Newmark block model of seismic displacement of a slope. A valid model for slopes restrained by structural elements?

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Keywords: Seismic slope displacement, Newmark sliding block, ground reinforcement

ABSTRACT

The sliding block model proposed by Newmark (1965) is an accepted methodology for assessing the accumulated displacement of a soil slope during an earthquake. For slopes restrained by elastic structural elements, such as geotextile reinforcement or ground anchors, the assumptions behind the Newmark block model may not be valid. The Newmark model assumes the resistance against acceleration remains constant with displacement, however, the restraint provided by an elastic structural element increases with displacement as it stretches. This paper considers the significance of this in design of restrained slopes and discusses possible modifications to analyses to allow for this elastic behaviour.

1 INTRODUCTION

The Newmark block model estimates accumulated displacement of a slope during an earthquake by modelling the ground as rigid-plastic, i.e. it assumes that relative displacement of the slope does not occur until the downslope ground acceleration exceeds the slope's yield acceleration. The slope is then assumed to accelerate downslope at a rate of the ground acceleration less the slope's yield acceleration. A double integration of this period of downslope acceleration over the full duration of the earthquake gives the displacement.

This rigid-plastic model is considered to adequately represent the behaviour of soils. Once yielding of the soil has occurred, the resistance of the soil is assumed to be constant with increasing displacement. However, if restraint to ground movement is provided to the ground by adding structural elements, this rigid plastic assumption may not reliably model the system. For example, if the slope is restrained by geotextile reinforcement or ground anchors, displacement will stretch these elements increasing the restraint they provide (provided they are designed not to yield/rupture under the full expected displacement). With these structural elements in place, a rigid-elastic model may be more representative than the Newmark block rigid-plastic model.

This paper considers the validity of the Newmark block model for slopes with structural elements by first presenting an analytical framework, then considering a simple example.

2 NEWMARK BLOCK MODEL (RIGID-PLASTIC)

Figure 1 describes the Newmark sliding block analysis. The slope is modelled as a block sliding on an inclined frictional plane (Figure 1a). The yield acceleration (a_y) is calculated as the ground acceleration which just starts the block moving (i.e. factor of safety of 1) (Figure 1b). During an earthquake, when the ground acceleration exceeds this yield acceleration, the block is assumed to accelerate downslope at a rate of the ground acceleration (a) less the yield acceleration (a_y) (Figure 1c). Integration of these periods of downslope acceleration with time gives the downslope velocity (Figure 1d) and integration of the velocities gives displacement (Figure 1e).

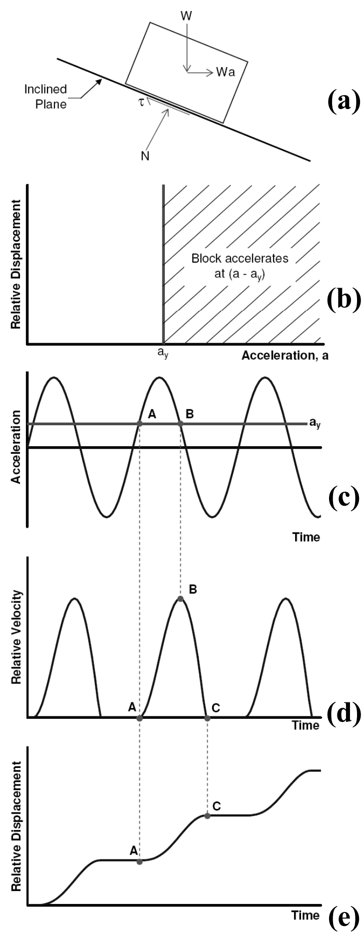

Figure 1: Rigid-plastic Newmark block

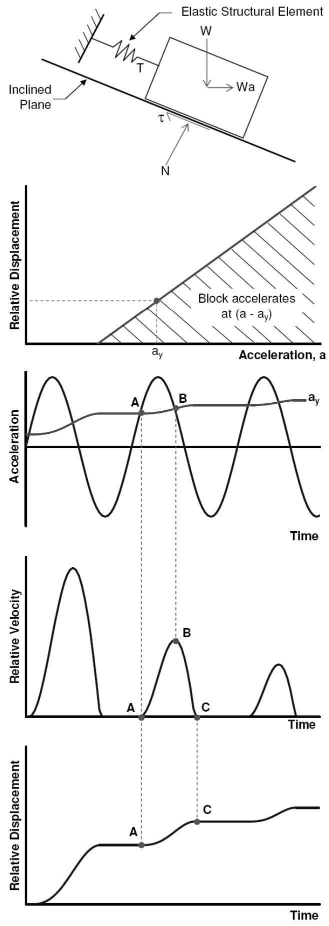

Figure 2: Modified rigid-elastic block

The Newmark model assumes the movement of the block can be modelled as "rigid-plastic":

- "Rigid" in that the block (the sliding mass) is assumed to accelerate with the ground, i.e. the sliding mass has a natural period $T_s = 0$. Bray (2007), and other researchers, have considered the dynamic response of a deformable sliding mass (i.e. a "flexible" block with a natural period $T_s > 0$) and the associated dynamic amplification of accelerations which may be significant for relatively high embankments.
- "Plastic" in that the resistance to sliding is independent of the relative displacement. Where relative displacements of a number of tens of millimetres or more are expected, residual soil strengths should be assumed in the analysis. The model was originally developed to assess potential lateral displacement of earth dams during earthquakes. Given the stress strain behaviour of soils, this "plastic" model is not unreasonable. However, when elastic structural elements, such as geotextile reinforcement, ground anchors or relatively flexible piles are added to the slope to improve stability, this "plastic" assumption may not reliably model the modified slope.

3 MODIFIED NEWMARK BLOCK MODEL (RIGID-ELASTIC)

The authors have considered modification of the Newmark model to "Rigid-Elastic", to provide a better representation of slopes with structural elements. This "rigid-elastic" model is described by Figure 2. The block is restrained by base friction as for the Newmark model, to represent the soil shear strength, but additional restraint is provided by a spring representing a structural element (Figure 2a). Resistance to acceleration (a_y) increases with relative displacement as shown in Figure 2b. Consequently, the response of the block reduces with increasing displacement as the structural element is stretched and provides greater restraint (Figures 2c-2e).

4 DESIGN CHARTS

Convenient design charts have been developed by Ambraseys & Menu (1988), Martin & Qui (1993) and other researchers to estimate slope displacements due to earthquakes assuming the Newmark model. These charts estimate slope displacement based on the ratio of the slope's yield acceleration to the design earthquake's peak ground acceleration. The design charts have been developed by double integration of example earthquake acceleration/time histories and empirical correlations developed from records of slope displacements in earthquakes.

These design charts have been prepared for unrestrained soil slopes. Can they reliably be applied to slopes which are restrained by elastic structural elements? If limit-equilibrium analysis, assuming the full design capacity of the structural elements, is used to estimate the yield acceleration of the restrained slope, the design charts may under estimate the seismic displacement. This is because the restraint provided by the structural element will be less than assumed for at least the early part of the earthquake, because inadequate displacement (stretch) would have occurred to develop the restraint in the structural element.

5 SPECIFIC ANALYSIS FOR SIMPLE EXAMPLE EMBANKMENT

Specific analysis was undertaken for a simple fictional example embankment, to investigate the significance of the elastic response of structural elements restraining a slope. As shown in Figure 3, the example embankment is founded on soft soils, and includes basal geotextile reinforcement. This example was modelled using a range of structural response assumptions, to demonstrate the range of displacements which would be predicted in design based on these various assumptions.

5.1 Displacement / yield acceleration relationship

The geotechnical finite-difference software FLAC was applied to assess the relationship of yield acceleration as a function of accumulated relative displacement for the example embankment. To investigate the effect of reinforcement stiffness, three basal reinforcement options were considered: a single and double layer of 160RE geogrid, and a single layer of WX800 high-strength geotextile. A case with no reinforcement was also considered. Figure 4 shows the relative displacement / yield acceleration relationship calculated for the double layer of 160RE geogrid, and the rigid-plastic and rigid elastic models used to model this response. Similar curves were derived for the other reinforcement options.

The relative displacement / yield acceleration relationship was determined by gradually increasing the pseudo-static horizontal acceleration applied to the FLAC model, and recording the maximum equilibrium displacement of the sliding mass at each acceleration increment. Permanent (non-recoverable / plastic) displacement of the sliding mass relative to the surrounding ground (as recorded in Figure 4) is calculated by running a FLAC model with elastic soil parameters, and subtracting these displacements from the plastic analysis. In the FLAC model, the reinforced embankment is at equilibrium for the applied pseudo-static acceleration at the resultant displacement (i.e. stretch of the structural elements), and any increase in acceleration would cause additional movement. Therefore the desired relationship of yield acceleration as a function of displacement is considered equivalent (inverse) to the relationship derived from the FLAC analysis of resultant displacement as a function of applied pseudo-static acceleration.

In Figure 4, the displacement / yield acceleration relationships derived from the FLAC models for the unreinforced and reinforced embankment are shown as solid lines. Traditionally when undertaking a Newmark sliding block analysis, the non-linear response demonstrated by the FLAC analysis is idealised as a bilinear rigid-plastic relationship. This rigid-plastic assumption is shown as the long-dashed lines in Figure 4, with a constant value for the yield acceleration regardless of the accumulated relative displacement. It can be seen that this rigid-elastic model provides a reasonable approximation for the relationship derived from the FLAC analysis for the unreinforced embankment, confirming this is a reasonable assumption for unreinforced ground. However, for the reinforced embankment a rigid-plastic assumption does not provide a good fit to the displacement / yield acceleration response observed in the FLAC analysis. As shown by the short-dashed line in Figure 4, a rigid-elastic model would appear to provide a more appropriate representation, with the ground possessing an inherent magnitude of yield acceleration at zero displacement which is supplemented by elastic support from the structural reinforcement as displacement accumulates.

As an alternative to the rigid-elastic model and to enable use of design charts, rigid-plastic behaviour could be assumed - but with particular care given to choosing a constant yield acceleration which is compatible with the actual magnitude of accumulated seismic displacement. When choosing this displacement-compatible yield acceleration it is important to consider not only the final displacement, but how this displacement accumulates over the course of the earthquake. For this study, the constant rigid-plastic yield acceleration was chosen from the FLAC displacement / yield acceleration relationship at approximately half of the final predicted seismic displacement, to represent the "average" yield acceleration during the course of the earthquake. There was no rigorous basis for this choice of compatible displacement however – application of this method requires engineering judgement, and lower or higher compatible displacements may be appropriate for different situations. The authors stress that it is often inappropriate to choose a constant rigid-plastic yield acceleration which corresponds to the full design or ultimate strength of the structural reinforcement. As shown in Figure 4, this assumption tends to give higher yield acceleration (and thus less displacement) than would be predicted if displacement-compatibility was considered.

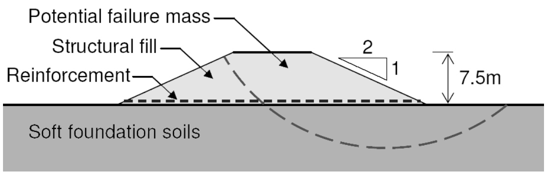

Figure 3: Simple example base-reinforced embankment

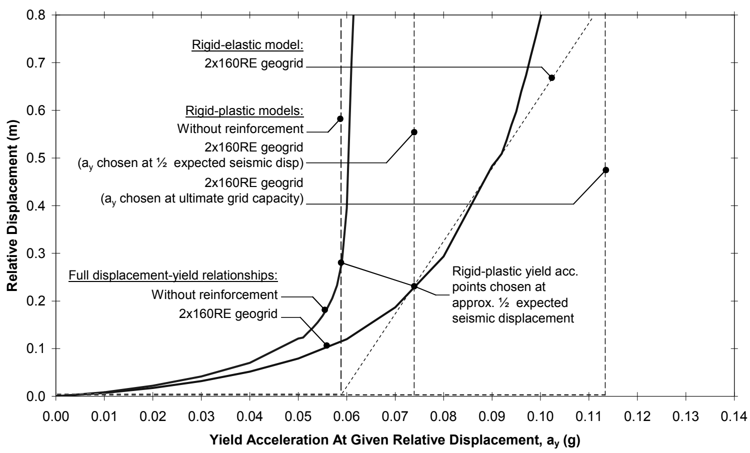

Figure 4: Displacement / yield acceleration relationships for example embankment

5.2 Time-history integration

Earthquake time-history records for analysis were selected based on the recommendations of NZS1170 that records have similar magnitude, fault distance and source mechanism characteristics as the site, and that a record does not require scaling up or down by a factor of more than 3. For the simple example embankment, a deep soil site was assumed, with seismic characteristics for the Wellington region. The PEER NGA strong motion database returns 38 time-history records from 9 separate events matching these criteria (76 horizontal records in total). Records were scaled to match the assumed ULS design PGA of 0.45g (1/500yr event).

A numerical integration scheme was developed using the Visual Basic, in which the displacement/yield acceleration relationship is input as an array. This allowed flexibility to use a rigid-plastic or rigid-elastic model, or enter the full yield acceleration vs. relative displacement curve directly. It also allows control of whether displacements accumulate only downslope (chosen for the example embankment), or if cyclic "lurching" is permitted. The integration operated as shown in Figure 2, with the block accelerating when the earthquake acceleration exceeds the yield acceleration (which was updated as a function of accumulated displacement), and decelerating once the earthquake acceleration dropped below the yield acceleration.

While entering the entire yield vs displacement curve appears to offer promise for future use of this procedure, care would be needed to ensure permanent displacement was not overestimated by allowing only downslope movement of the block. This approach would overlook the fact that displacements at lower acceleration levels tend to cancel out due to reversals in cyclic loading. The results shown in Figure 5 for the full displacement/yield acceleration curve do not model this cyclic reversal, so are likely to overestimate displacements. While it is possible to make some allowance for reversals in cyclic loading using the current integration, proper implementation of this concept would require elastic and plastic displacements to be treated separately, to model hysteresis in the system. A more practical option for many cases could be a bilinear rigid-elastic model of the form shown in Figure 4, which makes approximate allowance for recoverable cyclic displacement by suppressing downslope displacement when the applied acceleration is less than the traditional rigid-plastic yield acceleration of the unreinforced soil.

5.3 Summary of Results

Figure 5 below summarises the results of the displacement prediction using time-history integration and design charts. Provided the yield acceleration selected for use with the rigid-plastic model is chosen taking into account development of displacement over the course of the earthquake, good agreement can be achieved with the full yield / displacement and rigid-elastic models. The rigid-plastic model (including design charts) tends to under-estimate displacements when the yield acceleration is determined based on the ultimate reinforcement capacity.

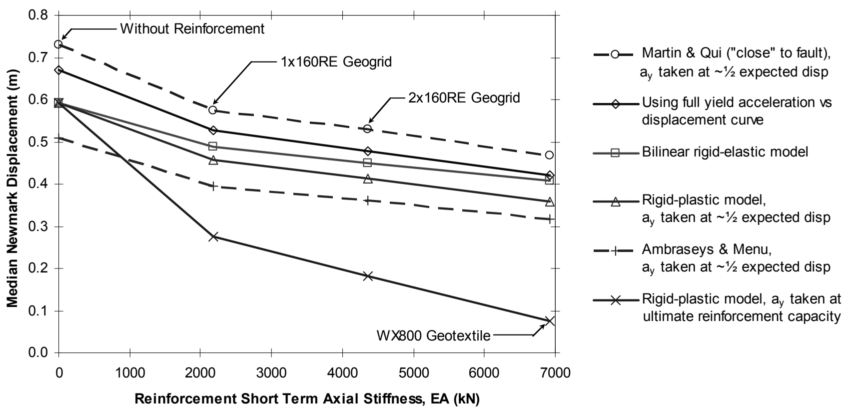

Figure 5: Estimated seismic displacement for example embankment, for PGA=0.45g

6 CONCLUSIONS

The methods of analysis available for predicting accumulated displacement of slopes restrained by elastic structural elements are summarised below.

(a) Dynamic Analyses:

Dynamic analysis packages are available where ground and structural response can be calculated in response to selected earthquake time histories. The Newmark block simplifications discussed in this paper are not made in these analyses. These are complex analyses and are only warranted for critical structures. It is recommended that simpler analyses be undertaken to verify the magnitude of results from these complex analyses.

(b) Modelled Displacement/Yield Acceleration Relationships:

Finite-element or similar analysis is undertaken to compute the relationship between displacement and yield acceleration, and this response (or rigid-elastic approximation) is used with selected time histories to estimate displacement. Alternatively, the relationship could be modelled as rigid-plastic (constant yield acceleration specified irrespective of displacement) and displacement assessed using published design charts. If this alternative is used, judgement is required to ensure that a displacement-compatible yield acceleration has been chosen. These analyses are appropriate for most large projects.

(c) Limit-Equilibrium Analysis and Published Design Charts:

Limit-equilibrium analysis can be used to estimate the yield acceleration, which is applied to published design charts to estimate seismic displacements. Such analysis is appropriate for smaller projects, however the following must be carefully considered:

- At the predicted displacements, will the structural elements remain stable? For example, if the system includes ground anchors, can the anchors displace to these levels without suffering a brittle failure or substantial loss of strength?
- The restraint by the structural element assumed in limit-equilibrium analysis needs to be compatible with the level of displacement predicted during the earthquake – sensitivity analyses and engineering judgement may be required to choose an appropriate yield acceleration. Restraint from structural reinforcement at the accumulated displacement could be substantially less than the ultimate capacity of the element. For the example presented in this paper, the yield acceleration was selected to correspond to the restraint provided at half the expected final seismic displacement.

This investigation has shown that provided proper care and judgement is applied, the Newmark block model can be appropriately extended to slopes restrained by structural reinforcement. However it is clear that if proper consideration is not given to its implicit assumptions then the Newmark approach can provide misleading and unconservative displacement predictions.

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