6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

An Improved Newmark Method for Predicting the Whole-Life Performance of Pile-Reinforced Slopes

A. H. Al-Defae[1], J. A. Knappett[2]

ABSTRACT

In this paper a recently-developed Newmark-sliding block procedure, which can be applied to both unreinforced slopes, and slopes reinforced with a discretely-spaced row of vertical piles, is validated against dynamic centrifuge test data having a large number of sequential earthquakes causing a significant cumulative response. Five dynamic centrifuge tests conducted at 1:50 scale are reported here, two on unreinforced slopes with different input motion series' and three on a pile-reinforced version of the same slope, all with normalized spacing of S/B = 4.7. The piled cases focus on reinforced concrete piles made with a new damageable scale model reinforced concrete, but also include an elastic pile case for comparison. The two input motion series consisted of four successive Chi-Chi (1999) motions and twelve successive Kobe (1995) earthquakes. It is shown that the Newmark method predicts permanent slope deformations well in all cases, and is therefore a promising tool for the analysis of the whole-life sesimic performance of slopes considering the cumulative effect of a number of strong earthquakes during the slope's design life. Finally, it is also demonstrated that cumulative Arias intensity is an excellent index for correlating cumulative permanent slope slip across multiple sequential earthquakes for both reinforced and unreinforced cases.

Introduction

The technique of slope stabilisation by piles is widely used by geotechnical engineers in static applications (e.g. Hassiotis et al., 1997), utilising the bending response of the piles to restrain the sliding mass by making effective use of the significant resistance available in deeper, stronger stable strata. These are normally installed as a discretely-spaced pile row running along the slope at a centre-to-centre spacing, S. The technique may also be applied to stabilise slopes against seismic actions., In this case, seismically-induced ground movements generate relative soil-pile movement, which in turn leads to lateral earth pressures developing along the piles, inducing bending moment at different depths. In the analysis of piled slopes, it is important to be able to determine (i) the reductions in seismic permanent displacement for a given pile arrangement (e.g. S/B, where B is the pile size) so that the piling can be designed to give the required improvement to the geotechnical performance and (ii) internal forces (e.g. bending moments) within the piles, so that they can be structurally detailed.

In this paper a recently-developed Newmark-sliding block procedure is presented, which can be applied to both unreinforced slopes and slopes reinforced with a discretely-spaced row of vertical piles, and which incorporates both strain-dependent geometric hardening (re-grading) with continuing slip and strain dependent development of pile resistance (i.e. lateral force

[1]BSc. MSc and PhD, College of Engineering, University of Wasit, Wasit, Iraq, asadaldefae@enguowasit.org
[2]MA. MEng. PhD, Civil Division, University of Dundee, Dundee, UK, emailaddress2@dundee.ac.uk

mobilisation). The strain dependency of the yield acceleration in this model allows performance in successive strong earthquakes (e.g. mainshock followed by aftershocks, or pre-shocks followed by mainshock) to be determined, allowing it to potentially be used to determine the whole-life seismic performance of remediated and un-remediated slopes under different earthquake scenarios representative of its entire design life. This methodology has previously been validated against centrifuge test data for the case of unreinforced slopes under multiple earthquakes (Al-Defae et al., 2013). In this paper the method will be applied to pile reinforced slopes where the piles are made from a highly representative scale model reinforced concrete, with unreinforced cases as a benchmark, and a further test on an identical configuration with elastic piles for comparison.

Centrifuge Testing

Five 1:50 scale centrifuge model slopes were tested during the programme of work reported in this paper. The dimensions of the slope in each model were identical to those described by Al-Defae et al., (2013) and Al-Defae and Knappett (2014), being 8 m tall from toe to crest, having a slope angle of 28° (≈ 1:2) and underlain by a further 6 m of sand prepared to the same state, as shown schematically in Figure 1. Dry HST95 Congleton silica was used in all five tests. This sand is very fine and uniformly rounded and has minimum and maximum void ratio values of 0.467 and 0.769 with particle sizes of D_{10} = 0.09 mm, D_{30} = 0.12 mm and D_{60} = 0.17 mm. All centrifuge models described in this paper were air pluviated to 55% nominal relative density, at which state the peak friction angle was 40º. A slot pluviator was used to prepare all the centrifuge models and it has been widely used by many geotechnical researchers at University of Dundee (e.g. Lauder, 2010; Bertalot et al., 2013 and aldefae and knappett, 2014). An ESB (Equivalent Shear Beam) container exists at the University of Dundee which is fabricated from aluminum alloy is used for these tests. The container has internal dimensions of 669 mm (length), 279 mm (width) and 338 mm (height). During pluviation, the soil was instrumented with ten accelerometers within the slope (which were not referred in this paper) and two external Linear Variable Differential Transformers (LVDT's) measuring settlement at and behind the crest of the slope along the centreline of the model. This instrumentation is shown in Figure 1.

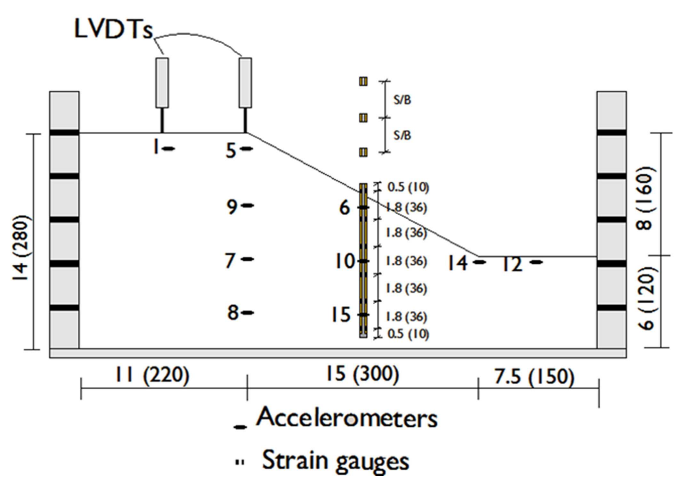

Figure 1. Centrifuge model layout, with instrumented elastic piles shown, dimensions in m prototype scale (mm model scale in brackets; after Al-Defae and Knappett, 2015).

After preparation of the model slopes, the ESB container was installed onto the centrifuge and model piles, representing a B × B square cross-section (B = 0.5 m at prototype scale), were pushed vertically into the model at 1-g in a discretely-spaced row midway between the toe and crest of the slope. A pair of perforated wooden jigs were fabricated and used to do this which ensured that the piles remained vertical and the pile centre-to-centre spacing (S) was uniform.

Two of the models were subjected to twelve successive recordings from the M_w = 6.7 Kobe Earthquake in 1995 (tests AA16, AA17), while the remaining three were subjected to four successive recordings from the M_w= 7.6 Chi-Chi earthquake from 1999 (tests AA01, AA10 and AA14). By using successive earthquakes the permanent deformation of the models under strong aftershocks could be observed. Both input motions are shown in Figure2.

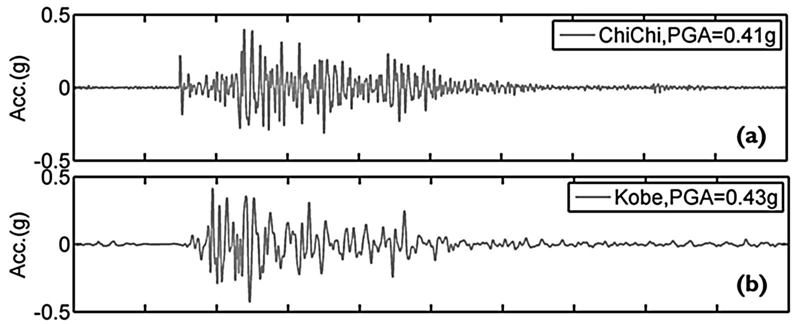

Figure 2. Input motion; (a) ChiChi and (b) Kobe

Model Reinforced Concrete Piles

Two types of pile model were used in this study. The first model ('RC pile') was made from a recently developed set of materials and procedures for producing a reinforced micro-concrete which can replicate damage realistically (Knappett et al., 2011). The second type of pile was fabricated from aluminium alloy and strain gauged and is hereafter termed 'elastic pile'. This type was used to measure the bending moment mobilised along the pile due to slope mass movement. The RC piles were designed (and tested) first, such that the elastic pile models could be designed to have (as closely as possible) the same bending stiffness, EI = 48.9 MNm^2, to give similar soil-pile interaction during the tests, prior to yield. In this way, the two pile models would be considered to be nominally the same within the elastic range. However, due to their construction, the RC piles are able to realistically simulate damage (i.e. they have similar shear and moment capacities at prototype scale as real reinforced concrete), and can also sustain changes in residual mechanical properties due to fatigue effects. The former characteristic has been demonstrated for generic reinforced concrete elements at highly reduced scale by Knappett et al. (2011). The piles were designed to represent a 0.5 × 0.5 m square cross section pile of 10 m length (dimensions at prototype scale).

The 'elastic' analogue of the model RC piles was modelled using 6063-T6 Aluminium-alloy with E = 68 GPa and this was machined to give a central plate with dimensions of 5.2 mm in the direction of slope movement and 10 mm perpendicular to this, resulting in EI = 50.4 MNm^2. The strain gauges were fixed along the length of the pile in pairs to measure bending strains at six locations.

Modified Newmark Procedure

The standard Newmark sliding block analysis procedure was modified in a number of different aspects to be applicable to pile reinforced slopes subjected to multiple earthquakes. Firstly, the pile resistance was incorporated into the formulation of the yield acceleration according to:

$$k_{h,yield} = \frac{c' + \left(\gamma z_{slip}\cos^2\beta - u\right)\tan\phi' - \gamma z_{slip}\sin\beta\cos\beta + \dfrac{P}{LS}\cos\beta}{\gamma z_{slip}\cos^2\beta + \gamma z_{slip}\sin\beta\cos\beta\tan\phi'} \tag{1}$$

as shown in Figure 3, where c′ is the apparent soil cohesion, ϕ′ the operative soil friction angle, γ is the soil unit weight and u is any pore pressure at the slip plane. The dimensions are defined in Figure 3(b). The pile resistance, P, as a function of strain (soil slip) depends on a number of parameters describing the relative soil-pile stiffness and strength of the soil in the unstable material (as it yields around the piles). Clearly, at the start of the analysis before any slip has taken place, the net additional resistance from the piles is zero. As the soil slips, the relative displacement between the soil and the pile increases, providing a progressively larger resistance to slip (P). Eventually, the resistance from the pile will reach a maximum limiting value when either the soil yields around the pile, or the pile yields structurally, whichever occurs first. In all cases reported herein, the piles remained elastic, i.e. soil yield occurred first.

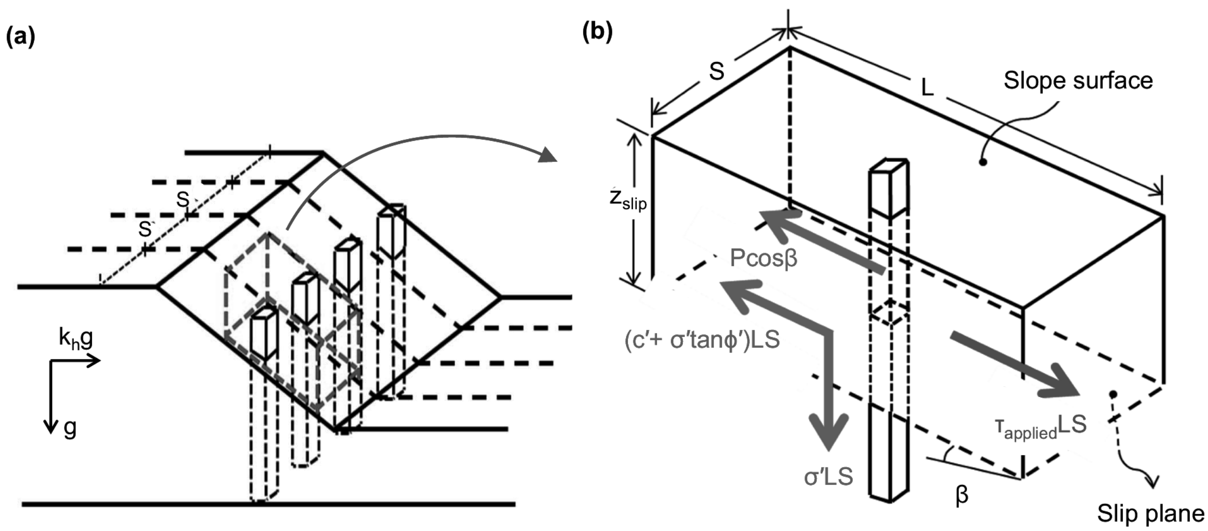

Figure 3. Slip mechanism in pile-reinforced slope; (a) overall configuration; (b) forces acting on a pile-stabilised slipping soil element (after Al-Defae and Knappett, 2015).

The relationship between the amount of soil slip and the pile resistance is developed assuming that the soil in the slipping mass (i.e. the soil above the slip plane) will yield around the piles. The interaction in this zone of soil was described using a single non-linear elasto-plastic P-y curve (API, 2002) describing the force applied on the pile, P, by the slipping soil in terms of the relative displacement between the soil and the pile (y_s − y_p) at the position of resultant load application. The part of the pile within the 'stable' soil (below the slip plane) was modelled using a linearised elastic response model ('Modified elastic model' in Figure 4(a)) describing the response of the pile (y_p) under the applied load P. By substituting for y_p, between these two expressions, a unique relationship between the soil movement (y_s, determined from Newmark analysis) and pile resistance is determined. The modelling procedure is shown schematically in Figure 4a, and the soil-pile interaction (SPI) model (P – y_s relationship) for the case of S/B = 4.7 used throughout this paper is shown in Figure 4b. The initial condition P = 0 is used to determine the initial yield acceleration within the Newmark sliding block analysis. After a timestep of the analysis where the soil slips, the cumulative displacement at this point is used in the SPI model to determine an updated (increased) value of P to recalculate the new higher yield acceleration for the subsequent timestep. In this way, the pile resistance is mobilized as the soil slips. Further details of this conglomerate analysis procedure, including a flow chart, may be found in Al-defae and Knappett (2015).

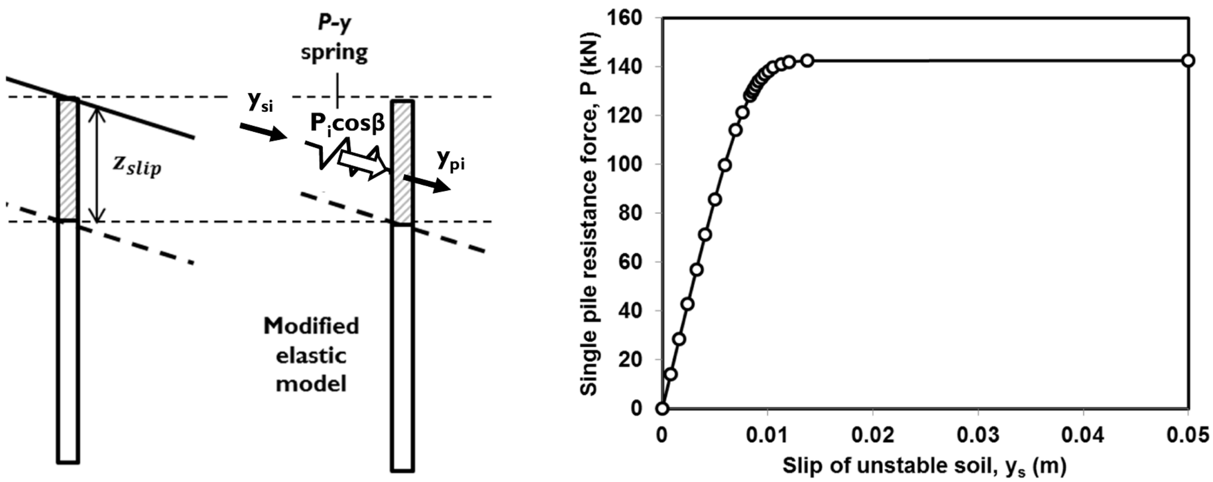

Figure 4. (a) Modelling approach for soil-pile interaction; (b) soil-pile interaction model for piles in this study (S/B = 4.7, EI = 50 MNm^2)

The slope angle β will also change during an earthquake, as slip will cause settlement at the crest and accumulation of material at the toe, i.e. the slope will become shallower (re-grading). Provided that β is relatively small (such that the slope is long compared to its height), the geometry of this mechanism will be well approximated by infinite slope theory. Al-Defae et al. (2013) developed a simplified equation for determining the new slope angle in step i+1:

$$\beta_{i+1} = \tan^{-1}\left(\frac{H_i - d_i \sin\beta_i}{H_i \cot\beta_i + d_i \cos\beta_i}\right) \tag{2}$$

As the soil starts to slip P will increase, while β will reduce. This will result in progressive hardening of the slope response via an increase in the yield acceleration. Even once the piles are providing the maximum resistance, the slope response will continue to be reduced compared to the unreinforced case due to (i) the then constant value of pile resistance, P, so long as the soil or pile are yielding in a ductile way, and (ii) the continued geometric hardening. By incorporating the effects of strain fully within the model (in terms of the mobilization of pile resistance and the geometric regrading of the slope), the behaviour of a seismically damaged slope during subsequent earthquake or aftershocks can be determined from the initial conditions (pile resistance, amount of slip, re-graded slope angle) from the end of the previous ground motion.

Validation of Newmark Method against Centrifuge Data

The extreme sequences of strong motion applied in the centrifuge tests are here used to observe whether the modified Newmark method could be used to continue to predict permanent seismic slope deformation over a 'storm' of strong earthquakes occurring in rapid succession (e.g. as occurred in the 2011 Tohoku earthquake) Figure 5 shows the results from the Kobe series. From Figure 5a, the measured crest settlement for the unreinforced case (AA17) was extremely close to the predicted crest settlement even to the twelfth earthquake. The rate of increase of the yield acceleration decreases with further shaking due to slope re-grading after each earthquake. Figure 5b shows that the model's predictive abilities are not limited to just the unreinforced case, working well also for RC piled slopes over a similarly large number of earthquakes.

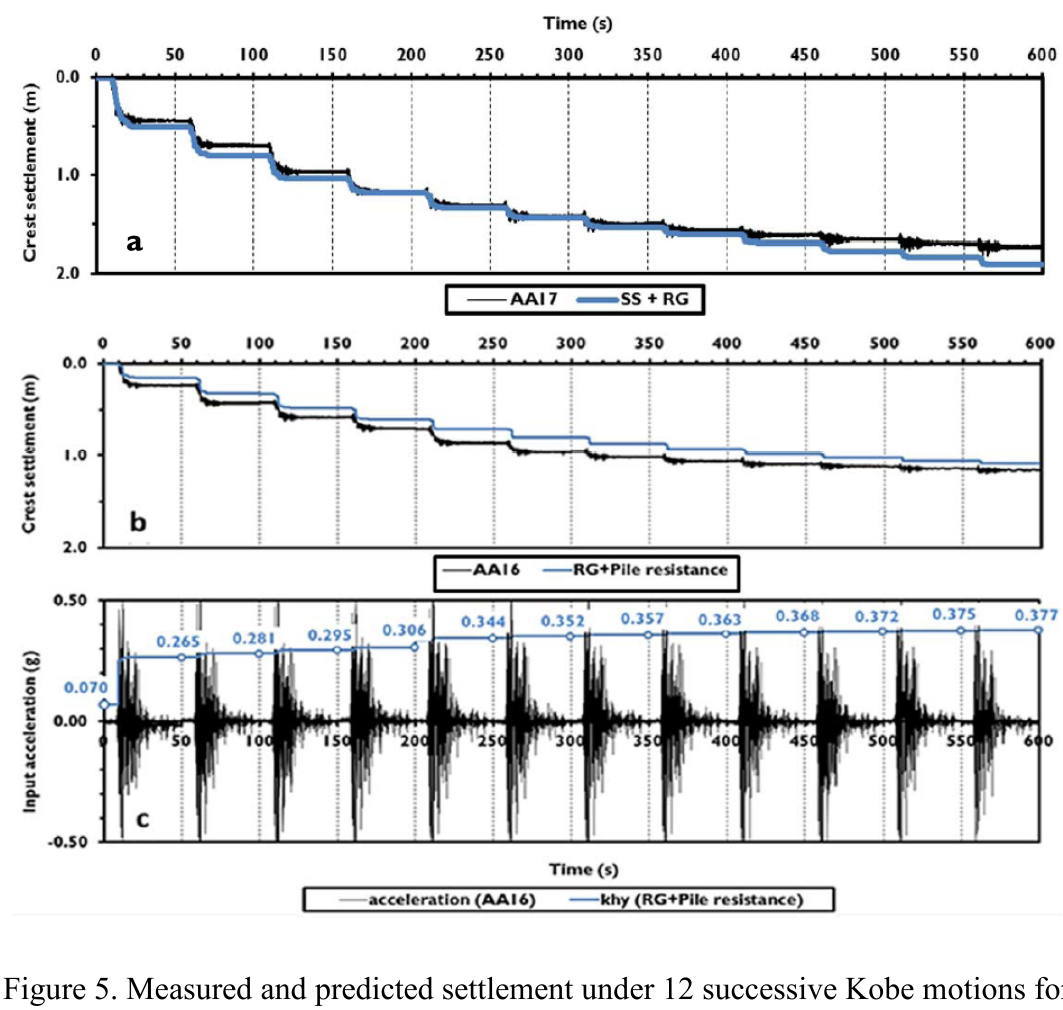

Figure 5. Measured and predicted settlement under 12 successive Kobe motions for:
(a) unreinforced slope; (b) RC pile reinforced slope; (c) input motion and yield acceleration.

Figure 6 shows the settlements at the crest of the slope for the Chi-Chi models, including model AA01 (i.e. the reference model of unreinforced slope) and both AA10 and AA14 (i.e. piled slope, S/B=4.67 using RC piles and elastic piles, respectively). It is clearly shown that the permanent deformation prediction is not influenced by change of earthquake and the modified Newmarkian procedure works well for both the RC pile reinforced slope and the elastic pile reinforced slope.

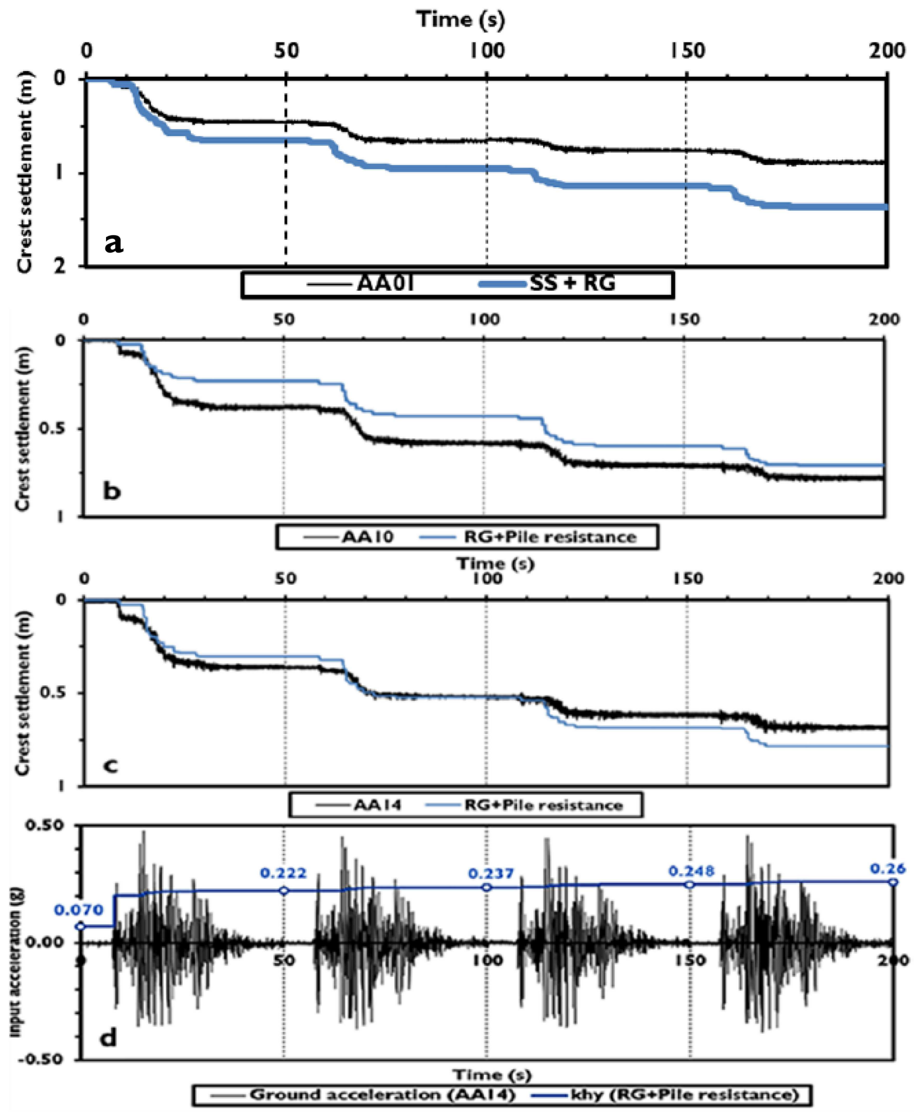

Figure 6. Measured and predicted settlement under 4 successive Chi-Chi motions for:
(a) unreinforced slope; (b) RC pile reinforced slope; (c) Elastic pile reinforced slope;
(d) input motion and yield acceleration.

Comparison of Figures 5(b) and 6(c) to Figures 5(a) and 6(a) indicate that there is potentially a slight underprediction of deformation in the elastic pile cases, suggesting that the SPI curve may be slightly too strong in this case. Comparing Figure 6(b) and (c), measured deformations are more significantly larger than the predicted values for the RC piles, which is ascribed to degradation of the model concrete properties under dynamic loading, as previously indicated in Al-Defae and Knappett (2014). Improving the SPI model to incorporate the effects of stiffness and strength degradation would be a useful future direction for extending this research.

Conclusions

A modified Newmark sliding block procedure has been validated against centrifuge test data for a dry cohesionless sandy slope under the action of both multiple sequential recorded ground motions from recent strong earthquakes. It has been demonstrated that the effects of geometric hardening are significant when the ground motions are strong and there are many of them (as would be the case for real slopes over their design life). The Newmark method gives reasonably good predictions of permanent seismic slope deformation for both unreinforced slope and reinforced and for different input motions.

Acknowledgments

The authors would like to express their sincere gratitude to Mark Truswell and Colin Stark at the University of Dundee for their assistance in performing the centrifuge tests. The first author would also like to acknowledge the financial support of his PhD studies at Dundee from the Ministry of Higher Education and Scientific Research (MOHESR) of the Republic of Iraq.

References

Al-Defae, A.H., Caucis, K. and Knappett, J.A. Aftershocks and the whole-life seismic performance of granular slopes. *Géotechnique* 2013; **63**(14):1230-1244.

Al-Defae, A.H. and Knappett, J.A. Centrifuge modelling of the seismic performance of pile-reinforced slopes. *Journal of Geotechnical and Geoenviornmental engineering*, ASCE 2014; **140**(6):04014014:1-13.

Al-Defae, A.H. and Knappett, J.A. Newmark sliding block model for pile-reinforced slopes under earthquake loading. *Soil Dynamics and earthquake Engineering* 2015; **75**: 265-278.

American Petroleum Institute (API) *Recommended practice for planning, designing and constructing fixed offshore platforms.* API Recommended Practice 2A (RP-2A-WSD) 2002.

Bertalot, D. & Brennan, A. J. Influence of bearing pressure on liquefaction-induced settlement of shallow foundations. *Géotechnique* 2012; **63**(5): 391–399.

Hassiotis, S., Chameau, J.L. & Guanaratne, M. Design method for stabilisation of slope with piles. *Journal of Geotechnical and Geoenviornmental Engineering*, ASCE 1997; **123**(4): 314-323.

Knappett, J. A., Reid, C., Kinmond, S. & O'Rielly, K. Small- scale modeling of reinforced concrete structural elements for use in geotechnical centrifuge. *Journal of Structural Engineering*, ASCE 2011; **137**(11): 1263-1271.

Lauder, K. *The Performance of Pipeline Ploughs.* Ph.D. Thesis, University of Dundee, UK 2011