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ABSTRACT

The soil response effects for two sites in San Salvador (IGN and UCA) were evaluated using one-dimensional wave propagation models. The strong motion records of the October 10, 1986 earthquake, were used to verify the numerical simulations. The recording at the Sheraton Hotel, after the process of deconvolution, was used as the reference bedrock outcrop input motion in all simulations. Results of the analyses showed that the non-linear, time domain model (AMPLE) gave somewhat better results compared to the quasi-linear, frequency domain model (SHAKE). However, there were some discrepancies between the AMPLE simulations and the recorded motions at frequencies lower than 1.4 Hz. This was probably caused by the presence of low frequency surface waves, which were not modelled in the simulations.

1. INTRODUCTION

El Salvador is located in one of most seismically active areas of the world. The high earthquake hazard is mainly the result of the subduction of the Cocos plate beneath the Caribbean plate. This has created the Central American volcanic chain, within which the largest city in El Salvador, San Salvador, lies. Epicenters of the major earthquakes which have occurred in El Salvador during the last few decades, like the one on October 10, 1986, have been located on the volcanic chain mentioned above.

Experiences from previous earthquakes have shown that the largest damage often occurs on loose or semi-compacted silt/sand and soft clay deposits. The former soil type is typical for San Salvador, which is mainly comprised of volcanic ash deposits (silt or silty sand) whose origin was the collapsed cladera of Ilopango lake. The general trend of this profile is in the east-west direction. The thickest part of the profile is at east. The soil thickness decreases towards west as one approaches the the San Salvador volcano.

The scope of this study was to assess the local soil response, using the computer programs SHAKE and AMPLE, by means of which it is possible to obtain synthetic records at the bedrock, as well as at the soil surface. In the analyses, the real records of the October 1986 earthquake at the IGN, UCA and Sheraton sites, with the objective to calibrate the SHAKE and AMPLE models were used. The first step of the analysis consisted of performing a deconvolution of the recorded surface motion at the Sheraton site to obtain a bedrock outcrop motion. The obtained rock outcrop motion was then used to perform soil response analyses (convolution) at the UCA and IGN sites, and the simulated motions were compared with the real records at the surface for each site.

2. GEOTECHNICAL CONDITIONS OF THE STUDIED AREA

Most of the Metropolitan Area of San Salvador (AMSS) is basically composed of silt or silty sand, locally named tierra blanca because of its light colour in dry state. The source of these material has been the eruption of the collapsed caldera named "Lago de Ilopango", located on the east side of San Salvador, where the thickness of tierra blanca is greatest (approx. 50 m). The thickness decreases towards the west where the bedrock is relatively shallow. The rocks found in San Salvador are classified into of two kinds: basaltic and andesitic rocks. The water table is below the depths of interest for this study.

The sites chosen from the AMSS for this study were "Instituto Geográfico Nacional" (IGN), "Universidad Centroamericana José Simeón Cañas" (UCA) and "Hotel Sheraton" (SHE), see Fig. 1. The geotechnical information available at these sites include, among other things, soil classification, natural moisture content, and standard penetration resistance. The blows count of the Standard Penetration Test, N , were used for the estimation of the shear wave velocity by means of empirical relationships.

3. DYNAMIC PROPERTIES OF SOIL PROFILES

The dynamics properties of soil used in site response analyses are the shear wave velocity, V_s , or shear modulus for small strains, $G_{\max}$ or G_0 , shear strength under rapid dynamic loading and damping characteristics. These parameters have not been previously characterized through systematic laboratory or in situ tests for the typical soils of San Salvador. However, in a study performed by Italian scientists (Italconsult-Italtekna, 1987), one year after the October 1986 earthquake, a number of down hole tests were performed at several sites in San Salvador. Some of the soil properties used in this study are based on that work, for example:

- G/G_0 vs γ (cyclic shear strain) curves (see Fig. 2)
- Damping vs γ curves (see Fig. 3)
- Relationship between V_s and N_{SPT} : $V_s = 81 \cdot N^{0.36}$

The above relation was developed on the basis of the Italian study by González (1988). The shear wave velocities obtained with this relationship were compared to the values obtained by the empirical relationships used in Costa Rica. The comparison showed some differences (see Figs. 4 and 5), with the Costa Rican relationships predicting somewhat lower shear

wave velocities. The relationship derived based on the Italian work was utilized as the starting point in this study.

The calculation of $G_{\max}$ was based on the following equation:

$$G_{\max} = \rho \cdot V_s^2$$

where ρ is the mass density.

4. STRONG MOTION RECORDS

The seismic hazard in Central America, and in particular El Salvador, has been the theme of several studies (e.g. Atakan and Torres, 1993). Within the country, the city of San Salvador is characterized by its high seismicity. Besides the subduction of the Cocos plate, the high seismicity in San Salvador is due to the complex geological fault system in the region. Reactivation of one of the NNE-SSW faults caused the October 10, 1986 earthquake, which provided the strong motion records at IGN, UCA and Sheraton that were used in this study.

5. RESULTS OF THE ANALYSES

The computer programs SHAKE(N) (Selnes, 1987) and AMPLE (Nadim, 1991) were used for the site response analyses. In addition to these, the GRAPHER and Norton Editor software were used to process the results.

SHAKE solves the one-dimensional wave propagation problem through a horizontally layered, visco-elastic medium in the frequency domain. The conversion of time histories to frequency domain and vice versa is done by Fast Fourier Transformation (FFT). The non-linear soil behaviour is approximated by an iterative, quasi-linear procedure in SHAKE. The control input motion in SHAKE can be specified at any point within the soil profile, including the soil surface and bedrock, or at the outcropping of any point.

AMPLE models the horizontally layered soil profile as a non-linear shear beam. The resulting non-linear wave propagation equations are solved in the time domain by the explicit central difference method. Several constitutive laws, such as linear elastic, failure-seeking with hyperbolic initial curve, and plastic with nested yield surfaces, are available in AMPLE. The failure-seeking model with hyperbolic initial curve was used in this study. This is one of the simplest non-linear soil models and is

defined by only two soil parameters, namely the initial shear modulus and shear strength. The control input motion in AMPLE can only be specified at the bedrock within the soil profile, or at the bedrock outcrop.

5.1 SHAKE results

5.1.1 Deconvolution of Sheraton Hotel record

The recorded surface motion at Sheraton Hotel (Fig. 6) was specified as the input motion in the SHAKE model. Using the geotechnical profile for this site (Fig. 7), SHAKE provided a synthetic record of the reference bedrock outcrop motion (Fig. 8). This motion was used as input in all the SHAKE and AMPLE analyses described below.

5.1.2 UCA site

Using the synthetic record of the previous section and the convolution process for the UCA site, the following results were obtained:

- a. In the first test, the dominant frequency of the real record (Fig. 9) was higher than that of the synthetic record (Fig. 10). To obtain a better match, it was necessary to change the shear wave velocity of the whole soil profile by a factor of two, such that the soil stiffness and the natural frequency of the profile would increase.
- b. Doubling the shear wave velocity improved the agreement between between the frequency contents of the synthetic and recorded motions, but the peak acceleration value also increased slightly (Fig.11). This simulation showed a relatively good agreement with the real surface record.

5.1.3 IGN site

Using the same input motion as for the UCA site, the convolution process was performed for IGN site. The following results were obtained:

- a. In the first test, the peak acceleration of the synthetic surface record (Fig. 12) was higher than that of the real record (Fig.13). Therefore, the shear wave velocity of the bedrock and the damping multiplier for the soil profile were changed, the first one from 2100 to 1000 m/s and the second one from 1 to 2 (effectively doubling the soil damping).

- b. The first change mentioned above was made to increase the bedrock flexibility. The increased bedrock flexibility increases the energy radiation into the half-space (radiation damping), hence it has a similar effect to increased damping of the soil. Thus both changes will produce an increase in the damping: the first one in rock and the second one in soil. This test (Fig. 14) showed a good agreement with the real surface record.

5.2 AMPLE results

As mentioned earlier, the main differences between AMPLE and SHAKE are that the former accounts directly for the non-linear behaviour but is just applicable to the convolution process, while the latter one works with a (quasi-) linear soil model and thus is applicable to both deconvolution and convolution processes.

The synthetic motion at bedrock outcrop used in the AMPLE analyses was the same one obtained by SHAKE using the record at Sheraton Hotel (Fig. 8).

5.2.1 IGN site

Figure 13 shows the real record took obtained at the surface of this site during the October 1986 earthquake. The synthetic records obtained with AMPLE are described below.

- a. Since AMPLE is based on a finite element formulation, it was necessary to adjust the model of soil profile from 5 (number of soil layers used in the SHAKE analyses) to 12 layers to be able to model the high frequencies. The results of the first test are shown in Fig. 15.
- b. To check the sensitivity of the results to the time step used in the simulations, the time step for the analysis was reduced by a factor of 5. The simulated record (Fig. 16) showed a good resolution and the high frequency numerical noise which shows up after 20 s in Fig. 15 disappeared. However, the peak acceleration value was significantly lower than recorded value.
- c. Same as (b), but the viscous damping ratio of soil was changed from 2 to 1 %. The difference between the new (Fig. 17) and previous simulations was not notable.

- d. To obtain a better match with between the peak accelerations of simulated and recorded motions, the shear modulus values of soil were reduced by 33%. However, this did not increase the peak acceleration notably (Fig. 18) and the agreement with the recorded motion actually deteriorated.
- e. In this test, the $G_{\max}/s_u$ (initial shear modulus/shear strength) of soil was changed from 800 to 400. When this ratio decreases, the shear strength, s_u increases. This means that, with the hyperbolic stress - strain behaviour, the hysteresis loop becomes less fat, and less energy is dissipated (i.e. less material damping). The record obtained in this simulation showed a good agreement with the real record at the surface of this site (Fig. 19 vs Fig. 13).

5.2.2 UCA site

For this site, only two tests were required to obtain a good match between the simulated and recorded motions. The results of the second test, which showed a good agreement with the real record at the surface of this site, is shown in Fig. 20.

5.3 Response spectra

Figures 21 to 24 compare the pseudo-velocity response spectra of the best AMPLE and SHAKE simulations with those of the recorded motions at UCA and IGN sites. The real records seem to have more low frequency (high period) energy than the simulations. This may be due to the presence of low frequency surface waves, which cannot be accounted for in the simple one-dimensional models of SHAKE and AMPLE.

6. CONCLUSIONS

Based on the results of this study, the following conclusions may be drawn:

- The SHAKE and AMPLE computer programs give results that are in good agreement with the real data. This means that the local soil response effects can be adequately accounted for by simple one-dimensional models at the sites studied.
- Both SHAKE and AMPLE provide very accurate results for frequencies greater than 1.4 Hz ($T < 0.7$ sec.), Figs. 21 - 24. This frequency range is important for typical high-rise buildings in San

Salvador. For design of important buildings, these computer programs are useful tools in the structural analyses, since for typical buildings in San Salvador, natural frequencies lower than 1.4 Hz are not expected.

- Regarding the pseudo-velocity response spectra at frequencies below 1.4 Hz, the lack of agreement between the real and synthetic records may be due to the presence of low frequency surface waves, which are not modelled in AMPLE and SHAKE.

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- Norwegian Seismic Array (NORSAR)
- Norwegian Geotechnical Institute (NGI)
- Centro de Coordinación para la Prevención de Desastres Naturales en América Central (CEPREDENAC)
- Centro de Investigaciones Geotécnicas (CIG)

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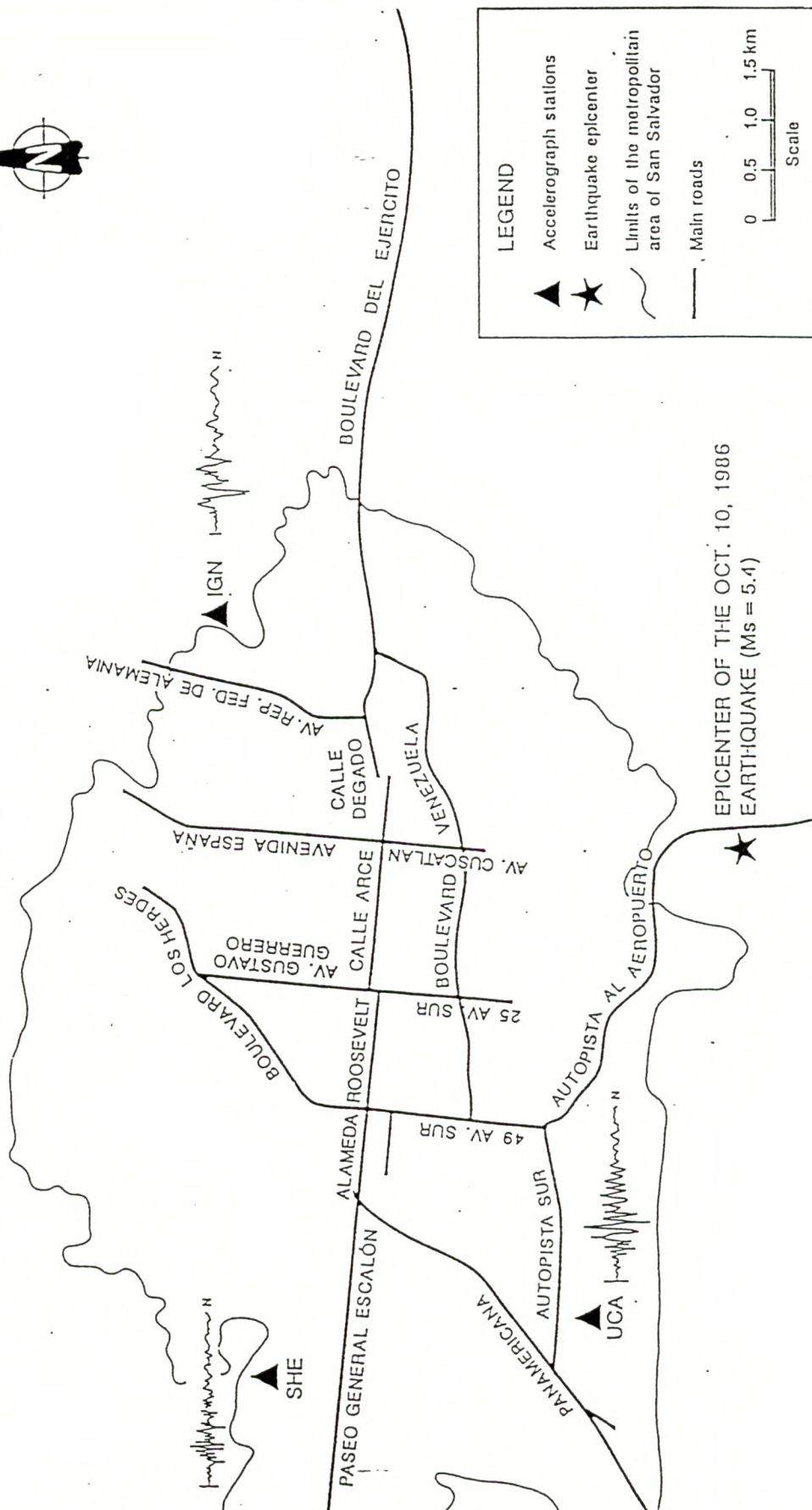
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Soil Response Study at 2 Sites in San Salvador

Locations of the sites in San Salvador and epicenter of the October 10, 1986 earthquake.

Report No.
913009-3

Figure No.
1

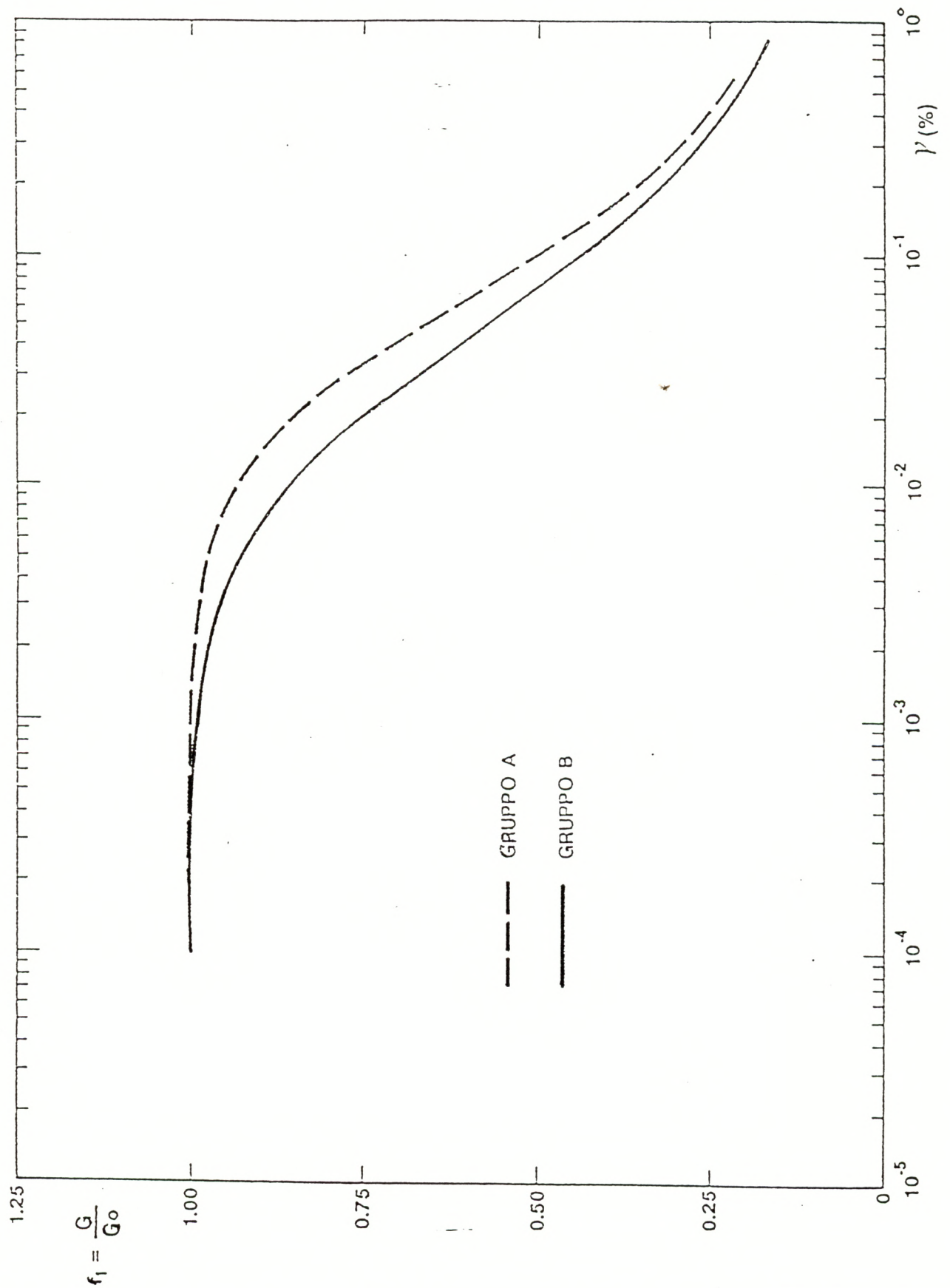
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Soil Response Study at 2 Sites in San Salvador

Normalized shear modulus vs cyclic shear strain used in the SHAKE analyses (Italtekna-Italconsult, 1987).

Report No.
913009-3

Figure No.
2

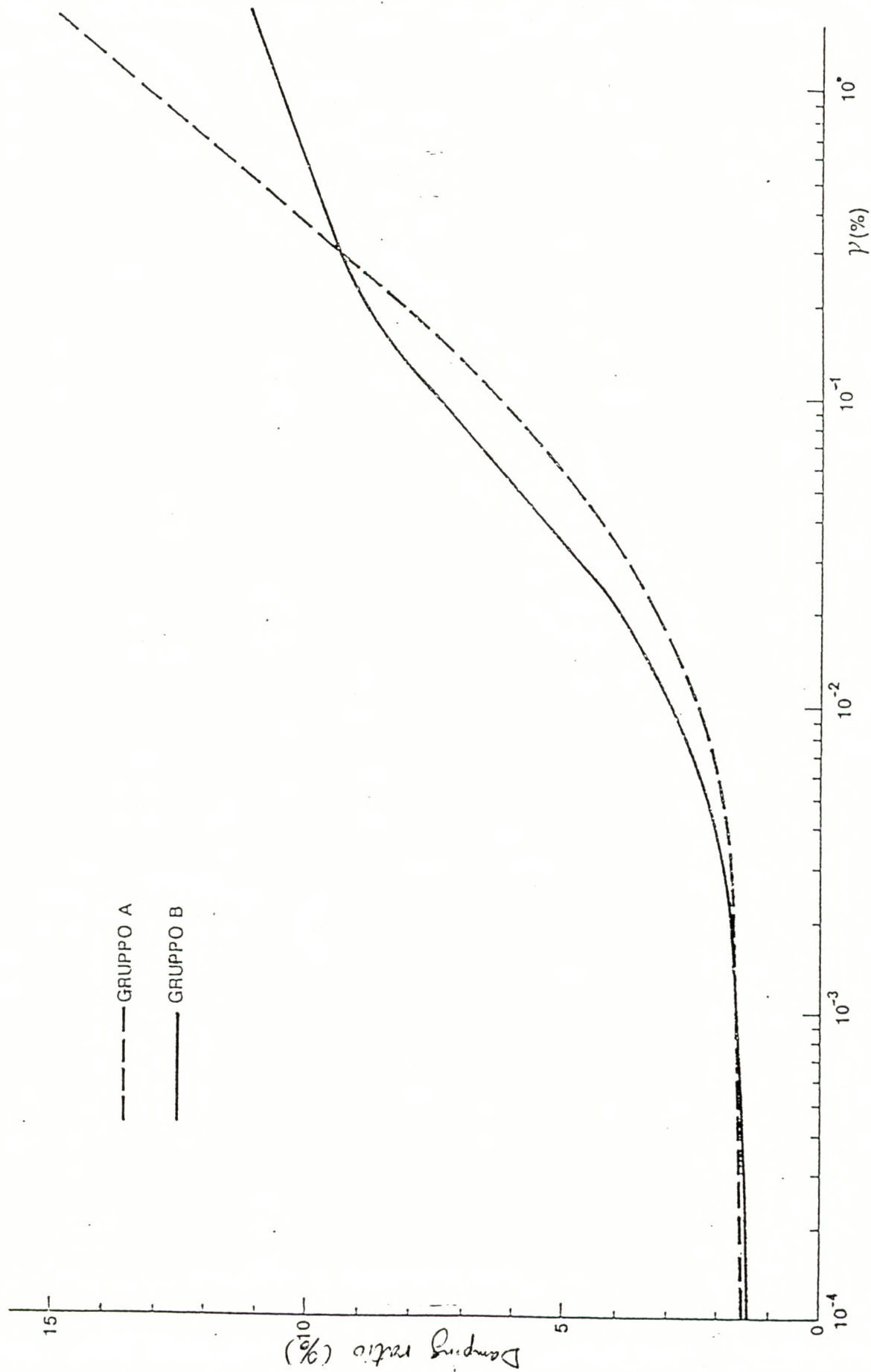
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Soil Response Study at 2 Sites in San Salvador

Soil damping vs cyclic shear strain used in the SHAKE analyses (Italtekna-Italconsult, 1987).

Report No.
913009-3

Figure No.
3

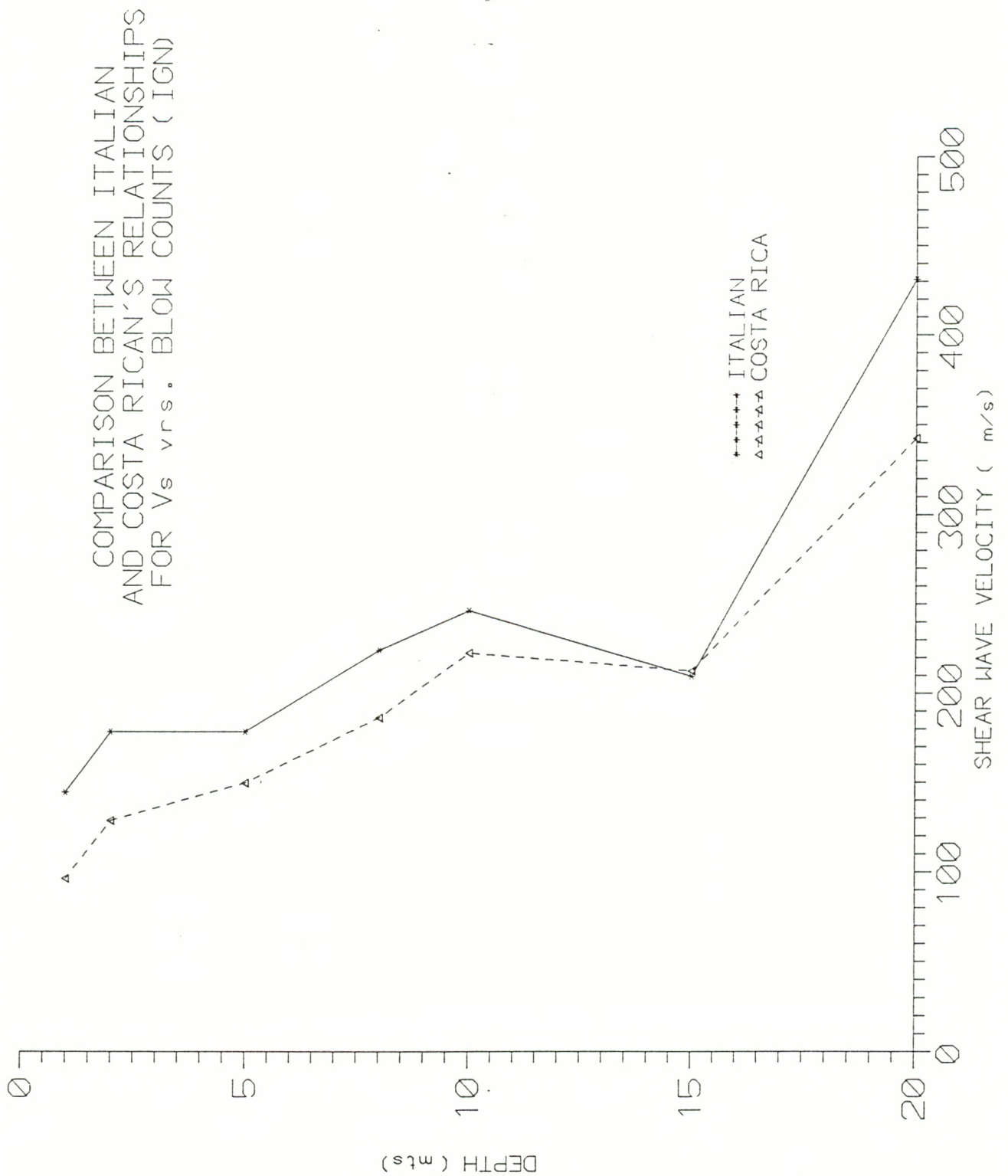
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Soil Response Study at 2 Sites in San Salvador

Shear wave velocity profile for the IGN site obtained from different empirical relationships.

Report No.
913009-3

Figure No.
4

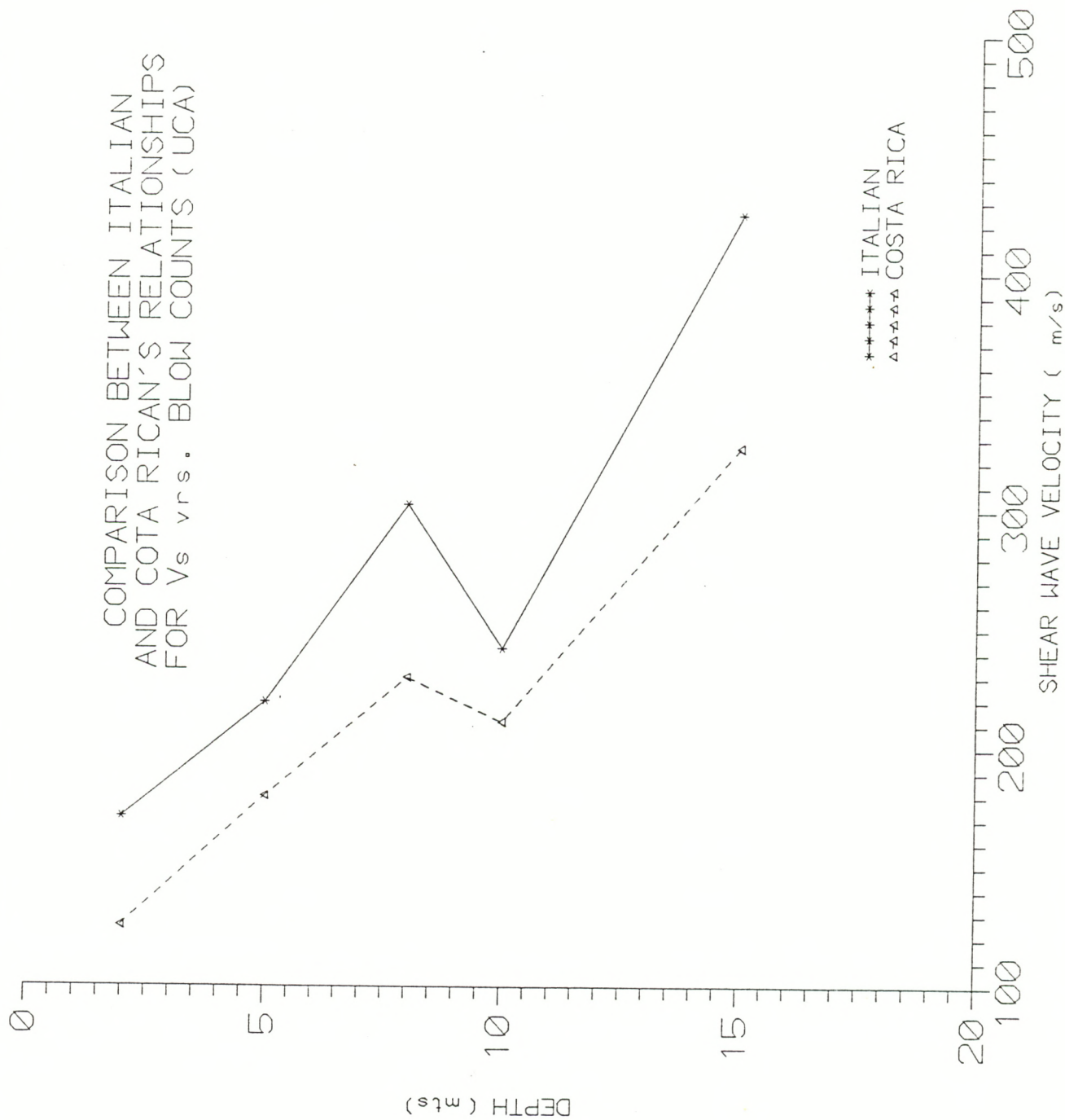
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Soil Response Study at 2 Sites in San Salvador

Shear wave velocity profile for the UCA site obtained from different empirical relationships.

Report No.
913009-3

Figure No.
5

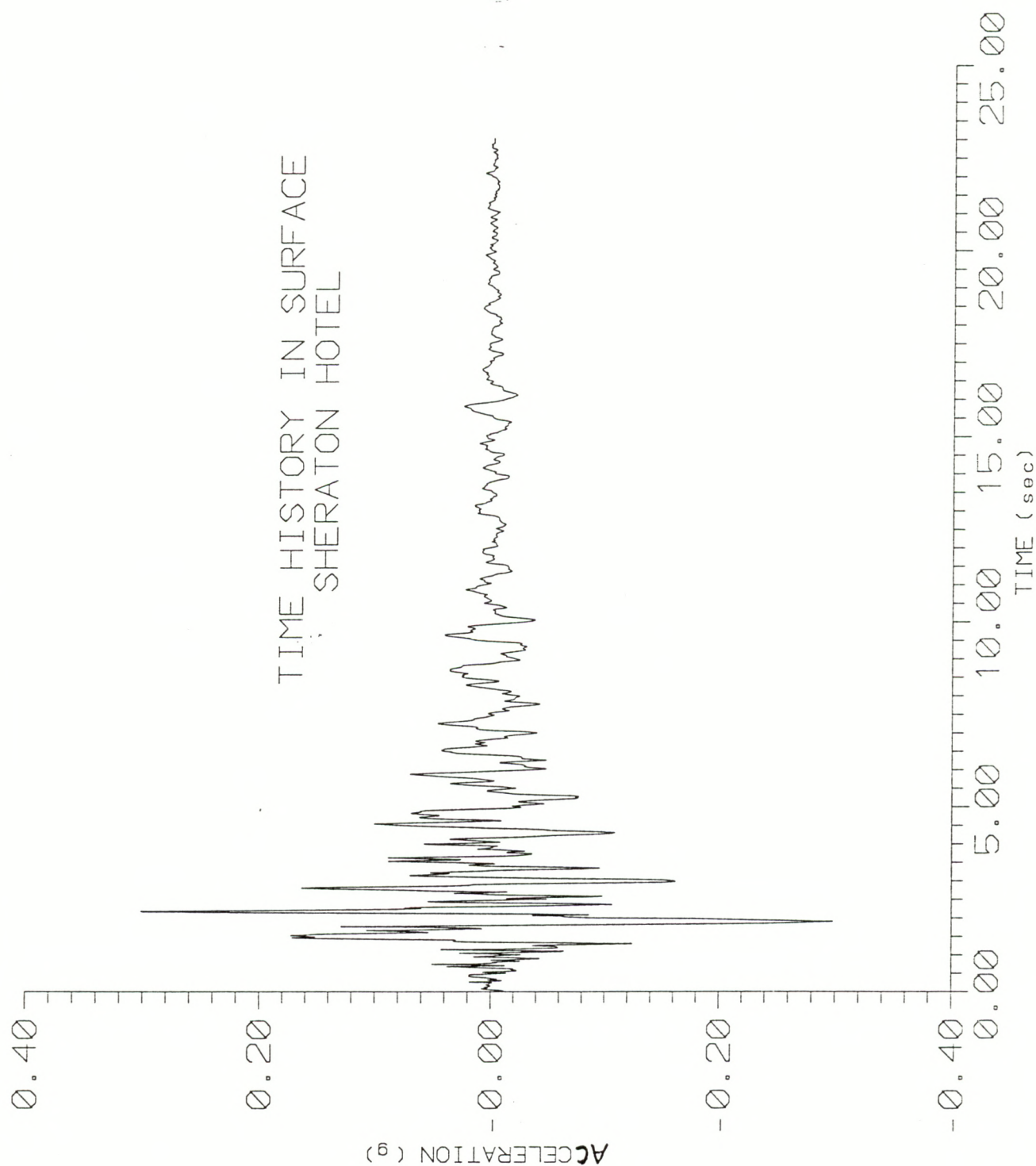
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Soil Response Study at 2 Sites in San Salvador

Recorded principal horizontal surface motion at the Sheraton Hotel site during the October 10, 1986 earthquake.

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Figure No.
6

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SOIL PROFILE MODELS

LAYER	SHERATON			I G N			U C A		
	γ (T/m^3)	THICKNESS (m)	V_s (m/s)	γ (T/m^3)	THICKNESS (m)	V_s (m/s)	γ (T/m^3)	THICKNESS (m)	V_s (m/s)
1	1.4	1.2	150	1.55	2.0	178.7	1.65	2.0	171
2	1.4	1.2	150	"	2.0	180	"	2.0	203
3	1.5	2.0	230	"	0.5	180	"	1.0	220
4	1.5	2.0	230	1.65	1.5	190	"	2.5	291
5	1.8	ROCK	2100	"	1.25	213	"	2.5	242
6				"	1.25	230	"	1.25	285
7				"	3.5	235	"	1.25	330
8				"	3.5	237	"	10.5	250
9				"	2.0	325	"	10.5	250
10				"	2.0	410	"	10.5	250
11				1.7	5.25	431	1.8	ROCK	1000
12				"	5.25	431			

1.8 ROCK $\begin{cases} 2100 \\ 1000 \end{cases}$

$$\frac{G_{max}}{S_u} = \begin{cases} 800 \\ 400 \end{cases} \text{ in AMPLE analyses}$$

Soil Response Study at 2 Sites in San Salvador

Unit weight and shear wave velocities of the soil profiles used as the base case in the analyses.

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913009-3

Figure No.
7

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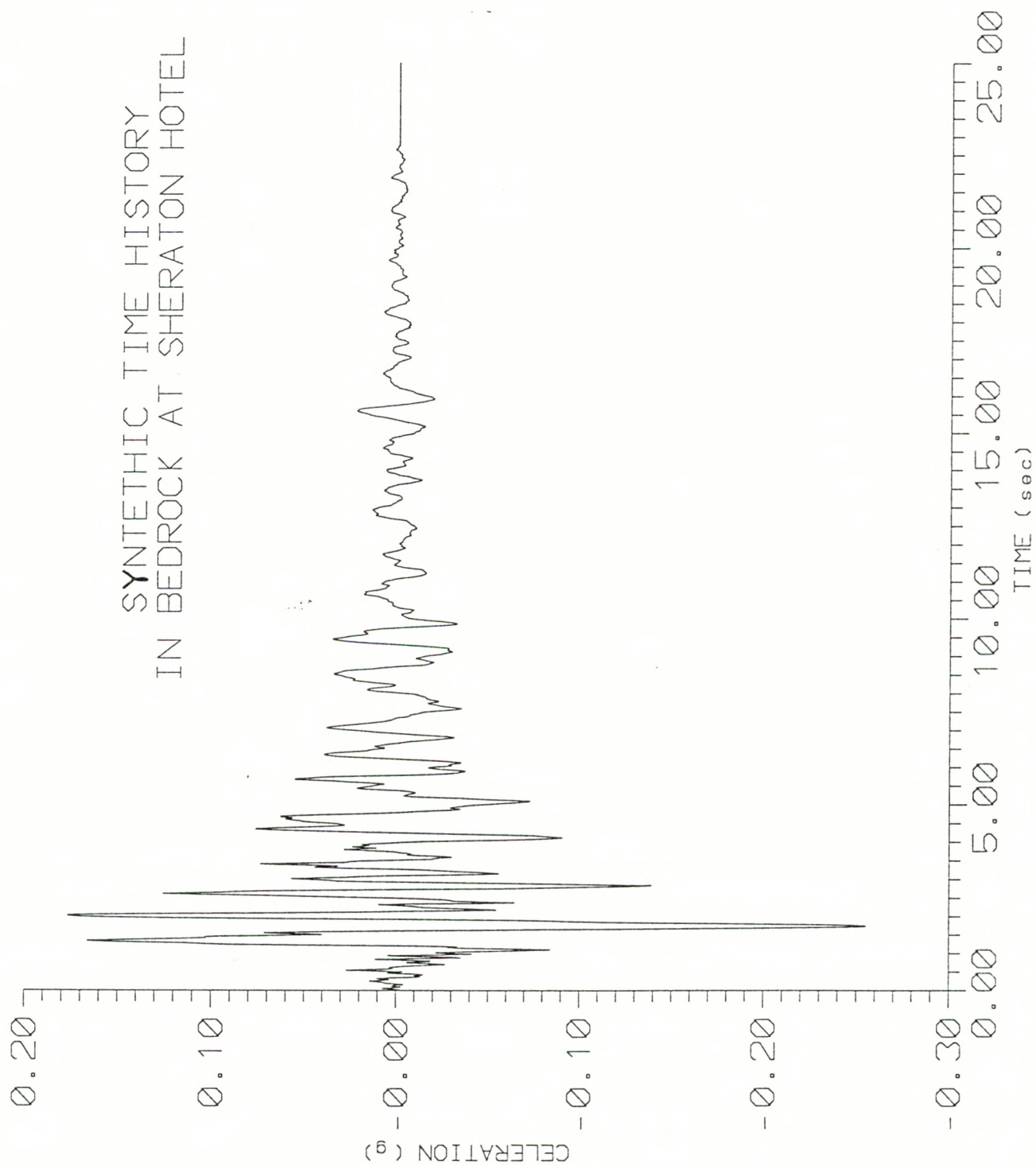
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Soil Response Study at 2 Sites in San Salvador

Report No.
913009-3

Figure No.
8

Bedrock outcrop motion obtained for the Sheraton Hotel site
by SHAKE.

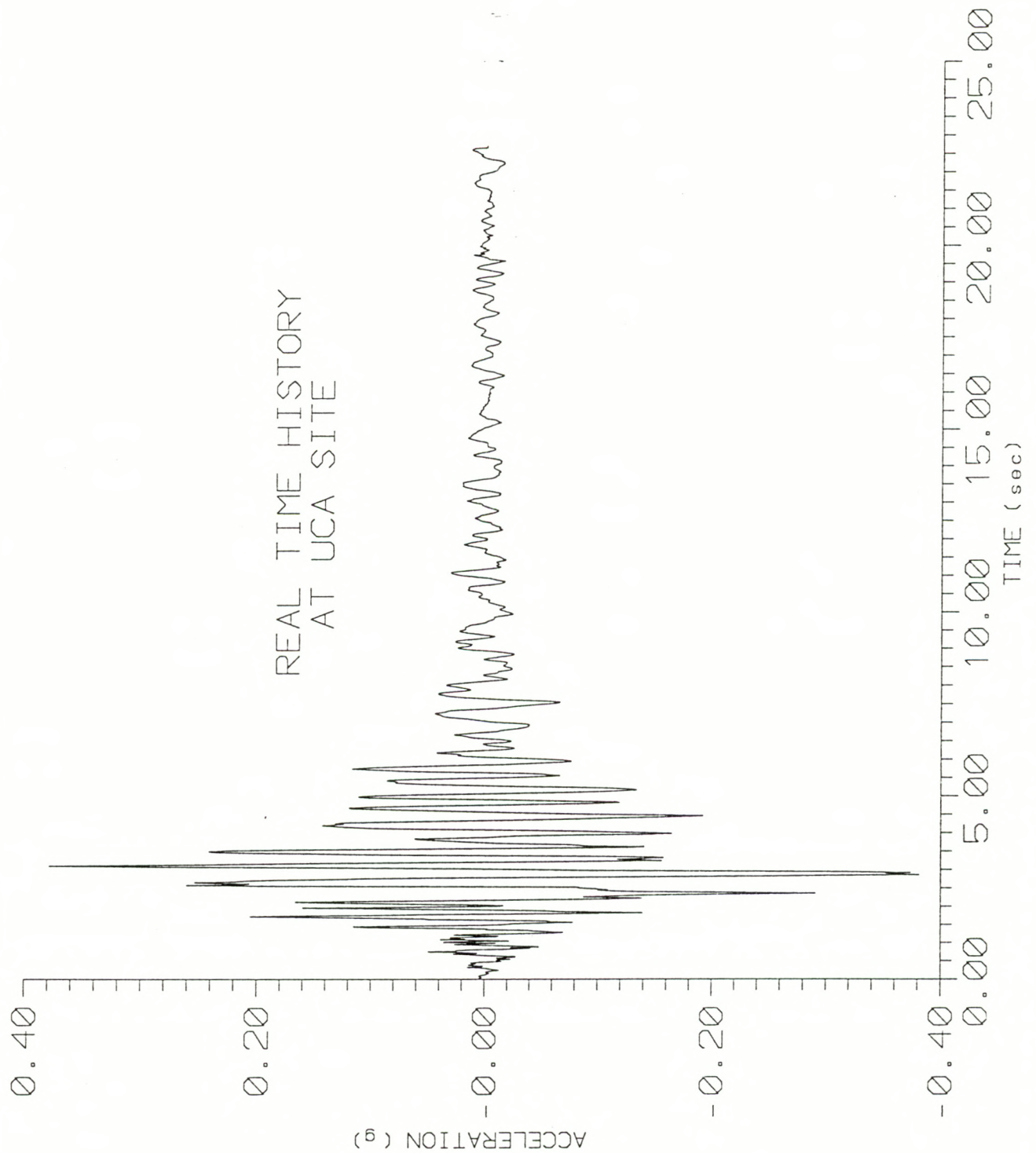
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Soil Response Study at 2 Sites in San Salvador

Recorded principal horizontal surface motion at the UCA site during the October 10, 1986 earthquake.

Report No.
913009-3

Figure No.
9

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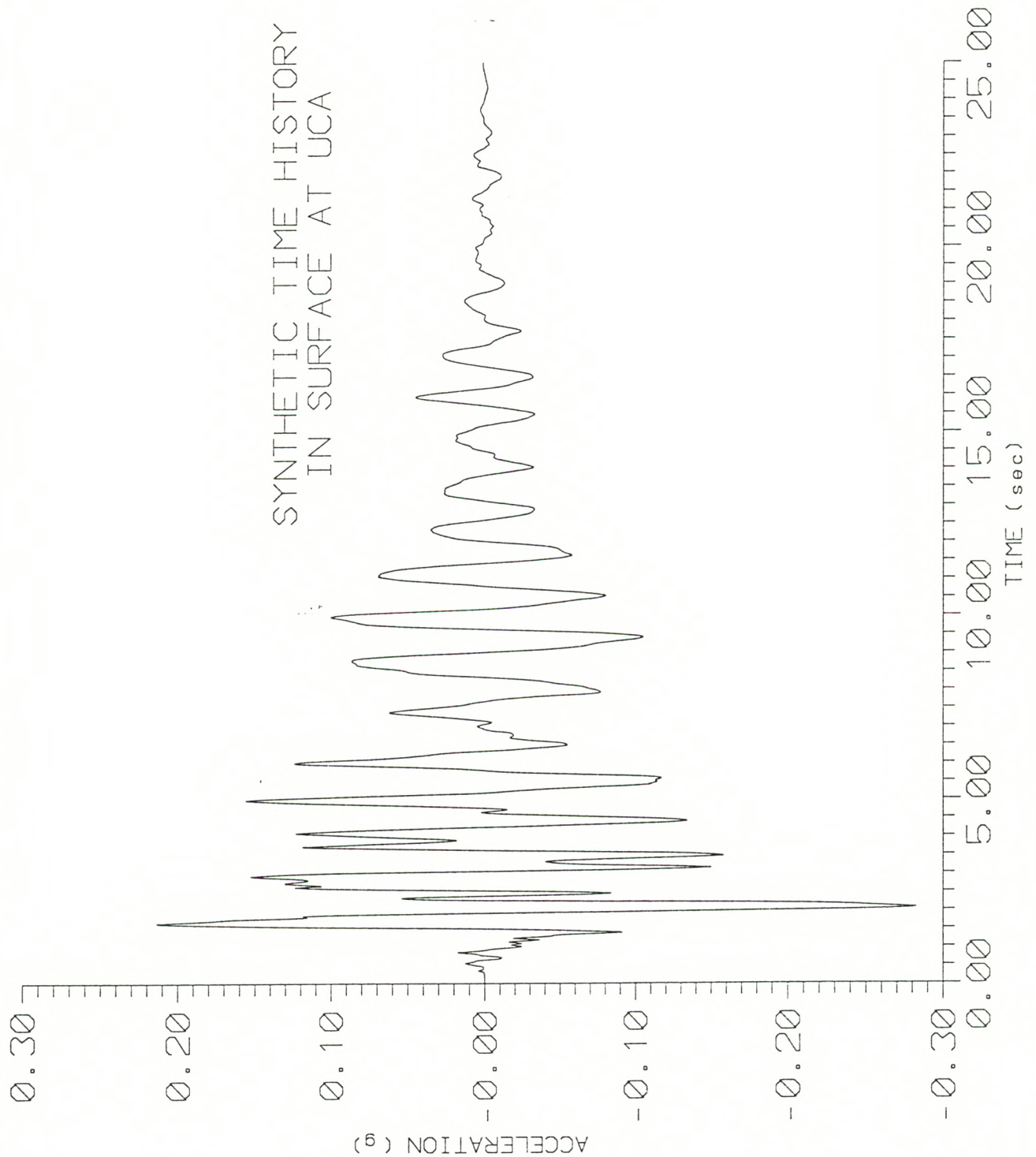
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SYNTHETIC TIME HISTORY IN SURFACE AT UCA



Soil Response Study at 2 Sites in San Salvador

Surface motion computed by SHAKE at the UCA site, see
Sec. 5.1.2 a.

Report No.
913009-3

Figure No.
10

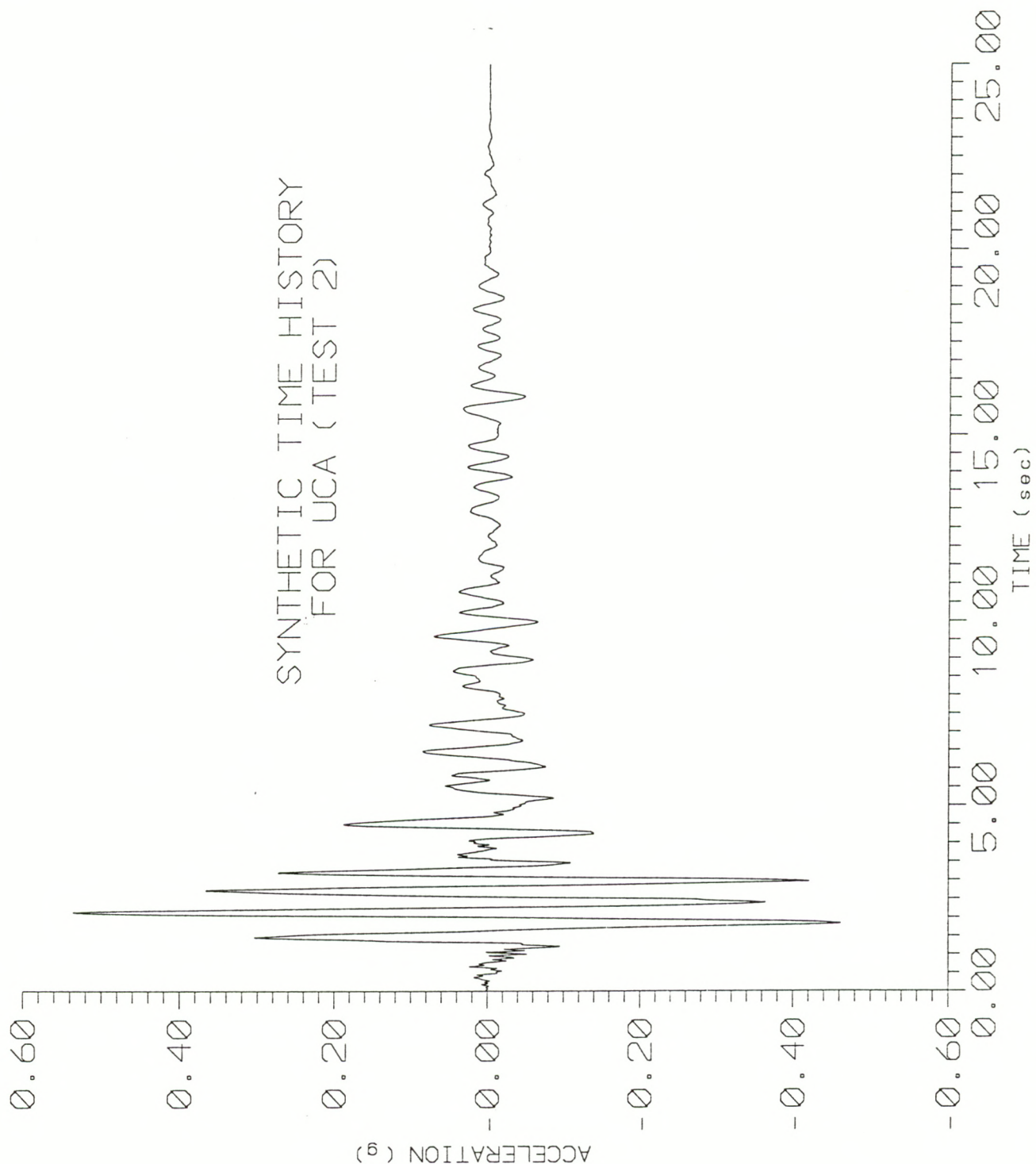
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Soil Response Study at 2 Sites in San Salvador

Surface motion computed by SHAKE at the UCA site, see Sec. 5.1.2 b.

Report No.
913009-3

Figure No.
11

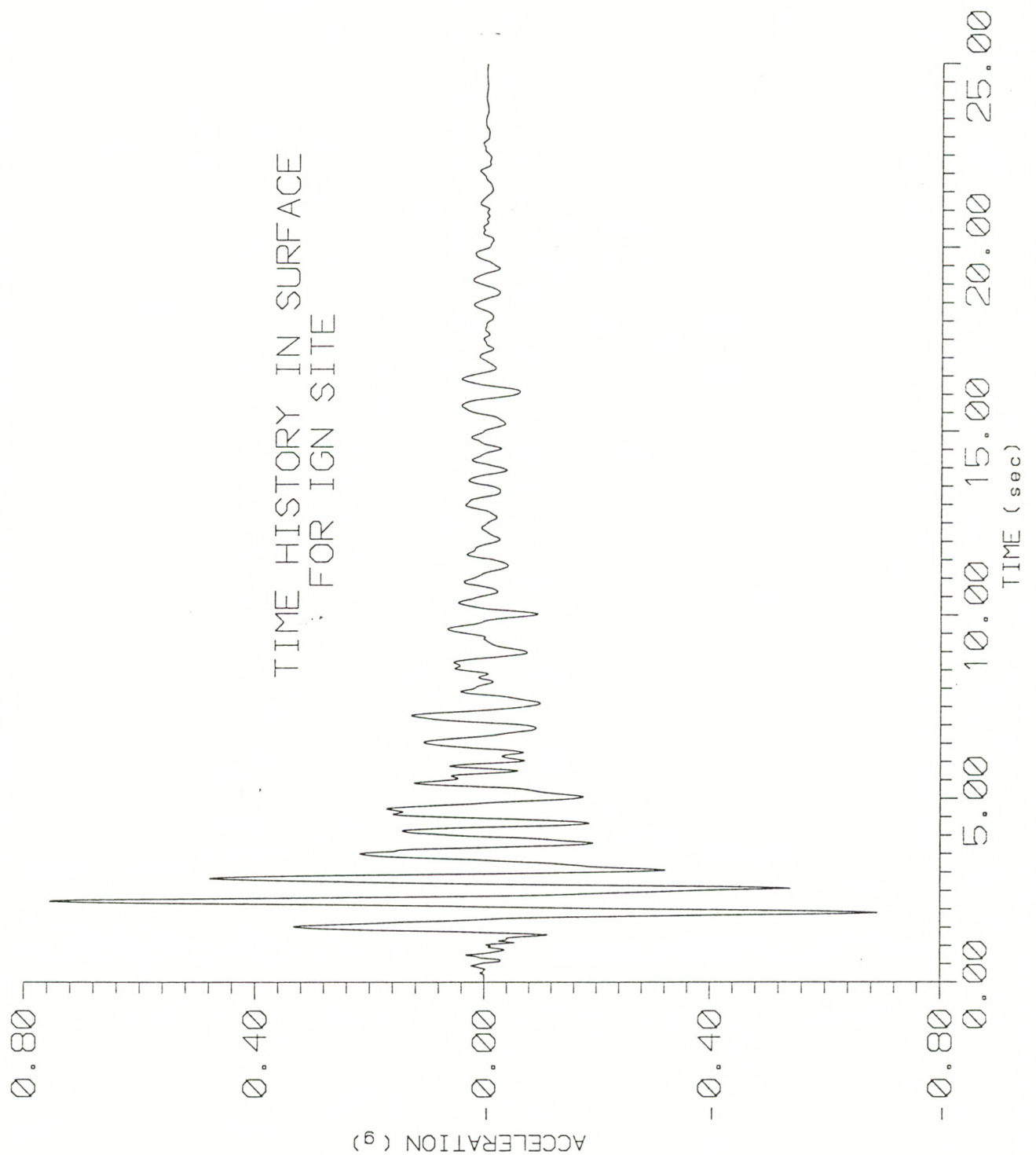
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Soil Response Study at 2 Sites in San Salvador

Surface motion computed by SHAKE at the IGN site, see Sec.
5.1.3 a.

Report No.
913009-3

Figure No.
12

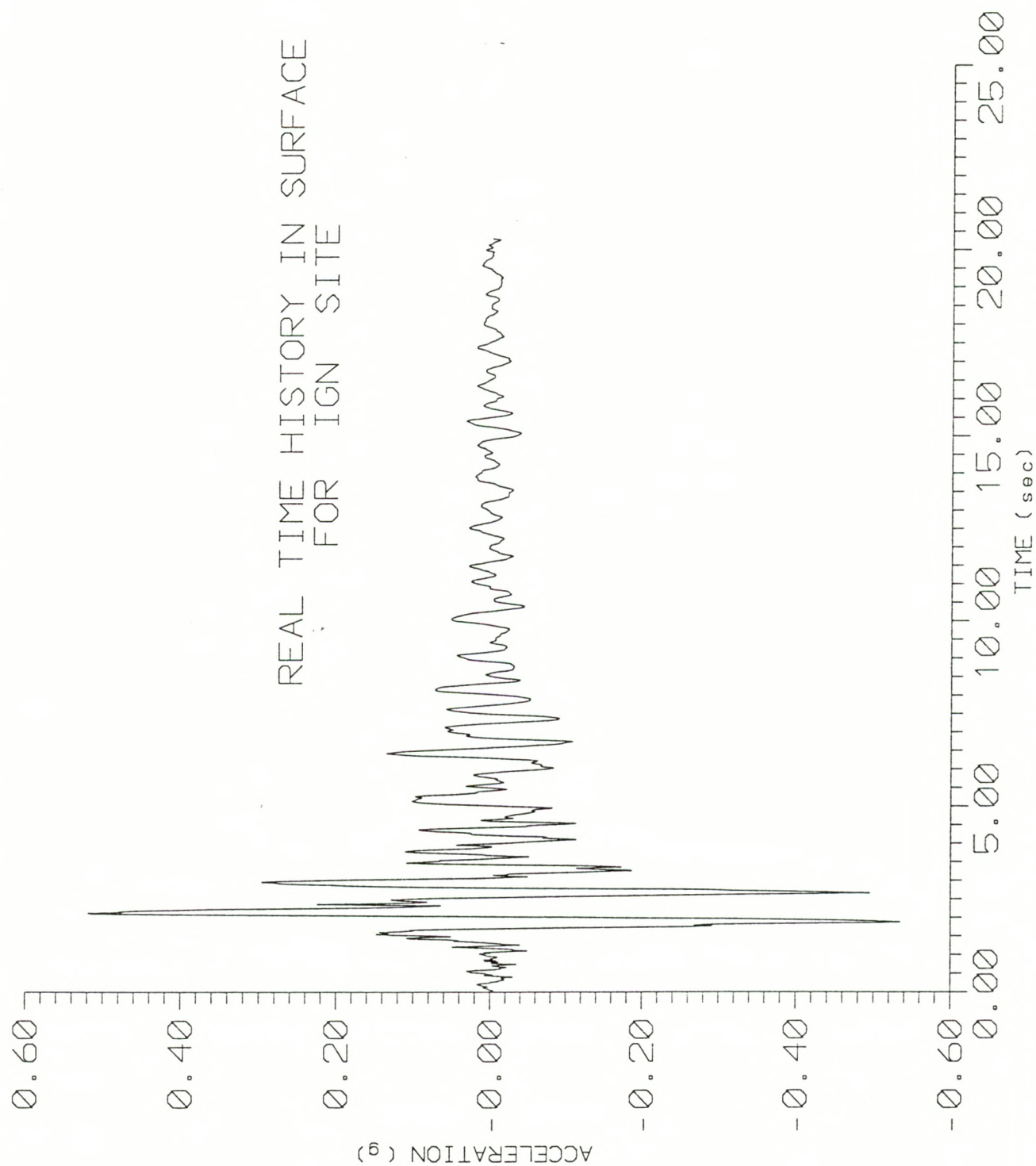
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Soil Response Study at 2 Sites in San Salvador

Recorded principal horizontal surface motion at the IGN site during the October 10, 1986 earthquake.

Report No.
913009-3

Figure No.
13

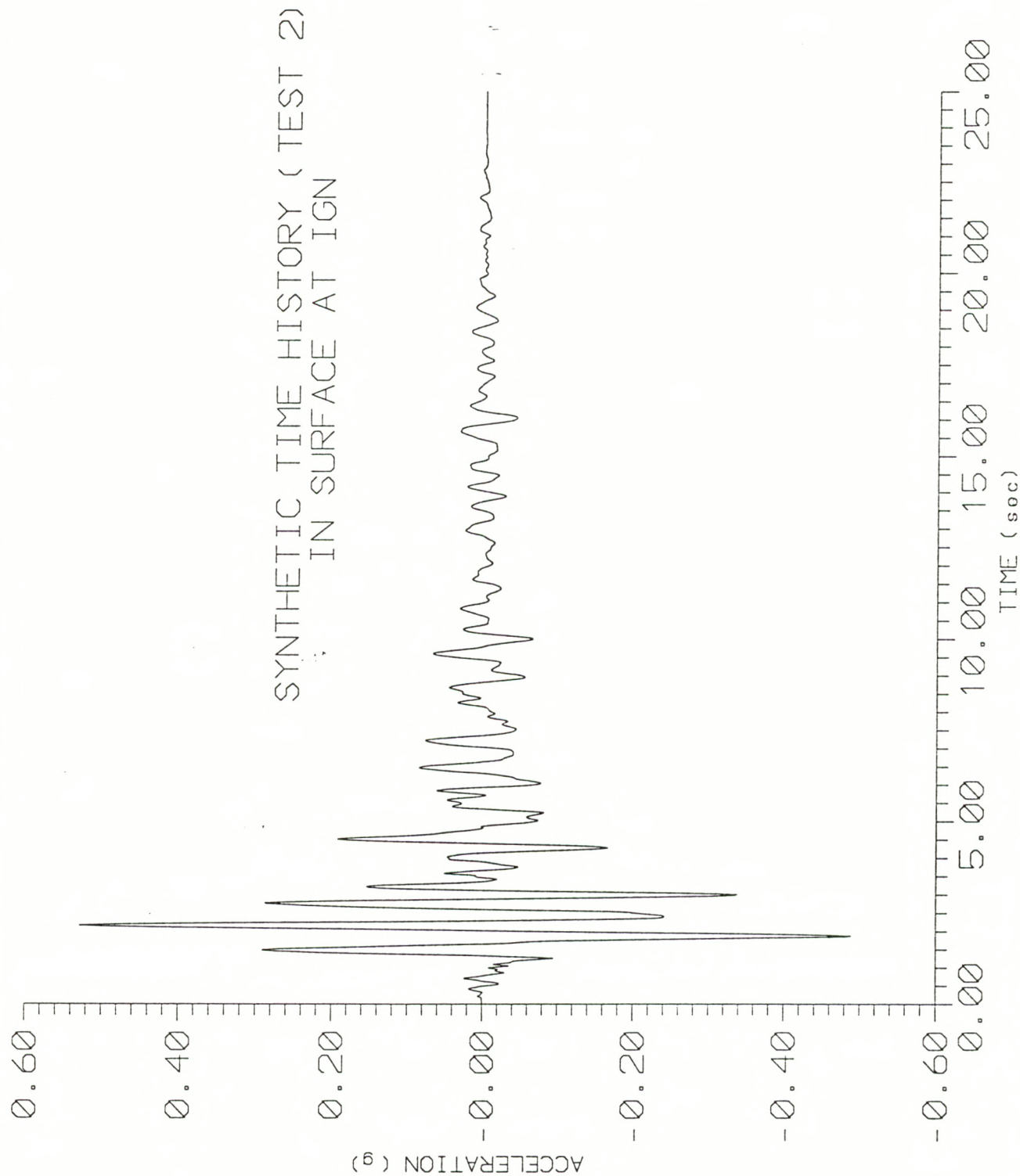
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Soil Response Study at 2 Sites in San Salvador

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Figure No.
14

Surface motion computed by SHAKE at the IGN site, see Sec.
5.1.3 b.

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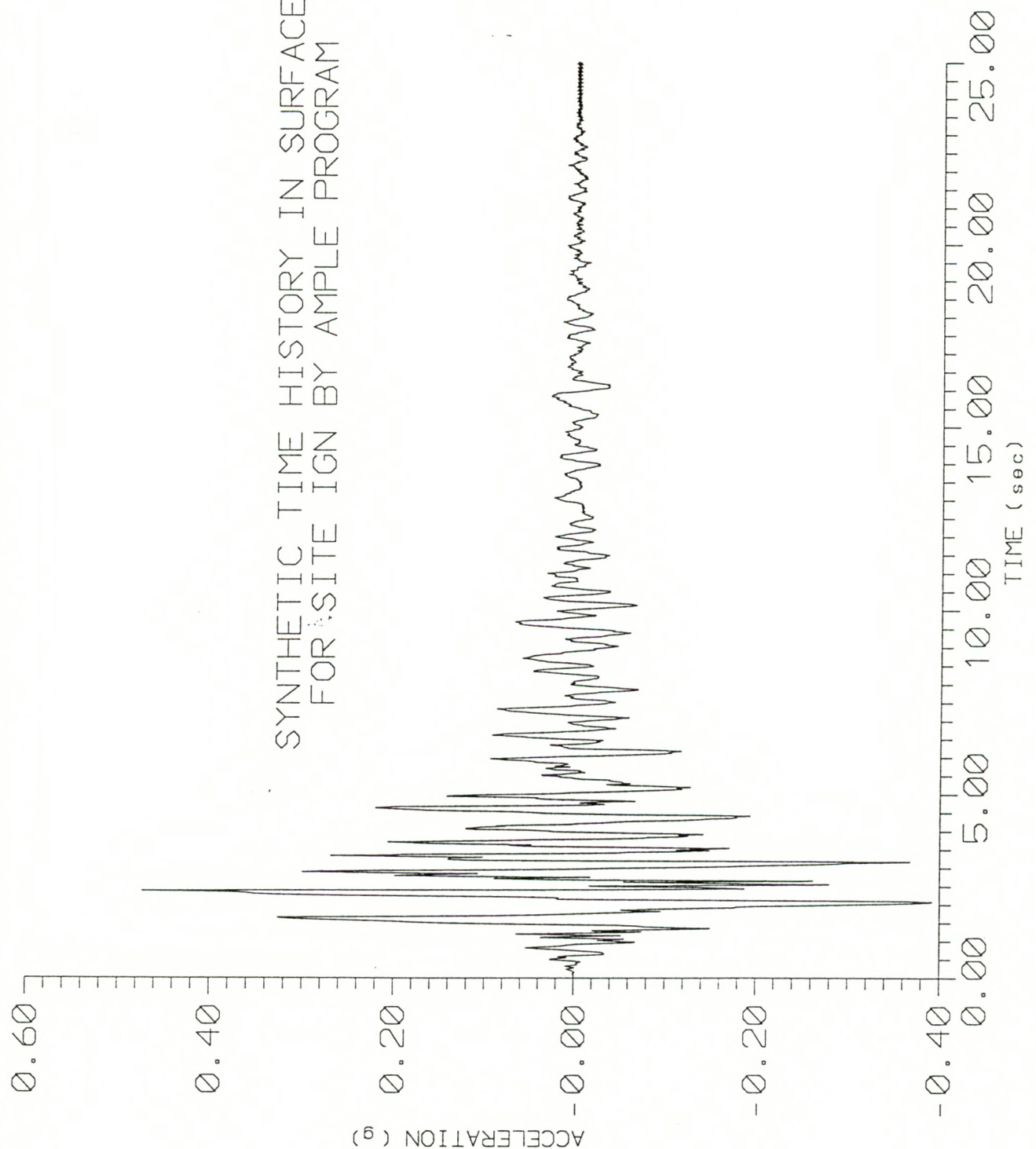
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE IGN BY AMPLE PROGRAM



Soil Response Study at 2 Sites in San Salvador

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913009-3

Figure No.
15

Surface motion computed by AMPLE at the IGN site, see Sec.
5.2.1 a.

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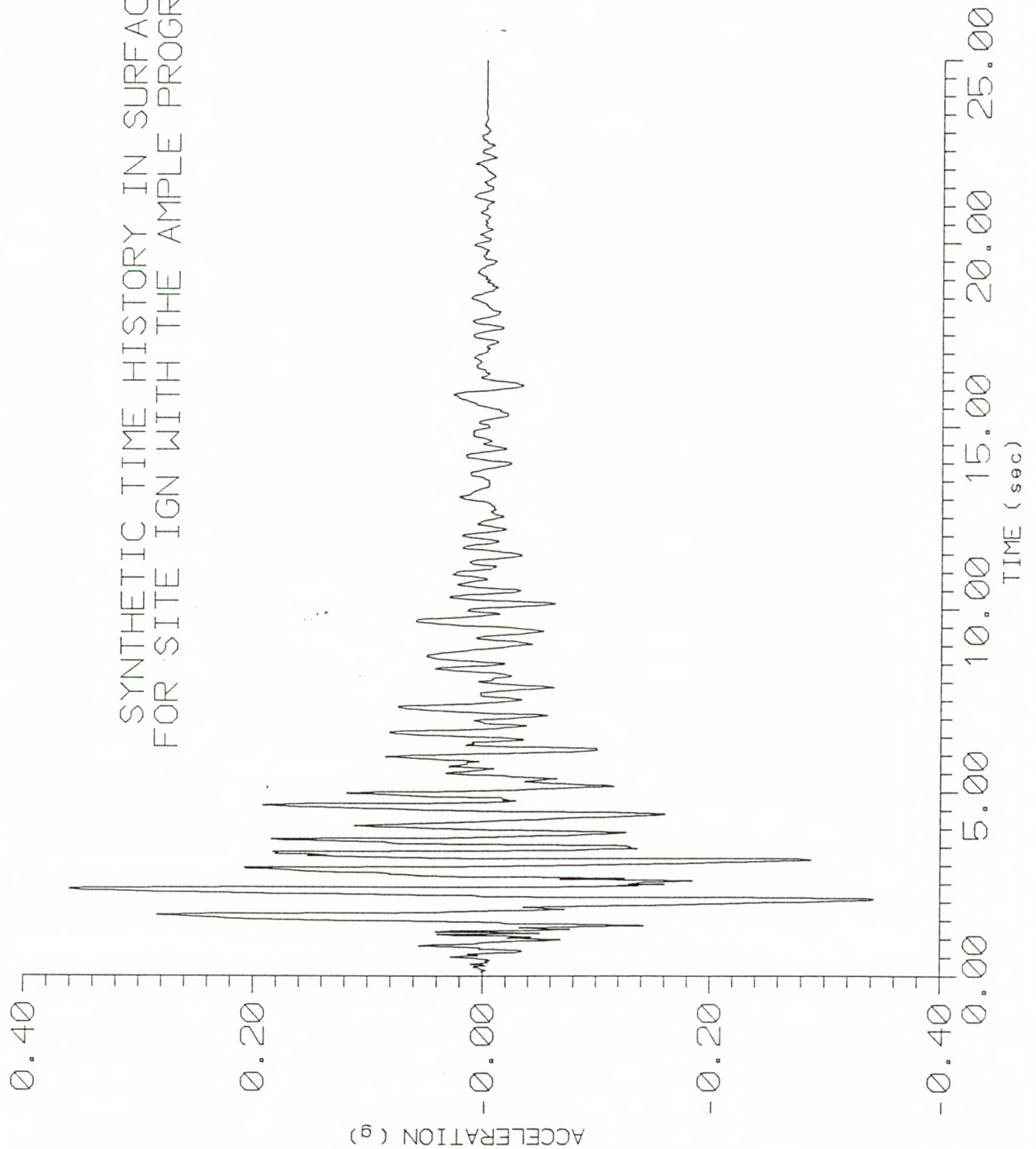
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE IGN WITH THE AMPLE PROGRAM



Soil Response Study at 2 Sites in San Salvador

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Figure No.
16

Surface motion computed by AMPLE at the IGN site, see Sec.
5.2.1 b.

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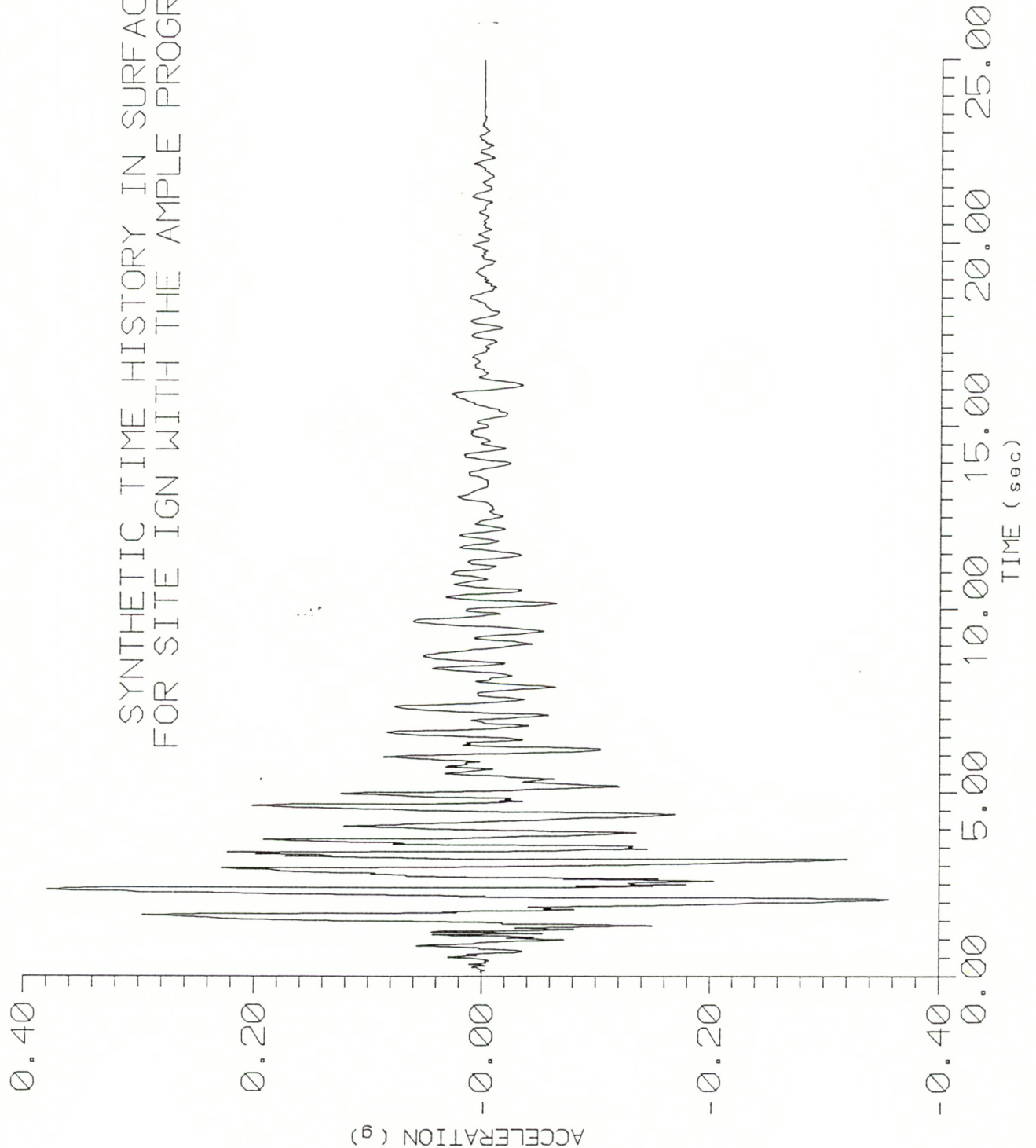
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE IGN WITH THE AMPLE PROGRAM



Soil Response Study at 2 Sites in San Salvador

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913009-3

Figure No.
17

Surface motion computed by AMPLE at the IGN site, see Sec.
5.2.1 c.

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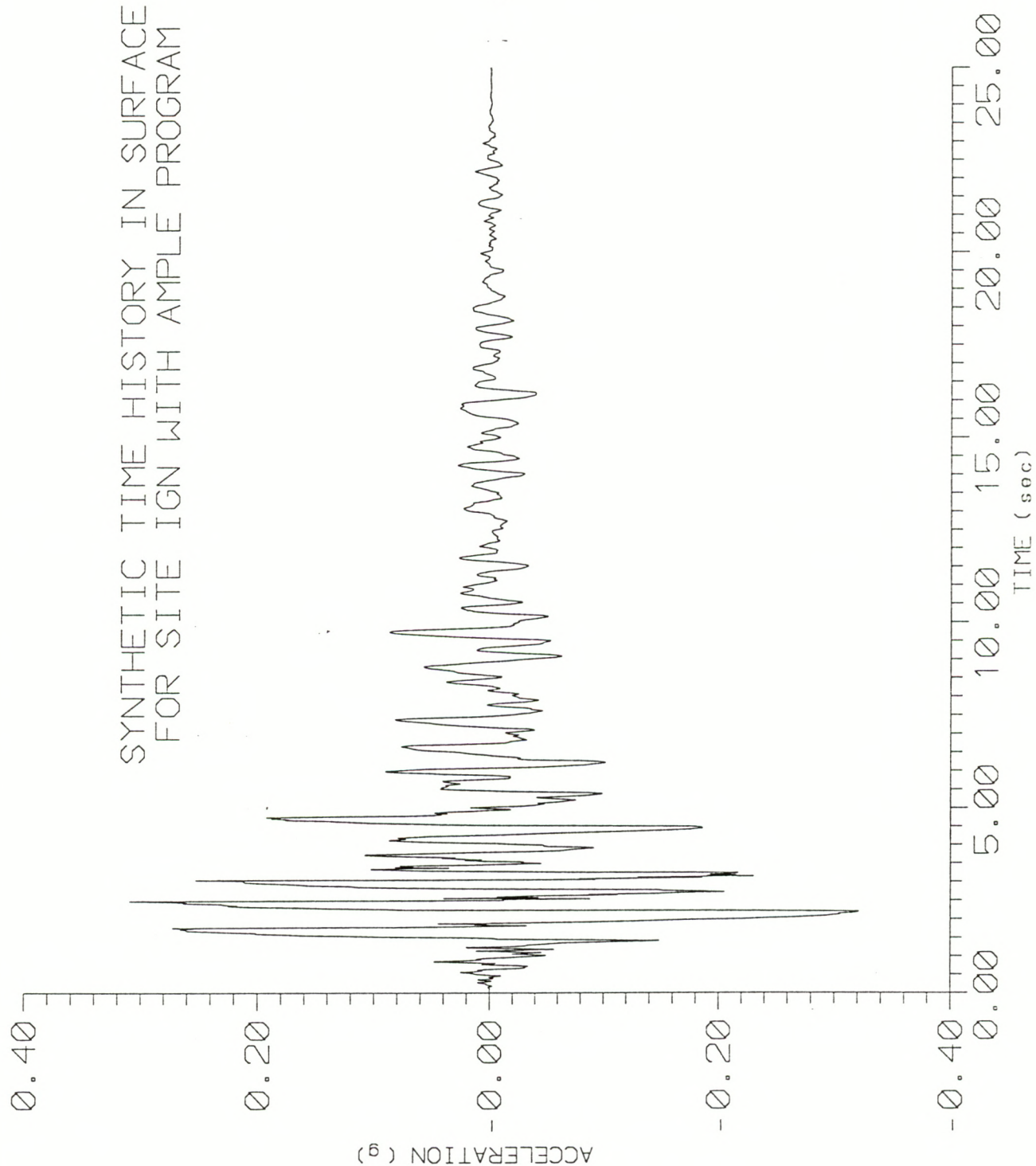
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE IGN WITH AMPLE PROGRAM



Soil Response Study at 2 Sites in San Salvador

Surface motion computed by AMPLE at the IGN site, see Sec. 5.2.1 d.

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913009-3

Figure No.
18

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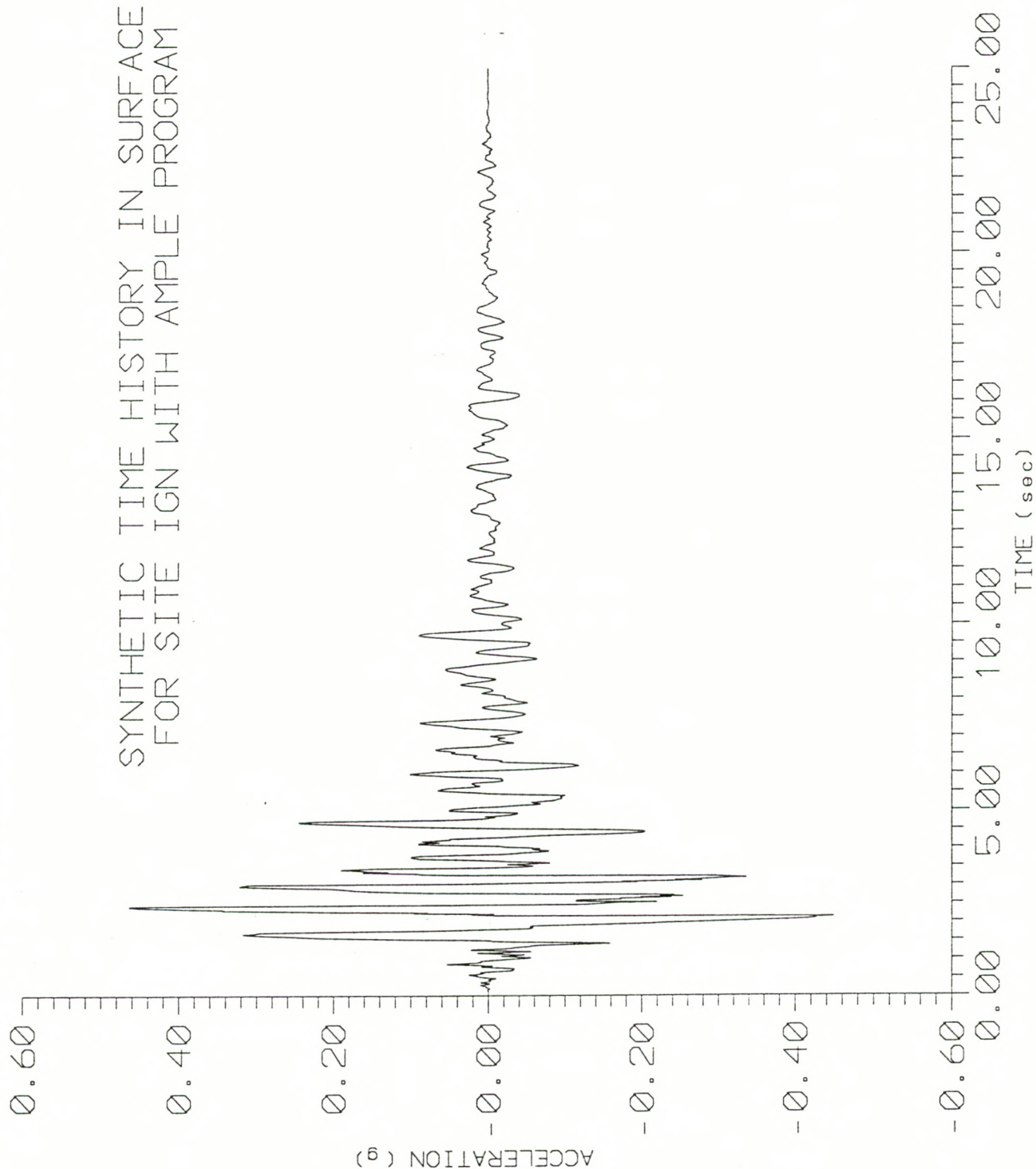
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE IGN WITH AMPLE PROGRAM



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Figure No.
19

Surface motion computed by AMPLE at the IGN site, see Sec.
5.2.1 e.

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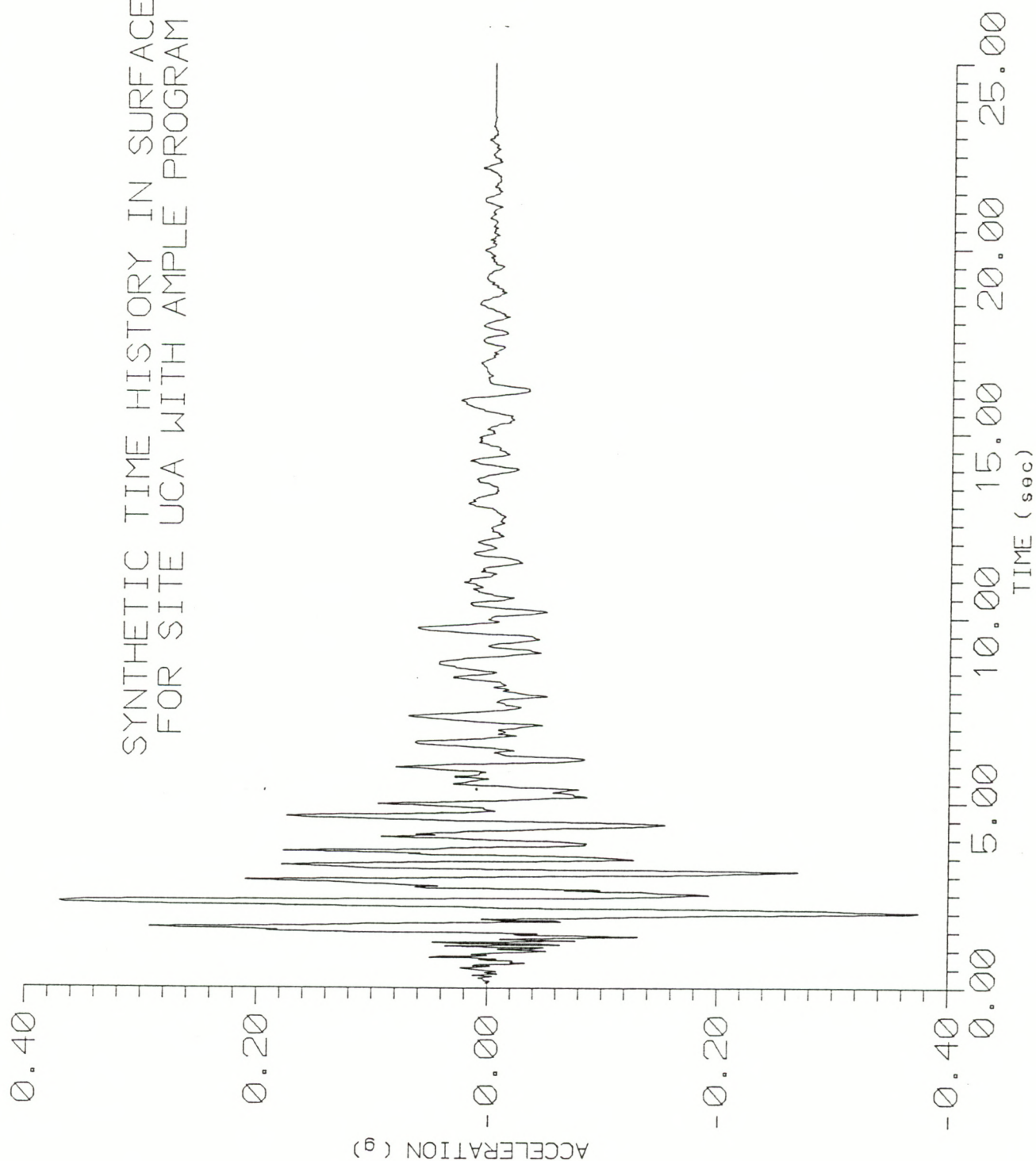
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SYNTHETIC TIME HISTORY IN SURFACE
FOR SITE UCA WITH AMPLE PROGRAM



Soil Response Study at 2 Sites in San Salvador

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913009-3

Figure No.
20

Surface motion computed by AMPLE at the UCA site, see
Sec. 5.2.2.

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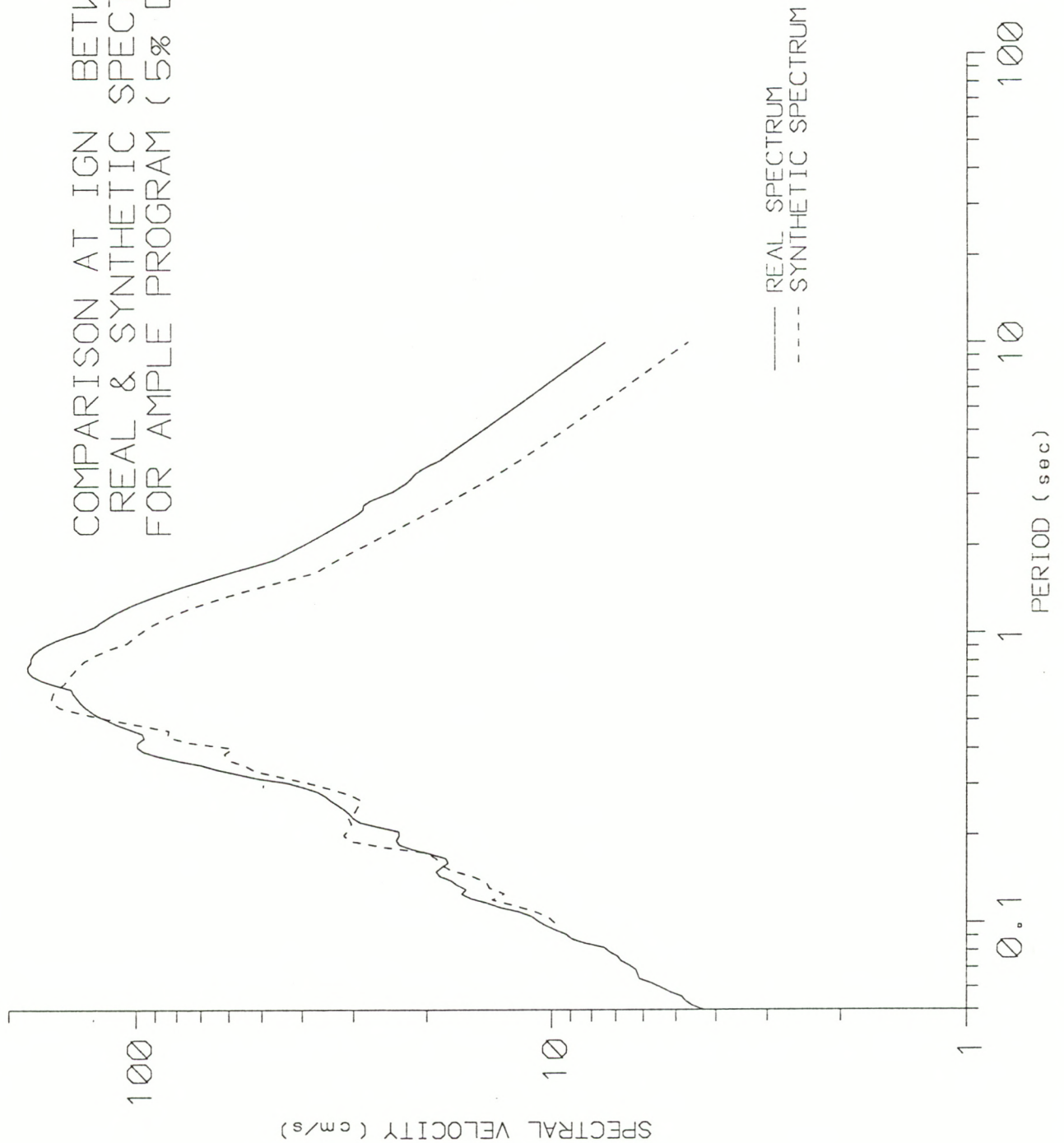
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COMPARISON AT IGN BETWEEN
REAL & SYNTHETIC SPECTRA
FOR AMPLE PROGRAM (5% DAM.)



Soil Response Study at 2 Sites in San Salvador

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Figure No.
21

Pseudo-velocity response spectra of the surface motions at the IGN site at 5% damping. AMPLE results vs recorded motion.

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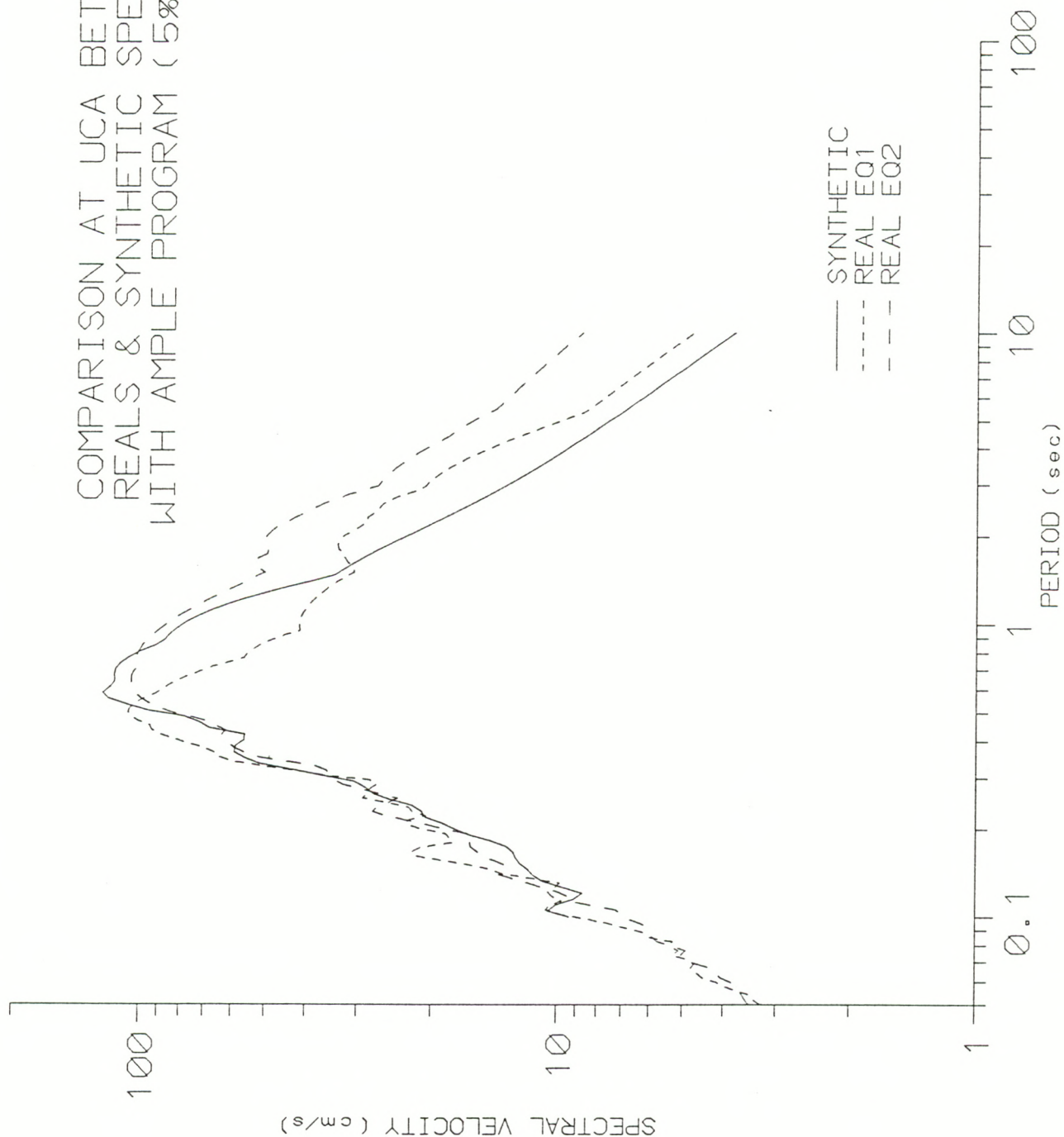
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COMPARISON AT UCA BETWEEN
REALS & SYNTHETIC SPECTRA
WITH AMPLE PROGRAM (5% DAM.)



Soil Response Study at 2 Sites in San Salvador

Pseudo-velocity response spectra of the surface motions at the UCA site at 5% damping. AMPLE results vs both components of recorded motion.

Report No.
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Figure No.
22

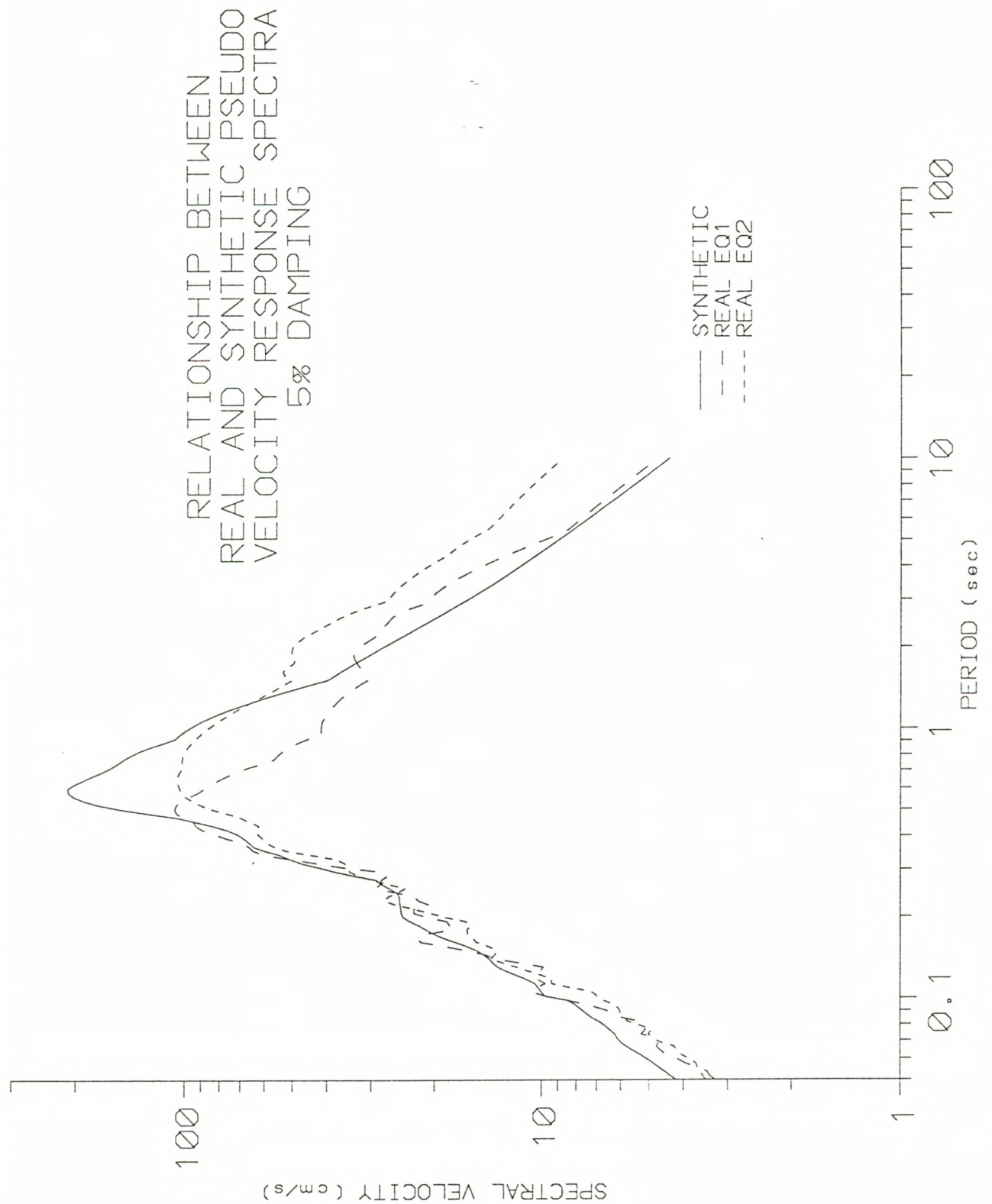
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Soil Response Study at 2 Sites in San Salvador

Pseudo-velocity response spectra of the surface motions at the UCA site at 5% damping. SHAKE results vs both components of recorded motion.

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Figure No.
23

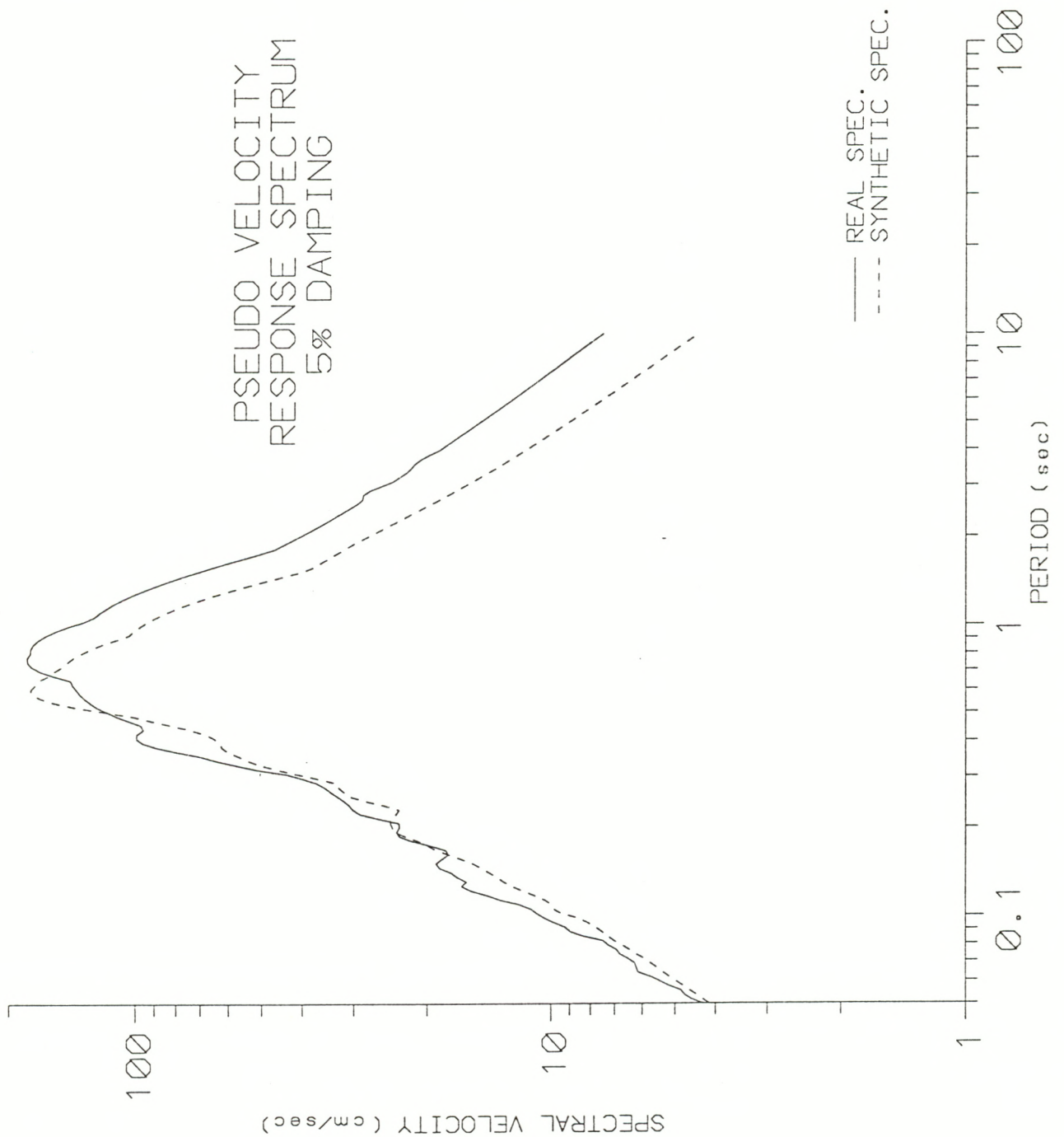
Drawn by
JCF

Date
93.07.30

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FNa





Soil Response Study at 2 Sites in San Salvador

Report No.
913009-3

Figure No.
24

Pseudo-velocity response spectra of the surface motions at the IGN site at 5% damping. SHAKE results vs recorded motion.

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93.07.30

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