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PROCESSING OF THE UPPER LEFT ABUTMENT RECORD FROM PACOIMA DAM FOR THE NORTHRIDGE EARTHQUAKE

by

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Summary

The Pacoima Dam was strongly shaken during the Northridge earthquake. Analysis of the record from the upper left abutment site indicates that the site tilted about 3° to the northeast (downslope) during the earthquake. This is obtained by subtracting a simple tilting function determined from the record. The 3° is independently confirmed by level measurements at the site. The concrete pier to which the instrument is bolted appears to be well connected to the rock ridge, and there is no relative displacement apparent between the pier and the rock. In contrast, the gunite and thin concrete on the rock is badly broken up and shifted.

Introduction

Processing of the Pacoima upper left abutment record from the Northridge earthquake presents several challenges. In general, the high amplitudes and the number of trace crossings make the record difficult to digitize and require careful attention. To assist the effort the high amplitude section of the record was photographically enlarged by nearly a factor of 16 by an aerial photogrammetry firm. An area originally 6 cm square on the film became approximately a meter square. This allowed a human to carefully follow the traces, providing a check of the curve-following that was done by the computer and operator.

After the curve following was completed and checked, two problems remained, the peak value and a base shift. The peak value is a problem on Channel 3, in the easterly (104°) direction. The trace on the film is not visible beyond about 1.2 g, at which point the trace image is lost because the reflected light beam misses one of the mirrors along the optical path. (This also occurred for the 1992 Cape Mendocino record and is described in Shakal et al., 1992). Straight-line extrapolation of the traces from where they disappear implies a peak value as high as 2.0 g. However, considering that there is some curvature at the turning point, a lower value of 1.7 g was estimated as the peak value. The peak value itself has little impact on the velocity or displacement, and not much impact on the response spectra.

The remaining problem deals with the base line shift. During processing of the record, it became clear that there was an unusual amount of long period noise in the record, higher than normal for the CSMIP system (given in Shakal and Ragsdale, 1984). This indicated a closer study of the noise at long periods was necessary. Note that the processed data in the period band most important for engineering studies (e.g., 0.25 to 4 seconds) should not be significantly affected by this long-period noise. Therefore a preliminary release was made of the data (Darragh et al., 1994), to be followed later by a broader bandwidth data release after completion of this study. A very simple model was assumed in this study, assuming as little as possible about the shape of any correction functions, and not using a model-dependent correction approach.

Study of Base Line Shift

A copy of the film accelerogram recorded at the upper left abutment is shown in Fig. 1. The result of the CSMIP digitizing of the film accelerogram is shown in Fig. 2, from Darragh et al. (1994). The Channel 1 (194°) response spectrum for the full bandwidth of .04 to 15 seconds considered in standard quality control procedures in CSMIP is shown in Fig. 3. At long periods the spectrum begins increasing after about 9 seconds, a pattern characteristic of normal noise, but the level is nearly 10 times the level at which this should be occurring. The normal noise floor average is also shown on the plot. That the upturn is occurring at about 10 in/sec instead of at about 1 in/sec indicates a problem in the digitized data for Channel 1. The Channel 3 spectrum (not shown) has a noise level only slightly higher than normal, while the vertical spectrum appears normal.

The many steps in the standard processing (e.g., Hudson et al., 1972), designed to yield the best result possible, can, by their involved nature, mask aspects that might be observable by simple steps. The first simple step is to perform a straight numerical integration of the raw result produced in the Volume 1 process. The result of that integration process for the three channels is shown in Fig. 4. A strong ramp-like nature to the velocity is immediately apparent for Channels 1 and 3. Tilting of the instrument will cause changes in the zero acceleration level which, when combined with a zero-mean integration of the accelerogram, will yield this pattern. In an enlarged view of Channel 1 in Fig. 5 the two slopes are very clear, and a third can be inferred. A small offset can be seen at the beginning and end of the acceleration record in Fig. 6. The first 5 seconds are shown enlarged in Fig. 7a, and the last 5 seconds are in Fig. 7b. The total change in reference level is more than 50 cm/sec^2.

A sudden tilting of the instrument will cause an additive step function effect on the zero level of the acceleration. This will cause a 'v' shape in the velocity integral if the acceleration has been made zero-mean, which is standard in Volume 1 processing. Two distinct tilts are indicated by the shape of the velocity in Fig. 5. The velocity after careful correction of the baseline with a three-sectioned tilting function is shown in Fig. 8. This can be compared to the uncorrected velocity (Fig. 4). The corrected velocity is obtained by adding the tilt correction function (Fig. 9) to the raw acceleration (Fig. 6) before numerically integrating.

The tilt-correction function of Fig. 9 has some, although limited, ambiguity. The starting and ending levels are confined by the difference in offsets at the start and end of the accelerogram. The actual zero of the function is arbitrary, but the total offset and the overall shape of the function are constrained. The velocity record in Fig. 8 can only be obtained if a third section like that indicated in Fig. 5 is used. The timing of the steps is not tightly controlled by the record, but they cannot be moved too much without causing significant effects in the velocity. The times correspond to the times of the slope changes indicated in Fig. 5, at approximately 4 and 8 seconds. To set the times more precisely, the times of the maximum excursion of the record near these approximate times were used. These are shown in Fig. 10, at about 3.85 and 7.69 seconds. The amplitudes of the three steps were determined by repeated solutions, attempting to remove the drift in velocity and obtain a displacement which was relatively constant at the end of the record. Other methods, such as the algorithms discussed by Iwan et al. (1985) and Graizer (1979) will be used to investigate the uniqueness and stability of these results.

The Channel 1 displacement estimate corresponding to the corrected velocity of Fig. 8 is shown in Fig. 11. This indicates that there was a short displacement pulse of about 20 cm at about 4 seconds, and that a permanent displacement of 40-50 cm occurred in the southerly direction (194°). The long period displacement is necessarily less certain than the tilt. The tilt is actually measurable by the accelerometer, while the long period displacements are derived from the acceleration.

A similar procedure was followed for Channel 3. The velocity is less distorted in Fig. 4, and a lower noise level was reflected in the response spectrum. Paralleling the approach for Channel 1, the velocity after the tilt correction is applied is shown in Fig. 12. The tilt function is of lower amplitude (see Fig. 13), and has a total amplitude of only about 15 cm/sec^2 versus the 55 cm/sec^2 of Channel 1. The offset times were taken to correspond to those found for Channel 1. The displacement is shown in Fig. 14. It indicates several oscillations in displacement between 4 and 8 seconds. The final displacement is around 10 cm, in the easterly (104°) direction.

Total Tilt

Tilt angles can be calculated from the tilt-correction functions in Figs. 9 and 13. Since the projection of the vertical acceleration vector on a horizontal component is $\sin\theta$, where θ is the angle between the gravity vertical and the vertical of the instrument reference frame, then

$$\theta = \sin^{-1}(a_{tilt}/G).$$

For Channel 1, $\theta_1 = \sin^{-1}(50.7\ \text{cm/sec}^2\ /\ 980\ \text{cm/sec}^2) \approx 3.0°$.

Similarly for Channel 3, $\theta_3 = \sin^{-1}(14.8\ \text{cm/sec}^2\ /\ 980\ \text{cm/sec}^2) \approx 0.9°$.

The total tilt angle for the vector sum of the accelerations is

$$\theta_{Tot} = 3.1°.$$

The azimuth angle of the final tilt vector is

$$\phi = \tan^{-1}(14.8/50.7) = 16.3°$$

The instrument axes, at 104° and 194°, are 14° counterclockwise (CCW) from east and south (this is the same as the 1971 instrument orientation, as corrected (Hudson, 1976)). Thus, the azimuth obtained for the tilt vector is 14° + 16.3° = 30.3° or N30E.

Comparison with Field-Measured Tilt

Independent of the efforts to improve the processing of the record, the final tilt angle of the instrument and pad were measured by CSMIP staff during a subsequent field trip to confirm the instrument orientations. The result of the tilt measurement is very close to that obtained above. The measurement obtained, 3.5° tilt at N40E, which corresponds to the downslope direction of the ridge. The correspondence with the calculated tilt amplitude and azimuth is very good. The accuracy of the electronic level used to measure the tilt is estimated to be 0.1°.

The tilt measured by the electronic-level is the tilt at that time. In contrast, the tilt measured from the record is the tilt that occurred during the course of the earthquake. This implies that the pre-earthquake tilt was quite small. To consider that further, the tilting in the 1971 earthquake needs to be considered.

Comparison with 1971 San Fernando Record

During the 1971 San Fernando earthquake, the recorder at the upper left abutment continued to record after the main shaking, apparently because a tilt occurred during the shaking. The instrument in place at that time was an AR-240. The starter on this instrument is a vertical pendulum which, when the pendulum mass moves too far to one side, closes a path for current flow. If the instrument stays tilted, the pendulum stays to one side, and the instrument runs until it is out of film.

Trifunac and Hudson (1971) inferred that the tilt that occurred in the 1971 earthquake was on the order of 0.5 degrees, to the northwest. Note that the tilting calculated for the 1994 event is nearly 6 times that inferred for the 1971 event.

Recalculated Spectra

When the tilt correction discussed above has been made, the spectra can be recalculated. The results are shown in Fig. 15; comparison to the initial spectrum (Fig. 3) shows that the long-period noise level has been lowered significantly, to near the normal CSMIP level, and the noise has been corrected.

Vertical Component

Another test of the tilt solution is to apply the solution obtained from the horizontal components to the vertical component. When the vertical component of the instrument is tilted away from the vertical of the gravitational field, the signal on the accelerometer will be increased (since it is balanced to be zero under 1 g acceleration) by

$$a_v = G\ (1 - \cos\ \theta)$$

where θ is the total angle of departure from the vertical, and G is 980 cm/sec^2. The vertical correction is small, since 1 - cos θ is very small for small angles. For a tilt angle of 3.1°, and assuming verticality pre-earthquake, the acceleration signal on the vertical will increase by about 1.4 cm/sec^2, a small amount. As can be observed in Fig. 2, the vertical signal has little of the characteristic 'v' shape. However, as a confirmation, the application of the vertical tilt correction function determined from the horizontal functions should reduce the noise in the vertical component and allow good velocity and displacement estimates. Application of the correction removes most of the small 'v' shape, and the initial part of the displacement looks good (Fig. 16). Noise problems dominate beyond about 15 seconds into the record. Study of the noise characteristics are continuing in order to isolate the source of the noise in the later part of the record. The displacement record indicates that there is a permanent displacement downward of perhaps 30 cm, which follows a short upward pulse.

Other Sources of Noise

The other main sources of noise in the record have been considered and should not be significant. One issue to consider is the problem generated by film shifting in the camera. During strong shaking the film, due to its own inertia, may shift in the recorder because of space around the holes for the sprockets on the drive wheels. However, the position of the fixed trace is constant relative to the instrument chassis, and any motion of the film can be removed by subtracting the motion on the fixed trace from the data traces. This is a standard correction that occurs in routine processing.

Note that in the tilt analysis above, a sudden tilt was assumed, basically a step function. This may represent a limit, and tilting over a short interval of time may be a better approximation. However, the approach used is the simplest possible and best solution with the smallest number of assumptions.

References

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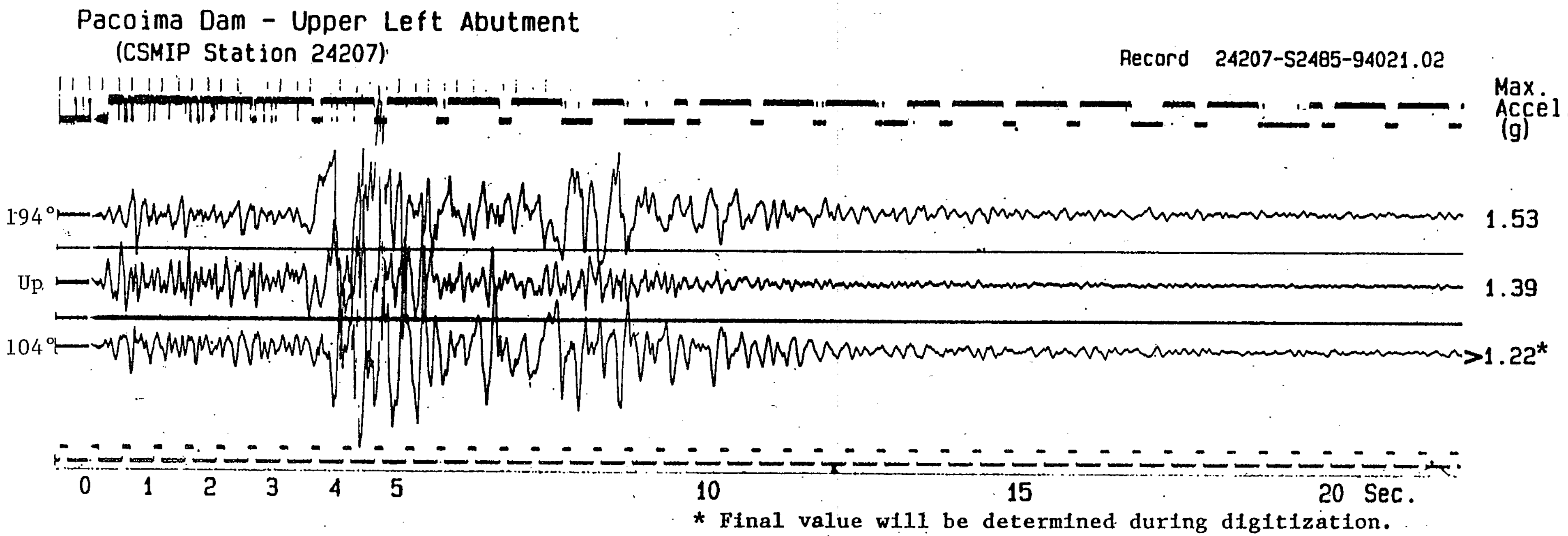


Fig. 1. Accelerogram from the instrument at the Upper Left Abutment of the Pacoima Dam from the Northridge Earthquake (from Shakal et al., 1994).

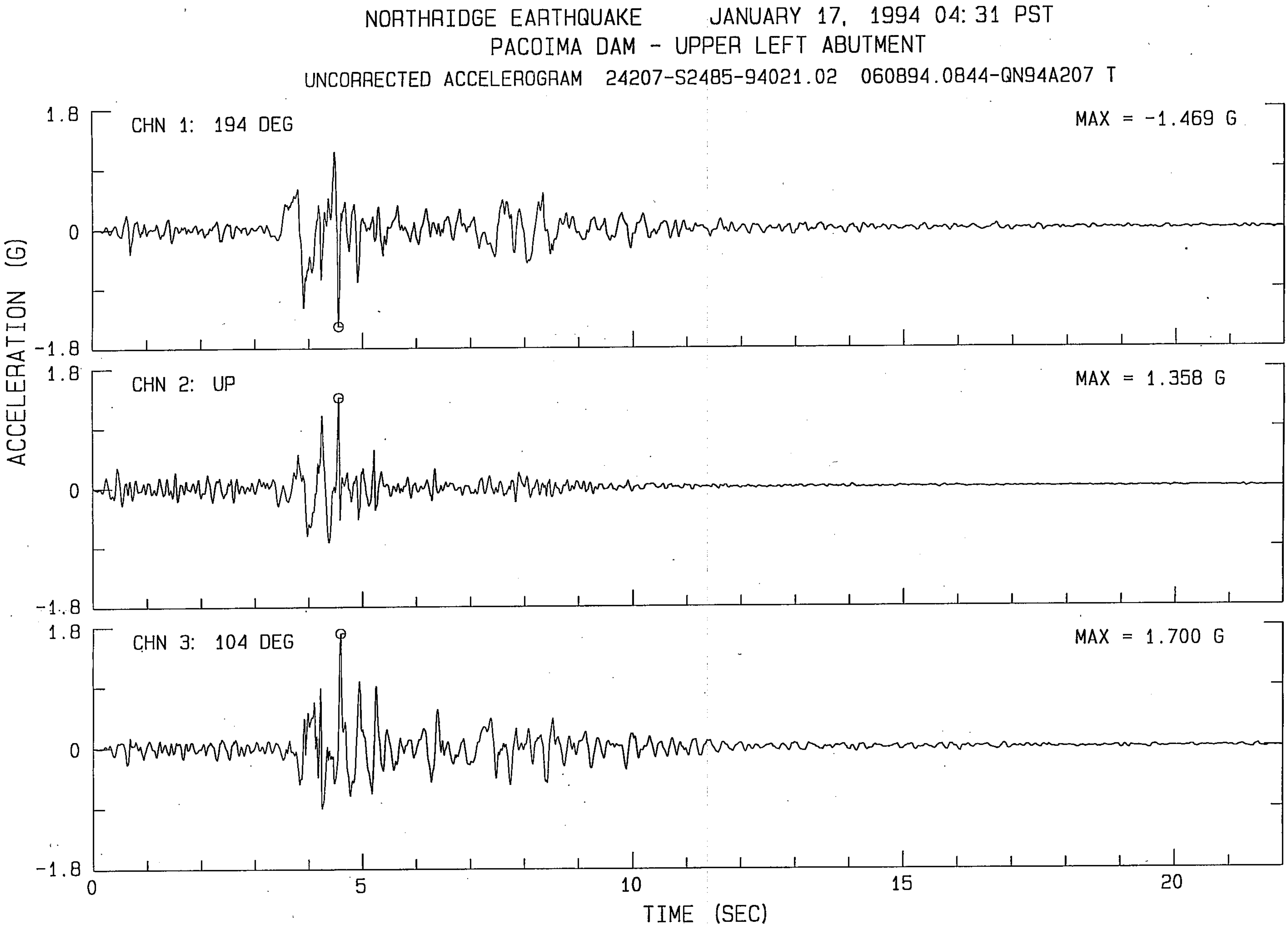


Fig. 2. Digitized accelerogram from Upper Left Abutment.

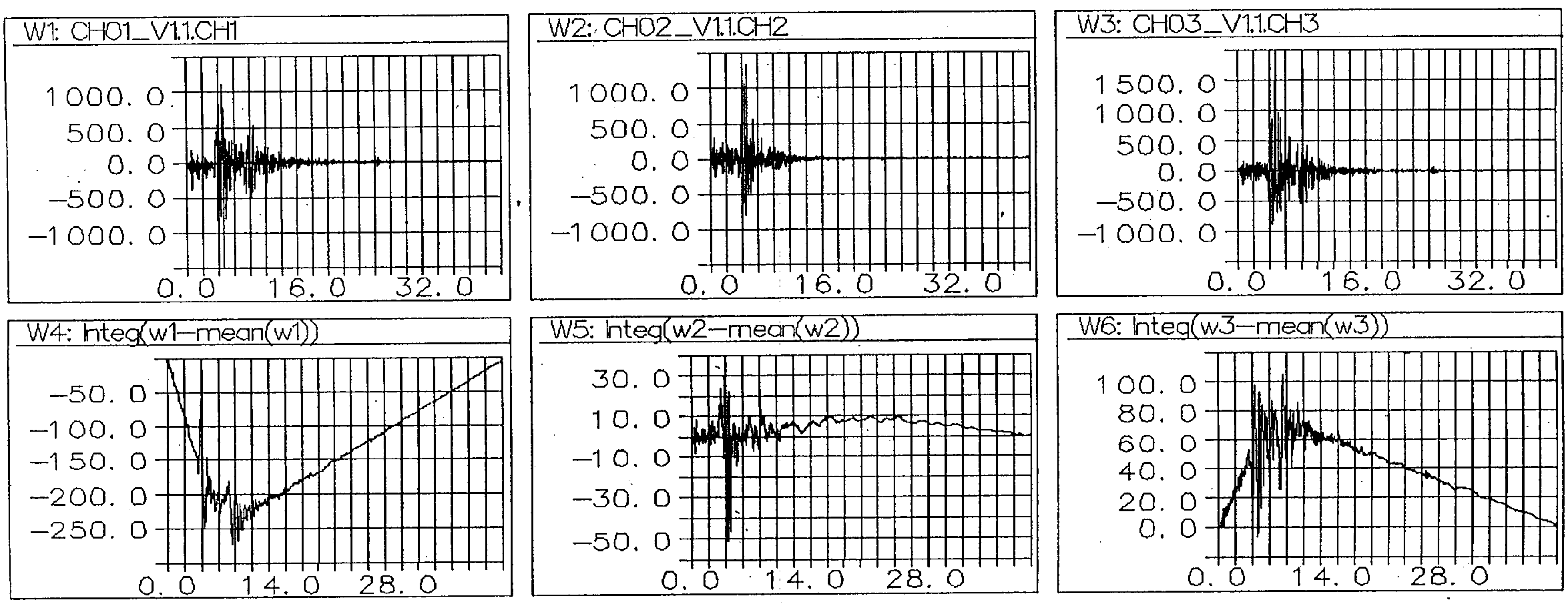


Fig. 4. (Upper) Raw digitized acceleration (cm/sec^2) for Channels 1, 2 and 3 (from Fig. 2).
(Lower) Velocity obtained by numerical integration of the acceleration (cm/sec).

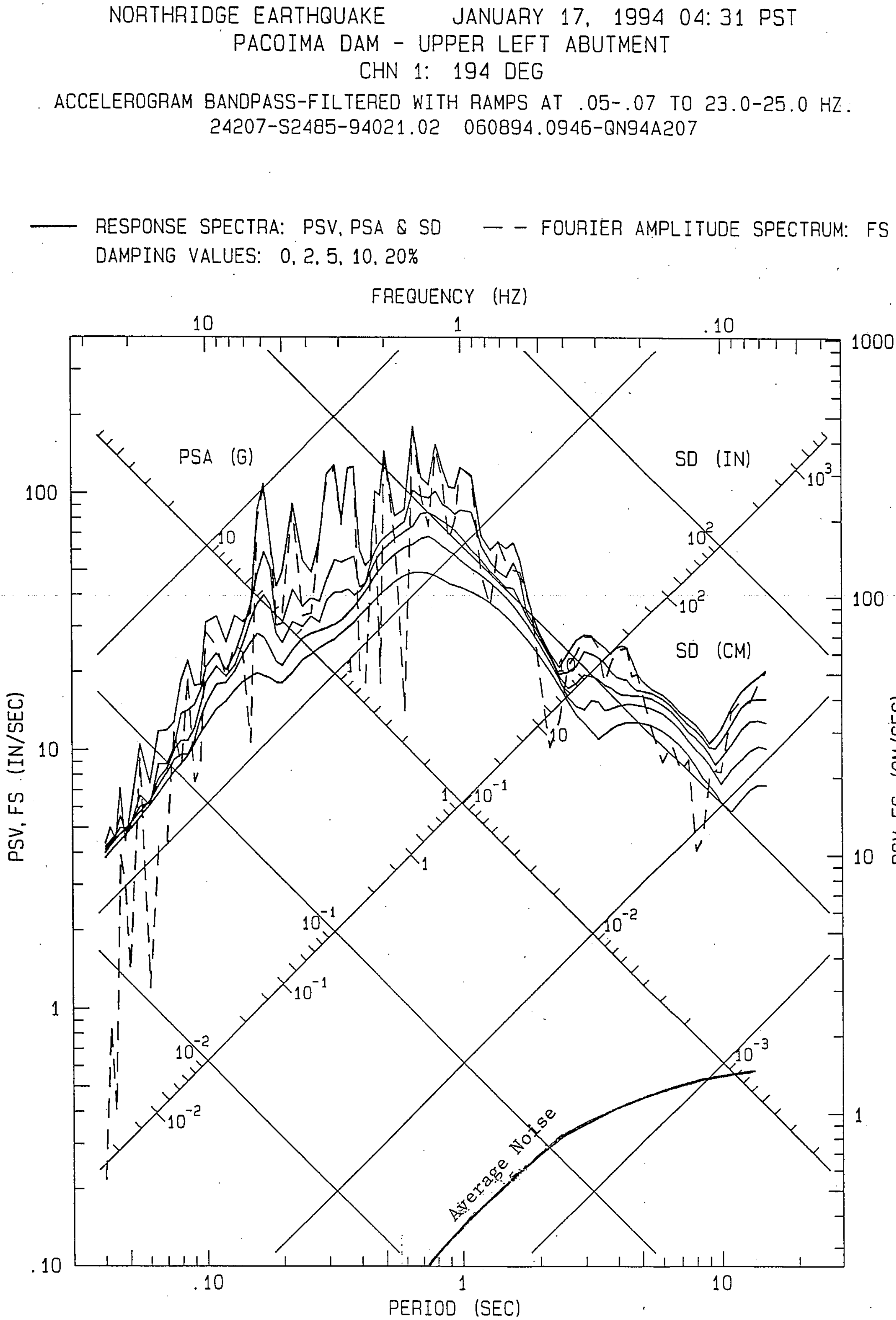


Fig. 3. Full bandwidth (.04 - 15 seconds) initial raw response spectrum for Channel 1 of the Upper Left Abutment record.

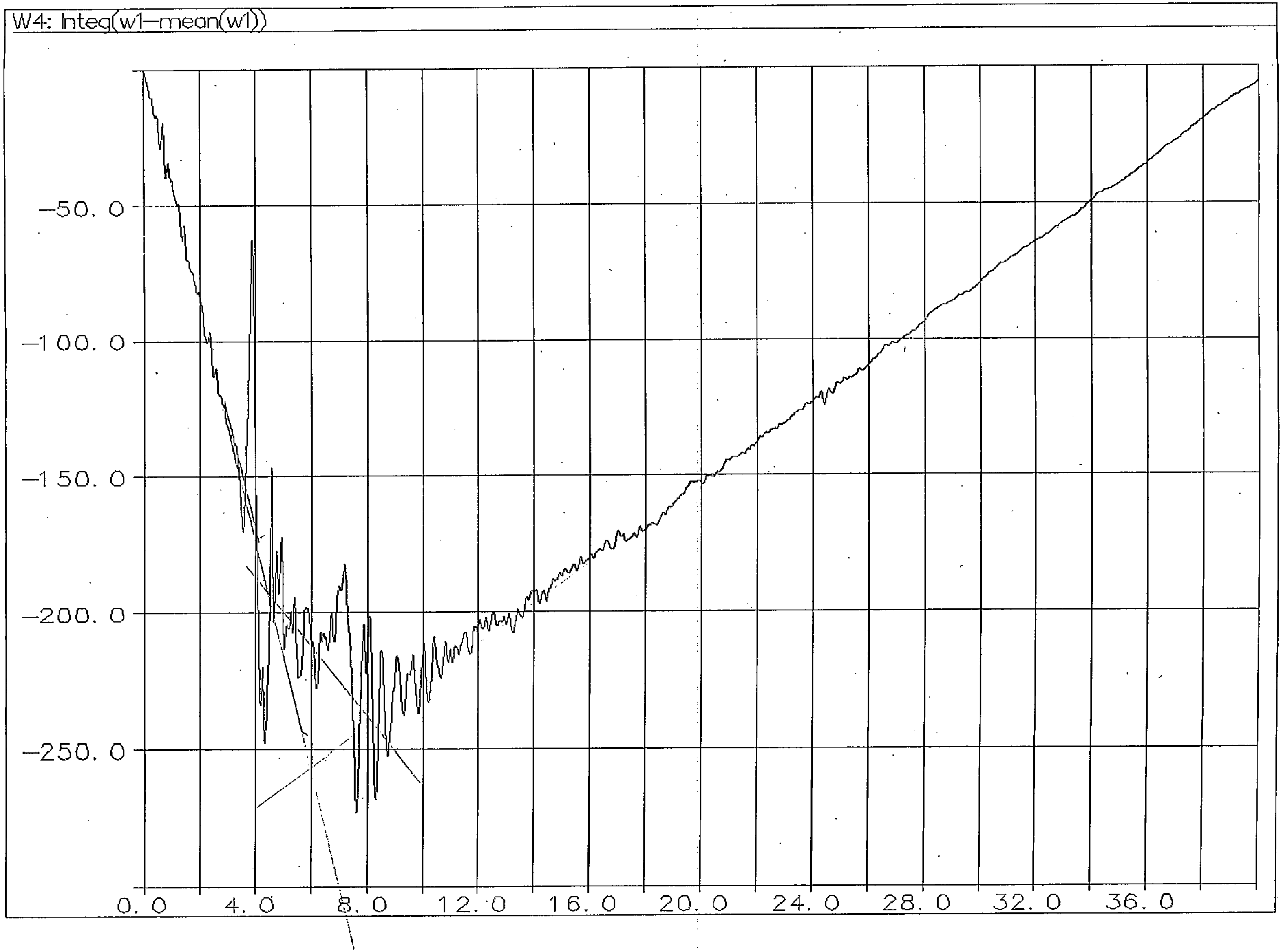


Fig. 5. Enlarged plot of Channel 1 velocity in Fig. 4.

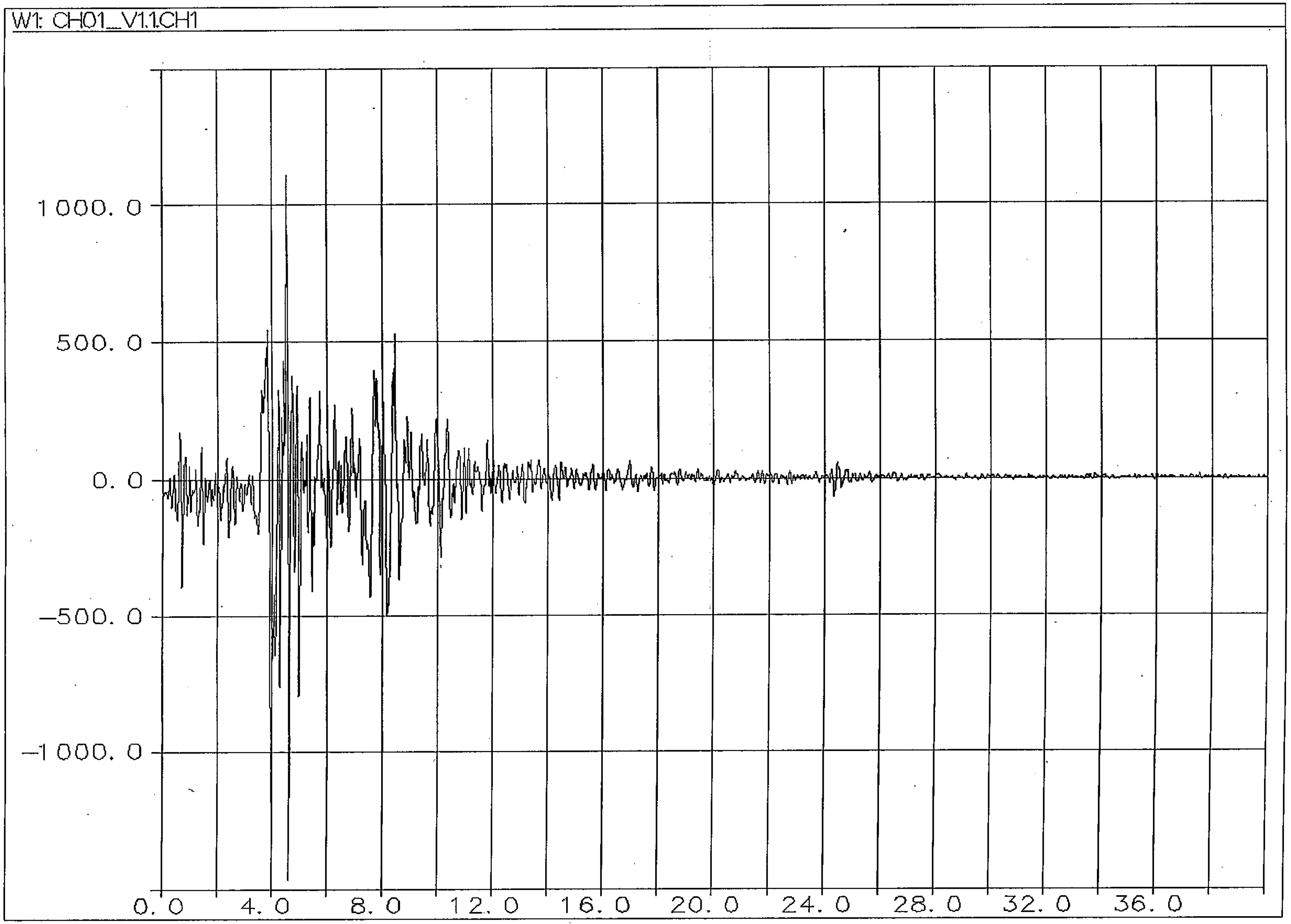
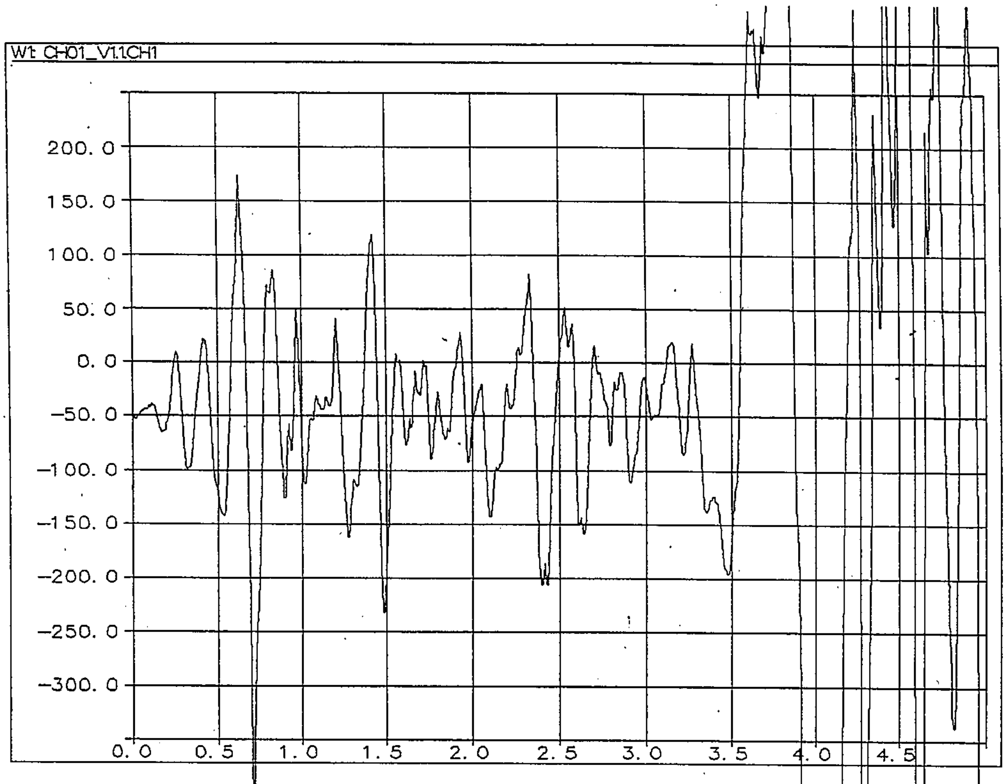


Fig. 6. Enlarged plot of the Channel 1 acceleration in Fig. 4, showing different zero levels at the beginning and end of the record.



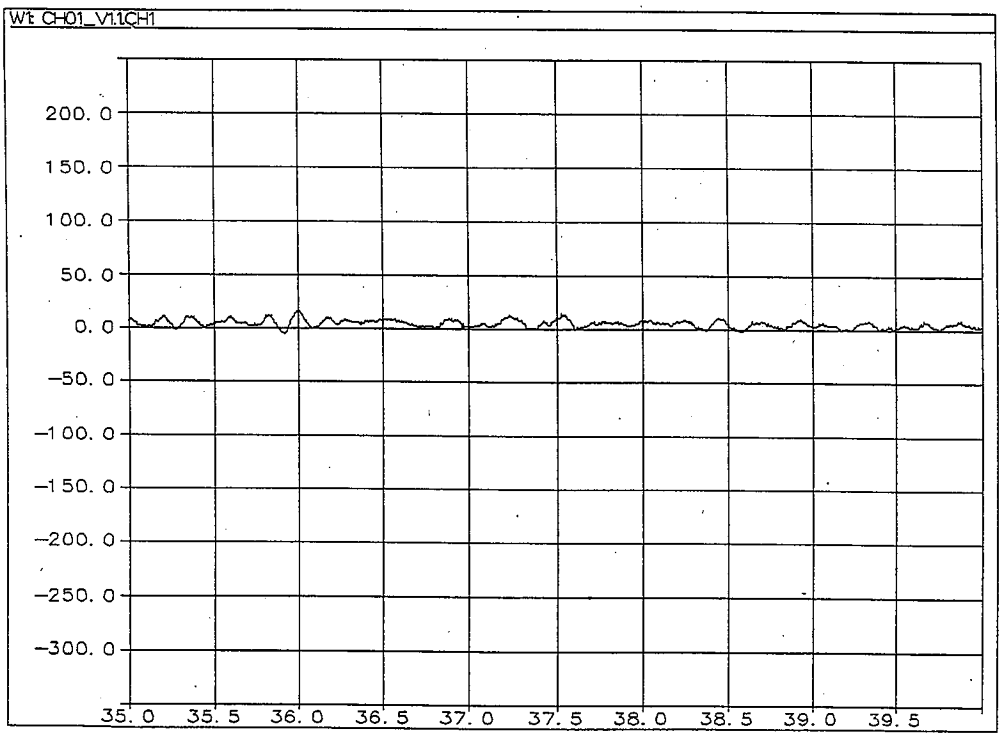


Fig. 7. a) Enlarged plot of first 5 seconds of the Channel 1 acceleration in Fig. 6 (Upper).

b) Enlarged plot of last 5 seconds of the Channel 1 acceleration in Fig. 6 (Lower).

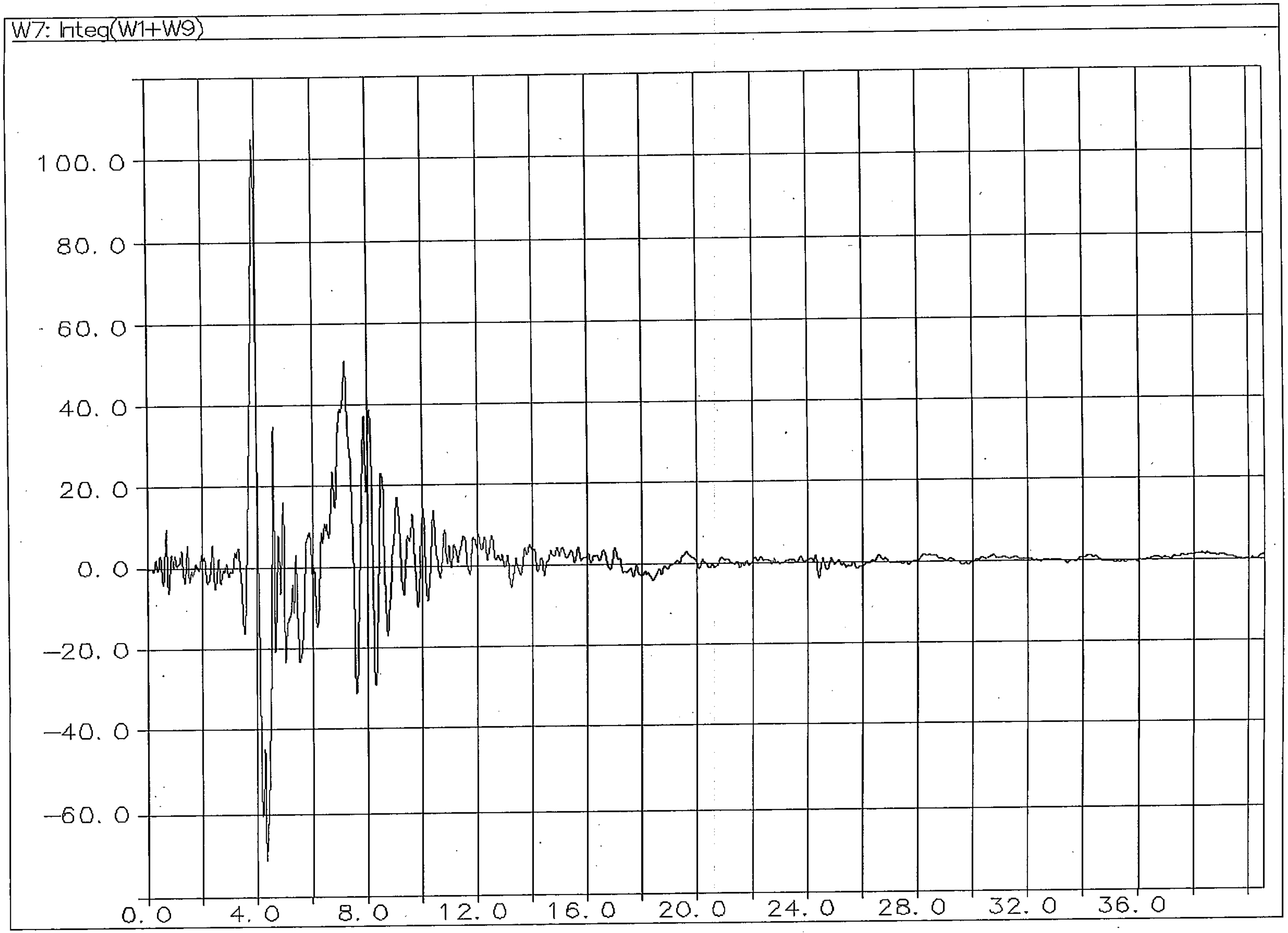


Fig. 8. Channel 1 velocity obtained from integration of acceleration of Fig. 6 after subtraction of the tilt-correction function in Fig. 9 (cm/sec).

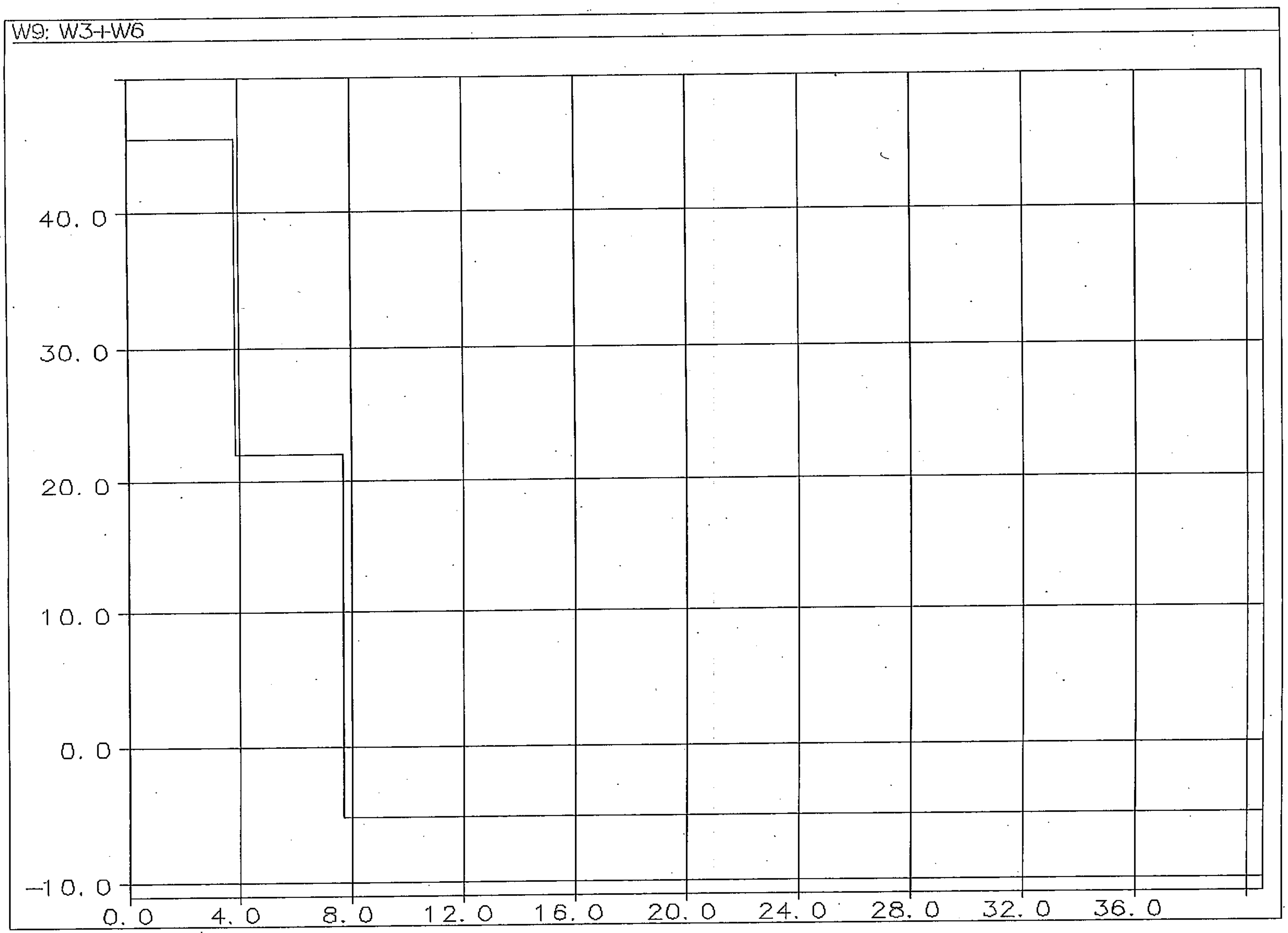


Fig. 9. Tilt-correction function obtained for the Channel 1 (194°) acceleration component (cm/sec^2).

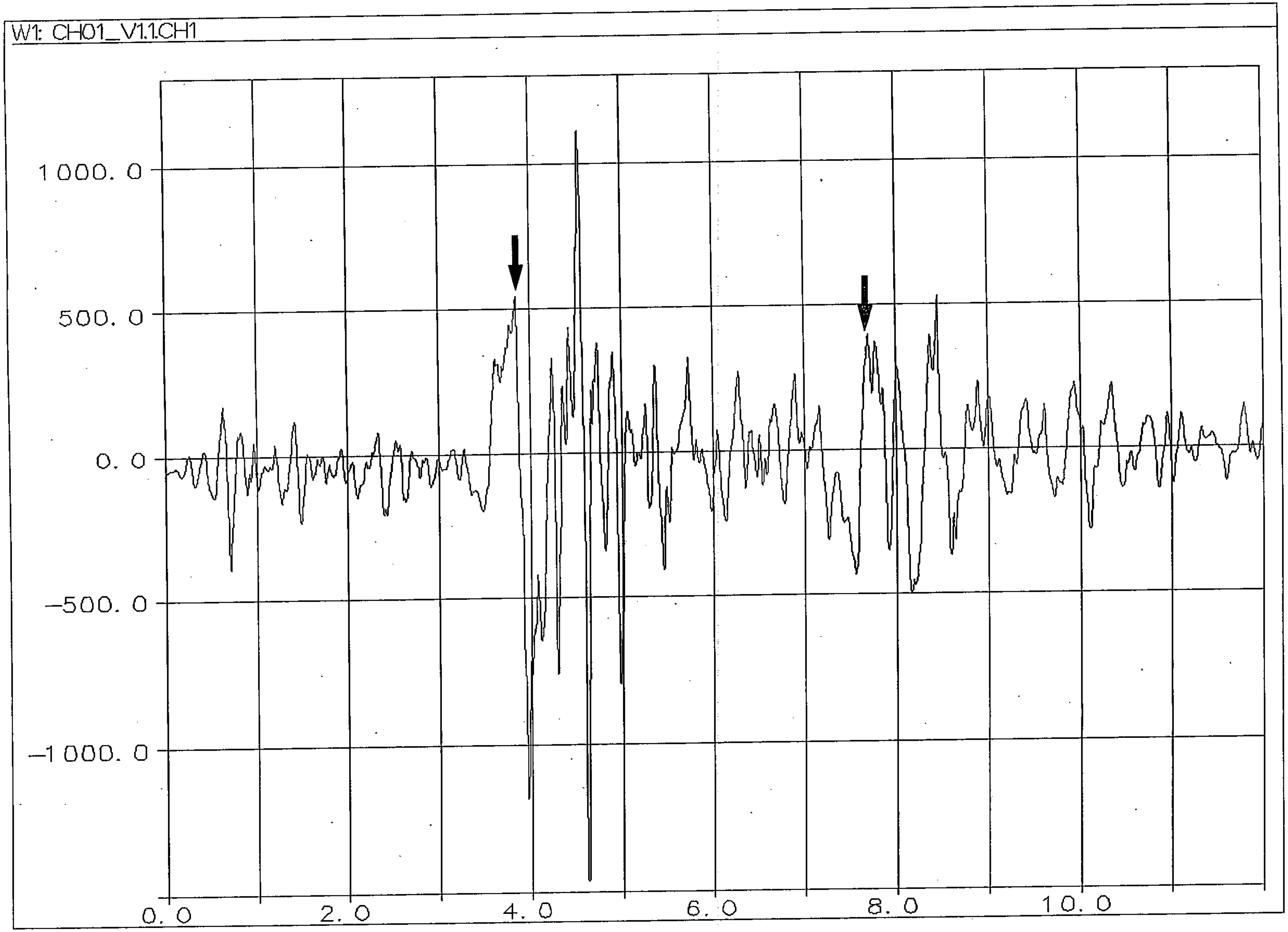


Fig. 10. Times for the step changes in tilt, indicated approximately in Fig. 5, are set to the times indicated (3.85 and 7.70 seconds).

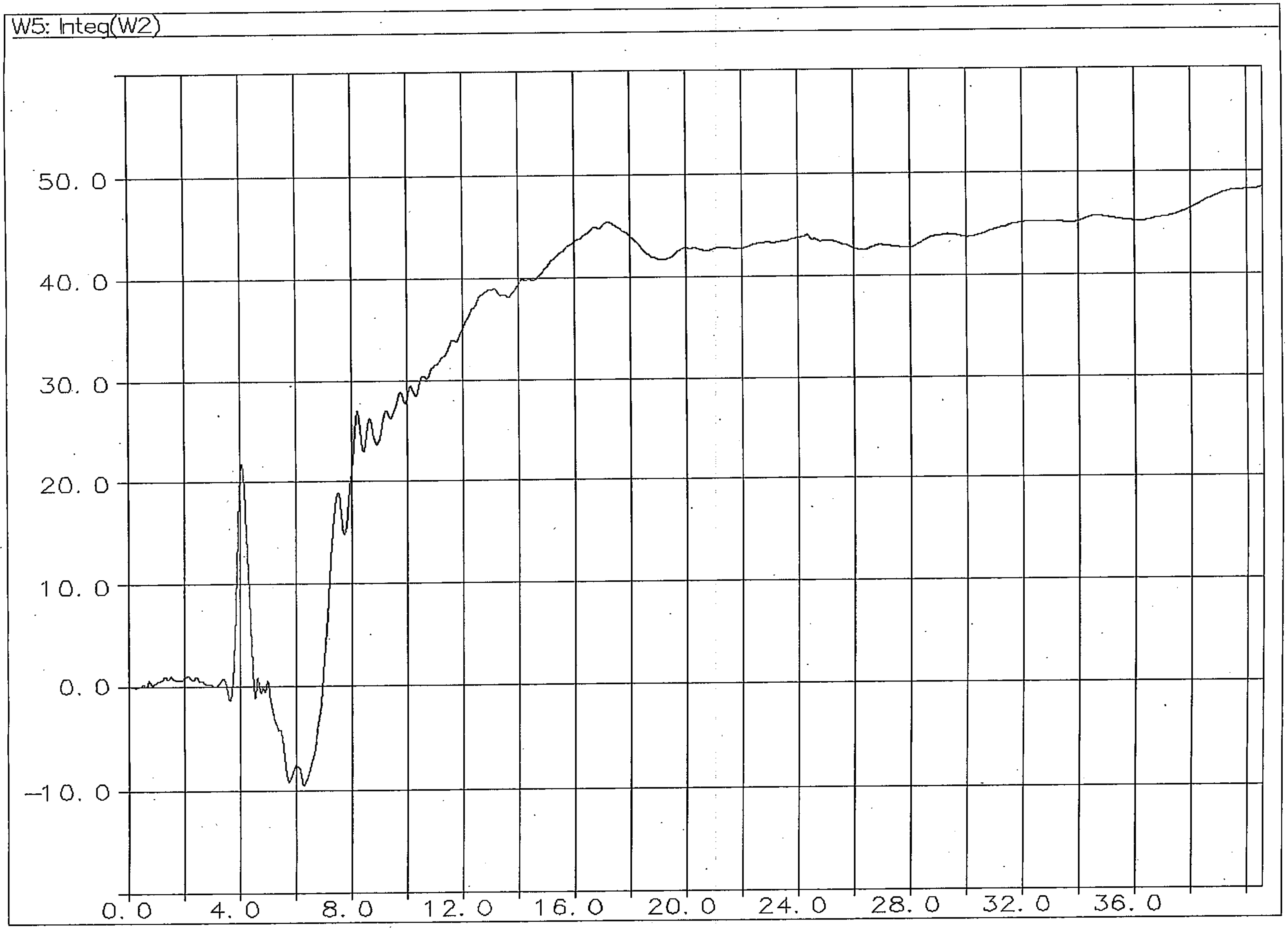


Fig. 11. Displacement for Channel 1 (195°) obtained for the corrected velocity in Fig. 9 by direct integration.

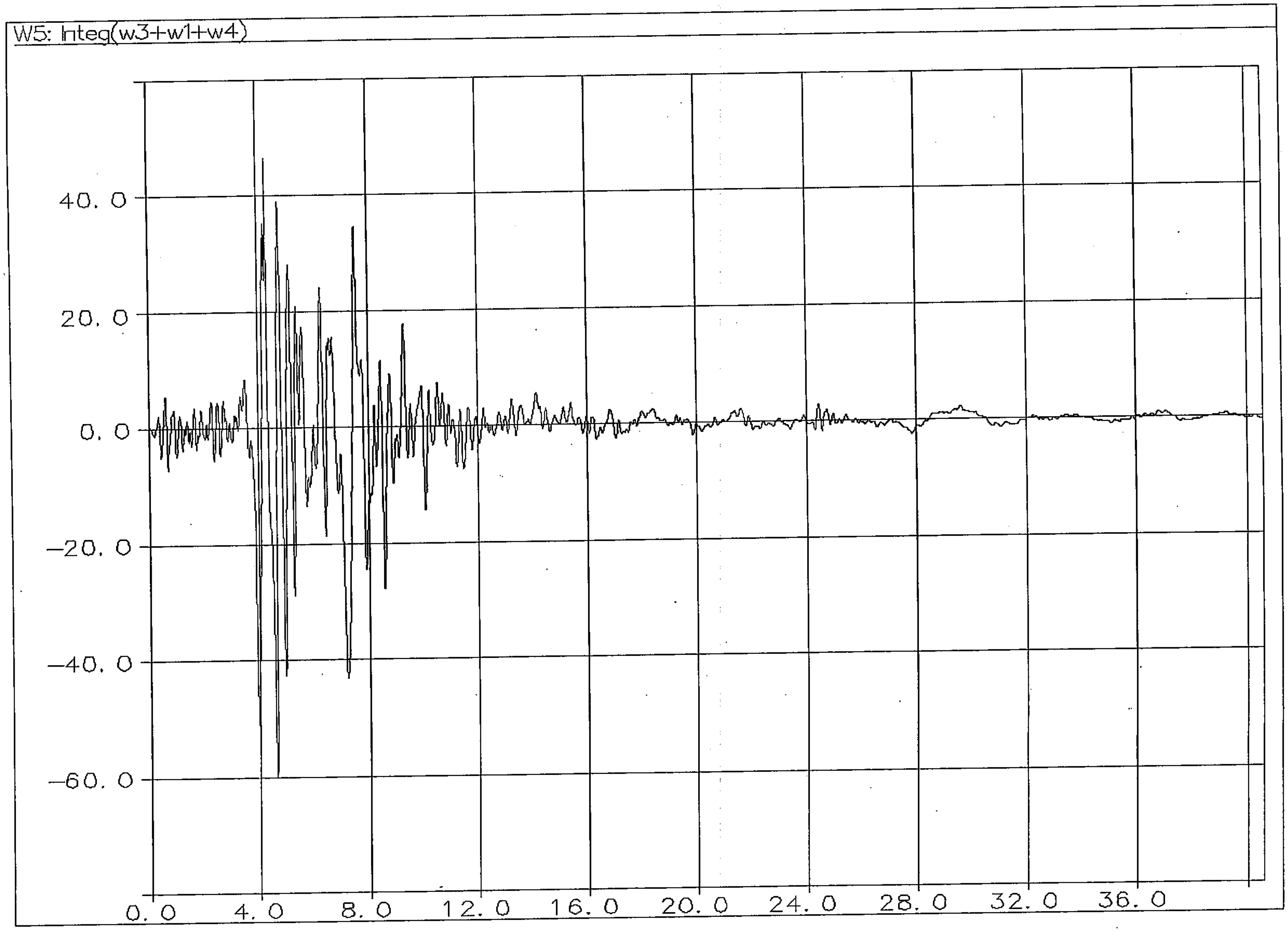


Fig. 12. Channel 3 velocity (cm/sec) obtained from the integration of acceleration after subtraction of the tilt-correction function in Fig. 13 (compare to Channel 3 in Fig. 4).

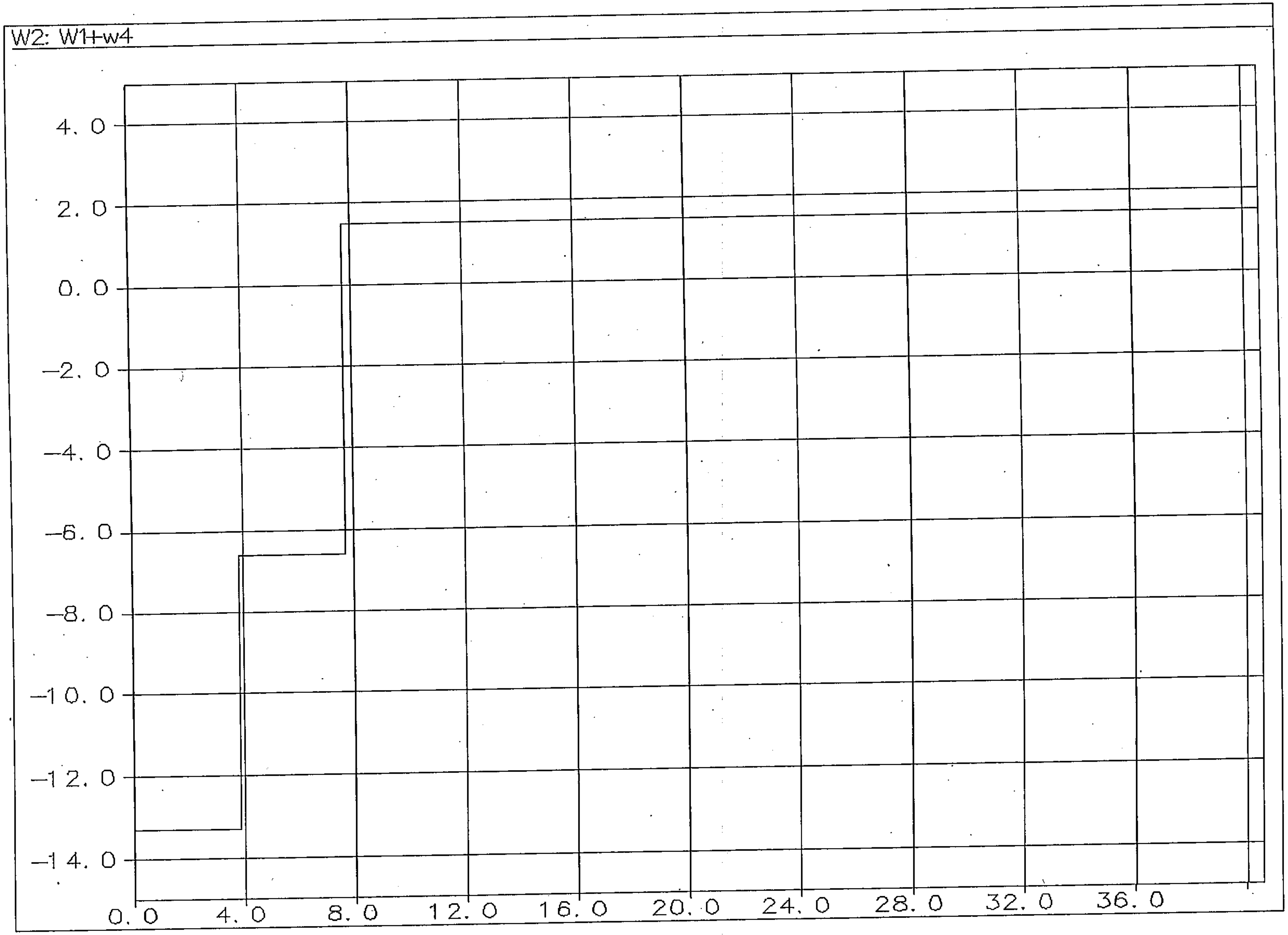


Fig. 13. Tilt-correction function for the Channel 3 (104°) acceleration component (cm/sec^2).

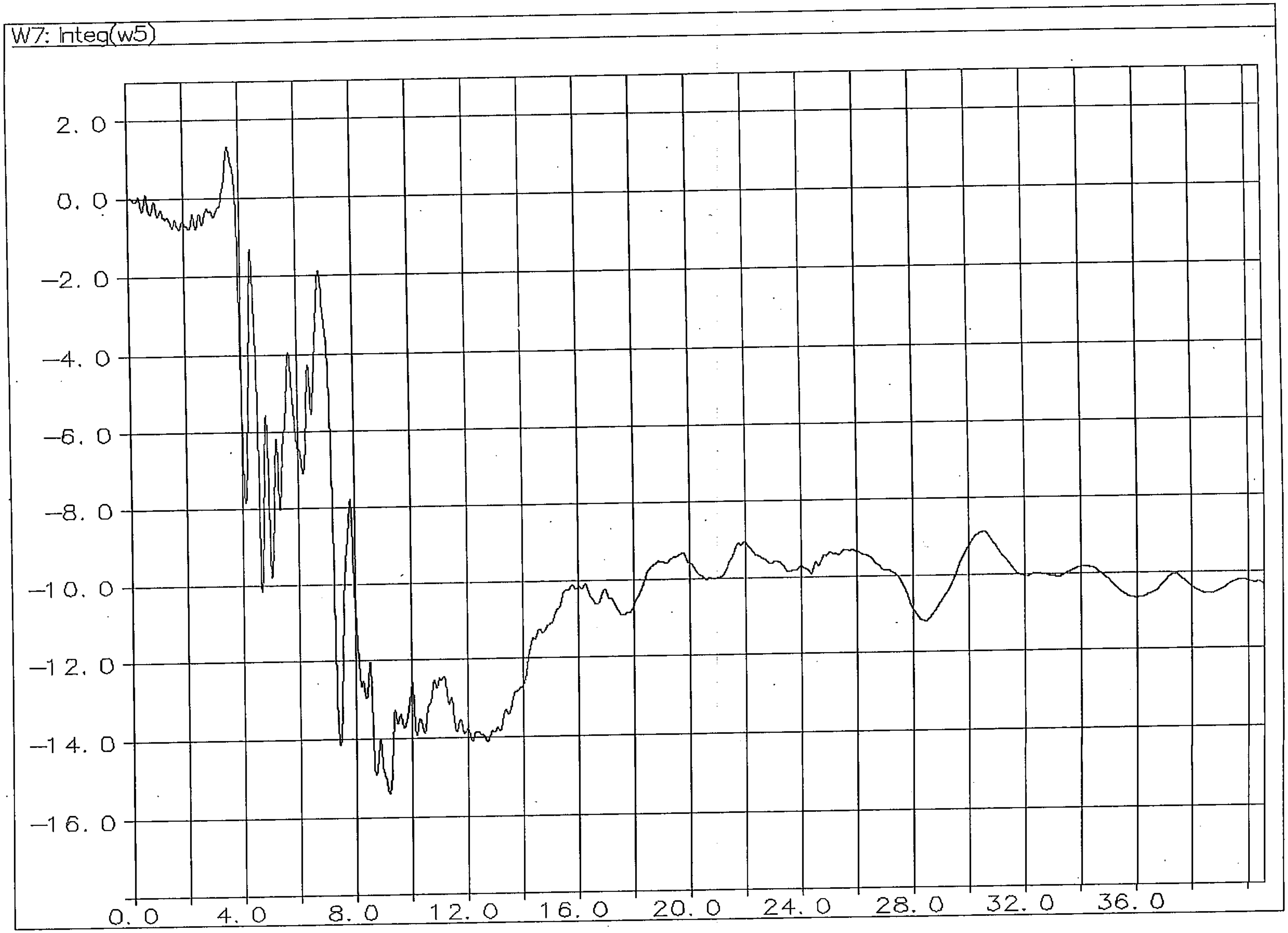


Fig. 14. Displacement for Channel 3 (104°) obtained for the corrected velocity in Fig. 12 by direct integration.

NORTHRIDGE EARTHQUAKE JANUARY 17, 1994 04:31 PST
PACOIMA DAM - UPPER LEFT ABUTMENT
CHN 1: 194 DEG
ACCELEROGRAM BANDPASS-FILTERED WITH RAMPS AT .05-.07 TO 23.0-25.0 HZ.
24207-S2485-94021.02 060894.0927-QN94A207

—— RESPONSE SPECTRA: PSV, PSA & SD — — FOURIER AMPLITUDE SPECTRUM: FS
DAMPING VALUES: 0, 2, 5, 10, 20%

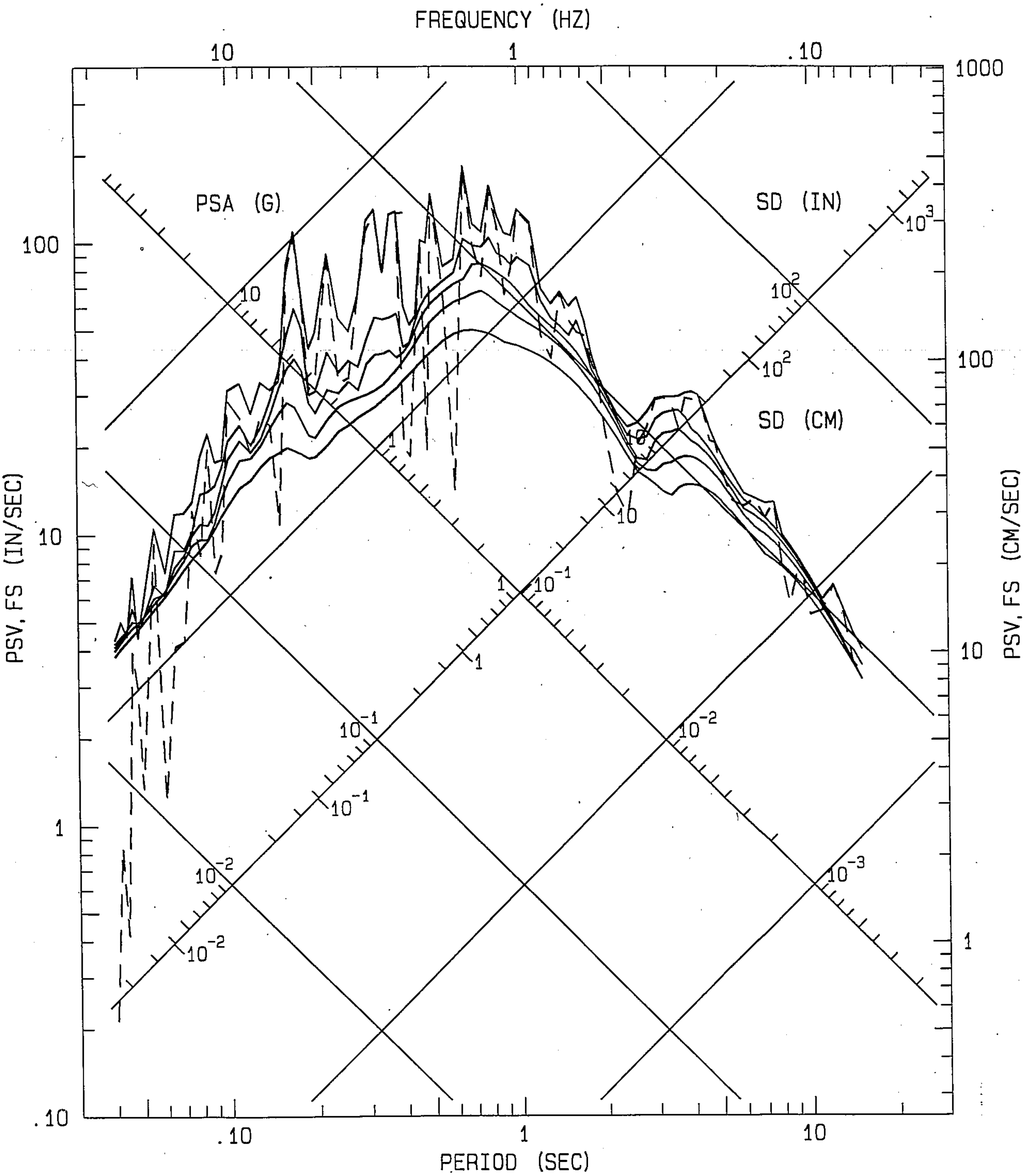


Fig. 15. Channel 1 response spectrum of Fig. 3 recalculated after tilt correction.

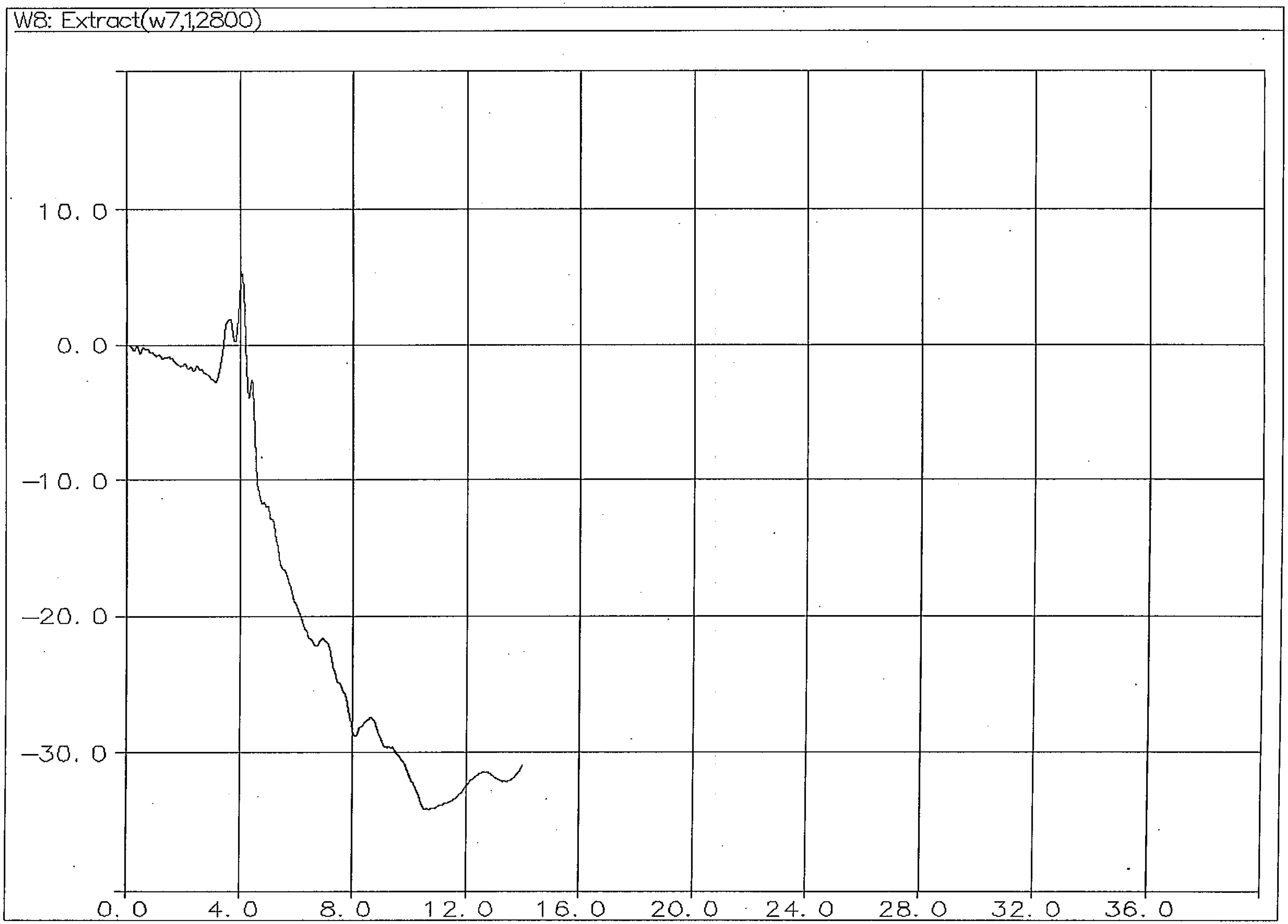


Fig. 16. Vertical displacement obtained for the vertical acceleration corrected as implied by the horizontal component solutions. Noise dominates after about 15 seconds into the record.