

NEWMARKIAN ANALYSIS OF LIQUEFIED FLOW IN CENTRIFUGE MODEL EARTHQUAKES

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ABSTRACT

This paper describes the application of a modified Newmarkian analysis method to the estimation of slope deformations during liquefaction-induced lateral spreading. The analysis method requires a pore-pressure history either predicted using a suitable constitutive model, or measured during a centrifuge or shaking-table test, to calculate the variation of threshold acceleration with time. Comparison of predicted displacements using this procedure and displacements measured in centrifuge model tests with the same pore-pressure history shows good agreement.

INTRODUCTION

Gentle slopes of loose liquefiable soil exist in many earthquake-prone areas around the Pacific Rim and worldwide. These slopes have been seen to experience lateral spreads of several metres during most of the major earthquakes this century, such as the Niigata earthquake of 1964 and the more recent 1994 Northridge and 1999 921 Ji-Ji, (Taiwan) earthquakes.

A large amount of field data is available from previous earthquakes, with the magnitude of lateral spread normally being measured by aerial photogrammetry, comparing images from before and after the earthquake and measuring the positions of objects dragged with the flow such as the corners of buildings, manhole covers etc relative to certain fixed points.

Post-earthquake investigation of the area around the Shinano river after the 1964 Niigata earthquake by Hamada & O'Rourke (1992) revealed that 10m of surficial displacement had occurred. These large ground displacements can cause great damage to both structures and roads founded upon them and to lifelines such as water pipes passing through these liquefiable deposits, as the strains accumulated during these movements can be huge. Large displacements particularly occur when the flow of ground is towards a free boundary such as a river, sea-shore or quay wall, as in these cases the water-table is high giving ideal conditions for liquefaction and the boundary conditions are favourable for large movements of soil to occur. These ground movements have been reported to cause more damage during

earthquakes than any other form of liquefaction induced ground failure, National Research Council (1985).



Fig. 1. Nantou new bridge after the 1999 Ji-Ji Earthquake



Fig. 2. Nantou bridge pier showing build-up of soil on the upslope face.

Figures 1&2 show the Nantou new bridge in Taiwan after the 1999 Ji-Ji earthquake. From Fig. 2 it can be seen that liquefied soil has flowed down the slope past the bridge pier, piling up on the up-slope side of the pier. This will have exerted large horizontal forces on the pier, the magnitudes of which are difficult to calculate and design for.

Lateral spreading has been widely investigated in the last ten years or so, with centrifuge modelling being carried out using sloping laminar boxes at RPI by Abdoun (1997) and finite element modelling at Cornell by Meyersohn (1994). In engineering practice, displacements tend to be predicted using the multilinear regression (MLR) equations developed by Bartlett and Youd (1992) and most recently modified by Youd et al. (1999). These equations were derived by taking an enormous data set of lateral spread cases from previous earthquakes and taking a best fit to this data using linear regression for each parameter considered, including thickness of the liquefiable layer, fines content, ground slope and mean grain size. Back-calculation to the data set shows displacements to be predicted to within a factor of two for around 95% of cases.

The large amount of scatter in the MLR data set is due to the fact that whilst many of the parameters affecting liquefaction-induced lateral spreading have been incorporated into the equations, significant other factors have been ignored. Considering the mechanism by which lateral spreading occurs, with shear strain being accumulated whilst the driving shear stresses exceed the shear strength of the soil, it can be seen that the amount of time that pore pressure is retained within the liquefied layer will play a large part in the magnitude of lateral spread observed. This is a parameter ignored by the MLR equations, being a function of earthquake duration and the seepage boundary conditions above and below the liquefiable layer.

Newmark (1965) in his Rankine lecture proposed a simple two-block model to calculate the displacement of dry slopes during earthquakes. This conceptual model assumes that as there exists a limiting angle of friction between the block and slope, any base acceleration requiring a greater angle of friction than this for stability will cause slope movement to occur. Using a Mohr-Coulomb failure criterion, this implies that, for no movement to occur on a slope with angle β and angle of friction ϕ :

$$\frac{\tan \beta + \tan \phi}{\tan \beta \tan \phi - 1} < \frac{a}{g} < \frac{\tan \beta - \tan \phi}{1 + \tan \beta \tan \phi} \quad (1)$$

where a is the horizontal base acceleration.

This method can be modified to an effective stress based approach and can hence incorporate the effects of pore pressure on the resultant movement. As excess pore pressures are generated leading to liquefaction, the limiting accelerations fall. Asymmetry of the thresholds due to the slope angle leads to an

accumulation of down-slope displacement during and after the earthquake.

This paper describes a series of centrifuge tests carried out at Cambridge University investigating the lateral spreading of slopes, and examines the applicability of a Newmarkian analysis method incorporating excess pore pressures to the estimation of the resultant deformation of the slopes.

CENTRIFUGE TESTING

Principles of Centrifuge Modelling

Because soil is a highly non-linear material, reduced scale models of geotechnical structures at 1g will not behave in the same way as prototype structures. As much of the loading on soil comes from self-weight, an effective way of replicating the correct stress and strain states at points in a reduced-scale model is to test a 1:N scale model in the Ng gravity field of a geotechnical centrifuge.

The necessity for stresses and strains to be identical in model and prototype leads to a set of scaling laws for other physical properties, summarised in Table 1.

Table 1. Centrifuge Scaling Laws. After Schofield (1980 & 1981)

Parameter	Scale
Length	1/N
Stress	1
Strain	1
Velocity	1
Acceleration	N
Time (dynamic)	1/N
Time (consolidation)	1/N ²
Frequency	N

It can be seen that there is a conflict between the scaling laws for dynamic and consolidation time. This is important when modelling situations in which both inertial and seepage flow effects are important to behaviour, e.g. dynamic liquefaction events. This anomaly is corrected by replacing the pore water with a more viscous fluid, N cS silicone oil, thus slowing down seepage by a factor of N. Research has been carried out on the effect of the change of pore fluid on soil behaviour and has shown that the stress-strain curve is almost unchanged. (Bolton & Wilson 1990)

Experimental Programme

A series of six centrifuge tests on the stability of gentle slopes of

liquefiable sand during earthquakes have been carried out on the Cambridge University 10m beam centrifuge. The models consisted of loose sand beds of various slope angles between three and twelve degrees with differing base boundary conditions as illustrated by Fig. 3 and Table 2.

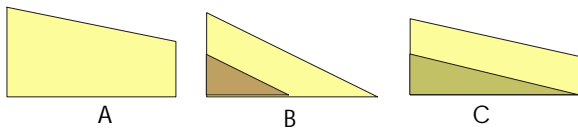


Fig. 3, Centrifuge Model Geometries.

A: no base slope, B: wooden base slope, C: dense sand base slope

Table 2. Centrifuge Test Properties at Prototype Scale.

Test	Geometry	Angle	Layer Thickness
SKH-5	A	3°	5m
SKH-8	B	6°	3m
SKH-9	B	12°	5m
SKH-10	A	6°	5m
SKH-11	C	6°	5m
SKH-12	C	6°	5m

(dry)

Models were prepared by air pluviation from an overhead hopper to give a relative density of approximately 20%, corresponding to a voids ratio of about 0.9. The sand used was Fraction E Leighton Buzzard silica sand with a D_{50} size of 0.14mm. The models were instrumented with miniature accelerometers and pore-pressure transducers at various locations, the output from which is used as input to the numerical code described in this paper for the prediction of displacement. Several of the test also incorporated marker layers and columns of coloured sand in order to investigate the displacement profile through the model.

The models were subjected to approximately sinusoidal base shaking using a Stored Angular Momentum (SAM) earthquake actuator, Madabhushi et al. (1998), with the model contained within an Equivalent Shear Beam (ESB) model container, Zeng & Schofield (1996). This model container has stiffness identical to that of the enclosed soil column, minimising the effects of the end-walls of the box on the behaviour of the model.

NEWMARKIAN NUMERICAL MODELLING

Newmarkian deformation modelling is based on the existence of certain critical accelerations, above which relative movement will occur between two blocks of soil. In sloping ground, the static shear stresses present will cause the acceleration thresholds in the up and down-slope directions to be non-equal. This can result in

non-zero final displacement even for a symmetrical input acceleration, predicting the occurrence of lateral spreading.

The numerical code used in the modelling described in this paper was implemented in the MATLAB mathematical modelling language. The scheme used was as follows:

1. Calculate the static stress condition at the point of interest.
2. Using a digitised record of excess pore pressure at this location, calculate the limiting accelerations at each time interval.
3. From the digitised record of base acceleration, integrate to calculate base velocity and base displacement at each time interval.
4. Starting from the beginning of the time record, calculate response acceleration, velocity and displacement using the following criteria:

- a) if no sliding is occurring, (velocities are equal) and input acceleration is within the allowable accelerations for no sliding to occur, the response acceleration is set to that of the base.
- b) if sliding is occurring the response acceleration is set to the threshold in the direction which would stop relative movement occurring, regardless of input acceleration.
- c) if no sliding is occurring but the input acceleration exceeds the thresholds, the response acceleration is set to the threshold value which is exceeded.

This procedure is repeated for each time step available from the acceleration records and is used to produce a history of response acceleration, velocity and displacement. Care needs to be taken when calculating the transition from sliding to non-sliding, as otherwise alternating small sliding velocities in different directions can cause the response acceleration to fluctuate between the positive and negative threshold values of acceleration.

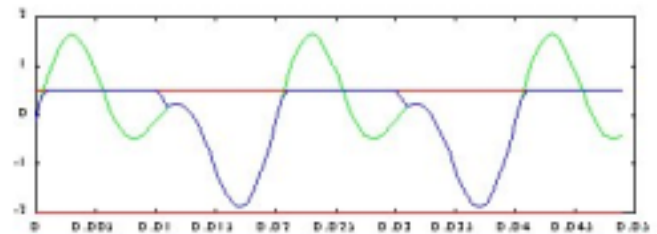


Fig. 4. Acceleration histories predicted by the numerical code. Input acceleration in Green, Response in Blue, Thresholds in Red.

Figure 4 shows how the procedure works on a synthetic input acceleration trace with constant pore pressure. The response follows the input until the threshold is breached, then follows the threshold until velocity convergence between input and response is achieved. The response then again follows the input until the

threshold is once again breached.

The validity of this scenario can be examined by looking at accelerometer traces recorded from near to the base and the surface of the centrifuge models during earthquakes. An example of this is shown in Fig. 5.

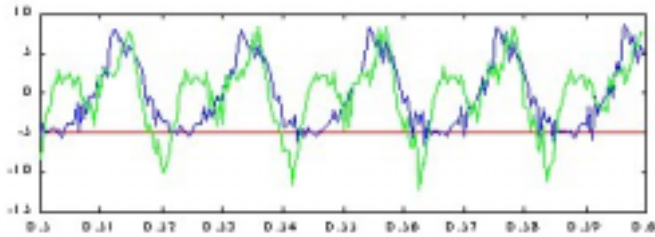


Fig. 5. Accelerations recorded in Centrifuge Test SKH-10. Base acceleration in green, surface response in blue, proposed threshold acceleration in red.

It can be seen that whilst within the acceleration thresholds, (the positive one being off the scale of the graph), there is no exact compliance between base and surface motion, for approximately half of the cycle the accelerometers move together. When the base acceleration approaches the threshold, progressive softening occurs, with the acceleration at the surface following the threshold for a time before reconnecting with the base.

The non-exact agreement with behaviour predicted by the numerical code is due to the Newmarkian modelling assuming a rigid-perfectly plastic transition on yield, whereas in reality there is some elastic and non-perfect plastic behaviour occurring, giving non-ideal behaviour.

Nonetheless, this centrifuge model data shows that despite the fact that no discrete slip plane occurs within the liquefied sand layer, a fact verified by the observation of columns of coloured sand within the model, observed acceleration behaviour shows close agreement with data predicted using this simple numerical code. As displacement data is merely a double integral of acceleration data, the agreement of observed acceleration data with that predicted gives a degree of confidence in the predicted displacement data.

The analysis was run on data from the set of centrifuge tests described in the previous section in an attempt to predict the observed displacements. The results of the analysis procedure are summarised in Table 3. It can be seen that correlation is achieved to within about 33%. This is better than the predictions obtained with the much more complex MLR method, which gives predictions only accurate within a factor of two on the field data used to obtain the MLR parameters.

Parametric studies carried out on the method show that the most critical parameter in affecting the displacement predicted is the amount of time for which the pore pressure exceeds the value required for static stability to be maintained. During this

period the soil accelerates down the slope, accumulating velocity. Because of this, the accrued displacement is approximately proportional to the square of the time for which static stability cannot be maintained.

Table 3. Predicted and observed slope displacements in Centrifuge Tests. (scaled to prototype scale)

Test	Predicted Displacement /m	Observed Displacement /m
SKH-5	n/a	1
SKH-8	0.8	0.6
SKH-9	0.9	0.75
SKH-10	1.1	1

For this analysis procedure to be extended to be a useful method for predicting the displacement of field slopes during earthquakes, the development and retention of pore pressures needs to be accurately estimated. This parameter is obviously related to both earthquake parameters such as acceleration amplitude and duration, but also to soil parameters such as permeability, relative density, water-table level and drainage conditions above and below the liquefiable layer. This last parameter may make order-of-magnitude changes to the lateral-spread displacement observed, as, for example, a liquefiable layer sandwiched between two reasonably thick impermeable clay layers may retain pore pressures greater than the maximum at which static stability of the slope can be maintained for a significant duration after cessation of the earthquake.

The exact shape of the pore pressure time-history is less important to the analysis method than is the rate of dissipation of pore pressure. A linearised pore-pressure history incorporating linear generation, a constant pore-pressure peak and linear dissipation post-earthquake, following the initial slope of the dissipation curve, will give little change in displacement predicted relative to the true time history. This gives a final error of around 20%, significant but not huge compared to the accuracy of the prediction from the model. An example of this history can be seen in Fig. 6.

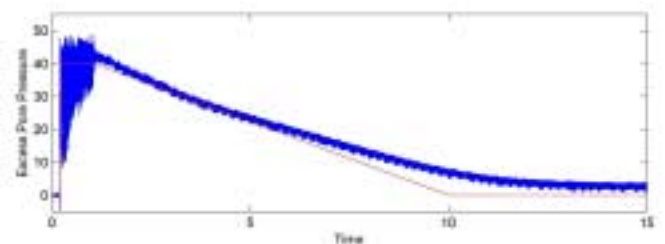


Fig. 6. Real and linearised pore pressure histories used for analysis. Real in Blue, Linearised in Red.

Effects on Newmarkian sliding on Acceleration Frequency.

The input acceleration produced by the SAM earthquake actuator has roughly equal frequency components at the fundamental and

first harmonic, with other components at higher harmonics, as can be seen from the frequency spectrum shown in Fig. 7.

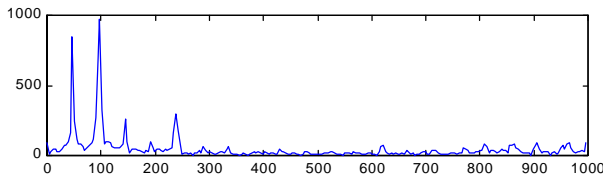


Fig. 7. Fourier spectrum of SAM input acceleration.

Investigation of the Fourier spectrum obtained by analysis of the accelerations observed near the surface of the model gives the spectrum shown in Fig. 8.

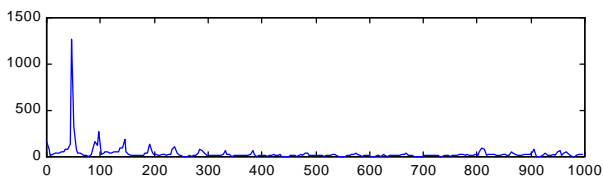


Fig. 8. Fourier Spectrum of surface acceleration.

It can be seen that whilst the fundamental earthquake frequency at 50Hz shows some amplification through the soil layer, the higher harmonics, especially the first harmonic at 100Hz, show severe attenuation, the first harmonic falling by 90% from its value at the input.

This behaviour can also be predicted using a Newmarkian sliding model. If we analyse the theoretical sliding behaviour shown in Fig. 4 using the same Fourier analysis, the spectra shown in Figs. 9 & 10 result.

It can be seen that the Newmarkian analysis predicts attenuation of the first harmonic relative to the fundamental due to the thresholding of the acceleration trace. It can be shown that the more severe the threshold, i.e. the greater the excess pore pressure generated and the more sliding occurring, the more attenuation of the harmonics will result.

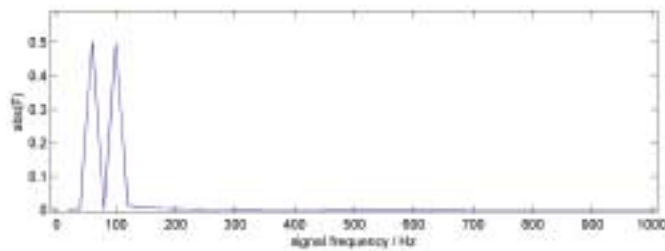


Fig. 9. Fourier spectrum of synthetic input motion.

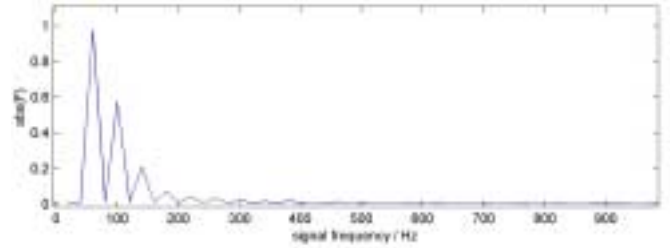


Fig. 10. Fourier spectrum of response to synthetic input motion.

Running the analysis on a synthetic input motion with equal components at many harmonic frequencies shows an increase of attenuation with frequency.

Whilst Fast Fourier Transforms (FFTs) are a useful tool for examining the dynamic behaviour of stationary systems, i.e. those whose behaviour does not change with time, for earthquake modelling a more complex method is required to examine the complete behaviour of the system in the time-frequency domain. Wavelet analysis, an analysis method developed by Newland (1993), is a method allowing the visualisation of the variation of frequency components within a signal through time. The plots in Figs. 11 & 12 are plots of energy in the time-frequency domain with peaks of energy shown as light colours. Application of this analysis method to signals measured from accelerometers at various positions within the model allows investigation of the development of sliding with time within the model.

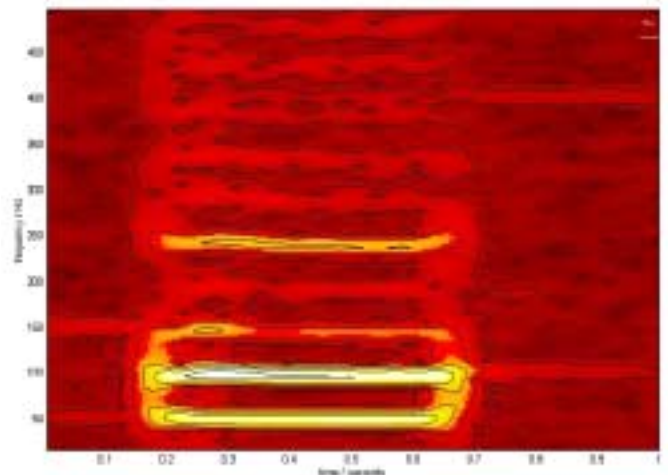


Fig. 11. Wavelet transform of SAM input acceleration.

Figure 11 shows a plot of the wavelet transform of the acceleration measured at the base of a liquefiable sand slope subjected to strong base shaking. The horizontal yellow bands in Fig. 11 shows that the base shaking has roughly constant energy components at the harmonic frequencies, (specifically 50, 100, 150 & 250 Hz), during the duration of the earthquake. This is to be expected as the input motion is a purely mechanical phenomenon, being unaffected by the soil behaviour.

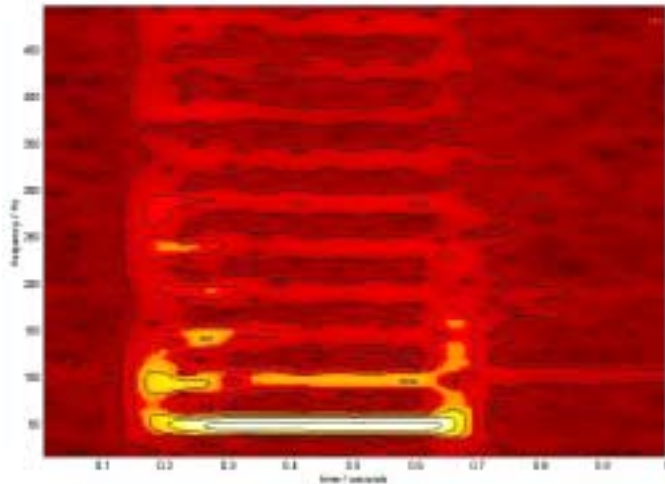


Fig. 12. Wavelet transform of surface acceleration.

Figure 12 shows the corresponding behaviour at the surface of the slope. The major difference between the two plots is the huge decline in the 100Hz component of the acceleration through the duration of the earthquake. It can also be seen that the energy values at the harmonic frequencies fall through the earthquake, from 0.2 to 0.7s, with the colours becoming darker. The higher harmonics are progressively attenuated relative to the input as excess pore pressures rise and liquefaction and sliding occur. This phenomenon results in a surface acceleration which is almost sinusoidal by the end of the earthquake whereas the base motion has large higher frequency components.

It can be seen that the model follows exactly the behaviour predicted by Newmarkian theory, showing that this analysis method has some basis in true soil behaviour, rather than just being a useful analogue for the behaviour of liquefiable slopes.

CONCLUSIONS

Newmarkian modelling provides a powerful tool for investigating the behaviour of slopes, both due to purely dynamic effects and when liquefaction behaviour is important. Whereas in the past this technique has been used solely to investigate the magnitude of movement which could be expected to occur, its true capabilities are much greater.

Use of Harmonic Wavelet Analysis allows the variation of acceleration components through time to be visualised, and this shows that the differential attenuation of frequency components due to progressively more severe sliding does occur through the earthquake, as predicted by the Newmarkian model.

REFERENCES

- Abdoun, T.H. [1997] Modelling of Seismically Induced Lateral Spreading of Multi-layered Soil and its effect on Pile Foundations. PhD Thesis, Rensselaer Polytechnic Institute, Troy, NY.
- Bartlett, S.F. and T.L. Youd, [1992] *Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-induced Lateral Spread*. Technical Report NCEER-92-0021. National Centre for Earthquake Engineering Research, Buffalo, NY.
- Bolton, M.D. and J.M.R. Wilson [1990] Soil Stiffness and Damping. Proc. Eurodyn '90, Bochum, FR Germany, pp. 209-216.
- Hamada, M. and T.D. O'Rourke, [1992] *Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes*. Technical Report NCEER-92-0001, National Centre for Earthquake Engineering Research, Buffalo, NY.
- Meyersohn, W.D. [1994] Pile Response to Liquefaction-Induced Lateral Spread. PhD Thesis, Cornell University, Ithaca, NY.
- Madabhushi, S.P.G., A.N. Schofield, and S. Lesley, [1998] A new Stored Angular Momentum based Earthquake Actuator. Proc. Centrifuge '98, Tokyo, pp. 111-116.
- Newland, D.E., [1993] *An Introduction to Random Vibrations, Spectral and Wavelet Analysis*, Longman, Harlow, UK.
- Newmark, N.M. [1965] Effects of Earthquakes on Dams and Embankments. Géotechnique Vol.15 No.3 pp.139-160
- National Research Council [1985] *Liquefaction of Soils During Earthquakes*. Report No. CETS-EE-001, Committee on Earthquake Engineering. National Academy Press, Washington, D.C.
- Schofield, A.N. [1980] Cambridge Geotechnical Centrifuge Operations. Géotechnique Vol.30 No. 3 pp. 227-268
- Schofield, A.N. [1981] Dynamic and Earthquake Geotechnical Centrifuge Modelling. Proc. Int. Conf. Recent Adv. in Geo. Erthq. Eng and Soil Dyn., St Louis, MO, Vol.3, pp.1081-1100
- Youd, T.L., C.M. Hansen and S.F. Bartlett, [1999] *Revised MLR Equations for Predicting Lateral Spread Displacement*. In Technical Report NCEER-99-0019, National Centre for Earthquake Engineering Research, Buffalo, NY, pp. 99-114.
- Zeng, X. & A.N. Schofield. [1996]. Design and performance of an equivalent-shear-beam container for earthquake centrifuge modelling. Géotechnique , No.46(1), pp.83-102.

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ABSTRACT

This paper describes the application of Newmarkian sliding-block modelling to the calculation of earthquake-induced lateral-spread displacements observed in a set of dynamic centrifuge tests. A series of centrifuge tests has been carried out at Cambridge University, subjecting slopes of loose liquefiable sand with slope angles of between three and twelve degrees to approximately sinusoidal base shaking using a Stored Angular Momentum (SAM) earthquake actuator.

Gently sloping beds of loose liquefiable sand exist in many earthquake-prone regions around the Pacific Rim. Earthquake shaking can cause these slopes to liquefy and to accumulate down-slope movements of several metres. This lateral spreading can obviously cause great damage to both buildings founded upon them and to lifelines such as pipes passing through them. Analysis of these slopes is usually carried out using the MLR formulae developed by Bartlett and Youd. These fit curves to available data to give predictions of displacement within a factor of about two, but give no indication of the mechanics of the deformation occurring, being merely a best-fit to available data.

Newmarkian modelling is based on the analysis of the behaviour of rigid blocks of soil sliding on inclined planes when subjected to base shaking. A numerical code has been developed to extend this method into an effective-stress based approach, using pore pressures measured during centrifuge tests. This analysis procedure has generally only been used in the past for analysing dry slopes. It is shown in this paper that this analysis method when extended to saturated slopes can tell us more about slope behaviour than merely predicting the final slope displacement with a given base shaking.

It is seen that despite the fact that no discrete slip plane forms within the sand bed, displacement instead being steadily accumulated through the liquefiable layer, both the shapes of acceleration traces observed close to the surface of the model and the ultimate displacement observed bear close correlation to that predicted by the Newmarkian model. Specifically, acceleration traces show truncation of one half of the acceleration cycle, corresponding to shear stresses exceeding the shear strength of the liquefied soil, causing sliding to occur.

Use of Harmonic Wavelet Analysis to investigate the variation of attenuation of each harmonic of the accelerations measured through the centrifuge model with time revealed that, as excess pore-pressures develop causing liquefaction and sliding occurs, harmonics are attenuated at progressively lower frequencies, exactly as is predicted by the Newmarkian analysis method.