of the line of action of the total thrust.

The total lateral thrust on the wall was obtained by integrating the lateral earth pressure profile at each time step. A straight line approximation through the data points was deemed appropriate. The line of action of the force was found by using standard centroidal analysis. The time histories of the total dynamic lateral thrust normalized with respect to the static thrust and its line of action are plotted in Fig. 5.

The above rotations increase after each earthquake due to base accelerations leading to wall accelerations which produces wall displacements which results in mobilization of earth pressures on either side of the wall. However, while examining the figures closely, it is possible to see that rotation is not the only mode of displacement.

Using simple geometry once again, it can be shown the wall is also experiencing translation laterally during the earthquakes, which is one of the global modes of failure.

Table 5 summarizes the translation values calculated during test RW-2. These values also accumulated with each earthquake.

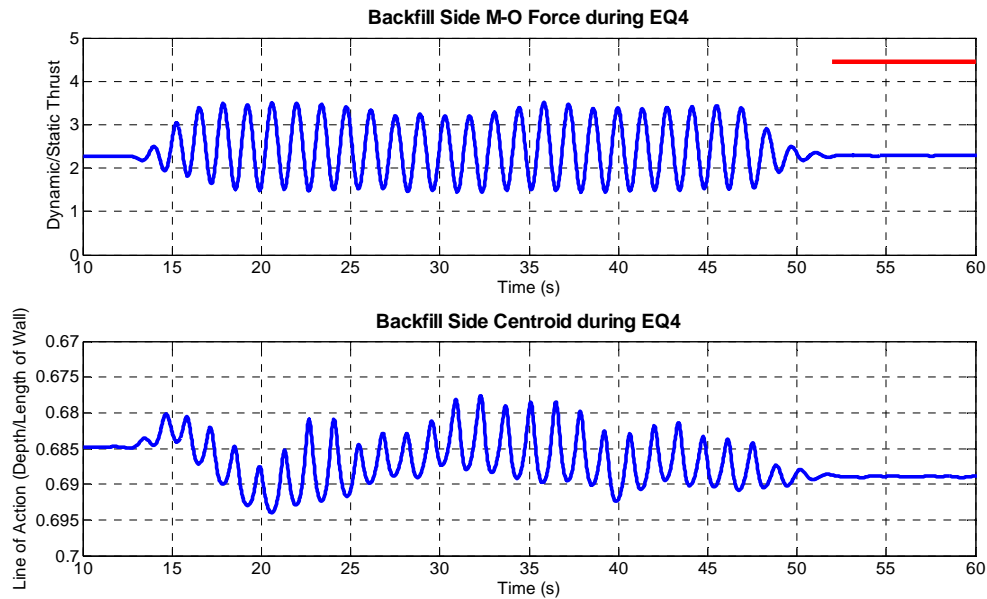


Fig. 5. Thrust and Centroid Location from EQ4: 0.28g during test RW-3

The maximum thrust increase recorded during the shaking was about 3.5 times more than the static thrust, which compares favourably with 4.7 predicted by M-O (shown in red on RHS of plot). This result is evidence of Mononobe-Okabe theory predicting the active pressures fairly accurately. The line of action for the total static thrust was calculated to occur at approximately 0.68L, which is close to the usual assumption during static conditions of 0.67L.

During the earthquakes, the line of action oscillated between 0.67L and 0.70L. The line of action for dynamic pressures did not rise up the embedded sheet pile retaining wall to 0.37-0.50L as predicted by Seed & Whitman (1970). Instead, it stayed at approximately the same location as for static analysis, as assumed by M-O analysis.

Effects of Flexural Stiffness

The wall stiffness is well known to play an important role in the distribution of earth pressures. Potts and Fourie (1985) showed that higher wall stiffness leads to bigger bending moments because earth pressures are prevented from falling to

active values. Earlier, Baransby and Milligan (1975) showed that the magnitude of wall deflections is inversely proportional to the flexibility of the wall.

In order to study the effects of wall stiffness, a comparison can be made of the centrifuge tests carried out on walls of thickness 488mm and 264mm. The wall stiffness was calculated to be 663 and 107 kNm²/m respectively for each wall. The dynamic earth pressures, normalised with respect to static pressures, were plotted against wall displacements as shown in Fig. 6 and Fig. 7. Each data point represents conditions after swing up, earthquake 1 and through to earthquake 5.

The tip displacement during static conditions for each test was found to be 0.4% of the overall wall height which compares well with current practice limits of 0.5% (Powrie et al., 1998). It is evident from Fig. 6 that that the relatively stiffer wall attracts greater active earth pressures proportionally to tip displacement as the relatively flexible wall. It is also apparent that the relatively flexible wall experiences greater tip displacement for the first three earthquakes, before both walls begin to suffer large tip displacements without significant change in pressures.

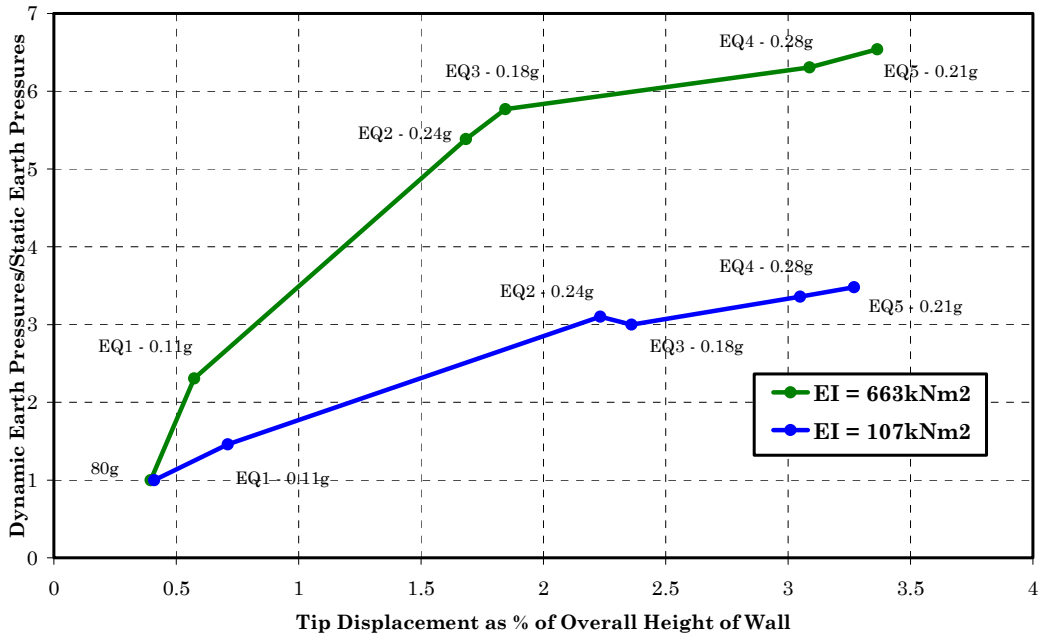


Fig. 6. Comparison of Dynamic Earth Pressures on Active Side for different Wall Stiffness

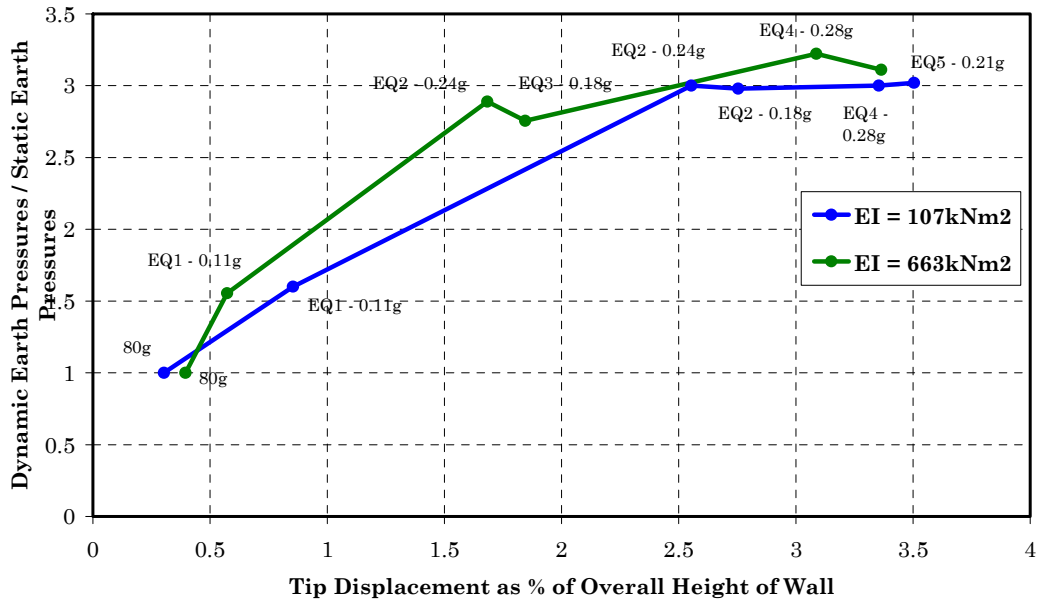


Fig. 7. Comparison of Dynamic Earth Pressures on Passive Side for different Wall Stiffness

Fig. 7 shows the change in passive pressures on the backfill side below the pivot point with increasing tip displacement. It is evident again that the relatively stiffer wall experiences greater pressures and is less likely to suffer excessive tip displacements during the early earthquakes. However, the stiffer wall suffers a big displacement after EQ4 with

relatively little change in earth pressures. It can hence be concluded from the above data that the lateral earth pressure coefficients increased behind both walls in active and passive conditions. However, a bigger change was registered for stiffer walls, which also suffered less displacement.

Influence of relative density of soil

It is important to investigate the effects of the relative density of soil on the seismic behaviour of retaining wall. This is necessary because the relative density of the soil has been shown in the past to influence the maximum friction angle and hence maximum bending moments on the wall. Although, all of the three tests in the present study had a loose to medium dense backfill with the relative density ranging from 50-60%, a researcher, part of the Reluis project, was specifically looking at the influence of relative density of soil on similar models.

The dilatancy of sand is an important concept used in the investigation of the interaction of soil and the retaining structure during earthquakes. Bolton (1986), using data from a number of laboratory tests on different sands, suggested that the mobilized angle of friction is dependent on the relative

density and confining pressure. This dilatancy theory for sands was hence used to calculate the peak internal friction angle of backfills with different relative densities.

Fig. 8 shows the bending moment results from the centrifuge tests carried out during the study and the Reluis project by Conti & Madabhushi (2008). The figure shows the difference in bending moments experienced by an embedded wall when a similar intensity earthquake was applied to models with relative density of 0.5 and 0.75 respectively. The maximum bending moments on the wall were consistently higher for a wall with loose sand backfill by about 20-25%. As explained above, this is due to different densities of sand corresponding to different friction angles within the backfill soil. This is why densification is often employed where extremely loose soils are encountered. (It may also be carried out where liquefaction is a particular threat).

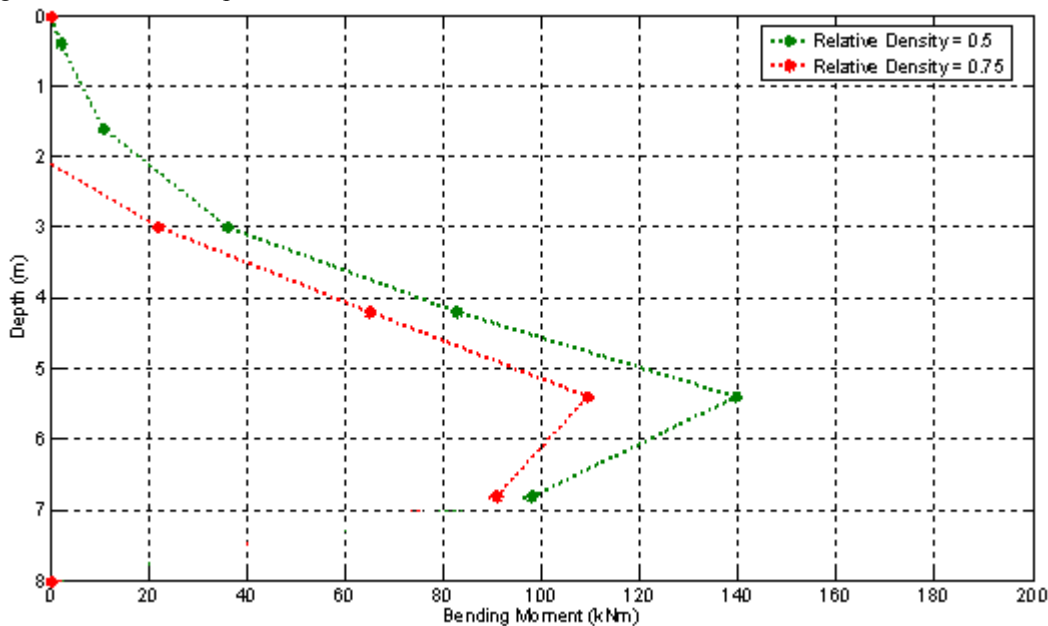


Fig. 8. Influence of Relative Density on Dynamic Bending Moment – 0.19g (RELUIS)

Comparison with Mononobe-Okabe: Passive Conditions:

A comparison of analytically calculated bending moments based on fully mobilized active/passive earth pressures and the bending moments obtained from RW-3 test was carried out and is illustrated in Fig. 9 to Fig. 11.

It was found that there was quite good agreement between the static analytical and experimental bending moments. A back analysis of the experimental bending moment was carried out above the excavation level to find the internal friction angle of the backfill to be 42° which compared well with the analytically calculated 44°. A comparison of experimental dynamic bending moment was also made with the bending moment calculated using Mononobe-Okabe analysis. The

experimental bending moments plotted are at the instant when maximum bending moment is recorded in the wall. It was found that bending moments were usually within the 20% range of each other. However, it was found that Mononobe-Okabe over-predicted the bending moment when the earthquake intensity was above 0.2g and under-predicted the bending moment when the earthquake intensity was below 0.2g. As will be shown subsequently, this is due to Mononobe-Okabe over-predicting the passive earth pressures. It is also important to note that although no failure was recorded during these centrifuge tests, the total dynamic bending moment in EQ4 was twice the maximum bending moment recorded in static conditions. It is hence prudent to design the embedded retaining walls for a high intensity earthquake where necessary.

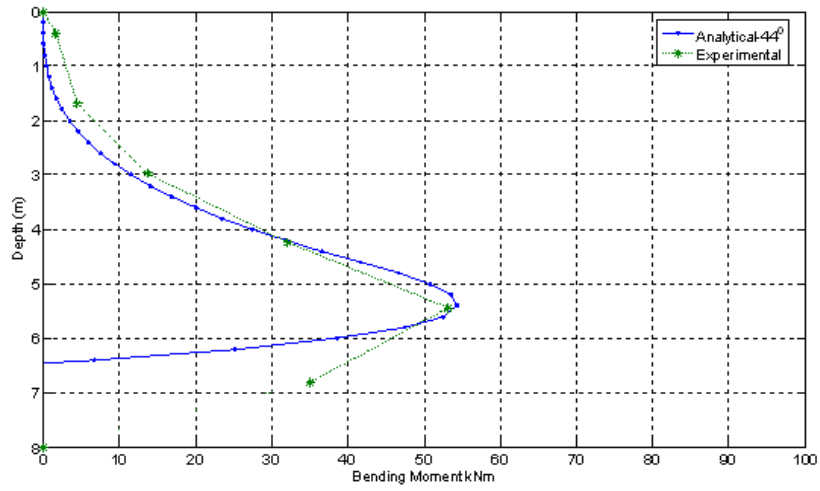


Fig. 9. Static Experimental-Analytical Bending Moment Comparison from RW-3

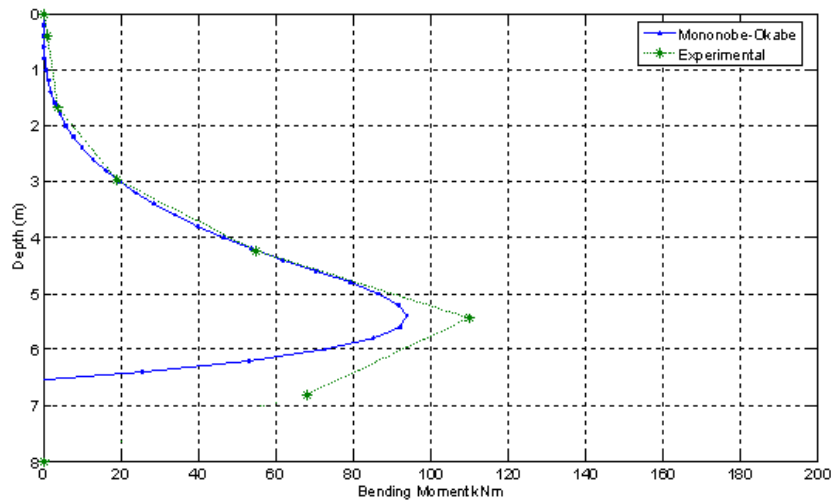


Fig. 10. EQ3 – 0.18g Experimental-Analytical Bending Moment Comparison from RW-3

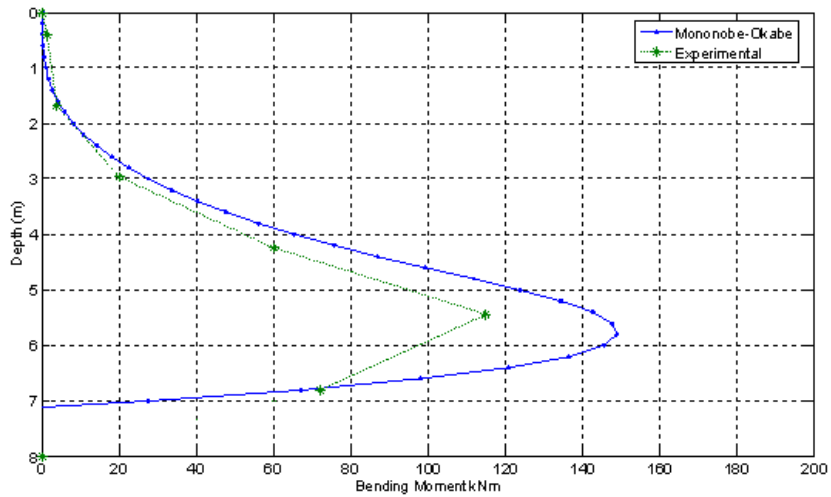


Fig. 11. EQ4 – 0.28g Experimental-Analytical Bending Moment Comparison from RW-3

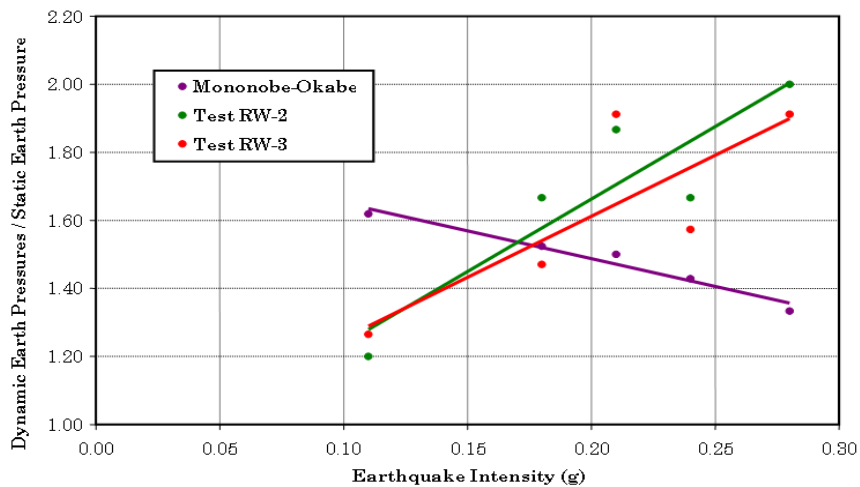


Fig. 12. Analytical – Experimental Passive Earth Pressure Coefficient

Fig. 12 shows that the pressures increased on the supporting side of the embedded wall with increasing intensity of earthquakes throughout the three tests whereas Mononobe-Okabe equations are well known to predict a decrease in passive earth pressures. As shown earlier, the experimental bending moment was under-predicted by the Mononobe-Okabe analysis for PGA of up to 0.2g. From **Error! Reference source not found.**, it is evident that the Mononobe-Okabe analysis over-predicts the passive pressures which results in an under-estimation of the peak bending moment for PGA of up to 0.20g. The Mononobe-Okabe analysis, based on these results, may be providing unsafe designs for base accelerations up to 0.2g, and exceedingly conservative designs for accelerations above 0.25g.

CONCLUSIONS

Dynamic centrifuge tests were performed on models of embedded sheet pile retaining wall retaining dry cohesion-less backfills. Direct measurements of the dynamic lateral earth pressures were made using miniature Earth Pressure Cells. Experimental measurements were then evaluated to study the seismic behaviour of the retaining wall system. Based on the results of the three tests, the following may be concluded.

a) Earthquakes had a significant effect on the earth pressures, bending moments and wall deflections for a sheet pile wall with dry sand backfill. Although, none of the centrifuge tests recorded a complete failure of the system, significant residual pressures, wall tip displacements, surface settlement on backfill side and surface heave on excavation side would render the structure as a failure according to serviceability limit state criteria.

b) Based on the results of this study, Mononobe-Okabe method of analysis provides a reasonable prediction of active earth pressures for the case of an embedded sheet pile wall. However, it was also found that the Mononobe-Okabe equations over-estimated the passive earth pressures for base

accelerations of up to 0.2g as shown in **Error! Reference source not found.** There was further evidence of this when bending moments were underestimated by Mononobe-Okabe method of analysis for base accelerations less than 0.2g. Therefore, the use of Mononobe-Okabe method of analysis may be deemed as unsafe for base accelerations of up to 0.2g and increasingly conservative for PGA levels beyond 0.2g.

c) A key objective of this study was to gauge the performance of the earth pressure sensors. It was found that Earth Pressure Cells were able to provide good qualitative data which matched well with static theories for different model layouts. It was also found that the sensors were able to capture the changes in earth pressures during dynamic conditions, as well as registering a residual earth pressure at the end of an earthquake as noted by other researchers measuring bending moments in the past. Hence, the Earth Pressure Cells were able to provide some valuable information. Further research aims to establish calibration between earth pressure measurements, strain gauge bending moment measurements and LVDT displacement measurements.

However, unfortunately, the sensors were not able to provide adequate quantitative data. It is suggested that better calibration of earth pressure sensors, which is close to the centrifugal test conditions, may yield better results.

d) It was found that with each earthquake, the lateral earth pressure coefficients increased as lateral stresses locked in behind the wall. It was also found that the relatively stiffer walls were likely to generate greater earth pressures as it underwent little displacement when compared with flexible walls.

e) A study of the influence of the relative density of soil on the bending moments revealed that greater maximum bending moment was registered for a loose soil when compared with a dense soil. This is because relative density influences the peak friction angle as suggested by Bolton (1986). It is hence

advisable that densification of soil is considered as a remedial measure when especially loose soils are encountered.

ACKNOWLEDGEMENTS

The first author would like to thank the second author who acted as his supervisor during his MPhil Research Degree. The authors would also like to Professor Malcolm Bolton for his input during the research project and his comments were always very helpful.

REFERENCES

B.Teymur and S.P.G. Madabhushi, [2003], “*Experimental study of boundary effects in dynamic centrifuge modeling*”, *Geotechnique*, 53, No.7, pp 655-663

Bolton, M.D. and Steedman, R.S. [1982]: “*Centrifuge testing of micro-concrete retaining walls subjected to base shaking*”, *Proc. Conf. Soil Dynamics and Earthquake Eng.*, Southampton, 13-15 July, pp311-329.

Bolton, M.D. and Steedman, R.S. [1984]: “*The behaviour of fixed cantilever walls subject to lateral shaking*”, *Proc. Conf. Appl'n. Centrifuge Modelling to Geotechnical Design*, Manchester, April, 1984, pp302-341.

Bolton, M.D. and Steedman, R.S. [1985]: “*Modelling the seismic resistance of retaining structures*”, XI International Conference on Soil Mechanics and Foundation Engineering, San Francisco

Bolton, M.D. [1986]: “*The strength and dilatancy of sands*”, *Geotechnique* 36, No.1, 65-78

Chua, H.Y. [2003]: “*Horizontal Arching of earth pressures on Retaining Structures*”, MPhil thesis, Cambridge University
Conti, R. & Madabhushi, G. [2008]: “*Centrifuge Tests on Retaining walls as part of Reluis project*”, Technical Report CW1 & CW2

Dewoolkar M.M., Ko H.Y., Pak R.Y.S., [2001]: “*Seismic Behaviour of Cantilever Retaining Walls with liquefiable backfills*”, *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 19, pp. 583-593

Egan, D., and Merrifield, C.M., [1998]: “*The use of miniature earth pressure cells in a multi-gravity environment*”, *Proceedings of the International Conference Centrifuge*, September 1998 (Editors: Kimura, Kusakabe and Takemura), Volume 1, pp. 55-59.

Kramer, S. L., [1996] “*Geotechnical Earthquake Engineering*”, Prentice Hall, New Jersey

Madabhushi, S.P.G., [1994], “*Dynamic response of the Equivalent Shear Beam (ESB) container*”, Technical Report,

TR270/D-Soils/CUED, Cambridge University

Madabhushi, S.P.G., Schofield, A.N. and Lesley, S., [1998], “*A new Stored Angular Momentum (SAM) based Earthquake Actuator*”, *Proc. Centrifuge'98, Intl. conf on Centrifuge Modelling*, Tokyo, Japan

Mononobe, N. and Matsuo, H. [1929]: “*On the determination of earth pressure during earthquake*”, *Proc. World Eng. Congress*, Vol. 9, pp. 177-185

Nadim, F. and Whitman, R.V. [1984]: “*Coupled sliding and tilting of gravity retaining walls during earthquakes*”, *Proceedings, 8th World conference on Earthquake Engineering*, San Francisco, Vol. 3, pp. 477-484

Newmark, N. [1965]: “*Effects of earthquakes on dams and embankments*”, *Geotechnique*, Vol. 15, No. 2, pp. 139-160

Okabe, S. [1926]: “*Experiment for earth pressure and seismic stability of retaining wall and dam*”, *J. Jap. Civil Eng. Soc.*, Vol. 10, No. 6, Dec.

Ortiz, L.A., Scott, R.F. and Lee, J. [1979]: “*Dynamic centrifuge testing of a cantilever retaining wall*”, *Research Report, Soil Mech. Lab., C.I.T., Pasadena*

Potts, D.M., and Fourie, A.B., [1985]: “*The effect of wall stiffness on the behaviour of a propped retaining wall*”, *Geotechnique* 35, No. 3, pp. 347-352

Potts, D.M., and Fourie, A.B., [1986]: “*A numerical study of the effects of wall deformation on earth pressures*”, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 10, pp. 383-405

Schofield, A.N. [1980]: “*Cambridge University Geotechnical Centrifuge Operation*”, *Geotechnique* 30, No. 3 pp. 449-469

Schofield, A.N. [1981]: “*Dynamic and earthquake geotechnical centrifuge modeling*”, *Proc. Int. Conf. Rec. Adv. Geotech. E'quake. Eng. And Soil Dynamics*, Missouri, April 26-May 3, 1981

Seed, H.B. and Whitman R.V. [1970]: “*Design of earth retaining structures for dynamic loads*”, *Lateral stresses in the ground and design of earth retaining structures*, ASCE, 1970, pp103-147

Taylor, R.N., [1995]: “*Centrifuges in modeling: principles and scale effects*”, *Geotechnical centrifuge technology*, Taylor R.N. (Editor), Blackie Academic & Professional.

Whitman, R.V. and Ting, N.H. [1993]: “*Experimental Results of experiment No. 10*”, *Proceedings of International Conference on Verifications of Numerical Procedures for the analysis of Soil Liquefaction problems*, pp. 881 – 89