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# Identification of the non-linear behaviour of liquefied and non-liquefied soils during the 1995 Kobe earthquake

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## SUMMARY

A method based on the non-linear system identification technique is suggested for estimating the contents of the non-linear components, which are the result of quadratic, cubic and higher-order non-linearities, in the ground response during the strong motion. The method is applied to data from the near-fault zone of the 1995 Kobe earthquake, and the contents of linear and non-linear components in the ground response, changing with time during the strong motion, are estimated for Port Island (PI), SGK and TKS sites, located at 2, 6 and 15 km from the fault plane, respectively. At PI, the non-linear part of the response increased with developing liquefaction, it was as high as ∼ 40–60 per cent of the intensity of the response. At SGK and TKS sites, the non-linear components of the response did not exceed ∼40 and ∼13 per cent of the intensity of the response, respectively. Odd-order non-linear components predominated in the soil response, whereas even-order non-linear components increased and became comparable with odd-order ones in liquefied soils and in cases of high intensity of the strong motion, when the loading parts of the stress–strain relations of the upper layers gained noticeable even components. As a whole, the contents of odd-order and even-order components in the soil response are determined by the shapes of the stress–strain relations in the upper most non-linear soil layers. At the three sites, changes in spectra of earthquake signals in subsurface soil layers were substantial as a result of the high non-linearity of the soil behaviour and spectra of signals on the surface tend to take the form of $E(f) \sim f^{-k}$. The limiting spectral shape was achieved during the Kobe earthquake at PI and SGK sites. The proposed methods for processing vertical array records allow understanding of seismic wave transformations in subsurface soils and are useful for predicting the soil behaviour during future earthquakes.

**Key words:** non-linear behaviour of soils, non-linear system identification, strong ground motion, types of soil non-linearity.



## 1 INTRODUCTION

The non-linear behaviour of soils in strong ground motion explains the well-known fact that on soil sites, records of weak earthquakes qualitatively differ from records of strong ones. Quantitative characteristics of the soil non-linearity and estimates of the ground response at a given site during the strong motion of any arbitrary intensity are necessary for practical applications in seismology. However, because the soil response depends on many factors, such as the composition and thickness of the soft deposits, their saturation with water, the level of the underground water, and the magnitude and frequency content of an earthquake, the problem is rather complicated, and for a long time it remained as one of the urgent problems in seismology, inducing controversies and discussions.

During the 1960s–1970s, after the catastrophic earthquakes in Niigata and Anchorage, laboratory (Hardin & Drnevich 1972) and field (Vasil'ev *et al.* 1969) experiments aimed at studying non-linear elastic properties of soils began. In these experiments, non-linear hysteretic stress–strain relations were obtained for various types of soils. The questions arose, what corrections should be introduced into state equations of soils and fractured weathered rock to account for their elastic non-linearity? How large are these corrections for various types of soils and what is the threshold of strains, when they become significant? What is the mutual influence of the non-linearity of the medium, dispersion and absorption on seismic wavefields?

To estimate characteristics of elastic non-linearity of geological media, field experiments were performed and non-linear wave effects in seismic fields were studied, such as, interaction of seismic waves, generation of combination-frequency harmonics and the constant components of the wavefields, seismic solitary waves, inversion of the seismic wave front, etc. (Aleshin *et al.* 1981; Gushchin