Earthquake induced residual displacements of shallow foundations

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ABSTRACT: The particular aspect of performance based design considered in this paper relates to shallow foundations on cohesive soils. The work discussed is part of a larger project in which we are promoting the acceptance of brief instances of bearing strength failure beneath the foundation during the course of an earthquake as long as the post earthquake permanent residual displacements are acceptable. Herein we compare three different methods of estimating post earthquake residual displacements. The calculations are checked against the displacements and actions measured in a centrifuge test. Our conclusion is that the three methods, although very different, produce results that are generally comparable.

1 INTRODUCTION

1.1 Objective

The particular aspect of geotechnical performance based design considered in this paper relates to shallow foundations on cohesive soils. The work discussed is part of a larger project in which we are promoting the acceptance of brief instances of bearing strength failure beneath the foundation during the course of an earthquake, and basing performance decisions on residual displacements after the earthquake. Herein we compare three different methods of estimating post earthquake permanent displacements. The calculations are checked against the actions and displacements measured in a centrifuge test. Our conclusion is that the three methods, although very different, produce results that are generally comparable.

1.2 Background

The motivation for the paper is the well established practice of considering the earthquake response of earth dams and slopes (Newmark 1965) and gravity retaining structures (Richards and Elms 1979) in terms of the residual, or permanent, displacement at the end of the earthquake. In taking this approach one admits that brief instances of failure of the system during the course of the earthquake might not be important if the permanent displacements generated during the earthquake are modest. Currently the ultimate limit state design of shallow foundations under earthquake loading is based on ensuring that under the maximum demand during the excitation a reserve of bearing strength is maintained. In old-style terminology we would expect the minimum bearing strength factor of safety to remain reasonably greater than unity. In New Zealand the LRFD (Load and Resistance Factored Design) is used and for shallow foundations only about half the bearing strength is mobilised. In Europe a partial factor approach is used. There the earthquake loading of a shallow foundation is restricted to mobilising about 75% of the foundation bearing strength. Given that earth dam design, slope assessment and gravity retaining walls are accepted as cases where yielding and permanent displacements can be tolerated, why should not the same be allowed for shallow foundations?
1.3 The content of this paper

As one step along the path towards answering this question, this paper will compare three different methods of estimating the residual displacements generated during an earthquake. Lacking good quality field measurements of such post-earthquake displacements we have used the output from centrifuge tests undertaken at the University of California, Davis (Rosebrook and Kutter, 2001).

1.4 The macro-element concept

The idea of a macro element is that a single computational entity represents the behaviour of a shallow foundation and soil adjacent. The approach is the antithesis of the finite element technique which requires discretisation of a substantial volume of soil beneath the foundation. In the macro-element we obtain only the response at some representative point or interface, but surprisingly this is able to provide a useful approximation to the foundation response. Even more interestingly, nonlinear foundation response can be captured. In this way the macro-element is an important part of practical approaches to soil-foundation-structure interaction calculations.

2 SHALLOW FOUNDATION MODELS

2.1 Bearing strength surface based model

This is a version of the macro element model developed by Paolucci (1997). A more sophisticated, but similar model, is that of Cremer et al (2001). This model is based on a bearing strength surface which defines the combinations of vertical load, horizontal shear, and moment that cause bearing failure beneath a shallow foundation. Herein the surface defined in Eurocode 8 for cohesive soils is used; it is shown in Figure 1. The surface shows how the amount of moment and shear that can be applied to a shallow foundation depends on the vertical load carried. This surface acts as a yield locus in that state paths inside the surface are elastic and those on the surface perfectly plastic, a non-associated plastic potential must also be specified. The model used herein was developed by Toh (2008). In addition to the bearing strength surface there are three springs which yield when the bearing strength surface is engaged.

Figure 1: EC8 cohesive soil bearing strength surface used as a yield locus for the macro-element model.

2.2 Spring bed model in the Ruaumoko software

The Ruaumoko software is capable of nonlinear dynamic time history structural analysis (Carr 2003). One of the elements provided is a nonlinear, compression only, detachable-reatachable spring. A bed of these springs provides the shallow foundation model which has the facility to uplift part of the foundation during cyclic loading and to reattach it when the direction of motion is reversed. The springs are bilinear so yielding is possible when the contact pressure reaches a limiting value. The details are shown in Figure 2.
Figure 2: Ruaumoko spring bed model supporting a single degree of freedom structure.

2.3 Spring bed model in the OpenSees software

This bed of springs model was developed in the OpenSees software (OpenSees 2008) and is very similar to the bed of springs model developed in Ruaumoko. The difference being that the springs in this model are non-linear. Forty eight $q$-$z$ springs were used in the vertical direction and one $t$-$z$ spring in the horizontal direction. These non-linear spring models, $QzSimple1$ and $TzSimple1$, found internally in OpenSees were developed by Boulanger (2000) and have been calibrated against pile tests in clay and sand. The $q$-$z$ model has subsequently been undated to include shallow foundation tests, $QzSimple2$, however for this paper the initial $QzSimple1$ was used in the numerical calculations. Backbone curves for these two springs can be seen in figure 3. These materials are characterised by a large initial stiffness followed by a broad hysteresis, enabling the stiffness degradation of soil to be captured. Tension capacity and far field radiation damping coefficients can be included. For this experiment, the tension capacity was set at zero, and the radiation damping coefficient set at 0.05.

![Backbone curves for the QzSimple1 (left) and the TzSimple1 (right) soil models in OpenSees.](image)

Figure 3: Backbone curves for the $QzSimple1$ (left) and the $TzSimple1$ (right) soil models in OpenSees.

3 CENTRIFUGE TESTS

Data from the response of a model structure in the UC Davis geotechnical centrifuge was used to evaluate the three macro-element models. The foundation was a layer of clay consolidated from reconstituted San Francisco Bay Mud. The clay layer had an undrained shear strength of 100 kPa. The centrifuge acceleration was 20 g. At prototype scale the weight of the structure applied a static vertical
force of 358 kN to each footing. The prototype dimensions of the footing are 2.67 m in length and 0.63 m in width. The effective height of the mass during dynamic excitation is 4.66 m. With these footing dimensions the static bearing strength factor of safety is 2.8.

The recorded dynamic input to the centrifuge model, in the form of a cosine wave of gradually increasing amplitude, is shown in Figure 4; what is omitted is a further 10 seconds during which recording of the instruments continued under zero input acceleration. The shaking occurs about the short axis of the footing.

![Figure 4: Prototype scale dynamic centrifuge input (PGA = 0.52g).](image)

Three aspects of the measured responses of the centrifuge are shown in Figure 5; these are moment against rotation, footing settlement against rotation, and horizontal shear against horizontal displacement. It is quite clear from all these plots that all three aspects of the response of the foundation are well beyond linear elastic behaviour, but even so the residual displacements after the dynamic loading, as presented in Table 1, are modest.

<table>
<thead>
<tr>
<th>Table 1. Comparison of prototype scale residual displacements after the centrifuge dynamic excitation.</th>
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<tbody>
<tr>
<td>Settlement (mm)</td>
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<td>Rotation (mrad)</td>
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<tr>
<td>Horizontal displacement (mm)</td>
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4 CALCULATED RESPONSE OF THE MODEL STRUCTURE

Figure 6 presents the calculated response of the centrifuge model structure for the three macro-element models. Figures 5 and 6 are presented on one page to aid comparison of the responses. The three columns of figures on the page each have the same plot, so like outputs are found in each column. In Figure 6 the upper row is for the bearing strength surface based macro-element model. The middle row in the diagram is for the Ruaumoko spring bed model. The bottom row is for the OpenSees spring bed model.

These three sets of calculations were done with different software. Thus before proceeding to the nonlinear calculations intended to represent the centrifuge output we made a check on the results obtained when the foundation was modelled with linear elastic springs – one for the vertical stiffness, one for the horizontal stiffness, and one for the rotational stiffness. The stiffness values for these were estimated using the relations given by Gazetas (1991). The Young’s modulus value required to estimate the stiffness was taken as 500s_u, that is 25 MPa. The dynamic input shown in Figure 4 was
Figure 5: Measured response of a shallow foundation model in the UC Davis centrifuge (centrifuge acceleration of 20 g). Prototype scale footing dimensions: 2.7m long by 0.6 m wide; static bearing strength factor of safety 2.8; rocking about the 0.6 m axis subject to the acceleration history shown in Figure 4.

Figure 6: Prototype scale computed dynamic response of the three models to the centrifuge input motion: upper – Macro-element, middle – Ruamoko, bottom – UC Davis QzSimple1 spring model.

used for these elastic trials. The damping values were also calculated from Gazetas (1991). Once we established that all three software packages gave the same elastic output we moved on to estimating the nonlinear response.

It is apparent in Figure 6 that all three models give a reasonable representation of all the observed plots. That is moment-rotation, horizontal shear-horizontal deformation and settlement-rotation behaviour. The OpenSees model predicts the sliding of the structure to be greater than what the
experiment suggests, however this is still an ongoing development at the University of Auckland. Despite this the consistency of the results from all three models are very pleasing.

5 DISCUSSION

5.1 Bearing strength surface macro-element model

This model used the bearing strength surface for cohesive soils given in Eurocode 8. As the vertical load on the foundation was constant the actions are constrained to a vertical section through the bearing strength surface prior to yielding. Initially the spring stiffnesses were evaluated, as explained above, using the expressions given by Gazetas (1991). But as explained below the results plotted in Figure 6 were obtained using the same rotational stiffness as obtained from the bed of springs used in the Ruaumoko model. To obtain the vertical settlement plotted in Figure 6 we found that is was necessary to adjust the flow rule we had been using for the plastic part of the computation. The original flow rule, taken from Cremer et al (2001), predicted a much higher settlement (30 mm), but by adjusting the flow rule the result obtained was achieved. Note that this adjustment of the flow rule does not affect the rotation or horizontal displacement. In doing these calculations we also found that the residual vertical displacement of the foundation was relatively insensitive to the vertical elastic stiffness of the foundation.

This model produces rather “boxy” graphs for the moment - rotation curve and the horizontal shear – horizontal displacement plots. The reason for this is that all behaviour within the yield locus, that is the bearing strength surface, is elastic and nonlinear behaviour occurs only when the action path reaches the bearing strength surface.

5.2 Ruaumoko spring bed model

We considered two approaches to using the Ruaumoko software to model the centrifuge response. In the first we had single bilinear springs to represent the vertical, horizontal and rotational degrees of freedom of the foundation. Since the vertical load was constant we could use the bearing strength surface to indicate when yield would occur. We found that this produced reasonable results for the moment – rotation and horizontal shear – horizontal deformation plots. However, this has no effect on the vertical degree of freedom and so no residual settlement is generated.

The second approach used a bed of the detachable, that is no-tension, spring element provided in Ruaumoko. The footings on the centrifuge model are comparatively rigid with respect to the underlying soil, so when rotation occurs the load in the springs on one side of the foundation decreases and on the other side increases. When the load in a spring reaches zero that spring detaches and so there is a reduction in stiffness of the foundation. We set the maximum vertical stress on any spring to 5.14s. From Figure 6 it is apparent that this model represents what was observed in the centrifuge reasonably well.

For this model the springs are bilinear but the moment – rotation curve in the middle row of Figure 6 shows much more nonlinearity than the corresponding plot for the macro element. The reason is that the process of detaching and reattaching the springs introduces geometric nonlinearity into the system. On the other hand the horizontal shear - horizontal displacement plot is controlled only by the bilinear nature of the one spring used to represent the horizontal stiffness.

For the first of the approaches using Ruaumoko, the yielding was determined from the point at which the action path would reach the bearing strength surface. For the second no consideration of the bearing strength surface was used and yielding of the vertical springs was controlled by the local contact pressure reaching 5.14s. It is of some interest that, despite this, the maximum moment reached was about the same as that for the bearing strength surface macro-element model.

The final point to make with regard to the Ruaumoko model relates to the rotational stiffness of the bed of springs. We calculated the elastic stiffness of our footing using the Gazetas relations. One can then determine the vertical stiffness of the bed of springs so that it is the same as that for an elastic half
space. However, if this is done, then the rotational stiffness from the bed of springs is considerably less than that of the half space. We have dealt with this in the past, Pender et al (2006) and Wotherspoon (2007), by adding an additional rotational spring to the centre of the footing. For the calculations herein we did not use this additional rotational spring. In effect, then we started with a degraded rotational stiffness for the system, but it is clear from Figures 5 and 6 that the displacements generated by the initial stiffnesses are a very small fraction of the displacements observed and calculated.

5.3 The OpenSees spring bed model

In the OpenSees model, the calculated moment-rotation plot is adequate. The computed settlement appears to be similar to that of the Ruaumoko model. On the other hand the horizontal sliding range of 27 mm overpredicts the experimental sliding range of 11 mm. A similar numerical model was run with the rotational damping factor reduced to zero, the range of horizontal sliding was found to be 10 mm – more comparable to the centrifuge data. However, the moment and settlement predictions were then found to be less satisfactory. This leads to be observation that, although one would think a rotational damper would affect only the rotational response of a structure-foundation system, there is, in fact, more interaction happening and not only the rotation, but also the sliding and settlement data are affected. This is currently part of the ongoing investigation at the University of Auckland.

6 FOUNDATION STIFFNESS AND PERFORMANCE BASED DESIGN

Performance based design requires good estimates of foundation and other deformations induced during earthquake loading. It thus opens the way for the approach mentioned at the beginning of the paper in which brief instances of bearing strength failure in the soil beneath the foundation are allowed during earthquake motions. This is a plausible enough statement, but for successful performance based design it will be necessary to have reliable methods of estimating the residual displacement of the foundation at the conclusion of the earthquake. Figure 6 is encouraging in this regard as the displacements obtained by three methods of calculation are comparable. As commented above these give broadly similar results, so we conclude that there is apparently nothing special about the technique of estimating the displacements, as these can be obtained with any of the three methods. Furthermore, we can appeal to the fact that these residual displacements compare well with those measured in the centrifuge test as an indication that the values calculated are likely to be realistic.

The small magnitudes of the residual displacements set-out in Table 1 are the basis for our conclusion that allowing brief instances of shallow foundation bearing strength failure during the course of an earthquake may be a viable approach to earthquake resistant design of shallow foundations. If these foundations had been designed following the LRFD approach used in New Zealand there would have been no yielding but the foundations would have been larger and hence more expensive.

The above paragraph enables us to adopt an optimistic stance towards the estimation of foundation residual displacements. The next question is what stiffness should be used for the ground. One approach would be to start with the small strain elastic stiffness of the ground and have a degradation of soil stiffness as the strain increases. Another would be to use a reduced elastic stiffness to allow for the degradation in an approximate manner, such as is suggested in Eurocode 8, part V. Herein we set the elastic modulus of the soil to 500 times the undrained shear strength. However, what Figures 5 and 6 reveal is that once some yielding occurs then it is this that controls the apparent stiffness of the system, simply because the deformations generated along the “plateau” part of the curves are so much greater than those generated by even the reduced elastic modulus. In this way we suggest that another important consequence of considering the possibility of some yielding of the shallow foundation is that the need for accurate estimates of the soil stiffness, possibly the most difficult part of earthquake resistant foundation design, is reduced.
7 CONCLUSIONS

We reach three main conclusions:

- We have presented three quite distinct methods for calculating shallow foundation residual displacements and find that they provide roughly comparable values, and these values compare well with those measured in centrifuge testing.
- Even a small amount of foundation yielding has a significant effect on the apparent stiffness of the system.
- We think the results presented in this paper, particularly the residual displacements in Table 1, indicate that shallow foundation yielding is a potentially useful contribution to performance based foundation design. Alternative designs obtained by following the LRFD approach result in larger more expensive foundations.

REFERENCES:


