

Estimation of nonlinear time-dependent soil behavior in strong ground motions using vertical array data

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Abstract

Strong motion records made by vertical arrays allow estimation of nonlinear soil behavior in layers at different depths. As an example, records obtained during the 1995 Hyogo-ken Nanbu earthquake at Port-Island, SGK, and TKS sites are used to estimate the stress-strain dependencies of soils. For different layers, different types of nonlinear stress-strain curves are determined, showing the best-fit approximation to the observed data. Examining consecutive parts of the records, temporal changes of the curves are traced. At PI and SGK sites, the obtained dependencies are found to vary with time in surface layers showing a progressive reduction of shear modulus, and remain stable in deeper layers. At TKS site the behavior of soils is described by a nonlinear stress-strain curve not changing with time. Thus, the conclusion can be made that the stronger is the input motion, the more complex is nonlinear behavior of soils.

Introduction

Recent earthquakes provided representative experimental data on nonlinear soil behavior in strong motions, in particular, on liquefaction phenomena, and attracted attention of seismologists to nonlinear seismic effects. It was established that in strong motions soils behave nonlinearly, i.e., subsurface soils are taken as nonlinear systems transforming incident seismic signals into movement on the surface. Effective methods for studying nonlinear systems are developed in system analysis, based on the representation of an output signal (i.e., signal on the surface) as a sum of multiple integrals of the input signal, called Volterra-Wiener expansions. Signal on the surface is represented as a sum of the response of the linear system and a number of nonlinear corrections, due to quadratic, cubic nonlinearity, nonlinearities of the 4-th, 5-th, etc. orders. Such analysis seems to be promising in seismology, because it allows determination of types of soil nonlinearity (quadratic, cubic, the 4-th, 5-th order, etc.) and better understanding mechanisms of transformation of incident seismic signals into movement on the surface. However, to apply these methods to studying nonlinearity of soils, knowledge of nonlinear stress-strain dependencies in strong motions for all layers is required.

Numerical methods for calculating soil response to strong motions have been developed, but often there remains some disagreement between the observed and simulated records. As is known, equivalent linear models (SHAKE, QUAD-4, FEADAM, LUSH, FLUSH) are not applicable for calculation of such complex phenomena as soil liquefaction. Programs DESRA, TARA and their modifications allow determination of the possible level of pore pressure and the possibility of liquefaction; they can be applied for analysis of soil behavior after liquefaction. Changes in pore pressure are related to volume deformations of soils in drained

conditions, and one-dimensional diffusion is included in the algorithm. Programs DYSAC2, DYNAFLOW, and SWANDYNE are considered to be the most correct. Equations of motion of the liquid and solid phases are related to the equation of conservation of matter. Generation and dissipation of pore pressure are connected with deformation of the solid matrix due to Biot equations. However, some simplifications and assumptions are necessary, concerning the properties of the medium, as well as the mechanisms of processes. Any uncertainties and mistakes in modeling lead to improper calculation of soil movement.

This work is aimed at obtaining accurate estimates of stress-strain dependencies in soil layers in strong motions, based on seismic vertical array records and profiling data of medium structure. As far as these estimates are based only on real measurements, they are free of theoretical approximations and physical assumptions concerning mechanisms of processes in the medium.

Method

To determine stress-strain dependencies, vertical array records of strong ground motions and profiling data on medium structure are used. For calculations, the studied medium from the surface up to the depth of the location of the deepest device is divided into groups of layers, for which certain types of stress-strain dependencies are assumed. Usually, 3 main types of stress-strain dependencies are considered: (1) curves, similar to those obtained in laboratory experiments by Hardin and Drnevich, to describe the behavior of dense soils at large depths; (2) curves of “soft” type, similar to type (1), but much more sloping (close to horizontal for large strains), which are characteristic for liquefied soils; (3) curves of “stiff” type, declining to the stress axis at large strains, which are characteristic for clays and water-saturated sands. Sets of such curves are generated, and then item-by-item examination is applied to find groups of stress-strain curves showing the best-fit approximation to the observed data. We used the calculation algorithm described by Joyner and Chen (Joyner and Chen, 1975).

To account for temporal changes in soil behavior, records are divided into intervals of 1.5-sec. duration. Within each interval, the stress-strain dependencies are assumed to be stationary, and vary for different intervals. Calculations are performed successively, interval by interval. No discontinuities occur at the boundaries of the intervals, because, in the next interval, the whole cycle of loading (or unloading) is recalculated for the new curve from its beginning. Small variations in elastic parameters of the medium do not much influence the choice of curves; in this case, the observed records and the similarity of the curves obtained for the EW and NS components are the determining factors.

Results

The method is applied for determining the nonlinear behavior of soils during the 1995 Hyogo-ken Nanbu (Kobe, 1995) earthquake. Data of three vertical array recording sites are used, such as Port-Island, SGK, and TKS sites (the closest distances from the fault line are 2 km, 6 km, and 18 km, respectively). The medium structures are similar at these sites: reclaimed soil, clays, sands, gravel. Parameters used for nonlinear simulation are shown in Tables 1-3. They were taken from papers by Aguirre and Irikura (1997) and Soeda et al. (1999). Calculations show a good agreement between the observed and simulated records. The results are presented in Figures 1 – 3.

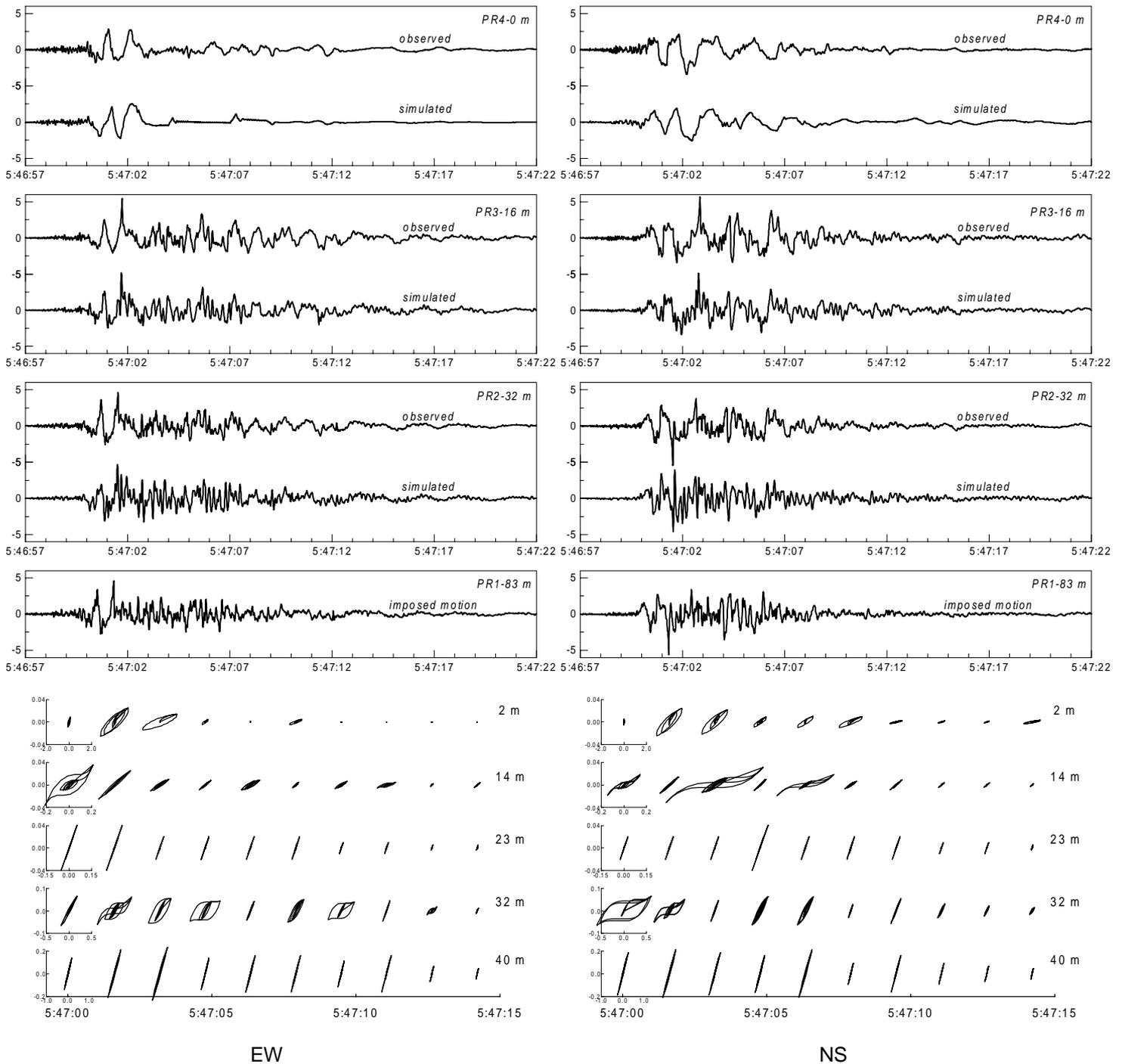


Figure 1: The acceleration time history of the main shock in Port Island (the vertical axis scale is m/s^2) and the obtained stress-strain dependencies changing in time. The axes scales of the stress-strain dependencies are in relative units, the same for all time intervals at a given depth.

The most intense and complex movements were observed at Port Island site. The vertical array contains 4 three-component accelerometers located at depths of 0 m, 16 m, 32 m, and 83 m. The strongest horizontal accelerations were measured at the deepest point of 83 m at this site: ~ 500 Gal for EW component and ~ 600 Gal for the NS component. According to the medium structure and the results obtained in the previous analysis (Kawase et al., 1995), the medium was divided into 5 groups of layers: 0 – 12 m (reclaimed gravelly fill), 12 – 18 m (alluvial clay), 18 – 27 m (alluvial clay and sand), 27 – 33 m (alluvial sand), and layers deeper than 33 m (diluvial gravel). For each group, some type of the nonlinear behavior was assumed. Figure 1

shows the observed and simulated records and the obtained stress-strain dependencies for different depths representing these 5 groups of layers.

We see from Figure 1 that the most noticeable temporal changes were observed in layers near the surface, i.e., in the upper 12 m: stress-strain dependencies become more sloping, showing the substantial progressive reduction of shear modulus and liquefaction. At depths of 12 – 18 m, some changes were also observed, such as, slopes of the curves are slightly decreased and then increased. This is in agreement with the results obtained by Kazama et al. (1998), who found a reduction and the following recovery of the initial shear moduli in the clay layer.

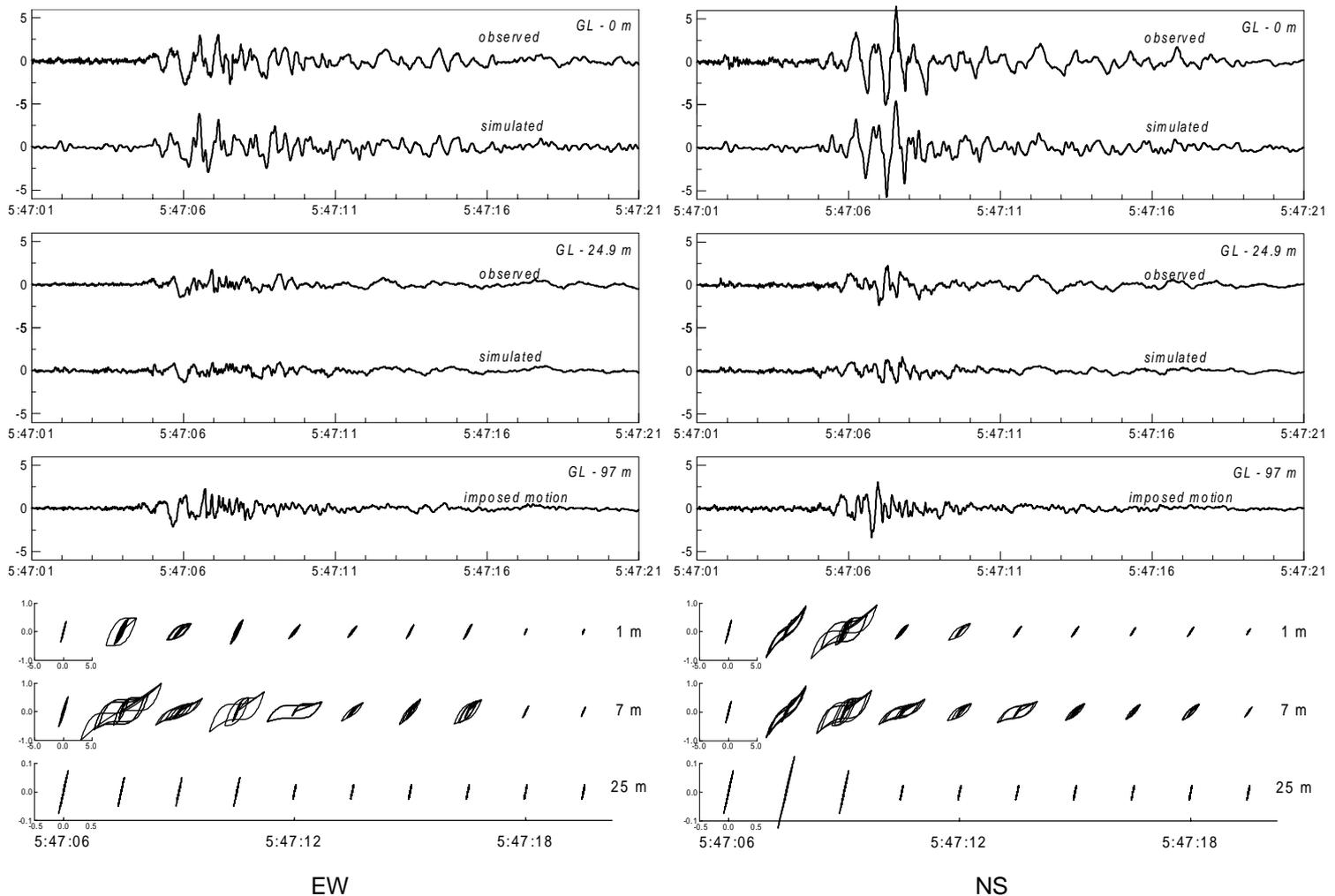


Figure 2: The acceleration time history of the main shock at SGK site (the vertical axis scale is m/s^2) and the obtained stress-strain dependencies changing with time. The axes scales of the stress-strain dependencies are in relative units, the same for all time intervals at a given depth.

Vertical arrays at sites SGK and TKS consist of 3 three-component accelerometers located at depths of 0 m, 24.9 m, and 97 m, and 0 m, 25 m, and 100 m, respectively. Maximum accelerations recorded at the SGK site are high (Figure 2), up to 650 Gal on the surface for the NS-component. At this site, nonlinear soil behavior can be described by a relatively simple model: the medium is divided by two groups of layers, such as, the near-surface layers, up to 11 m (alluvial silt, sand, gravel), and the deeper layers (mostly gravel and clays). Figure 2 represents the observed and simulated accelerograms and the obtained stress-strain dependencies for the SGK site. The behavior of the deeper layers is stationary, whereas the

behavior of the surface layers changes with time: slopes of the curves decrease, then increase again indicating reduction and recovery of the shear modulus.

At the TKS site, the soil profile is represented by reclaimed soil and alluvial layer in the upper part (0-14 m), and gravel, clays, and sands in the deeper parts. Maximum recorded accelerations are about 200 Gal, and the medium behavior can be described by a simple model, such as the stress-strain dependence obtained in laboratory experiments by Hardin and Drnevich, not changing with time (Figure 3).

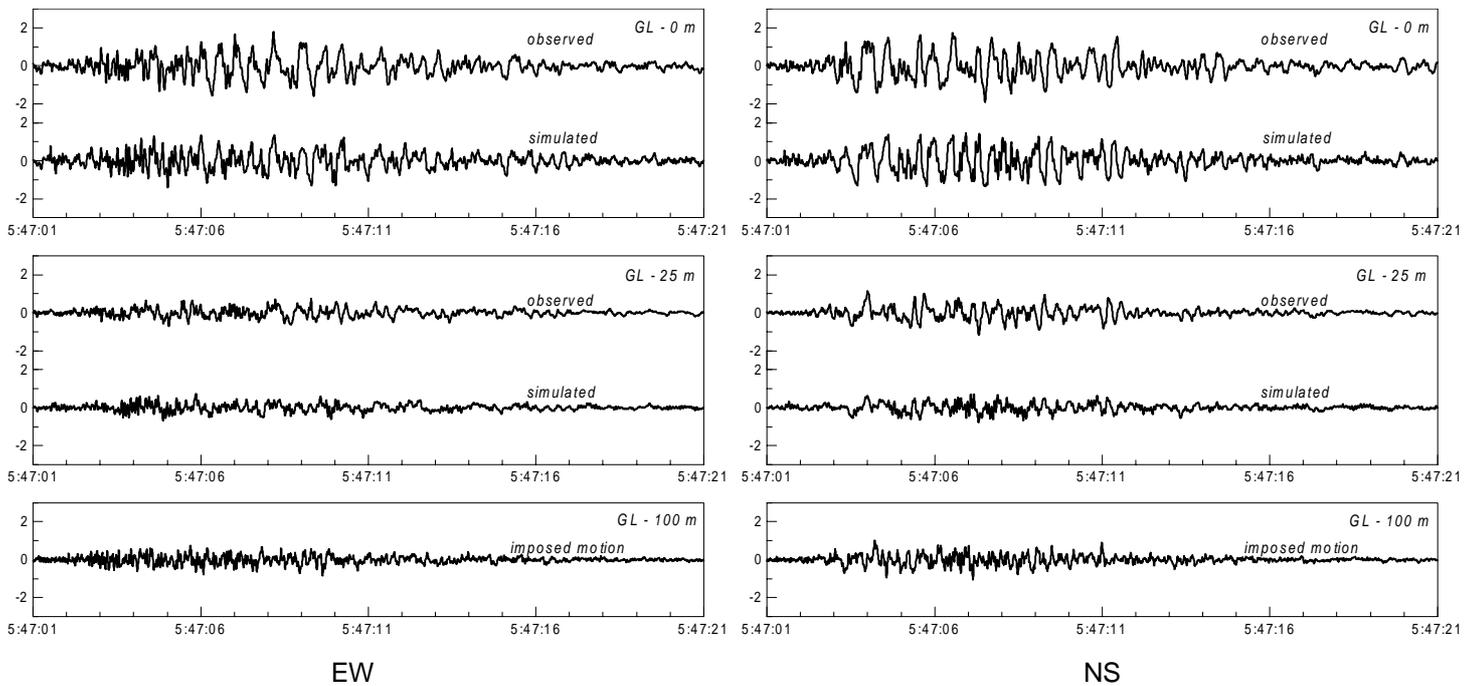


Figure 3: The acceleration time history of the main shock at TKS site (the vertical axis scale is m/s^2), observed and simulated.

Conclusions

Time-dependent model of nonlinear soil behavior in strong ground motion is constructed. The obtained stress-strain dependencies indicate temporal changes in shear modulus in the upper layers and stationarity in the deeper parts at sites Port Island and SGK, where the strongest horizontal accelerations were measured (~ 500 Gal at 83 m for the EW-component and ~ 600 Gal for the NS-component at Port Island, and up to ~ 650 Gal on the surface at SGK). For weaker motions (~ 200 Gal on the surface) at TKS site, more simple behavior is observed not changing with time. The medium structures are similar at these three sites, and differences in the nonlinear behavior of soils are due to the differences in acceleration amplitudes of the input signals. The higher is the amplitude, the more complex is the nonlinear behavior of the soil.

The obtained models of nonlinear soil behavior at the three sites were tested by monochromatic signals representing imposed accelerations. It was found that signals on the surface contain, together with the main frequency harmonics, their higher-frequency 3-d, 5-th, 7-th, etc. -order harmonics, i.e., odd types of nonlinearity are typical for soils. Even nonlinearities (i.e., generation of the 2-d, 4-th, etc. -order harmonics and the constant component of the wavefield) are observed only in liquefied soils, i.e., in final parts of the records at Port Island site.

Table 1. Parameters used for nonlinear simulation at Port Island

Thickness (m)	Density (kg/cm ³)	S-wave vel. (m/s)	Damping factor	Failure Strength (dyn/cm ²)
2.0	1.8	194.0	0.07	3.250 E06
3.0	1.8	194.0	0.07	5.150 E06
7.6	1.8	237.0	0.08	12.10 E06
3.4	1.8	237.0	0.08	13.70 E06
3.0	1.8	237.0	0.02	14.90 E06
8.0	1.5	191.0	0.5	16.40 E06
5.0	1.85	138.0	0.5	6.620 E06
1.0	1.85	138.0	0.5	0.673 E06
17.0	1.85	254.0	0.5	2.840 E06
11.0	1.85	208.0	0.5	2.110 E06
18.0	1.8	469.0	0.5	1187.0 E06
4.0	1.9	486.0	0.5	1386.0 E06

Table 2. Parameters used for the nonlinear simulation at SGK

Thickness (m)	Density (kg/cm ³)	S-wave vel. (m/s)	Damping factor	Failure Strength (dyn/cm ²)
2.0	1.4	98.0	0.07	0.114 E06
1.0	1.4	117.0	0.07	0.157 E06
2.0	1.7	117.0	0.07	0.290 E06
2.0	1.7	117.0	0.07	0.220 E06
1.0	1.7	149.0	0.07	0.266 E06
2.0	1.6	149.0	0.1	0.503 E06
1.0	1.6	149.0	0.1	0.620 E06
1.0	2.0	342.0	0.1	4.200 E06
5.0	2.0	342.0	0.1	2.670 E06
1.0	2.0	222.0	0.1	2.140 E06
2.0	2.0	154.0	0.5	0.760 E06
1.0	2.0	400.0	0.5	3.090 E06
6.0	2.0	400.0	0.5	2.510 E06
3.0	2.0	400.0	0.5	7.180 E06
3.0	2.0	375.0	0.5	3.980 E06
6.0	1.7	375.0	0.5	3.910 E06
3.0	1.7	231.0	0.5	1.416 E06
3.0	2.0	286.0	0.5	2.166 E06
7.0	2.0	255.0	0.5	2.204 E06
2.0	2.0	222.0	0.5	2.250 E06
4.0	2.0	177.0	0.5	1.990 E06
2.0	2.0	222.0	0.5	2.680 E06
7.0	2.0	389.0	0.5	5.190 E06
7.0	2.0	333.0	0.5	4.400 E06
1.0	2.0	303.0	0.5	4.400 E06
19.0	2.0	303.0	0.5	4.400 E06
1.0	2.0	455.0	0.5	4.110 E06
2.0	2.0	455.0	0.5	4.110 E06

Table 3. Parameters used for the nonlinear simulation at TKS

Thickness (m)	Density (kg/cm ³)	S-wave vel. (m/s)	Damping factor	Failure Strength (dyn/cm ²)
3.4	1.7	140.0	0.07	0.191 E06
3.75	1.7	130.0	0.07	0.163 E06
6.25	1.6	200.0	0.07	0.702 E06
5.6	1.9	310.0	0.1	0.648 E06
6.0	1.9	400.0	0.5	0.973 E06
5.05	1.8	330.0	0.5	0.800 E06
2.95	1.7	230.0	0.5	0.840 E06
4.0	1.7	320.0	0.5	1.493 E06
6.7	1.9	560.0	0.5	2.709 E06
4.8	1.8	250.0	0.5	1.125 E06
11.8	1.9	405.0	0.5	1.675 E06
13.2	1.9	650.0	0.5	6.414 E06
7.8	1.9	500.0	0.5	3.167 E06
18.7	1.8	460.0	0.5	2.920 E06

Acknowledgments

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