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Liquefaction Analysis of the Wildlife Site

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ABSTRACT

A major concern for soil-structures comprised of granular materials is the movements caused by earthquake induced liquefaction. Because of its potentially damaging effects, the modelling and prediction of liquefaction events has become a major topic of interest to many geotechnical researchers. During the 1987 Superstition Hills earthquake, a liquefaction event was recorded at an instrumented site in southern California, known as the Wildlife Site. The acceleration and pore pressure time histories recorded during this event allow a unique opportunity for researchers to assess the validity of numerical models. This paper briefly summarises an incremental stress-strain model for granular soils based on fundamental soil mechanics principles, followed by a comparison of the model predictions and the measured field response at the Wildlife Site.

INTRODUCTION

A major concern for soil-structures comprised of granular materials is the movements induced by cyclic loading. In certain geologic and hydrologic environments, cyclic loading can lead to excessive deformations and strength loss of soils as a result of liquefaction. Cyclic shear loading causes a tendency for volumetric compaction of granular material, whether it be in a loose or dense state. If the pores of the material are filled with a fluid that can either compress or escape during the loading, then volumetric contraction will occur. If, on the other hand, the pores are filled with an essentially incompressible fluid, such as water, and this fluid cannot escape during the period of shaking, then the tendency for volumetric compaction will transfer the normal load from the soil skeleton to the water, causing a rise in porewater pressure and a reduction in effective stress.

As the effective stress reduces, both the modulus and strength of the material reduce, leading to increased shear strains. If the effective stress drops to zero, the shear modulus will also be essentially zero and the soil will behave as a liquid - a state of transient liquefaction. Because of the potentially damaging effects of the liquefaction phenomenon, the modelling and prediction of liquefaction events has become a major topic of interest to many geotechnical researchers.

The analysis of a soil-structure system subjected to earthquake loading is complex. The structure is typically modelled as comprising a number of elements that, prior to the earthquake, are under a range of static stresses. Under earthquake loading each soil element will be subjected to a time history of

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cyclic normal and shear stresses. A rational analysis procedure must take into account the stress-strain-porewater pressure response of each element. The essence of the problem, therefore, is the formulation of an element stress-strain and porewater pressure model that captures the observed element response before and after the triggering of liquefaction. Once the element behaviour is captured, it can be incorporated in a finite element or finite difference code to predict the response of the soil-structure system to the specified time history of loading.

This paper briefly summarises a simple elastic-plastic model, based on fundamental soil mechanics principles and calibrated to capture laboratory cyclic test data. Then, as a means of validation, the model is used to predict the response at the Wildlife Site, where a liquefaction event was recorded during an earthquake in 1987. Acceleration and porewater pressure time histories recorded during the earthquake allow a unique opportunity for comparison between the predicted and measured field response.

MODEL DESCRIPTION

A one-dimensional stress-strain and porewater pressure model is discussed in detail by Byrne and McIntyre (1994). The model uses an incremental shear stress-strain law based on the Hyperbolic Formulation (Duncan and Chang, 1970) to compute the increment of shear strain. The increment of plastic volumetric strain is computed from an empirical shear-volume coupling equation, linking the increment of plastic volumetric strain to the computed increment of shear strain.

Under drained conditions, the increments of elastic and plastic volumetric strains are calculated and summed to determine the total volume change. If drainage of pore water fluid is prevented during the application of a load increment, a volumetric constraint is imposed on the skeleton. The response of the skeleton is predicted using the same skeleton model as for the drained case, but taking into account the volumetric constraint imposed by the porewater fluid.

If the porewater fluid and the solids are assumed incompressible, the overall volumetric strain will be zero. However, grain slip does occur within the skeleton with the result that the elastic and plastic increments of volumetric strain are equal and opposite. This assumption allows for the direct calculation of the excess porewater pressure increment. The total excess pore pressure is obtained by summing the pore pressure increments.

A more detailed description of the incremental model and its specific input parameters is given by Byrne and McIntyre (1994). Having summarized the key components of the incremental model, the next step is to assess its validity by incorporating the element response in a dynamic analysis, then predict and compare with a field event. This is described in the section which follows.

FIELD VERIFICATION

Background and Site Description

The model was used to predict the dynamic response of the Wildlife Site - an instrumented site where liquefaction occurred during an 1987 earthquake. The Wildlife Site is located in the floodplain of the Alamo River approximately 36 km north of El Centro, California. In-situ and laboratory investigations (Bennett et al., 1984) have shown that the site stratigraphy consists of a surficial silt layer approximately 2.5 m thick underlain by a 4.3 m thick layer of loose silty-sand, underlain by a stiff to very stiff clay. The groundwater table fluctuates within the surficial silt layer at a depth of about 2.0 m.

Instrumentation

The instrumentation at the Wildlife Site consists of two 3-component accelerometers and six electric piezometers. One accelerometer was mounted at the surface on a concrete slab supporting an instrument shed. The second accelerometer was installed in a cased hole beneath the liquefiable layer at a depth of 7.5 m. Five of the six piezometers were installed within the liquefiable sand layer. Details about the instrumentation and the installation procedure are given by Youd and Wieczorek (1984).

Recorded Site Response

In November, 1987 the Wildlife Site was shaken by two earthquakes - the Elmore Ranch earthquake and the Superstition Hills earthquake. Both events triggered the instrumentation at the site; however, only the Superstition Hills earthquake (M = 6.6) generated dynamic porewater pressures. Subsequent site investigations showed evidence of liquefaction in the form of sand boils and small ground fissures (Zeghal and Elgamal, 1994).

Fig. 1 shows the measured acceleration time histories for the North-South component of the Superstition Hills quake. Fig. 1(a) shows the surface time history while the downhole time history is shown in Fig. 1(b). Surface and downhole displacement time histories were obtained by double integration of the acceleration time histories.

Relative displacements between the surface and the stiff base are of prime interest and these were obtained by subtracting the surface and downhole displacement time histories at each time increment. The resulting relative displacement time history is shown in Fig. 2. Note that the relative displacements were essentially zero for about the first fourteen seconds of shaking despite the fact that significant displacements were measured both at the surface and downhole. This indicates for the first fourteen seconds, the soil units above and below the liquefiable sand layer essentially moved together. After fourteen seconds, significant relative displacements occurred, indicating the uncoupling of the soil units above and below the sand layer.

The recorded time history of surface acceleration versus relative displacement is shown in Fig. 3. This plot is similar to a shear stress versus shear strain plot, as shear stress would simply be the surface acceleration multiplied by the soil mass, and the strains would be the relative displacements divided by the thickness of the liquefied layer. Since neither the soil mass nor the thickness of the liquefied layer are known with certainty, presenting the data in this form introduces less error.

By isolating brief segments of the data from Fig. 3, it is possible to see how the soil modulus changes with cycles. Fig. 4 shows four discrete cycles at different times during the earthquake. For about the first 14 seconds of shaking, the soil is stiff as shown in Fig. 4(a) and there has been little degradation of modulus. At about 16 seconds (Fig. 4b) significant degradation of modulus occurs. At

35 seconds (Fig. 4c), further degradation of modulus has occurred with a flat zero modulus zone followed by strain-hardening and an abrupt increase in modulus upon unloading.

The behaviour shown in Fig. 4(c) is typical of a cyclic laboratory simple shear response after liquefaction has been triggered, and is caused by repeated dilatant and contractant response as the stress point cycles through the zero effective stress state. This same behaviour is seen in Fig. 4(d), except the base accelerations are considerably smaller at this stage of the earthquake.

The approximate 500 fold reduction in soil stiffness that occurs after roughly 17 seconds of shaking is a clear indication to the authors that effective stresses have reduced to near zero and liquefaction has been triggered, at least in some zones of the soil profile.

Analysis Procedure

The dynamic analysis of the site was carried using a single-degree-of-freedom lumped mass and spring model. The lumped mass involved both the mass of the 2.5 m surficial crust and the 1/2 thickness of the 4.3 m liquefiable layer. The spring was nonlinear and represented the stiffness of the liquefiable layer by incorporating the stress-strain model discussed earlier. The downhole time history of acceleration was applied as base input motion and the response of the system obtained by step-by-step integration in the time domain. The computed response in terms of surface accelerations, relative displacements, and porewater pressures are compared in the next section.

Results

The predicted and observed surface accelerations are shown in Fig. 5(a) where it may be seen that the general form of the predicted response is in reasonable accord with the observation. The predicted and observed relative displacements are shown in Fig. 5(b), where it may be seen that up to about 17 seconds both computed and measured relative displacements are very small. After 17 seconds relatively large displacement oscillations are predicted. It may be seen that both the pattern and magnitude of predicted and observed displacements are in reasonable accord.

The predicted surface acceleration versus relative displaement pattern is shown in Fig. 6(a). Prior to about 17 seconds the loops are very steep. At this point, liquefaction is triggered causing very flat loops that are in general accord with the observed pattern shown in Fig. 3. However, Fig. 3 shows a less abrupt degradation of modulus than the model prediction. This may be the result of a gradual spreading of the zone of liquefaction with time as compared to the assumption made in the analysis that the whole zone liquefied at one time.

The predicted effective stress path is shown in Fig. 6(b). It may be seen that the effective stress point gradually worked its way back from an initial state of σ'_{vo} = 66 kPa and $\tau_{st} = 0$. This occurred as the shaking caused cyclic shear stress pulses and associated porewater pressure rise. It may be seen that the stress point reached the phase transformation or ϕ'_{cv} line a few times before the developed strain was sufficient to trigger a large porewater pressure rise and drive the stress point to the zero effective stress state upon unloading. Once this state was reached, subsequent butterfly loops up the ϕ'_{cv} line and down below the ϕ'_{cv} line are predicted to occur, with accompanying porewater pressure oscillations.

The predicted and observed porewater pressure ratios are shown in Fig. 7. It may be seen that the predicted porewater pressure rise is much faster than the measured rise and shows significant oscillations due to dilation after liquefaction has been triggered. The measured porewater pressure response only shows significant oscillations after about 30 seconds when approximately 80% porewater pressure rise has occurred. Because of the unexpectedly slow and smooth measured porewater pressure response, some geotechnical specialists question the accuracy of the porewater pressure records, and cite system compliance in the electrical piezometers as a possible cause (Hushmand et al., 1992). However, numerous explanations have been proposed by others to support the validity of the measured porewater pressure response (Thilakaratne and Vucetic, 1989; Zeghal and Elgamal, 1994).

The measured relative displacements shown in Fig. 2 indicate that liquefaction was triggered at some depth within the liquefiable layer at about 17 seconds. If piezometer #5 (Fig. 7) was reading correctly, it would suggest that liquefaction did not occur at this location until about t=50 secs.

SUMMARY

An element stress-strain and porewater pressure model is briefly summarised. The shear behaviour in both loading and unloading is modelled by modified hyperbolas, and shear-volume coupling is included.

The model is incorporated in a dynamic analysis procedure and applied to the field case history recorded at the Wildlife site in California in 1987. The recorded downhole time history of acceleration was used as input to the dynamic model and the predicted response, in terms of surface acceleration, relative displacement, and porewater pressure compared with the measurements.

The predicted and observed surface acceleration are in reasonable agreement in terms of both the amplitude and characteristic frequency of response. The relative displacements are also in reasonable agreement with observations. In particular, the relative displacement pattern after 17 seconds, at which time we believe liquefaction was triggered, is in good agreement.

The predicted acceleration versus relative displacement (stress versus strain) curves are in very good agreement and indicate that prior to t = 17 seconds the stress-strain response is very stiff, whereas after this time a major reduction in stiffness by a factor of about 500 occurs. This indicates that liquefaction and essentially 100% porewater pressure rise was triggered at least in some zones at about t = 17 seconds.

The predicted porewater pressures are not in good agreement with the measurements. The predicted porewater pressure rise is much faster than the measured values. The slower measured response is thought to be due to either compliance in the measuring system or to the possibility that liquefaction did not occur simultaneously at all points in the liquefied layer.

ACKNOWLEDGEMENT

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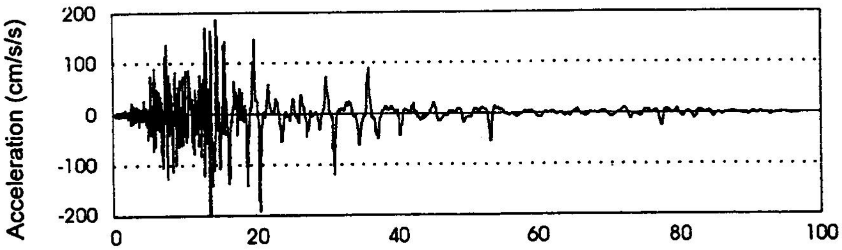
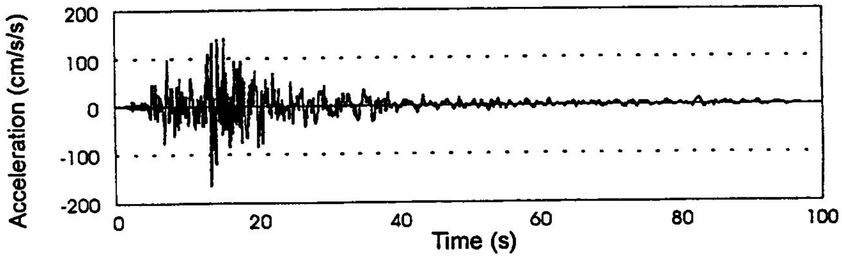
FIGURES



a) Surface acceleration time history, N-S component



b) Downhole acceleration time history, N-S component

Fig. 1: Acceleration time histories - Wildlife Site, 1987 Superstition Hills earthquake

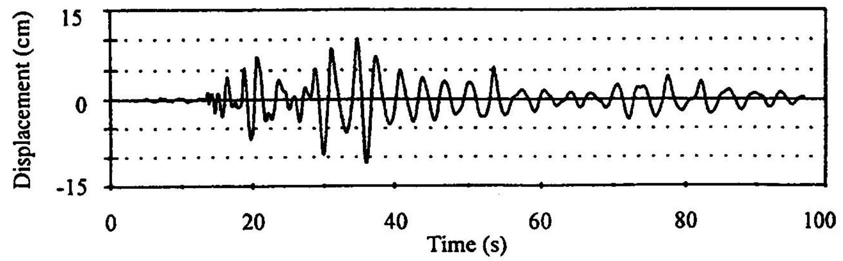


Fig. 2: Relative displacement time history - Wildlife Site, 1987 Superstition Hills earthquake.

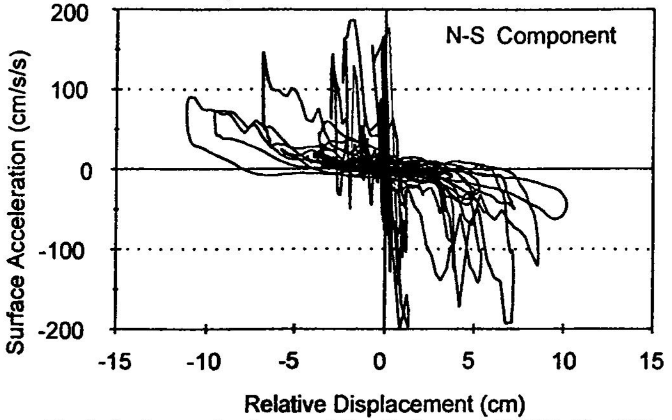
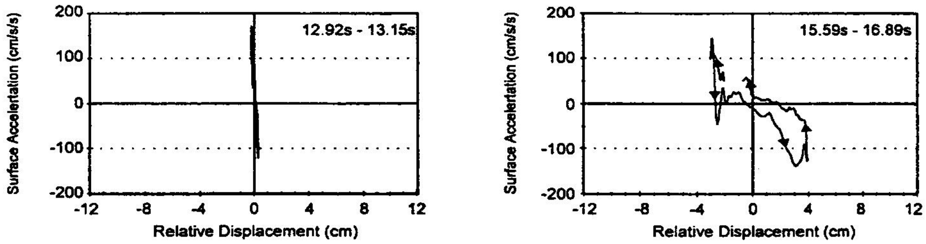
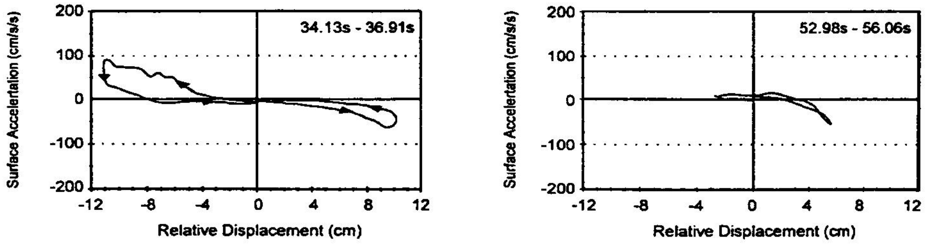


Fig. 3: Surface acceleration vs. relative displacement; Wildlife Site, 1987 Superstition Hills earthquake.



a) Initial stiff behaviour

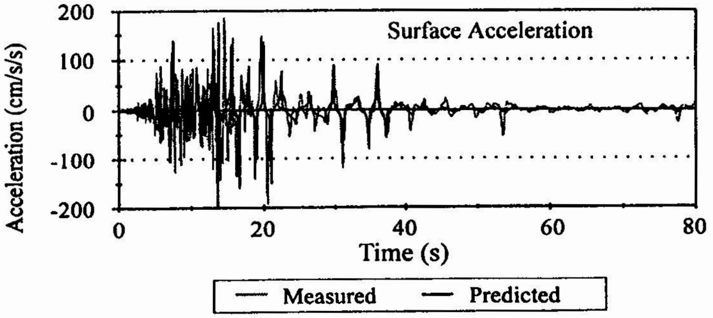
b) Modulus degradation at triggering.



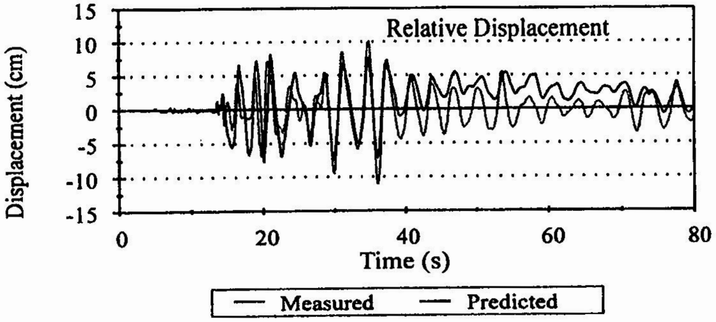
c) Peak relative displacements

d) Continued soft behaviour

Fig. 4: Change in soil stiffness during selected cycles - Wildlife Site, 1987 Superstition Hills earthquake.

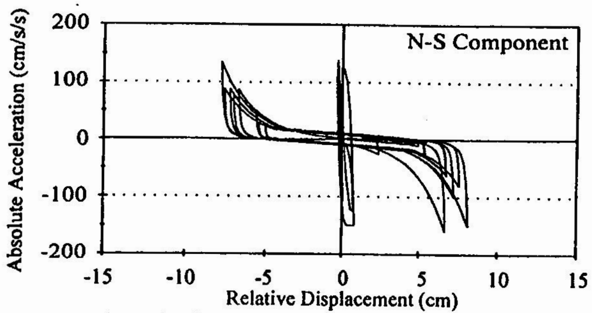


a) Measured and predicted acceleration time histories.

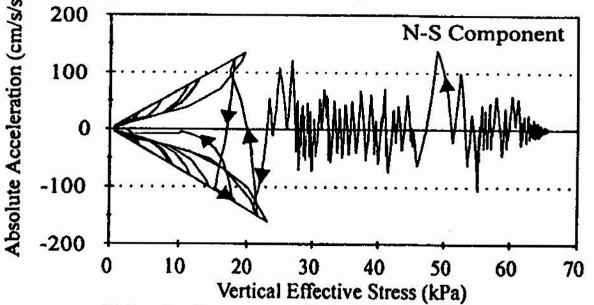


b) Measured and predicted displacement time histories.

Fig. 5: Comparison of measured and predicted time histories - Wildlife Site, 1987 Superstition Hills earthquake.



a) Acceleration versus relative displacement.



b) Acceleration versus vertical effective stress.

Fig. 6: Predicted dynamic response of Wildlife Site for 1987 Superstition Hills earthquake.

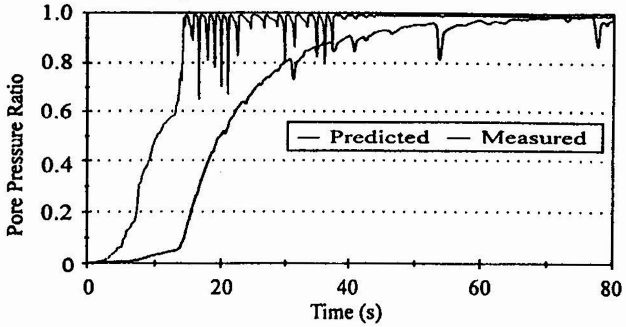


Fig. 7: Comparison between measured and predicted pore pressure ratios - Wildlife Site, 1987 Superstition Hills earthquake.