Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Three-dimensional earthquake site response on a CM-2

X. Li, J. Bielak & O. Ghattas
Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pa., USA

ABSTRACT: A finite element method is used to evaluate effects of site conditions on the three-dimensional seismic response of alluvial basins on the Connection Machine CM-2. Results for a shallow truncated semi-ellipsoidal valley subjected to oblique incident SV-waves illustrate body wave to surface wave conversion at the valley confluence and the large amplitude and long duration of surface ground motion, as well as spatial variation within the valley, compared to the surrounding rock and to one-dimensional models of the valley. Waves with near critical incident angles produce especially large response.

1. Introduction

The importance of site effects on seismic ground motion has been dramatically underscored by several recent large earthquakes, such as the 1985 Michoacan, Mexico; the 1987 Valparaiso, Chile; and the 1989 Loma Prieta, USA, earthquakes. In all three instances it was observed that surface ground motion at various locations within sedimentary valleys exceeded by factors of five or greater the corresponding motion on rock. The Loma Prieta earthquake also illustrates that surface ground motion can vary rapidly over short distances, as observed at a site in Santa Cruz where different levels of shaking were detected by seismometers located only 30 m apart.

Simple models that neglect the effect of lateral variation of the topography and subsurface layer interfaces by considering the problem as one-dimensional are sufficient in certain situations for explaining observed motion (Seed et al, 1988), but in many cases two- and three-dimensional models become necessary. The importance of including the continuous variability of material properties with depth, in addition to the lateral variability, is now well-documented (Aki, 1988).

Despite the significant progress to date in the study of ground motion, there is need to gain a better understanding of the seismic motion within realistic sedimentary basins. Most numerical simulations have been limited to one-dimensional models and homogeneous or simple layered two-dimensional models due to the prohibitive computational costs and memory requirements associated with three-dimensional simulations. With recent advances in computational resources and methodologies it is now becoming increasingly possible to analyze more realistic three-dimensional problems (Frankel, 1989; Eshraghi and Dravinski, 1991).

The desire to simulate the response of larger basins, softer materials, and higher excitation frequencies is accompanied by an increase in computational resource requirements. The temporal resolution requirements associated with wave propagation through a realistic complex, heterogeneous basin demand at least gigaflop speed, while the spatial resolution needed requires gigabytes of primary storage. It is now accepted among hardware designers that this performance will be achieved in the future by architectures consisting of hundreds to thousands of processors operating in parallel on data in local memories. Central to the effort of studying site response of basins such as Los Angeles, then, is the exploitation of these massively parallel architectures for simulating wave propagation through a complex, heterogeneous medium. The work reported herein employs a 32k Connection Machine CM-2. We will be reporting on algorithmic and communication issues related to the CM-2's architecture in a separate article.

Many methods have been used for solving wave propagation problems through elastic (or inelastic) media in earthquake engineering and seismology. Of these only finite differences and finite elements seem appropriate for dealing with highly heterogeneous, complex, and possibly inelastic situations. The main objective of this paper is to present some initial results of a study undertaken to examine the effects of site conditions on the seismic ground response of three-dimensional sedimentary valleys using the finite element method on the CM-2. We consider as a particular example a somewhat shallow elastic homogeneous valley in the shape of a truncated semi-ellipsoid for which one-dimensional theory might be expected to provide satisfactory results near the center of the valley. As will be seen, even this case exhibits interesting three-dimensional behavior.

2. Problem and method

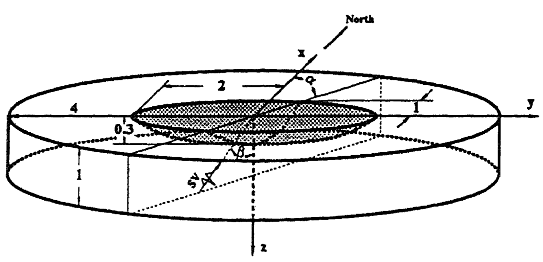

Figure 1: Model of 3d alluvial valley

Suppose one has a halfspace of isotropic, homogeneous, linearly elastic material with shear wave velocity β_r, Poisson's ratio ν_r, and mass density ρ_r, bounded by a traction free plane. In this material there is a transient incident wave that produces an incident displacement field u_i, which is a function of position and time (In the examples we consider a plane incident SV-wave). Suppose now that an arbitrary three-dimensional valley of heterogeneous elastic material is inserted in the free surface, as shown in Fig.1.

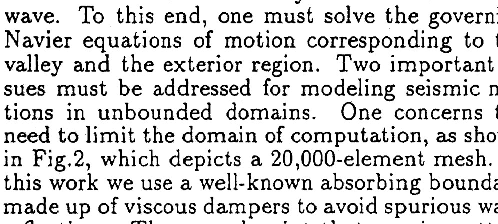

Figure 2: Finite element mesh

The problem is to determine the total displacement field within the valley due to the incident wave. To this end, one must solve the governing Navier equations of motion corresponding to the valley and the exterior region. Two important issues must be addressed for modeling seismic motions in unbounded domains. One concerns the need to limit the domain of computation, as shown in Fig.2, which depicts a 20,000-element mesh. In this work we use a well-known absorbing boundary made up of viscous dampers to avoid spurious wave reflections. The second point that requires attention is how to incorporate the excitation into the model if the earthquake source is located outside the region of computation. Here we introduce an updated version (Loukakis, 1988) of an exact procedure that allows one to specify the input motion at the interface between the valley and the surrounding medium in terms of effective forces for an arbitrary incident wave (Bielak and Christiano, 1984, Cremonini et al, 1988).

Trilinear eight-node isoparametric elements and standard Galerkin ideas are used for the spatial discretization of the governing Navier equations. The resulting ordinary differential equations are solved by an explicit, second order, central difference method directly in the time domain. To avoid solving equations at each time step, both the mass matrix and the absorbing damping matrix are lumped using standard procedures.

3. Numerical results

The model with the geometric characteristics depicted in Fig.1 is treated in this study as an example of a simple truly three-dimensional valley subjected to seismic excitation. This truncated semi-ellipsoid has an aspect ratio of 4:2:0.3, and is filled with a homogeneous material. We calculated synthetic seismograms due to vertical and oblique incident plane SV-waves for the following choice of physical parameters intended to represent a valley with a medium impedance contrast with respect to the halfspace: $\beta_s/\beta_r = 1/3$, $\rho_s/\rho_r = 0.93$, $\nu_s = 0.25$, and $\nu_r = 0.3$. (Radiation damping is taken into consideration by means of the absorbing boundary, but material damping is neglected in this study.) A typical realization of this combination would correspond to a valley with a shear wave velocity of $\beta_s = 0.6km/s$, and a surrounding rock with $\beta_r = 1.8km/s$. The plane of the incident wave forms an angle α with respect to the x axis and is polarized at an angle β with the y axis. The signal consists of a slightly modified Ricker wavelet of dominant period T_p, which is taken to be equal to the fundamental resonant period of a flat layer of alluvium with the same shear velocity as the valley, and same thickness as the maximum depth of the valley; i.e., $T_p = 4H/\beta_s$, where H is the valley depth. For a shallow valley with $H = 0.15km$ and $\beta_s = 0.6km/s, T_p$ is $1s$.

Fig.3 shows synthetic displacements at various locations within the valley (identified by their coordinates (x, y)) for several values of α and β. Horizontal components of displacement parallel to the x and y axes (NS and EW directions) are denoted by u and v, respectively, and w is the vertical component, all normalized with respect to the amplitude of the incident wave. Notice that outside the valley only the scattered components of motion are reported. For the cases of vertical incidence ($\beta = 0$), Fig.3 also shows the one-dimensional ($1D$) displacement for the corresponding flat layered system. Fig.3a illustrates the response of the valley for the simplest situation corresponding to a vertically propagating incident wave polarized in the EW direction. By comparing the displacement in the valley interior with the $1D$ response it is clear that the amplification of the response within the valley with respect to the free-field response (given approximately by the initial traces at $(1, 0)$ and $(0, 2)$) is significantly greater than that of the flat layer. For instance, the maximum response at the valley center is 5.3, versus 3.5 for the $1D$ case, for net amplifications of 2.8 and 1.8 with respect to that at the valley edge. Most important also is the extended duration of the significant portion of

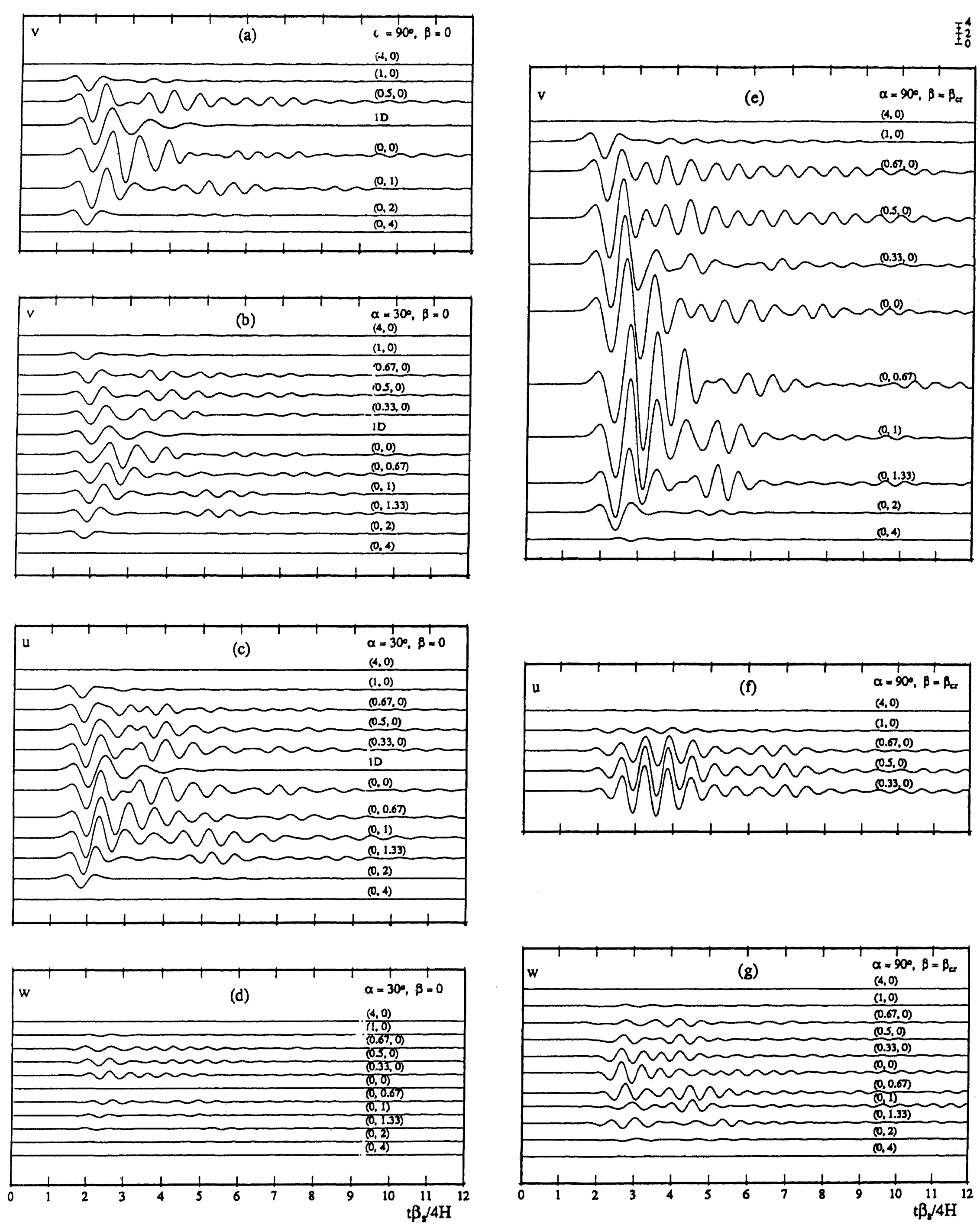

Fig.3(a-g): Synthetic displacements for various angles of incidence the response within the valley. Such differences in the response are caused primarily by the surface Rayleigh and Love waves generated at the confluence of the valley with the surrounding, stiffer, medium. The same pattern of behavior is observed in Figs.3b and 3c for the transverse incident wave ($\alpha = 30°$). Fig.3d shows the small resulting vertical motion due to the Rayleigh waves.

It is well known that a large total response can be expected if the incident wave has a critical angle of incidence ($\beta_{cr} = 32.3°$ for $\nu_r = 0.3$). This is illustrated in Figs.3e, 3f, and 3g, where even the response at the valley confluence has a peak amplitude of 3.34 as opposed to only 2 for vertical incidence. The peak response occurs off-center at $(0, 0.67)$ and it has a value of over 12. Notice also the significant transverse motion in the NS direction even though the incoming motion has no component in that direction.

To illustrate the spatial distribution of the response within the valley, snapshots of the three components of the displacement at various normalized instants $t\beta_s/4H$, denoted simply as t, are shown in Figs.4, 5, and 6. As before, displacements outside the valley represent only the scattered motion. This helps illustrate the virtual absence of spuriously reflected waves. Fig.4 shows the three components for $\alpha = 30°$ and vertical incidence. The curves on the xy plane are contour lines of the surfaces shown directly above. The tendency for the displacements at this instant to be polarized along the plane of the incident wave is apparent. Figs.5 and 6 correspond to the wave propagating in the EW direction with a critical angle of incidence. The evolution with time of the direct and the reflected waves can be visualized from these results. Notice that while the EW and vertical motion are symmetric about the EW axis, the transverse motion in the NS direction is antisymmetric. In addition to depicting the evolution of the ground motion within the valley, Figs.4, 5, and 6 dramatically indicate that at many particular instants large differential motion can take place over a short distance. This can have practical implications for the design of long structures.

Acknowledgment

This work was supported by the US National Science Foundation; Dr Clifford Astill is the cognizant officer. Thanks are also extended to the Pittsburgh Supercomputing Center for the use of the CM-2 We gratefully acknowledge this support. We also thank Carlos Orozco for freely sharing with us his knowledge of the CM-2.

References

Aki, K. 1988. Local site effects on ground motion *Earthq. eng. and soil dyn. II: Recent advances in ground-motion evaluation.* J. L. Von Thun, ed., ASCE, New York, N.Y., 103-155.

Bielak, J. & P. Christiano 1984. On the effective seismic input for nonlinear soil-structure interaction systems. *Earthq. eng. struct. dyn.* 12:107-119.

Cremonini, M. G., P. Christiano, & J. Bielak 1988. Implementation of effective seismic input for soil-structure interaction systems. *Earthq. eng. struct. dyn.* 16:615-625.

Eshraghi, H. & M. Dravinski, 1991. Transient scattering of elastic waves by three dimensional non-axisymmetric dipping layers. *Int. j. num. meth. eng.* 31:1009-1026.

Frankel, A. 1989. A review of numerical experiments on seismic wave scattering. *PAGEOPH* 31:639-685.

Loukakis, K. 1988. Transient respone of shallow layered valleys for inclined incident SV-waves calculated by the finite element method. *M.Sc. Thesis* Carnegie- Mellon University, Pittsburgh, PA.

Seed, H. B., M.P. Romo, J.I. Sun, A. Jaime, & J. Lysmer 1988. Relationship between soil conditions and earthquake ground motions. *Earthq. Spectra* 4:687-729.

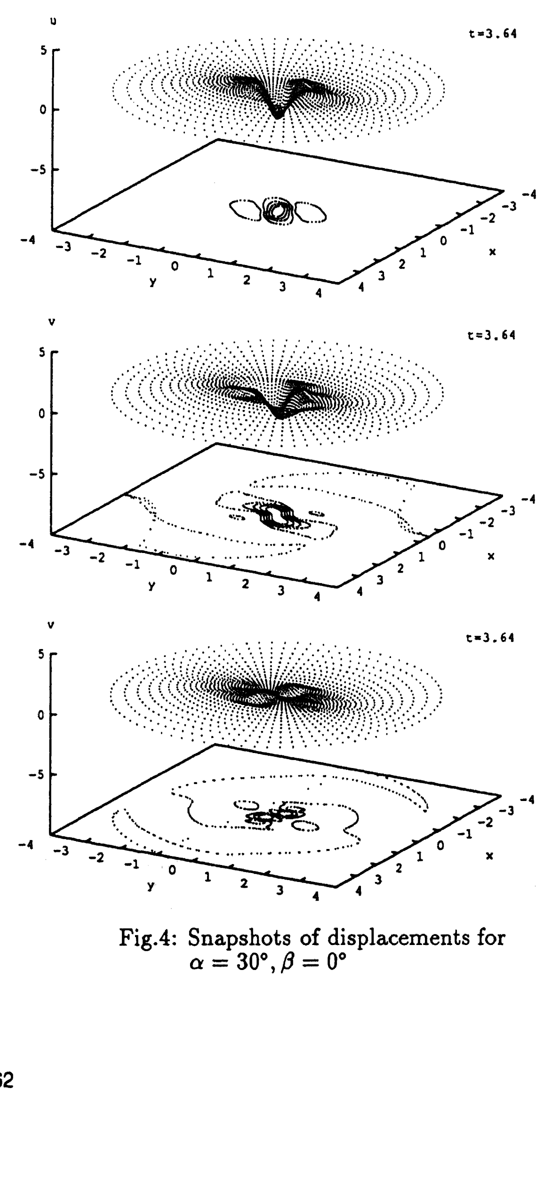

Fig.4: Snapshots of displacements for $\alpha = 30°, \beta = 0°$

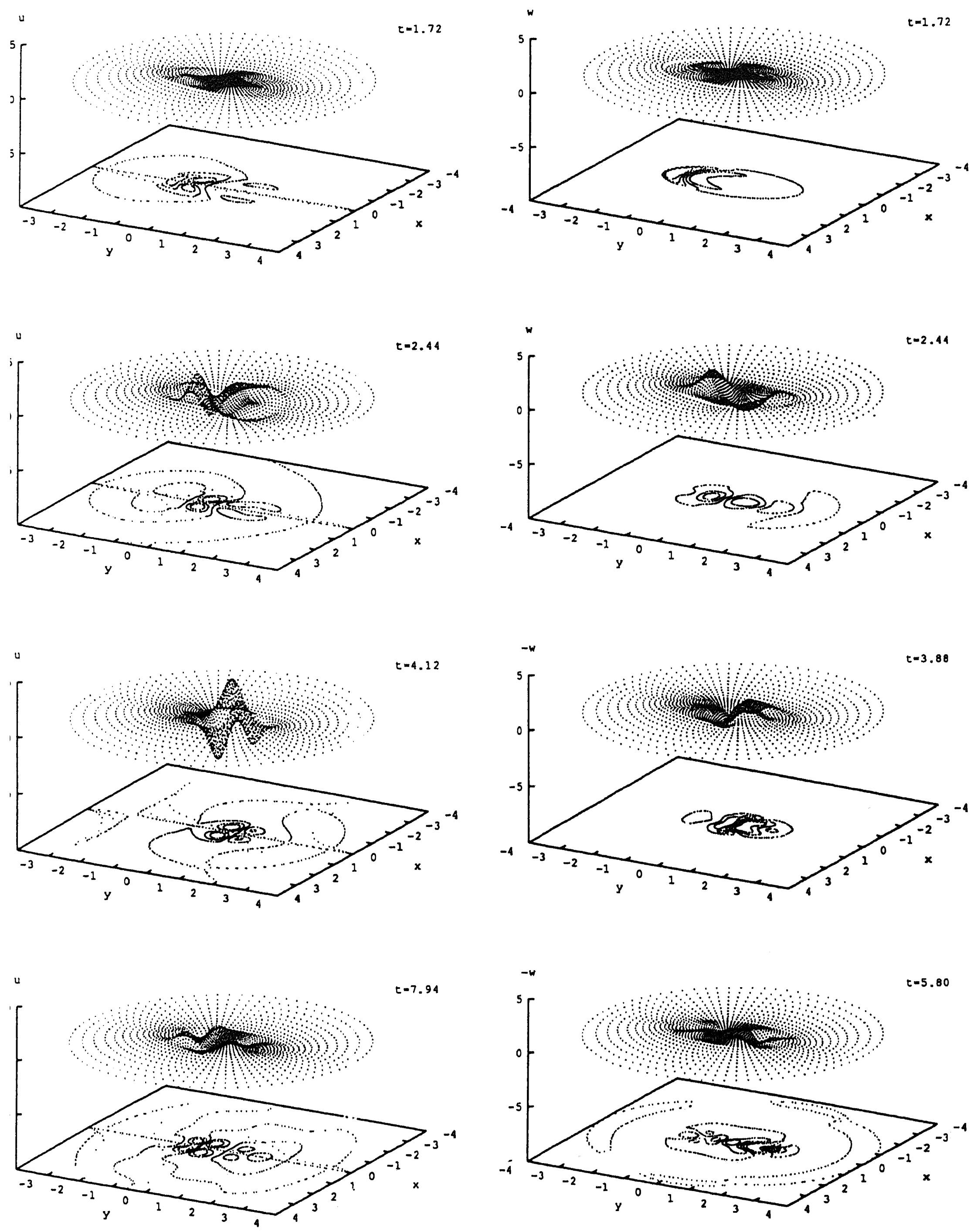

Fig.5: Snapshots of displacements for $\alpha = 90°, \beta = \beta_{cr}$

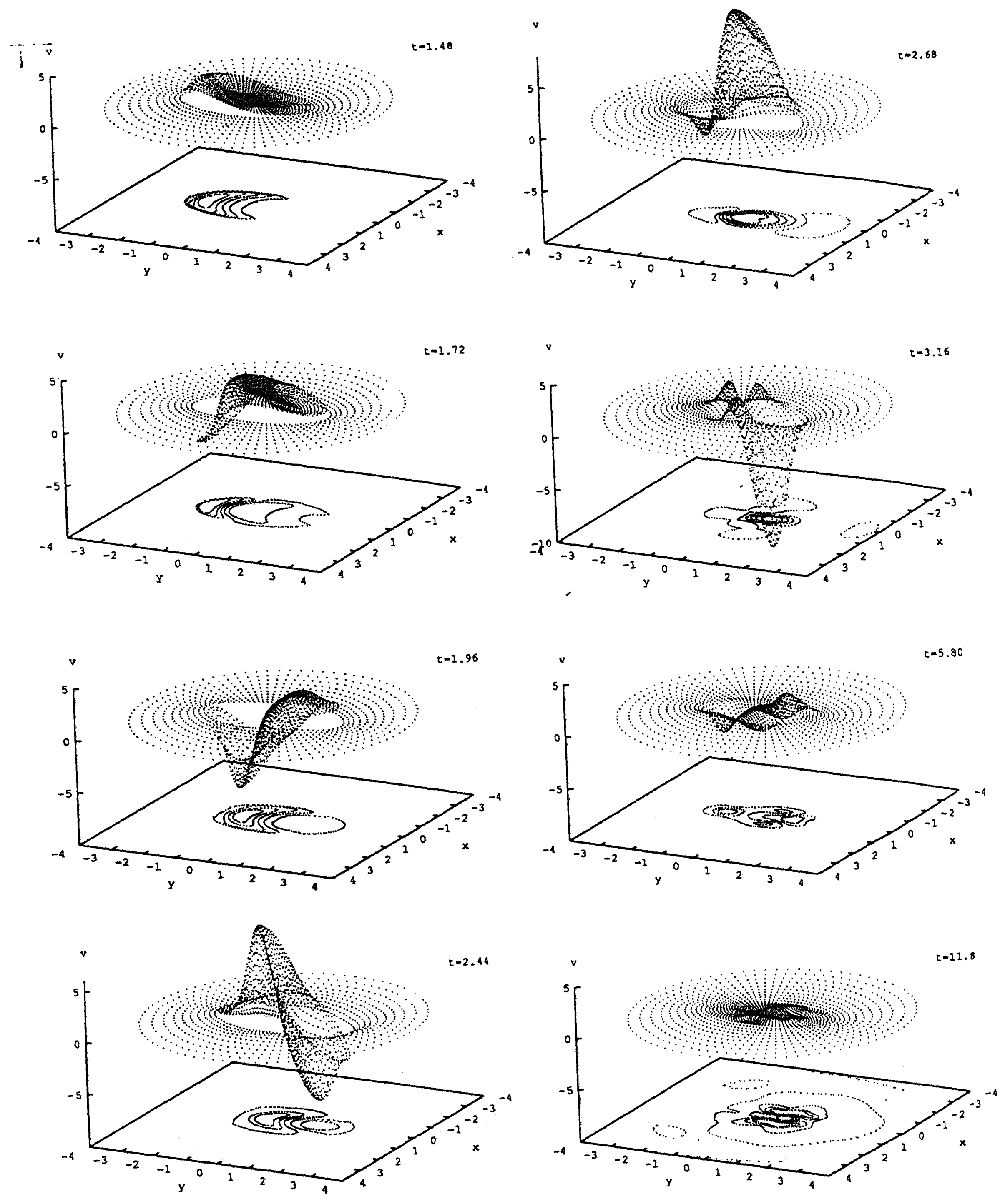

Fig.6: Snapshots of displacements for $\alpha = 90°, \beta = \beta_{cr}$