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TWO DIMENSIONAL LIQUEFACTION STUDIES

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ABSTRACT

Damage from liquefaction and soft soil site effects have been observed in many earthquakes over the years. Much of this damage as occurred in densely populated alluvial planes, which are commonly infill valleys. To investigate such valley structures, a two dimensional model may be used, which takes account of the lateral boundaries of the soil deposit, or more simply put, the valley walls. This paper presents a fully nonlinear two dimensional effective stress time domain site response and liquefaction model for the analysis of these valley structures. The strain history dependent pore pressure model is fully coupled into the site response program, and isotropic hardening/softening is incorporated to model the correct effective stress state at each time step. Five case studies are presented for valleys of different aspect ratios (with constant depth) to indicated the influence of the lateral dimension. The results show significant variations in response between wide and narrow valleys, and indicated the one dimensional assumption is not valid for these structures in many cases. The wide valley results are compared to an existing one dimensional nonlinear effective stress program as a means of validation of the results. This shows less agreement between the two solutions for sandy sites than for previously reported overconsolidated clay results.

KEYWORDS

Liquefaction; Site Response; Soil Dynamics; Two Dimensional; Valley Structures.

INTRODUCTION

Liquefaction damage and other site effects have been widely observed over the past 30 years. There has been a recent resurgence of interest in liquefaction research in the wake of significant liquefaction damage from the Loma Prieta (1989), Hokkaido (1993), and (in the New Zealand context) Edgecumbe (1987) events. Other site effects include the amplification of source motions by soft soils, with a resulting altering of the frequency components of the surface motion. Recent examples of significant site effects were observed in the Armenia (1988), Mexico City (1985) and Loma Prieta (1989) events. From preliminary data available it appears there were also significant site effects observed in Kobe (The Great Hanshin earthquake, 1995).

A fundamental understanding of the liquefaction response of uniform sand deposits has been developed over the past 30 years, with reasonable experimental and empirical techniques now available. Numerical techniques have not been as well developed however, and as a result are less widely used in practice. Numerical analyses have not been widely developed due to the difficulty in accurately and economically modelling the physical processes occurring. A reasonable understanding of these physical mechanisms has existed for many years (Martin *et al.* 1975), but incorporating this to an economic numerical technique has been difficult. The models have generally been complex in nature, requiring significant levels of specialised input data to accurately simulate the soil properties.

The majority of available numerical analyses for liquefaction and site amplification modelling are one dimensional in nature, only taking account of the vertical soil profile. To incorporate lateral boundaries, discontinuities, sloping ground surfaces, complex resonances and travelling waves, a two dimensional analysis procedure must be used. The two dimensional approach is very useful in the analysis of valley structures, where the valley shape can have a significant influence on the resulting surface motion (Marsh and Larkin 1991). By nature, infilled valleys tend to contain significant deposits of soft alluvial soils and also sandy deposits. As these soil types are most susceptible to both liquefaction and site effects, a two dimensional liquefaction model is a distinct advantage.

Due to the rich alluvial soils and coastal locations of many infill valleys, they are generally well populated commercial, industrial and agricultural centres. The Kobe region (Japan) and Hutt Valley (Wellington, NZ) are such examples. Any seismic event in such an area is therefore going to be of great concern and many critical infrastructures can be damaged, crippling the commercial business of a city, surrounding region, and in some cases influencing the economy of a country as a whole. For these reasons, it is vital to attempt to analyse and predict the response of valleys to seismic motion, the response consisting of both the possible amplification of source motions and the extent of any induced liquefaction.

This paper presents a two dimensional finite difference nonlinear site response and strain controlled liquefaction analysis method for the investigation of valley structures subjected to inplane seismic motion. Simple case studies are used to investigate the influence of the valley shape on both the liquefaction and site response of the soils. The effective stress method presented is compared to an existing one dimensional effective stress model, which allow both validation and investigation of the results to be undertaken..

REVIEW OF PREVIOUS WORK

There has been renewed interest in the area of numerical site response and liquefaction modelling in recent years after considerable effort in the 1960's and 70's had laid much of the groundwork. A number of approaches are available to numerically solve both the site response and liquefaction problem. This brief review shall focus on one and two dimensional methods of liquefaction and site response analysis only. Linear, equivalent linear and nonlinear solutions for the site response problem have developed, with the tendency for engineers to use either equivalent linear or nonlinear solutions, and seismologists tending towards linear solutions for their generally larger scale investigations. Both the stress and strain approach is used for liquefaction investigation, with the empirical stress method still the most commonly used.

The equivalent linear technique approximates nonlinear soil behaviour with the use of a linear solution and an iterative approach. These solutions have generally developed from the University of California, Berkeley, and their stable includes the well known SHAKE one dimensional program, and the two dimensional soil structure interaction programs FLUSH and QUAD4M. These total stress programs are generally used for liquefaction investigation in conjunction with the empirical Seed and Idriss (1971) method, with the computer programs determining induced stress levels. This type of dual analysis method is termed as uncoupled.

Fully nonlinear solutions are less well known, as their development has been slower. As the solution schemes must be solved in the time domain, pore pressure models may be incorporated directly into the solution. Such solutions allow for the influence of changing effective stress dependent soil properties to be modelled. Various liquefaction models have been developed and incorporated into these programs, including stress and strain controlled models and models based on endochronic theory. Of interest in this study is the shear strain dependent model, which has been incorporated in the one dimensional nonlinear programs NESSA (Larkin 1978) and the well known DESRA-2 (Lee and Finn 1978). It has also been used in the two dimensional

TARA-3 (Finn *et al.* 1986) which is primarily used for earth embankments. The reader is referred to the excellent review of dynamic analyses by Finn (1988) for more detailed information on available analysis methods.

SITE RESPONSE AND LIQUEFACTION MODEL

The response analysis program used in this study is an inplane two dimensional nonlinear site response analysis coupled with a strain controlled excess pore water pressure model. The site response program was originally developed in terms of total stress by Joyner (1975), and has been extended to include an excess pore pressure model by the authors. The pore pressure model was initially developed by Martin *et al.* (1975), and has been significantly improved and simplified by Byrne (1991). A brief outline of the theory involved shall be presented below, with a more detailed explanation available elsewhere (Marks 1996).

Two Dimensional Site Response Model

The two dimensional nonlinear site response program applies a discrete grid of nodes and elements to approximate the valley structure, and solves the wave propagation problem using an explicit finite difference time domain solution technique. The solution passes over the entire grid during each time step. Stresses and strains are defined in terms of both mean and deviatoric components. For the inplane solution there are three independent variables in the stress and strain tensors, and they are solved for simultaneously at each time step in the analysis.

The nonlinear constitutive relationship of the soil is modelled using an array of Iwan type nested yield surfaces, 10 of which are usually required to approximate the soil properties accurately. This type of system has the advantage over other methods as the stiffness and yielding parameters of each element may be set to closely simulate the nonlinear behaviour of the soil. Each nested surface obeys the Von Mises yielding criterion and exhibits Prager kinematic hardening. Isotropic hardening of the yield surfaces is also incorporated to allow for the change in sandy soil properties due to the fluctuations in the effective stress state of the sand. Either experimental of empirical methods must be used to determine the shape of the constitutive loading curves before the analysis can begin. For the results presented in this paper, the simple hyperbolic shape was used to determine the element parameters.

Pore Pressure Generation (Liquefaction) Model

The generation of excess pore pressures is determined from a fundamental, experimentally determined incremental model, as referenced above. It has been concluded by a number of researchers that pore pressure generation in sands is primarily a function of density, induced strain history and induced strain magnitude, rather than induced stress levels, as is the basis of the empirical Seed and Idriss method in wide use today. The pore pressure model used is therefore a function of the induced strain magnitude during a particular loading cycle and the associated strain history. Density is not incorporated directly into the model, but as a primary influence on the initial material properties of the sands.

Experimentally it has been shown that most of the pore pressure generation occurs on the unloading portion of the loading cycle, and therefore changes in pore pressure are applied only during this portion of the loading cycle. The pore pressure model has been experimentally determined from horizontal cyclic simple shear testing of sands, the controlling parameter being the horizontal shear strain (γ). The inplane two dimensional stress/strain state includes one horizontal and two volumetric components. The horizontal strain component is used as the "driving" shear strain for the pore pressure model, and hence compressional waves moving through the soil do not effect the calculated excess pore pressures.

The level of pore pressure increment for the current half cycle is determined at the peak shear strain level and applied over the unloading portion of that half cycle. Incomplete unloading during a half cycle is also accounted for. As the material properties of sands are a function of effective stress, alterations to the effective stress state with changing pore pressure are accounted for in real time during the same unloading portion by incorporating isotropic hardening in a coupled form with the site response analysis.

Post liquefaction behaviour is accounted for empirically with the assumption that the effective stress level remains constant at 5% of the initial value. This is an assumption but a suitable robust post liquefaction model has not yet been developed for this purpose. The analysis assumes undrained condition at this stage, which does not allows for pore pressure redistribution and the associated influence on the effective stress state of each soil element. A two dimensional redistribution solution is currently under investigation and shall be implemented shortly into the program.

RESULTS AND DISCUSSION

The results presented below consist of 5 case studies of sandy soil valleys subjected to in plane two dimensional motion. The aspect ratios of the valleys range from the wide 16 to 1 (width to depth ratio) to the narrow 2 to 1 case. This allows investigation of the two dimensional influence on both the site response and undrained liquefaction response of the valley. The wide valley is also compared to an existing one dimensional site response program in an effort to validate the two dimensional results presented here.

Source Motion

The earthquake record used for all of the results presented below is the horizontal and vertical motions recorded at the Castaic Old Ridge Route Station on February 9th 1971, during the San Fernando Earthquake. The recorded PGA of this motion was 0.3g, but for the purposes of this study the motion was scaled down to a PGA of 0.1g. The rational for this was the wish to show primarily the two dimensional influence on the site and liquefaction response of the valley without introducing a heavily nonlinear factor, which high motions tend to generate. In addition the generation of widespread liquefaction throughout the valley for all of the case studies would not provide a very useful basis for the comparison of the excess pore pressure response of different aspect ratio valleys.

Soil Parameters

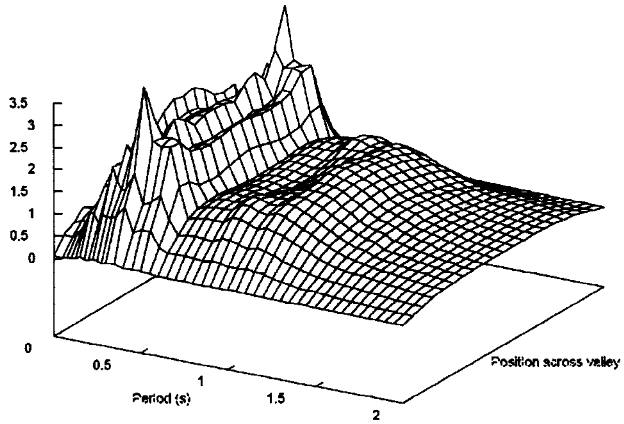
The soil parameters for the case studies presented in this paper were determined to be representative of a typical sand that is vulnerable to significant excess pore pressure generation. It has been widely concluded that strength and modulus parameters of sands are a function of the density and effective stress state, and a number of correlations exist to determine parameters for typical sands (Kulhawy and Mayne 1990, Seed and Idriss (1971)). The sands used in the case studies were based on a normalised blow count $(N_1)_{60}$) of 10 blows/ft. From this the friction angle, shear modulus and shear strength were determined.

The parameters for the liquefaction model were determined from backfitting the numerical model to a liquefaction strength curve determined from the standard Seed and Idriss empirical stress approach. This backfitting procedure is fully outlined in Larkin and Marks (1994). A single layer sand deposit was used so as to keep the case study as simple as possible, although in practice the lower layers of the 100m deposit would most likely have a higher blow count and therefore would be represented as separate layers.

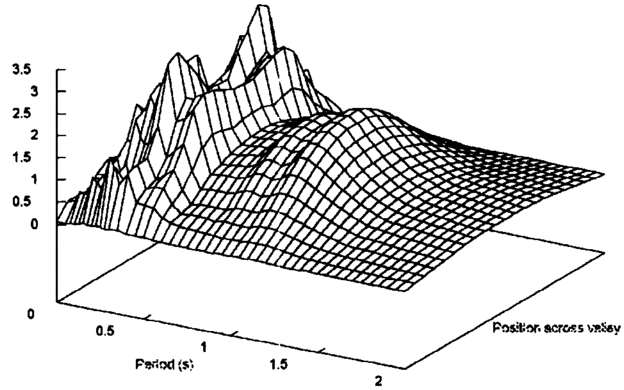
Case Studies

Five case studies were performed for valleys of different aspect ratios (width:depth) subjected to the same input motion. The resulting surface acceleration response spectra are shown in Fig. 1 and contours of the excess pore pressure response shown in Fig. 2.

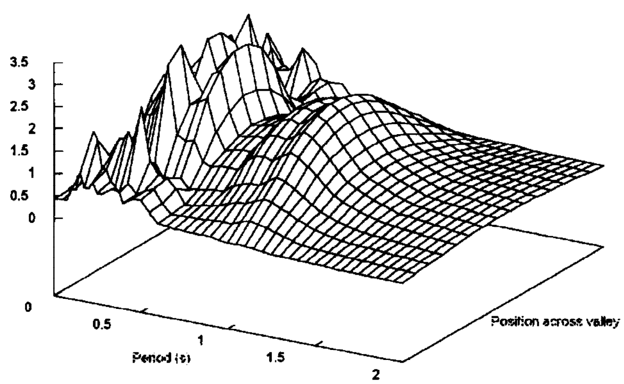
The surface response spectra clearly show the influence of the lateral dimension in the behaviour of the valley. The 16:1 and 8:1 aspect ratio valleys showed the most uniform responses over the surface, with lateral variations becoming significant for aspect ratios less than 8:1. The nonhomogeneous response of the other



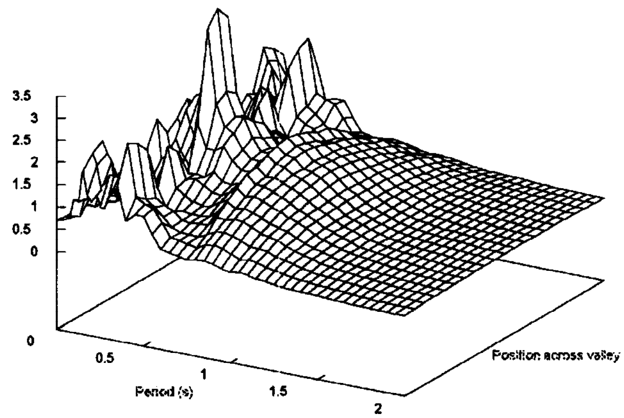
(a) 16:1 aspect ratio



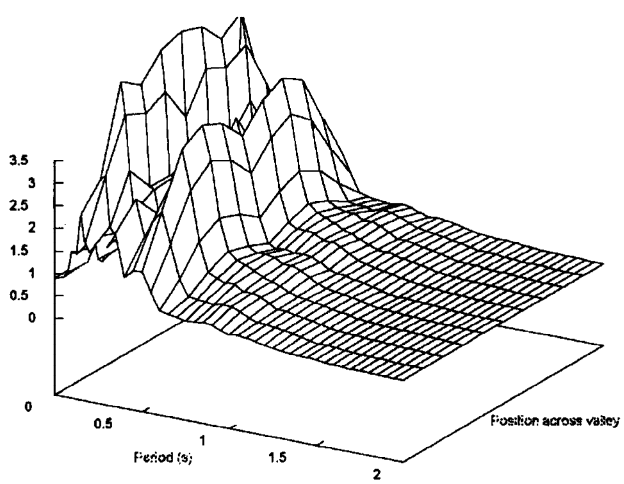
(b) 8:1 aspect ratio



(c) 6:1 aspect ratio



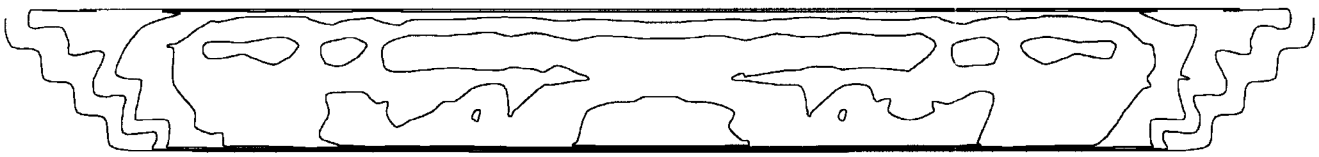
(d) 4:1 aspect ratio



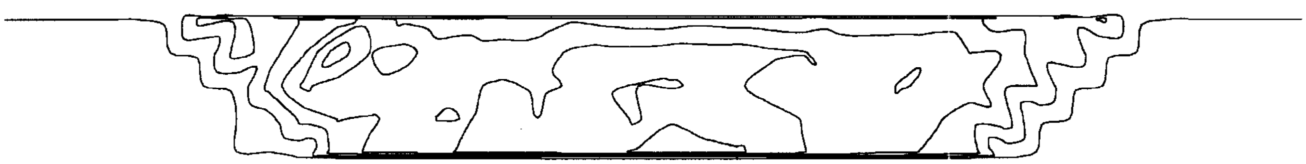
(e) 2:1 aspect ratio

Fig 1 (a-e). Surface acceleration response spectra of the valley structures for five different aspect ratios (vertical axes on all graphs are spectral acceleration in m/s/s)

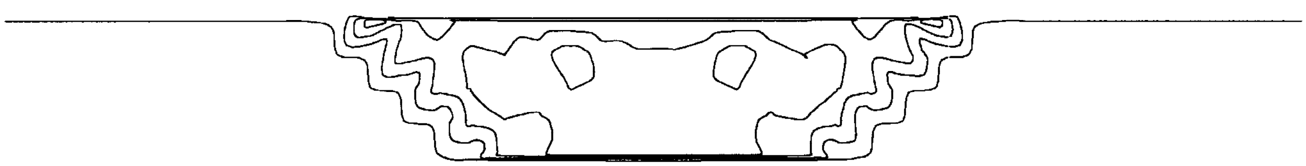
(a) 16:1 aspect ratio (Peak pore pressure ratio = 0.45)



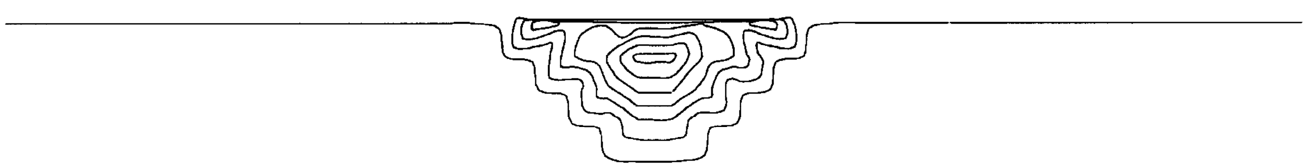
(b) 8:1 aspect ratio (Peak pore pressure ratio=0.5)



(c) 6:1 aspect ratio (Peak pore pressure ratio=0.55)



(d) 4:1 aspect ratio (Peak pore pressure ratio=0.45)



(e) 2:1 aspect ratio (Peak pore pressure ratio=0.63)

Fig 2 (a-e). Excess pore pressure ratio contours of the valley structures for five different aspect ratios (each contour step corresponds to a pore pressure ratio (u/σ_v') of 0.1) aspect ratios is due to the complex interaction between the confining boundaries and the soil deposit. This generates multiple reflections and refractions even in a valley of uniform soil, and for nonlinear media this phenomena is even more pronounced. The 2:1 valley shows a pronounced low period response, due to the alignment of the fundamental frequencies of the valley and the dominant frequencies in the source motion. It appears that the influence of the constrained geometry has reduced the fundamental frequencies of the valley from the longer period energy evident in the wider valley cases. This same phenomena is also evident in the 4:1 valley, although in a diminished sense.

Fig, 2 indicates the most significant excess pore pressure domain lies at the centre of the valley, for all aspect ratios. This is due to the influence of the lateral soil/rock boundaries where the transmitted shear strains are small, and pore pressure is a function of the shear strain magnitudes. There is a general trend of increasing pore pressure response with reducing aspect ratio, although the 4:1 case is an exception. From the spectra shown in Fig. 1(d), it is clear that the response of the valley is suppressed, and this is also observed in the excess pore pressure contours

Investigation using the One Dimensional Solution

An existing one dimensional nonlinear effective stress program (NESSA) was used to compare the 1-D and wide valley (16:1) 2-D results. The peak excess pore pressure response is shown in Fig. 3, and the surface response spectra comparison shown in Fig 4.

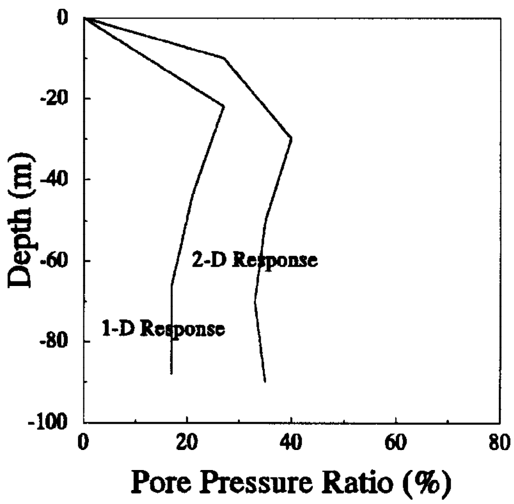


Fig.3 Peak Liquefaction response comparison for 1-D and wide 2-D valley

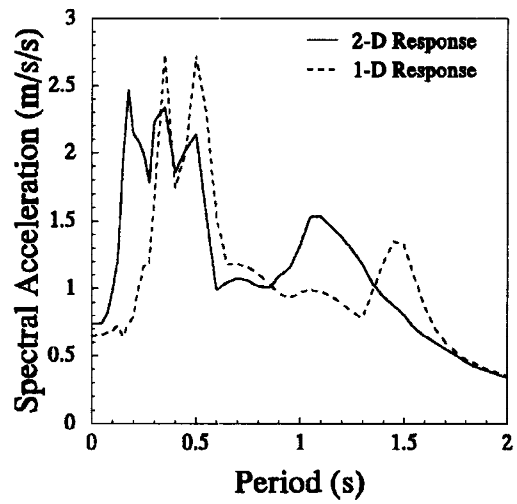


Fig. 4 Response spectra comparison for 1-D and wide 2-D valley

It can be seen that the two solutions do not give exactly the same results, and show less agreement for sand deposits than a corresponding comparison with overconsolidated clay deposits published elsewhere (Larkin and Marsh 1991). Both solution are incremental in nature and involve significant strain history effects in the constitutive models. It is therefore unlikely that the two solutions will yield the same results. The added complexities of the 2-D solution include some influence from wave scattering, even at the centre of the valley .alley, which will effect the agreement of the two.

Although relatively different in magnitude, the shape of the peak liquefaction response curves shown in Fig. 3 are similar, with the maximum response occurring at the same depth. As an undrained solution, the peaks all occur at the end of the shaking record, although the significant increase in pore water pressure occurs coincident with the arrival of the significant shear phase of the motion (at approximately 5 seconds).

CONCLUSION

This paper has presented a two dimensional nonlinear effective stress solution for the investigation of both the liquefaction and site response of valley structures. The results have shown that the geometry of the valley has a strong influence on the overall response of the soil deposit. This indicates that a one dimensional solution is not alway adequate for engineering purposes, particularly for confined valley geometries. Two dimensional structures exhibit complex response characteristics, which require investigation for a close understanding of ground and liquefaction response problems.

ACKNOWLEDGMENTS

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