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SLOPE-INSTABILITY DUE TO EARTHQUAKE-INDUCED RAYLEIGH WAVE INTERACTION WITH CANYONS

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ABSTRACT

The effect of variable surface topography and Rayleigh wave length on the displacement amplification during surface wave interaction with a canyon is investigated experimentally by means of 2D dynamic model testing. Numerically, the wave interaction process is simulated by the recently developed finite difference program SWIFD. Several types of canyon topographies will be considered. 3D visualisation of surface stress, position and time as well as the history of deformations of the canyon surface are presented to improve the understanding of Rayleigh wave induced dynamic canyon instability.

KEYWORDS

Dynamic photoelasticity, finite difference method, Rayleigh wave, earthquake induced canyon instability, numerical simulation, surface geometry, surface stress amplification, SWIFD, wave propagation, wave scattering.

INTRODUCTION

Wave interactions with irregular surfaces occur in a wide variety of engineering problems. Irregular surface topographies such as canyons and cliffs seriously affect the dynamic stress distribution. The subject of surface wave scattering has been treated in the literature as a problem of elastic wave diffraction. The influence of local surface geometry on ground motion due to earthquakes has been noticed as well as concentration of earthquake damage to certain regions. Most often damage is due to the large amplification of seismic and/or surface waves associated with local topography and surface soil and rock properties. Engineering designed barriers or inhomogeneities such as trenches or volumes of disintegrated rock mass within the surface boundary layer may reduce the intensity of dynamic stresses around buried or embedded engineering structures (May and Bolt, 1982; Wong, 1982; Ohtsuki and Yamamura, 1984).

Rayleigh waves play a dominant role in the transmission of seismic disturbances along the surface of the earth and therefore have been the subject of extensive research (Lamb,1904; Ash and Paige, 1985). On the other hand, Rayleigh waves may conveniently be employed in the field of nondestructive testing by means of acoustic surface waves. The wave scattering patterns associated with Rayleigh wave scattering about surface topographic features such as an array of grooves is fully utilized and exploited in the fabrication of micro miniature acoustic surface wave devices such as filters (Seshadri, 1979). Given appropriate scaling with respect to wave length and geometrical dimensions of the surface inhomogeneity, e.g. corrugation, grooves, canyons, the interaction processes between elastic surface wave and surface inhomogeneity in the micro-world of miniature device engineering and in the macro-world of earthquake and tectonic engineering are alike. The phenomena observed in the interaction process crucially depend on the ratio of the wave length to the dimensions of the scatterer for harmonic waves. For a Rayleigh-pulse with a broad frequency spectrum the interaction process becomes more involved.

Significant progress in the treatment of the interaction of a surface wave with a single inhomogeneity has been made by several authors. In the theory of groove reflector arrays (Sanford and Dally, 1979), a periodic weakly ondulative grating of shallow grooves in a semi-infinite elastically isotropic medium supports a traveling Rayleigh wave. For shallow grooves the incident Rayleigh wave is weakly scattered with the wave energy partitioned into reflected and transmitted surface waves and scattered bulk waves that propagate into the elastic half space. Results of many investigations and studies indicate that topographic features, such as shape, depth, and for the case of an array the periodicity of the topographic features, can have significant effects on the quantitative and qualitative partition of wave energy, distribution of wave patterns and spectral content. The interaction of Rayleigh waves with a deep groove or a canyon with steep cliffs with an aspect ratio of wave length to depth of canyon much smaller than unity differs considerably from the shallow groove diffraction problem.

In addition, the influence of boundary curvature on the behavior of a Rayleigh wave as expressed by dispersion and velocity dependence may become a nonnegligible factor. Theoretical predictions of Rayleigh wave dispersion and change of the pulse propagation speed with wave propagation on a curved cylindrical surface could experimentally be verified by using seismological modeling techniques and dynamic photoelastic techniques. The analysis of dynamic photoelastic fringe pattern recordings showed that for the concave part of the undulated surface the leading tensile pulse attenuates more rapidly with position as the radius of curvature is decreased. The Rayleigh wave velocity on a curved surface is a function of the ratio of wave length to the radius of curvature with the velocity increasing with increasing ratio.

This paper presents the results of experimental and numerical studies of the scattering process of a Rayleigh surface pulse with a single part-circular canyon of variable depth. The experimental procedure involved dynamic photoelastic fringe pattern and surface stress data reduction. Photoelastic results include profile and attenuation characteristics expressed in a Lagrangian type interaction diagram. Based on the numerically generated data the corresponding theoretical isochromatic fringe patterns and the time-dependent deformations of the canyon are shown. The two-dimensional finite difference code SWIFD (Rossmanith and Uenishi, 1995) is used for the numerical simulation of the problem and the results compare well with those obtained from the experiments. The deformation of the canyon indicates the critical location and time for a rockfall or landslide to occur.

THE CANYON PROBLEM

Dynamic photoelasticity in conjunction with high-speed photography (see e.g. Kuske and Robertson, 1974; Rossmanith, 1986,1988) have been employed to study experimentally the interaction process between surface waves and part-circular grooves (Rossmanith and Knasmillner, 1989). Due to lack of information about the orientation of the principal stresses in dynamic photoelasticity the stress tensor can only be derived for surface points. In the interior the isochromatic fringes represent the locations of constant principle shear stresses which can not be decomposed in principal stresses when the principal directions of the stresses are unknown.

The geometry of the model simulating the canyon is shown in Fig.1a. Three types of part-circularly shaped canyons of different degree of embedding of variable depth ratio h/a = 1/2, 1, 3/2 have been investigated. The sequence of isochromatic *snapshots* shown in Figs.1b-1c illustrates the scattering process of a Rayleigh pulse about the leading and trailing edges of a canyon. In Fig.1b the R-wave travels around the bottom of the canyon. A strong circularly crested diffracted shear wave spreading out from the canyon is clearly visible in Fig.1c where the R-wave continues to propagate along the rhs free surface.

It is very instructive and suitable for further data analysis purposes to visualize the surface stress along the free surface as shown in the columnar sets of Figs.2-4. The coordinate axes represent the *position* along the free surface, *time* elapsed with regard to an arbitrary reference point (e.g. begin of interaction), and the

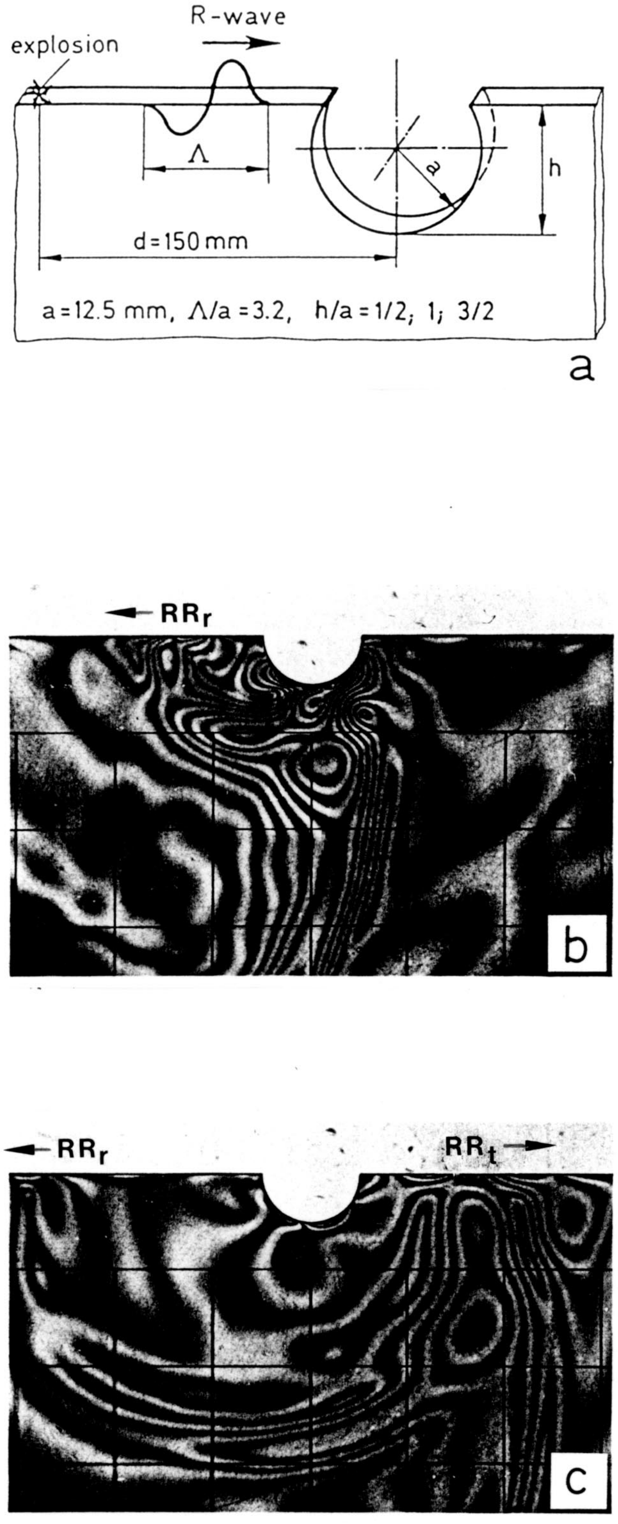

Fig. 1: Rayleigh-wave canyon interaction problem
a) model geometry,
b) R-interaction phase,
c) post-scattering phase

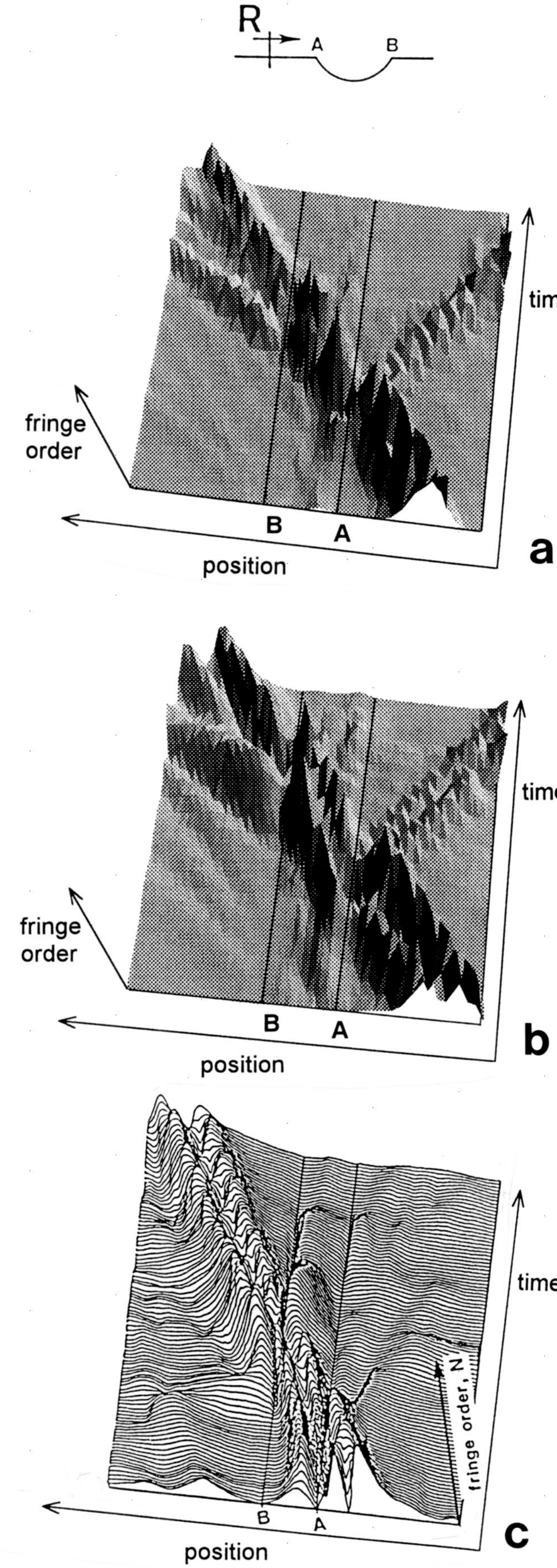

Fig. 2: R-interaction with a shallow canyon
a) short, b) medium and c) long R-pulse

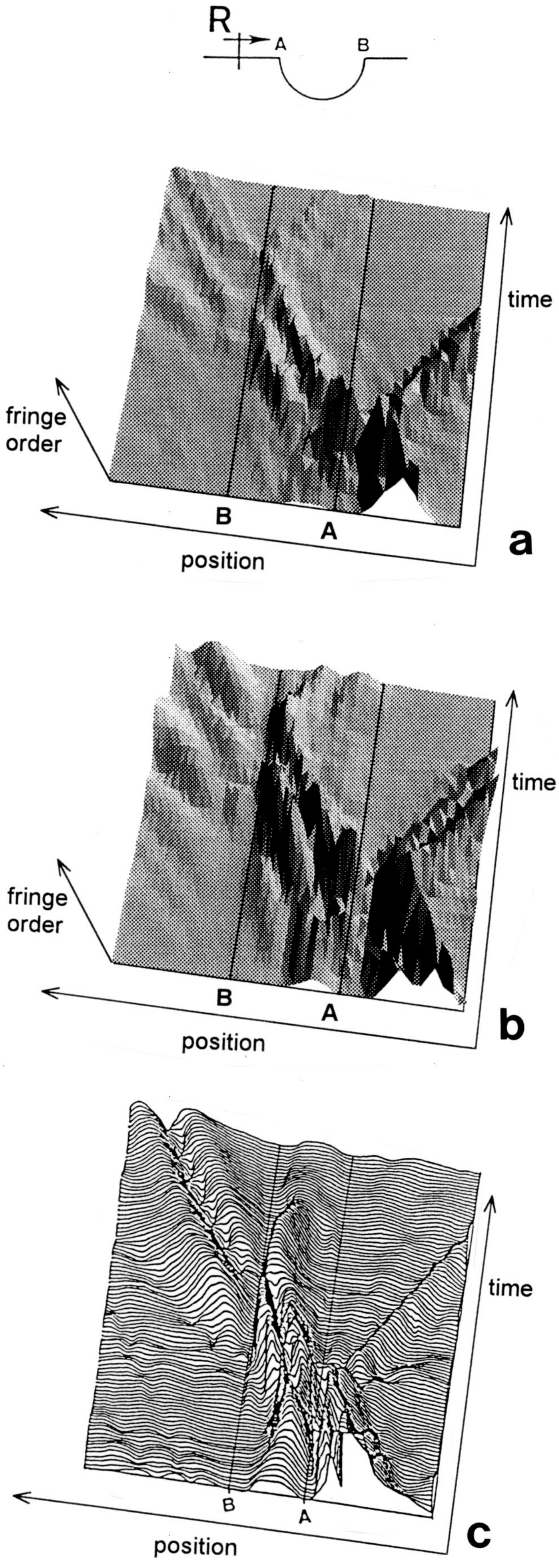

Fig.3: R-interaction with a central canyon
a) short, b) medium and c) long R-pulse

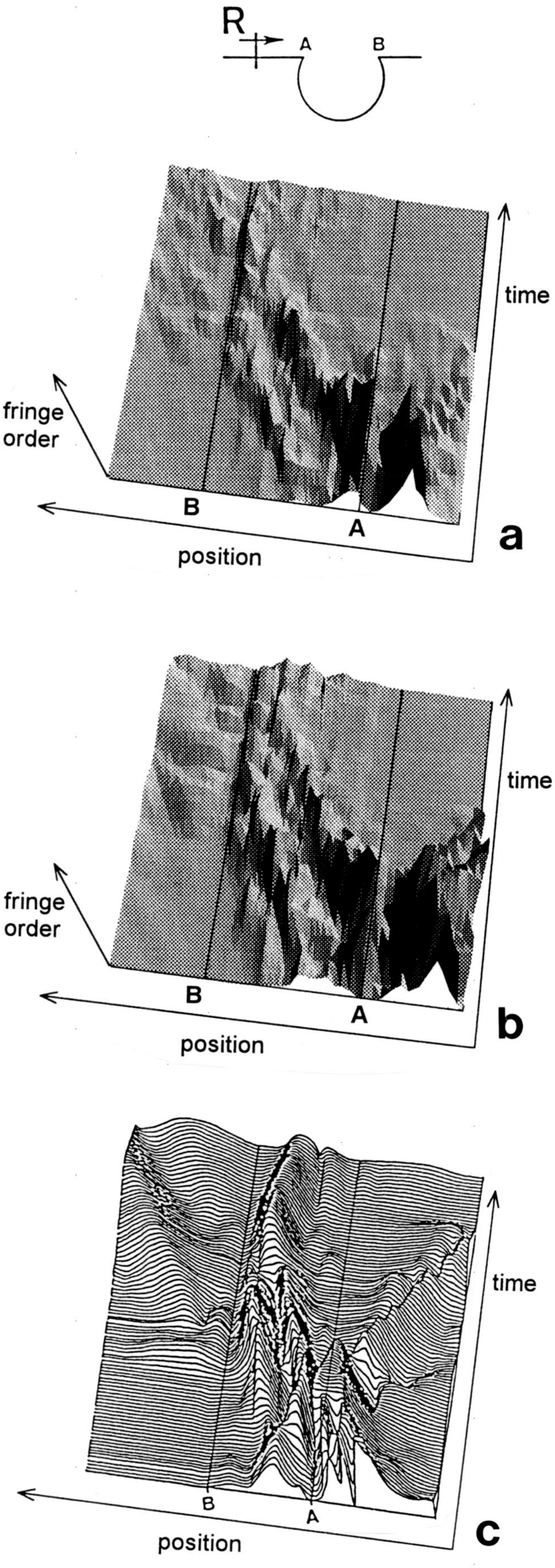

Fig.4: R-interaction with a deep canyon
a) short, b) medium and c) long R-pulse

surface stress in terms of isochromatic *fringe order*. This type of graphical representation has been selected for improved clarity and increased information about wave generation during the interaction process. The graphs in Figs.2-4 shall be read from rhs bottom (R-wave impinges on the canyon) to lhs top (end of interaction). Upon reaching the position of the groove the incident Rayleigh wave interacts with the inclined cliff of the canyon. This interaction process gives rise to energy partition associated with the generation of several distinguished waves: a reflected RR_r^1 and a diffracted RR_d^1 Rayleigh wave, and scattered RP and RS body waves which propagate into the bulk of the material. These waves are indicated in Figs.1b and 1c.

In Figs.2-4 a comparison of the stress intensification due to variable canyon embedding and R-wave length is made where the columns in Figures 2,3 and 4 pertain to a shallow, a central and a deep canyon, respectively. In these columns the top, middle and bottom figures pertain to a short, a medium and a long R-pulse length. The ratii between wave length, radius of curvature and burial depth of the canyon are the governing parameters in this study. In order to emphasize the excellent agreement between experimentally recorded and subsequently data reduced results and the numerically generated simulation results the bottom figures pertain to the laboratory model experiments and the top and middle figures in these columns are derived from numerical simulations using the SWIFD code.

A comparison of the rhs zones (position OA versus time) in Figs.2a-4c reveals an increase of the intensity of the reflected RR_r^1 wave with increasing depth of the groove with minimum reflection in Fig.2c. The diffracted Rayleigh wave RR_d^1 follows the curved section of the groove (distance AB) and is again scattered at the trailing edge of the groove (position B). The amplitude of this reflected wave RR_r^2 increases from lhs top (shallow canyon, short pulse) to rhs bottom (deep canyon, long pulse). The graphs also depict the fact that along the curved canyon bottom the RR_r^2 travels with slower speed than the Rayleigh wave along a flat surface.

The characteristics of the transmitted RR_t^2 wave (zone B-on versus time) strongly depend on both ratii mentioned before. Long pulses travel around shallow canyons almost undisturbedly (Fig.2c) whereas short pulses interacting with deep canyons suffer severe reflections with very little energy transmitted beyond the far edge (B) of the canyon (Fig.4a).

Sequences of snapshots of the deformation of the surface profile of a shallow, a central and a deep canyon are shown in Fig.5. The boundary deformations have been calculated from the output data of SWIFD and are associated to evenly spaced time intervals. The deformation history of the canyons illustrates the rather complicated motions of the canyon surface. Wave induced motion of surface material towards the canyon, e.g. the movement of the leading edge of the canyon, may give rise to landslides or rockfalls at the canyon walls.

CONCLUSIONS

Dynamic photoelasticity in conjunction with high-speed photography forms a suitable technique for the experimental investigation of the interaction of Rayleigh surface waves with irregular surfaces, exemplified in the case of a canyon. Lagrangian diagrams for the interaction and scattering process of Rayleigh waves with part-circular canyons of varying burial depth reveal the effect of surface curvature on the speed of Rayleigh waves and the magnitude of scattering.

The two-dimensional wave propagation simulator SWIFD has been employed in the numerical investigation of this rather complicated wave scattering problem. The numerically generated Lagrangian diagrams show the effect of surface curvature and depth of the canyon, and Rayleigh pulse length on the nature of scattering and stress amplification. The structure of SWIFD allows for numerical solution of a wide variety of wave propagation problems. The full-field representation of complete data obtained from SWIFD simulations can be used for the study of the detailed displacements as well as for the analysis of strain and stress.

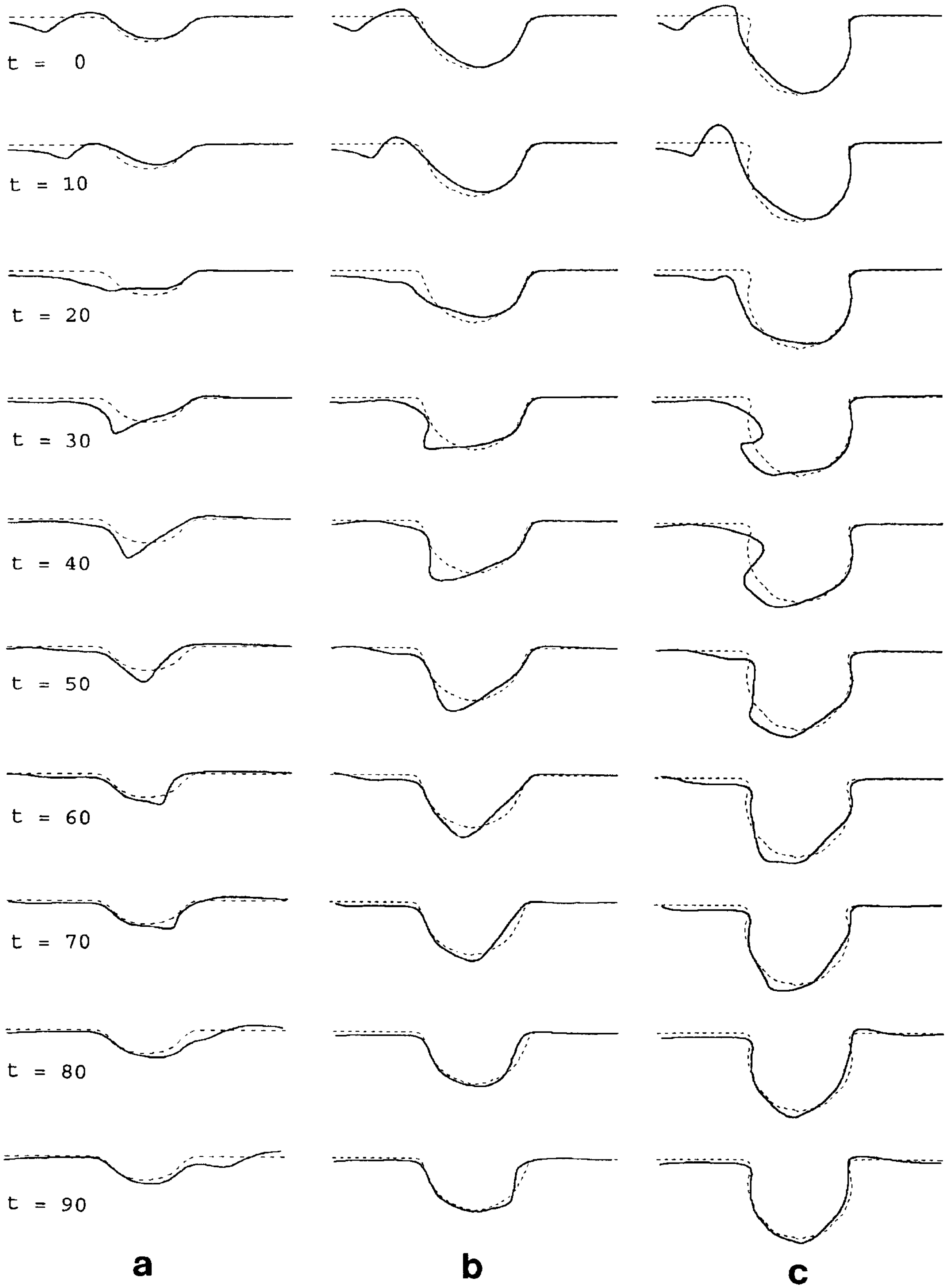

Fig. 5: Surface deformation history of a) a shallow canyon (left column), b) central canyon (middle column), and c) deep canyon (right column)

In this study dynamic photoelasticity has been employed with a change of paradigm. On the one hand, surface stress histories have been extracted from experimentally recorded isochromatic fringe patterns (the classical use of photoelasticity) while by a change of paradigm, these experimentally recorded isochromatic fringe patterns now only serve as "check-points" for the numerical analysis, i.e. they are utilized as a means for the assessment and evaluation of numerical codes in elastodynamics (contemporary use of photoelasticity).

ACKNOWLEDGMENT

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