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EXPERIMENTAL STUDY OF LEAD AND ELASTOMERIC DAMPERS FOR BASE ISOLATION SYSTEMS

by

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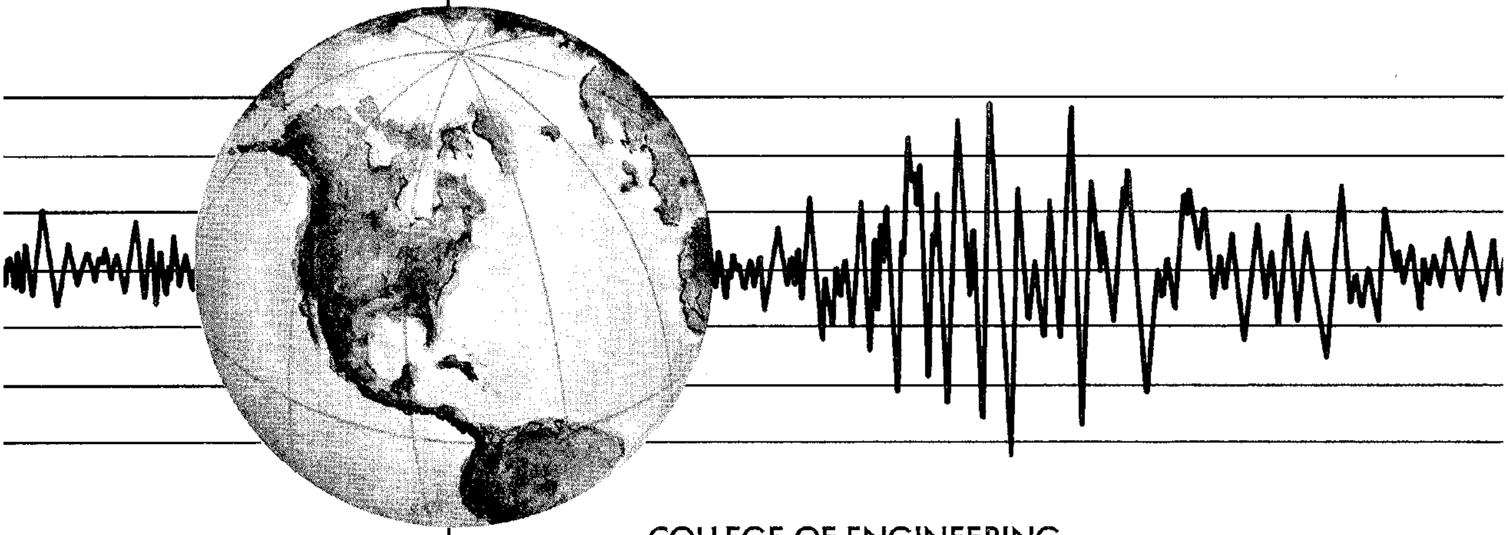

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by

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ABSTRACT

This report describes a series of experiments carried out on the shaking table at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Laboratory, involving a base isolation system which incorporated multilayer isolation bearings of polychloroprene rubber. The Neoprene for the bearings was manufactured by E. I. du Pont de Nemours & Co. (Inc.), Wilmington, Delaware: compounding and processing of the Neoprene and fabrication of the bearings took place at Oil States Industries Inc., Athens, Texas. Several forms of isolation system using the same basic bearing design but including inserts of different materials in a central hole in each bearing were studied. The inserts were used to enhance the damping properties of the system and to improve the response. The results indicate that there are no difficulties in designing an effective isolation system in polychloroprene rubber and that the multilayer elastomeric bearings can substantially reduce the seismic loads experienced by a building and its contents. Elastomeric inserts were effective in improving the response only to a limited extent. The use of lead inserts to enhance the damping was very effective in controlling the displacement. There is an increasing interest in the use of base isolation as a way of reducing the effects of earthquakes on structures. There is general acceptance of the concept but doubts about its implementation center on the question of suitable bearings. Experiments of the kind reported here, on large models where scaling effects are minimized, can allay the fears of the seismic engineering profession that bearings may not be available.

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I. INTRODUCTION

The many thousands of earthquakes that occur each year can cause great loss of life and damage to property when they happen in heavily populated areas. In addition to the buildings which collapse those left standing may have been weakened beyond use or may have had their contents totally destroyed. The damage from an earthquake is caused mainly by the horizontal ground motion, which is amplified by the vibratory response of the building. Standard methods of building for earthquake protection have concentrated on strengthening buildings to resist these horizontal forces. However, when the structure of the building is strengthened it may increase the degree of amplification of the ground motion and while the building may be saved in this way its contents may be more severely damaged and the danger to occupants increased.

This report describes an experimental study on the shaking table at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center of the University of California, Berkeley, of an alternative approach to earthquake protection of structures. This method is called aseismic base isolation. In this approach the building floats on foundation bearings that prevent horizontal ground motions from being transmitted upward into the structure.

The foundation system for the test program incorporated a new design of multilayer bearing in polychloroprene rubber (Neoprene). The bearings were designed by the Polymer Products Department of the Elastomers Division of E. I. Du Pont de Nemours & Co. (Inc.) and were manufactured by Oil States Industries, Inc. Two hardnesses of rubber were used and inserts were used in some tests to increase the damping in the bearings. Two elastomeric materials and lead were used for these inserts.

The results of the shaking table experiments indicate that the polychloroprene rubber bearings can produce effective isolation systems and can substantially reduce the seismic loads experienced by a building and its contents. The elastomeric inserts in the bearings were found to be of limited utility in improving the performance of the bearings, but the lead inserts resulted in improved performance.

There is an increasing interest in the use of base isolation as a way of reducing the effects of earthquake on structures. While there is general acceptance of the concept, doubts about its implementation center on the question of suitable bearings. Experiments of the kind reported here, on large models where scaling effects are minimized, can allay the fears of the seismic engineering profession that bearings may not be available.

II. ASEISMIC BASE ISOLATION

Base isolation is an antiseismic design strategy founded on the premise that a building can be decoupled from the damaging horizontal components of earthquake ground motion through a mechanism that prevents or at least attenuates the transmission of horizontal acceleration into the building. Many unimplemented base isolation systems have been proposed [1], ranging from ball bearings to inverted suspension systems, but the concept has become a practical reality in recent years with the development of multilayer elastomeric bearings. These bearings have been developed for highway bridges [2] to allow for thermal expansion, for helicopter rotors [3], and for wharf fenders [4]. They have recently been used to isolate buildings from the effects of ground-borne acoustic vibration [5]. Some very large buildings have been constructed on multilayer bearings, e.g. the Berlin Conference Hall [6].

Bearings for use in an aseismic isolation system are a natural development of acoustic isolation bearings, and although they differ in design, the manufacture, materials, and installation would be similar. In fact, there are two systems based on natural rubber which have been or are being implemented: namely, three small school buildings in France on a system designed by Delfosse [7] and a four story office building which has been designed and constructed in New Zealand using natural rubber laminated bridge bearings incorporating two inch diameter lead inserts [8]. A nuclear power plant (Kroeberg) on a Neoprene bearing topped by a slip plate system is presently under construction in South Africa [9].

There has been some resistance in the engineering profession to the use of base isolation as an aseismic design strategy connected with a lack of confidence and experience in the use of elastomeric materials in engineering applications, but experience with bridge bearings over many years has demonstrated that they are reliable, long lived, and resistant to environmental damage, including damage from oil and fire [10].

This form of seismic protection depends on lowering the fundamental frequency of the structure to below the range of frequencies which dominate in the earthquake input generally, for buildings on good soil, from 1 Hz to 10 Hz. This method of protection then is applicable to buildings of rigid construction, for example, masonry or reinforced concrete with story heights from 4 to 14 stories. A building of less than 4 stories is relatively easy to make earthquake resistant and one greater than 14 stories will have a natural frequency low enough to be below the dominant range of the earthquake, and will in any case be resistant to lateral loads due to wind load requirements. However, many buildings below 4 stories could benefit from base isolation if they house sensitive equipment which must continue to operate in the aftermath of an earthquake. Examples are hospitals, telephone exchanges, and pumping stations for water or gas pipelines. Recently, circuit breakers at the Edmonston Pumping Plant of the California State Water Project have been mounted on isolators for seismic protection [11].

An important consideration in the design of nuclear and, recently, geothermal power plants in seismically active regions is the assurance of the structural integrity of essential equipment such as pumps, valves, and control devices, and piping systems under earthquake-induced loading. These components are connected to the primary structure, and their response is determined by the response of the primary structure to the earthquake ground motion. The design process for such equipment and for piping systems is a particularly difficult one, complicated both by uncertainties in the specification of the ground motion and by uncertainties in the specification of the primary structure.

Since the secondary systems are driven by the primary structure during seismic motion, it is possible that very high accelerations could be induced in light equipment items. A further complication arises when the equipment or piping system has a natural frequency close to one of the natural frequencies of the primary system — a situation referred to as tuning and one almost inevitable in a large system. In this case, it can be shown that the interaction between the equipment and the structure can be very important, even in relatively light equipment. If this interaction is ignored, as is usually the case in design methods, equipment response will be significantly overestimated and excessively conservative equipment design will result.

Peak earthquake levels for which nuclear and geothermal power plants must be designed have been steadily increased by regulatory agencies over the past several years, leading to the proposal that inelastic action be permitted in the equipment and its supports or that energy-absorbing restrainers be used in piping systems. Since plastic deformation produces a drop in the frequencies of the system and an energy absorption, the response of the equipment or the piping would theoretically be lowered to a level below that which would prevail if the system were to remain elastic. However, plastic action inevitably involves some damage to the equipment supports of the primary structure and will require nonlinear deterministic analysis of both the primary and secondary systems.

Base isolation on elastomeric bearings is an alternative approach to aseismic design in which internal equipment or piping is protected from earthquake motion by constructing the entire power plant on a base isolation system. There are many possible systems, but in essence they all involve a double layer foundation system with a lower element fixed to the ground and an upper element separated from the lower by a decoupling system. The feasibility of a number of possible base isolation systems has been demonstrated by large-scale shaking table experiments at the Earthquake Engineering Research Center of the University of California, Berkeley. The major benefits of base isolation to equipment and piping design are that equipment-structure interaction and inelastic response need not be considered, and, due to the fact that the primary structure above the isolation system moves almost as a rigid body, all support points of a piping system have the same displacement time history. Multiple support response spectrum analysis, with its controversial aspects, thus need not be used.

The research work to be described here concerns an experimental study if different types of base isolation system using Neoprene bearings. It will be shown that in general base isolation will reduce the accelerations experienced by buildings and equipment.

The benefits that base isolation brings to the buildings and their contents in the sense of reduction in acceleration are achieved at the cost of increased relative displacement between the structure and the ground. These displacements can be very large. The recommended design spectrum for nuclear plant [12] specifies a relative displacement of around 30 inches for a 5% damped 0.5 Hz system subjected to a 1.0g peak ground acceleration, while that for buildings in California, according to the recommendations of ATC-3 [13], for the same system and for 0.4g peak ground acceleration, is around 8.0 inches. While there is a very real question as to the validity of these extremely large low-frequency displacements and while the 8.0 inches for buildings would be acceptable, it is unlikely that 30 inches would be acceptable and some control system would be required. In the test series reported here, three methods of controlling displacement through the use of inserts in the bearings have been explored, and these are described in the next section.

III. EXPERIMENTAL PROGRAM

a) Test Facilities

The experiments reported here were carried out at the Earthquake Simulator Laboratory of the Earthquake Engineering Research Center at the Richmond Field Station of the University of California, Berkeley. The main dynamic test facility is a 20 ft x 20 ft shaking table with associated control equipment, described by Rea and Penzien [14].

The shaking table is a 20 ft x 20 ft x 1 ft prestressed concrete slab, driven independently in the vertical direction by servo-controlled actuators. The 100 kip dead weight of the table, plus the weight of the model, is supported by differential air pressure during operation, thus relieving the vertical actuators of any static load-carrying function. The control signals for the two degrees of freedom are in the form of analog displacement time histories on magnetic tape, obtained normally through a double integration of acceleration time histories. The table motion has been demonstrated to have good repeatability.

The limits of table motion with no model are given in reference 13. The displacement limits result from the actuator strokes; oil-pumping capacity limits the velocity, and the acceleration is limited by actuator force capacities and the oil column resonance of the drive system. With a model on the table, the acceleration limits are somewhat lower; the other limits are not appreciably affected.

The data acquisition system, centered around a NOVA 1200 minicomputer equipped with a Diablo 31 magnetic disc unit, is capable of discretely sampling up to 128 channels at rates of up to 100 samples/sec/channel. Transducer signals, in analog form, pass through a NEFF system 620 analog-digital processor. The digitized data are then temporarily stored on a magnetic disc before being transferred to tape by a Wang 9-track magnetic tape drive for permanent storage.

b) Five-Story Frame Structural Model

The experimental model used is shown in Figure 1. It is a five-story frame mounted on two heavy (16WF) base floor girders that are supported by four sets of rubber bearings resting on load cells. The load cells are anchored onto the shaking table with high-tension stress rods. The dead load is provided by concrete blocks tied down to the frame at various floor levels as shown in Figure 1. The weight of the dead load adds up to 72 kip, which gives an approximate total weight of 80 kip for the entire structure. Thus, a compressive force of approximately 20 kip is produced in each bearing. The dead load provided by the concrete blocks produces stress levels comparable to those in a full-scale structural frame, and the geometrical scale factor of the model is roughly 1/3. The corresponding time scale factor will be $\sqrt{3}$.

Although the experimental model has four columns per frame, each frame is carried on only two bearings. It is impractical to carry each frame on a bearing under each column, as would be done in an actual structure, since this would require a very small bearing design and the bearings as manufactured are about as small as can be made by standard techniques. A disadvantage of the use of four bearings under the model rather than eight is that the base frame girders are much larger relative to the structural frame than they would be in a full-scale structure: the appearance of the model exaggerates the proportions that a base slab in a real building would have. Although unfortunate, this is unavoidable particularly in view of the fact that the stability of laminated isolation bearings becomes more critical as the isolation mass per bearing is reduced at a fixed isolation frequency [15].

c) Elastomeric Bearings

The elastomeric bearings for the base isolation tests were designed by the Polymer Products Department, Elastomers Division of E. I. du Pont de Nemours & Co. (Inc.), Wilmington, Delaware and were manufactured and donated by Oil States Industries Inc., Athens, Texas. The Du Pont Neoprene was compounded and compression molded with steel shims in a one-step process to form the multilayer bearings. Oil States Industries Inc. has been manufacturing similar maintenance-free Neoprene bearing pads for prestressed concrete bridges for over 25 years. Du Pont engineers designed the bearings to provide the structural model with a natural frequency of approximately 0.6 Hz in the horizontal direction and 16 Hz in the vertical. A cylindrical bearing design was preferred so as to minimize the formation of localized stress points. A hole was provided in the center of the bearing to facilitate the insertion of dissimilar elastomeric materials. The design of the bearing was based on concepts developed in reference 16.

The dimensions of each bearing were as follows: a cross sectional area of 20.6 square inches; an effective elastomer height of 2.5 inches; a total height of 5.5 inches; an outside diameter of 5.5 inches and an inside diameter of 2.0 inches; 44 layers of Neoprene, each layer approximately 0.057 inch thick; 43 layers of 16 gauge steel, each layer approximately 0.06 inch thick; and end plates 7 inches x 7 inches square and 0.250 inch thick. Two sets of bearings were manufactured, one set in 50A durometer hardness Neoprene and another in 40A hardness. A typical bearing as installed is shown in Figure 2.

Prior to the dynamic testing, the bearings were statically tested in a specially designed press in which a pair of bearings were loaded to a specified vertical force and then horizontally deflected at the midline as shown in Figure 3. These tests were done to verify the horizontal stiffness of the bearings under vertical load and to determine the vertical displacement consequent on horizontal displacement. It is typical of such elastomeric bearings that the horizontal stiffness decreases with increasing vertical load. Under a vertical load of 20 kip, the lateral stiffness of a single 50A durometer bearing was approximately 1.0 kip/in at zero lateral deflection. This stiffness steadily decreased with increasing lateral deflection, reaching a value of approximately 0.4 kip/in at a lateral deflection of 2 inches.

Static compression tests under purely vertical loading were conducted to determine the vertical stiffness under the working load and also to measure the buckling load in the bearings. As in the horizontal stiffness tests, a pair of bearings was tested: this allowed in the testing machine a buckling mode compatible with that under installation conditions beneath the structure. Vertical load-deflection curves for both the 50A and 40A durometer bearings are shown in Figure 4.

Under a vertical load of 20 kip, the vertical stiffness of a single 50A durometer bearing was measured at 600 kip/in, while that for a 40A durometer bearing was 420 kip/in. The peak load carried by the 50A durometer bearing was 53.8 kip, however the 40A durometer bearing was able to sustain a peak load of only 33.4 kip.

d) Damping-Enhancing Inserts

The controlling design criterion for base isolation systems is relative displacement between the ground and the building. As the isolation frequency is reduced the relative displacement increases. One way of reducing the relative displacement without increasing the acceleration is to increase the effective damping in the bearings. However, rubbers both artificial and natural with high damping are subject to creep and reduced strength and it is relatively difficult to produce rubber suitable for an isolation bearing with a damping factor (tan δ) greater than 0.1 which corresponds to 5% of critical equivalent viscous damping in the fundamental isolated mode of structure. Increasing the damping to around 10% of critical damping would improve the displacement characteristics of the isolation system while retaining low acceleration transmission.

One method of increasing damping is to include in the isolation system a set of energy-absorbing devices which operate on the principle of elastic-plastic cyclic deformation of mild steel. Examples of these have been tested on the shaking table, and some have in fact been implemented in practice, and have been shown to be reliable and effective. They have the disadvantage that they require a separate mechanical system to enable them to work with the isolation system.

An alternative method is to include a high damping material in the bearings themselves and this approach if successful eliminates the need for a separate mechanical system. Part of the present study is to assess the effectiveness of such inserts in increasing the damping in the bearings and improving the response of the isolation system.

The bearings were manufactured with a central hole 2.0 inches in diameter: this allowed the insertion of cylindrical plugs of other materials. The insert material is constrained by the steel plates of the bearing to deform almost entirely in pure shear. In the experimental program three damping materials were studied: two of these were elastomeric materials, ADIPRENE† urethane rubber and VAMAC† ethylene/acrylic elastomer, while the third was lead. At 20°C ADIPRENE® has a damping factor (tan δ) of 0.1 and VAMAC® has a damping factor‡ of 0.25. Cylinders of the three materials were cast and machined to 2.0 inches diameter and 5.5 inches high and pressed into the bearings. In the case of the lead inserts only two of the four bearings were filled. Since the table motion is in one horizontal direction, no complication arises if two are filled and two not. There were thus six different foundation systems in the test series, namely:

1) fixed base (FB);
2) 50A durometer hardness bearings (50D);
3) 40A durometer hardness bearings (40D);
4) 50A durometer hardness bearings with ADIPRENE® inserts (50/A);
5) 50A durometer hardness bearings with VAMAC® inserts (50/V);
6) 50A durometer hardness bearings with lead inserts (50/L).

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† ADIPRENE and VAMAC are registered U.S. trademarks of E.I. du Pont de Nemours & Co. (Inc.)

‡ Data obtained from Rhevibron (Toyo Boldwin Co. Ltd.)

IV. EARTHQUAKE SIMULATOR TEST PROGRAM

a) Earthquake Input

Four earthquake input signals, based on records of historical California earthquakes, were used for this test series: each was time scaled at a factor of $\sqrt{3}$. This time scaling of the earthquake inputs corresponds to the geometrical scale of the model, so that the acceleration response of the model to these inputs should correspond to the actual acceleration of a full-scale structure to the historical earthquakes. The displacements in the model will correspond to one third of those for the full-scale structure.

The four earthquake records used were the El Centro 1940 S00E component, the Pacoima Dam 1971 S14W component, the Taft 1952 S69E component, and the Parkfield 1966 N65E component. The El Centro and Taft are typical California earthquake records, one representing a long duration record and the other a short duration signal with dominant frequencies in the 1 Hz to 5 Hz range. The Pacoima record has frequencies in a slightly higher range but has a high-frequency pulse in the middle of the signal that produces a very high acceleration. The Parkfield signal is a short duration signal with low-frequency energy. The Fourier spectra of the four records, and their displacement and acceleration time histories are shown in Figures 5 to 7. It should be noted that each of the originally recorded signals has been filtered to provide an acceptable balance of motion for the table. This is particularly important in the range of frequencies below 0.5 Hz: these low-frequency components have been cut back in order that the table motion is not restricted by displacement limits.

In addition to testing the system with simulated earthquakes, pull-back tests were carried out to determine the response of the model with the various foundations in free vibration, In these tests the model was pulled in one direction by a wire attached to the second floor and a bolt was cut, allowing the model to snap back. Data were collected during the free-vibration period. This allows the frequencies of the system to be estimated and the damping in the fundamental isolation mode for the various isolation systems to be evaluated. The pull-back tests were carried out on the model for all foundation conditions except the lead-filled bearings.

b) Frame Response - Vertical Direction

The frequencies of vibration in the vertical direction for the fixed-base structure were very high and thus the vertical modes are not significantly excited for this case. However the vertical response of the structural model on the laminated rubber bearings must be considered. The frequency of symmetrical vertical vibration for the structural system mounted on the 50A durometer bearings was measured at 13.0 Hz. This is significantly lower than the 17.1 Hz frequency estimated on the basis of a rigid 80 kip superstructure, giving an indication of the effect of the flexibility of the base beam and the frame itself in altering system response. The frequency of rocking on the 50A durometer bearings was measured at approximately 15.8 Hz: this frequency would be significantly increased under full-scale installation conditions with bearings located under each column. A third mode with significant vertical amplitudes, corresponding to base girder flexure, was detected at a frequency of 18.6 Hz. None of these vertical mode frequencies are significantly altered by the inclusion of the elastomeric insert materials.

c) Frame Response - Horizontal Direction

The pull-back tests of the frame in the fixed-base condition gave fixed-base frequencies in horizontal vibration of 3.9 Hz, 12.4 Hz, and 20.0 Hz. On the 50A durometer bearings the first three frequencies were found to be 0.75 Hz, 6.1 Hz, and 14.8 Hz: time histories of base displacement and total base shear for this test are shown in Figure 8. The 0.75 Hz isolation frequency corresponds to a vibration mode which is roughly a horizontal rigid body translation of the frame, while the other two frequencies correspond to the first two structural modes of the model. It is characteristic of base isolation systems that they add a rigid body mode with a low-frequency and increase the frequencies of the deformational modes above their values in the fixed-base system.

The horizontal stiffness of a single 50A durometer bearing assuming that the total weight of the frame was 80 kip and on the basis of a 0.75 Hz isolation frequency is approximately 1.15 kip/in. This stiffness is 15% higher than that measured under static conditions, giving an indication of the difference between bearing properties measured statically and the same properties under dynamic conditions. For the 40A durometer bearings the pull-back test gave 0.50 Hz, 6.0 Hz, and 14.7 Hz for the three lowest frequencies. The estimated horizontal stiffness of a single 40A durometer bearing in this case is thus 0.50 kip/in.

When the ADIPRENE® cylinders were inserted into the 50A durometer bearings the three lateral vibration frequencies were 1.0 Hz, 6.2 Hz, and 15.0 Hz: the lateral stiffness of a single ADIPRENE®-filled bearing is thus 2.0 kip/in. For the bearings with the VAMAC® inserts the frequencies were 0.8 Hz, 6.1 Hz, and 14.9 Hz, and the individual lateral bearing stiffness was 1.3 kip/in. No pull-back tests were performed on the lead-filled bearings due to the inherent nonlinear response of lead.

The response of the frame to the three earthquake signals with combined horizontal and vertical input is summarized in Table 1: no vertical signal is available for the Parkfield record. Table 2 lists the responses to the signals with horizontal excitation only, with the vertical input suppressed.

The reason for conducting tests with horizontal input only is that the model as assembled tends to exaggerate the horizontal accelerations that result from vertical input. This is illustrated in Figure 9, which shows the peak amplitudes of *horizontal* acceleration at each level in the frame mounted on the 50A durometer bearings under combined vertical and horizontal excitation, and also under vertical only and horizontal only input. It is apparent that the horizontal accelerations due to the vertical motion dominate the peak horizontal accelerations recorded under combined excitation.

The spectral amplitudes of horizontal acceleration at each level in the frame under purely vertical excitation is shown in Figure 10. The broad band of significant response between 21 Hz and 26 Hz, particularly noticeable in the accelerations at floor 3 in the frame, is due to high-frequency local vibration modes of individual beams within the frame. These components tend to mask the accelerations produced by the horizontal signal, but due to their significantly higher frequency content have very small displacements and do not markedly alter the overall structural response. The local vibration of the beams is caused by the additional dead load applied in the model, and would occur at much higher frequencies in a full-scale structure.

To demonstrate the significant reduction in accelerations brought about through the use of the isolation bearings, the measured accelerations at all floor levels for the fixed-base, lead-filled and 40A durometer base conditions are shown in Figures 11 through 14. The accelerations for the fixed base case increase almost linearly from the bottom of the frame to a maximum at the fifth floor: generally this maximum is roughly four times the table acceleration.

The effectiveness of the various foundation conditions in reducing the forces applied to the structure is shown in Figures 15 through 18 where the measured accelerations at all floor levels are plotted. In these plots the accelerations for the model in the fixed-base condition are omitted: had they been included, the scale would have had to be so reduced that the differences in acceleration between the various cases would have been obscured. Figure 15 shows the accelerations in the frame when the El Centro signal is used. The maximum table acceleration is roughly 0.54g and the fifth floor acceleration for the fixed-base case is 1.9g. Each isolated case shows accelerations which are roughly constant with height and less than the table acceleration. The 50D bearings show accelerations of roughly 1.0g in the frame and adding the VAMAC® inserts increases the acceleration only slightly. Adding the ADIPRENE® inserts increases the accelerations to 0.12g and adding the lead inserts doubles the accelerations. Generally it can be said that the elastomeric inserts increase the accelerations slightly, but reduce relative displacements across the bearings. In the El Centro record the relative displacement is 2.6 inches with the unfilled 50D bearings, across the VAMAC®-filled bearings it is 2.3 inches, and across the ADIPRENE®-filled bearings it is 1.5 inches.

The 40D bearings show the greatest reductions in acceleration. The accelerations are 11% of the table input and 2.3% of the corresponding fifth floor acceleration in the fixed-base condition.

The results for the other records are similar. For the Parkfield signal, for example, the reductions are somewhat less than for the El Centro signal, but again the 50D bearings produce accelerations of 0.1g and the 40D bearings accelerations of 0.05g, but here the peak input is 0.375g. The maximum fixed-base acceleration is 1.75g, so that the reductions over the fixed-base case are still substantial. For the Pacoima Dam record and the Taft record the reductions are greater than those for the Parkfield signal.

d) Bearing Response

The bearings in the experimental program were mounted on shear load cells which record the shear forces experienced during a test. Relative displacement of the base frame with respect to the floor was measured using linear potentiometers. Time history plots of total base shear and relative bearing displacement for the the unfilled and filled bearings subjected to the El Centro signal are shown in Figures 19 through 22. The hysteresis loops generated by the bearings during a test can also be plotted: examples for the unfilled and filled bearings during a large cycle of displacement in the El Centro record are shown in Figures 23 through 26. From these curves it is possible to estimate the equivalent linear viscous damping ratio based on the ratio of the area of the hysteresis loop to the maximum stored energy. Denoting the area of the hysteresis loop by W_D and the maximum stored energy by W_S, the damping ratio ξ (*i.e.* the ratio of the viscous damping coefficient to that for critical damping) for the fundamental isolated mode is given by $\xi = W_D/4\pi W_S$. This assumes that the system is in steady state at resonance, however it will give a reasonable approximation to the damping ratio in this case. For the 40D bearings the damping is approximately 10% of critical, while for the 50D bearings the damping is 11% of critical. The estimate for the 50D bearings with ADIPRENE® inserts is 8% of critical and for the 50D bearings with VAMAC® inserts the damping ratio is 10%. These damping ratios are consistent with those obtained from the pull back tests which were found to be approximately 11% to 13% of critical.

The measured damping in the structural system is, in each case, much higher than would be expected from the damping factor for the Neoprene itself. The damping factor† tan δ of both the 50A durometer and the 40A durometer hardness Neoprene was recorded as 0.1 at 11 Hz. A value of 0.1 for tan δ corresponds to an equivalent viscous damping ratio of 5% of critical in the fundamental isolated mode of the structure. Damping factors in Neoprene do not vary much with frequency and if at all decrease with decreasing frequency. The shear strains are very much larger in the bearings than in the dynamic testing of the rubber: at the maximum displacement of the 50D bearings in the El Centro signal, 2.6 inches, the shear strain in the rubber exceeds 100%. The fact that the damping ratio for the bearing with ADIPRENE® inserts is only 9% is due to the doubling of the stiffness of the bearing, thus reducing the effective damping. It is clear that the reduction in displacement produced by the ADIPRENE® inserts is due to the increase in frequency rather than to increased damping. The VAMAC® inserts produce a 15% increase in stiffness and an increase in the energy dissipated but the damping ratio itself is unchanged. The conclusion to be drawn from these results is that the inserts are not effective in reducing response. The effect of the ADIPRENE® could be achieved more simply merely by using a larger bearing: the influence of the VAMAC® insert, although it adds some dissipation, is not significant. There simply is not enough material in the insert to dissipate enough energy to

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† Data obtained from Rhevibron (Toyo Boldwin Co. Ltd.)

produce a worthwhile change in the response.

The response of the 50D bearings without inserts was tested further to determine the limiting displacement to which the bearings could be subjected. The input signal was increased from a peak horizontal acceleration of 0.54g to 0.68g which produced a relative displacement of 3.5 inches across the bearings. The accelerations in the frame remained roughly around 0.10g to 0.11g, that is, the table acceleration was increased by 25%, but the response remained almost unchanged. This suggests that at larger strains the effective stiffness is reduced and the effective damping is increased. The input peak horizontal acceleration was again increased, to 0.835g, which produced a maximum bearing displacement of 4.2 inches: this displacement indicates a shear strain of 170% in the elastomer. The frame accelerations were now around 0.12g. The accelerations of the base and fifth floor are plotted as a function of the table acceleration in Figure 27. The structural accelerations change only slightly with increasing earthquake intensity: the explanation for this is that the bearing properties are changing in a manner favorable to protection of the structure. The increase in displacements with increased earthquake intensity is also shown in Figure 27. No external evidence of failure was observed. That the effective stiffness is reduced and the effective damping increased for these large bearing deformations is clear from the hysteresis loops show in Figures 28(a) through (d). The fattening of the loops at the large excursion is clear and in two bearings there is a reduction in stiffness. The two bearings with the reduced stiffness are those for which there is an increased compressive load due to the overturning moment. Although the overturning moment is small since the frame accelerations are small (the increase in bearing load is only 20%), the additional compressive load coupled to the large lateral displacement has a large effect on the horizontal stiffness.

e) Lead-Filled Bearings

The response of the structural model on the lead-filled bearings is markedly different from that on the unfilled or elastomer-filled bearings. The lead appears to act as if it were almost rigidly perfectly plastic with a yield shear stress of approximately 1.4 kip/in^2. The response of the frame for very small input motion is thus similar to the fixed-base response, however as the intensity of the motion increases the effective stiffness drops and the amplification of the input acceleration is reduced. As the lead yields, significant energy dissipation occurs. In effect, the lead acts as a mechanical fuse and an energy dissipator, and the damping per cycle increases almost linearly with displacement. In this way the lead produces an almost ideal isolation system and combined with the compactness of the lead/bearing assembly produces a very effective system.

The accelerations experienced by the frame on the lead-filled bearings are always less than the input accelerations for the comparison cases shown in Figures 15 through 18. They are higher than for the other foundation systems, but the relative displacements are lower. For the El Centro signal with a peak table acceleration of 0.54g, the frame accelerations (Figure 15) are between 0.20 and 0.25g and the frame responds more or less as a rigid body. The relative displacement at the bearings is reduced to 0.86 inches from 2.6 inches for the unfilled bearings. The lead is nonlinear in its response and in principle a permanent deformation after yielding is possible. The nonlinearity also implies that the response should be dependent on previous history. In fact no permanent deformation was observed after a test and there was no dependence on previous history. Four runs were carried out on the model using the same input signal (El Centro). As shown in Figure 29, the accelerations recorded on the model varied slightly but unsystematically and were no more than the variations in the peak table input acceleration. A possible explanation for the lack of permanent displacement and history dependence is that the portion of greatest intensity of the earthquake which would produce the largest accelerations and relative displacements and produce permanent set in the bearings is followed by a period of lower intensity where some yielding of the lead takes place. During this period the centering action of the rubber forces the lead back to the neutral position and over several cycles of reduced yielding the permanent force in the lead disappears, allowing the system to restart more or less in an unloaded, undisplaced initial condition.

The nonlinear response of the system and the increased isolation with increased input intensity is shown in Figures 30 through 34. To demonstrate this effect the model was subjected to a series of El Centro input motions with steadily increasing intensity from a peak acceleration of 0.115g to one of 1.46g. As the table accelerations increase over this range by a factor of more than ten, it is shown in Figure 30 that the fifth floor accelerations and the base accelerations increase only by factors of around five. The nonlinearity of the lead compared to the linearity of the unfilled bearings is shown in Figure 30. To demonstrate the increased isolation with increased intensity the accelerations in the frame have been plotted as normalized with respect to the peak table acceleration. The convergence to a reduction factor of 40% of the input acceleration is clear (Figure 32). A plot of normalized displacement, normalized fifth floor acceleration, and normalized base acceleration is shown in Figure 33. It is interesting to note that while the accelerations decrease, the relative displacement remains almost exactly equal to the peak table displacement over the entire range of input (Figure 34).

Hysteresis loops for the lead-filled bearings are shown in Figures 35 through 38. The first can be compared with those for the other foundation systems with the same earthquake input (Figures 23 through 26). The total effective base stiffness is 13 kip/inch, compared with 4.6 kip/inch for the unfilled bearings and based on the area of the hysteresis loop the equivalent viscous damping ratio is approximately 35%. For the much larger earthquake shown in Figure 36, the effective stiffness of the bearing system becomes 7 kip/inch and the equivalent viscous damping factor is again around 35%.

Since two bearings contained lead inserts and two did not it is easy to obtain the force in the lead by subtraction and this is shown in Figures 37 and 38. The force in the lead when yielding is almost constant at 9 kip, which corresponds to a shear stress of 1.4 kip/in^2. The shear strain in the lead at maximum displacement is roughly 45%. The yield shear strain is difficult to estimate from these plots, but based on a Young's modulus value of 2.4 x 10^6 lb/in^2 it is around 0.15%: the ductility factor for the lead is thus 300. This is an exceptionally large ductility factor in engineering practice, but lead appears to be capable of sustaining unlimited cyclic plastic deformation without failure. This ability is due to the fact that at ambient temperatures the lead is being *hot worked*: during cyclic plastic deformation the lead is continually able to recover its original mechanical properties [17].

It seems clear from the results that the amount of lead in the bearings was greater than optimum. Previous tests with an energy-absorbing base isolation system have suggested that the optimum response is obtained when the yield level is around .5% of the weight of the structure. Here the yield level was around 10% of the weight of the structure and thus the accelerations could be reduced and the degree of protection increased while maintaining displacements within safe limits for the bearings.

V. CONCLUSIONS

The experimental program has shown that the multilayer isolation bearings of polychloroprene can be effective in protecting buildings from damage by earthquake ground motion. The 50A durometer hardness bearings are capable of sustaining a relative lateral displacement of 75% of their diameter without buckling and the material itself is capable of sustaining a shear strain of 170% without failure. The reductions in acceleration experienced by the superstructure as compared to conventionally designed structures vary with earthquake signal, but are not less than a factor of 10 and can be much higher. Although the 40A durometer bearings achieved the greatest overall degree of structural protection under the simulated earthquake inputs considered, they were too close to their stability limit to be considered candidates for full-scale application.

The peak earthquake accelerations at which the maximum deformations of the bearings were achieved were 0.835g. For most buildings and structures in California the peak design accelerations are not greater than 0.4g [13] and in such cases a simple rubber bearing isolation system would suffice. At that level of peak earthquake acceleration the maximum relative displacement would be on the order of 6 inches for bearings with 10% of critical damping as in this study and around 8 inches if the bearings had a damping factor of only 5% of critical.

For nuclear plants the very low probability seismic events for which the plant must be designed could require a much higher design peak acceleration than could be accommodated by a simple rubber bearing base isolation system. The energy-dissipating base isolation system in which rubber bearings and lead inserts are integrated then becomes an ideal choice for seismic protection. No other structural design strategy can simultaneously protect a structure at such earthquake intensities and limit the forces applied to sensitive internal equipment.

The effectiveness of base isolation on multilayer elastomeric bearings has been demonstrated by these and other experiments. The remaining unanswered question is the cost. The bearings themselves are not expensive items, particularly if many are manufactured. Increased foundation costs are required mainly because of the need for a seismic gap around the structure. This would require the foundation pit to be surrounded by a retaining wall. The gap would be covered by an elastomeric seal and the foundation pit used for parking, for example, or mechanical purposes.

The savings on the other hand on the construction of the superstructure could offset these increased costs. Seismic shear walls would be diminished and other structural elements reduced. Bracing for ceiling suspended components and for mechanical and electrical components would be reduced.

A study was carried out [18] of the comparative cost of an isolated and a conventionally founded six-story medical building with roughly 170,000 square feet as shown in Figure 39. A potential savings using base isolation of $107,000 was estimated for the structural system alone. However, further savings could be possible since a major portion of the cost of a medical facility is in sensitive equipment. If this equipment must be braced or attached to walls in such a way as to protect it against earthquakes its mobility will be greatly reduced. Equipment that cannot be moved conveniently from one location to another within the building due to earthquake bracing will have to be replicated many times. Thus, it seems clear that base isolation must reduce the cost of buildings where the protection of equipment is paramount. Decreased costs with increased safety are the driving force behind all structural engineering research, but aseismic base isolation offers the best method for the achievement of these goals.

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LIST OF FIGURES

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	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	Rel Base Displ (in)	Base Shear (k)	V Table Accel (g)	V Fl 5 Accel (g)
Fixed Base	0.520	0.500	1.894	0.924	0.000	69.1	0.365	0.675
50/Lead	0.543	0.260	0.345	0.914	0.931	10.91	0.399	0.764
50/ADIPRENE®	0.553	0.235	0.408	0.914	1.509	8.01	0.400	0.752
50/VAMAC®	0.536	0.154	0.234	0.917	2.331	7.02	0.402	0.619
50 Durometer	0.562	0.171	0.208	0.914	2.362	7.13	0.415	0.664
40 Durometer	0.555	0.104	0.169	0.915	2.160	3.04	0.422	0.585

Table 1(a). El Centro input signal: V=200, H=200

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	Rel Base Displ (in)	Base Shear (k)	V Table Accel (g)	V Fl 5 Accel (g)
Fixed Base	1.042	2.602	4.550	1.522	0.200	166.0	0.622	1.914
50/Lead	1.282	0.466	0.716	1.534	2.450	16.32	0.583	0.804
50/ADIPRENE®	1.319	0.190	0.358	1.527	2.672	10.39	0.589	0.667
50/VAMAC®	1.296	0.181	0.205	1.527	2.058	6.69	0.613	0.656
50 Durometer	1.287	0.210	0.220	1.523	2.011	6.22	0.557	0.638
40 Durometer	1.290	0.165	0.266	1.534	1.734	2.95	0.618	0.655

Table 1(b). Pacoima Dam input signal: V=200, H=300

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	Rel Base Displ (in)	Base Shear (k)	V Table Accel (g)	V Fl 5 Accel (g)
Fixed Base	0.536	0.464	1.640	1.862	0.020	59.8	0.520	0.523
50/Lead	0.548	0.322	0.336	1.817	1.519	13.82	0.436	0.443
50/ADIPRENE®	0.546	0.244	0.230	1.806	2.761	10.96	0.441	0.523
50/VAMAC®	0.541	0.189	0.191	1.806	2.972	8.66	0.445	0.470
50 Durometer	0.527	0.173	0.225	1.804	3.430	8.03	0.404	0.480
40 Durometer	0.541	0.122	0.143	1.812	2.893	3.97	0.450	0.496

Table 1(c). Taft input signal: V=350, H=350

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	H Base Displ (in)	H Fl 5 Displ (in)	Rel Base Displ (in)	Base Shear (k)
Fixed Base	0.379	0.861	1.810	1.526	1.692	3.178	0.117	66.0
50/Lead	0.377	0.320	0.361	1.508	2.053	2.374	1.878	14.43
50/ADIPRENE®	0.374	0.202	0.218	1.511	3.174	3.407	3.366	11.81
50/VAMAC®	0.370	0.117	0.123	1.513	2.410	2.542	2.629	7.33
50 Durometer	0.375	0.098	0.112	1.514	2.321	2.373	2.565	6.76
40 Durometer	0.378	0.052	0.067	1.511	1.426	1.489	2.771	3.28

Table 2(a). Parkfield input signal: V=0, H=300

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	H Base Displ (in)	H Fl 5 Displ (in)	Rel Base Displ (in)	Base Shear (k)
Fixed Base	0.555	0.681	2.629	0.908	0.920	1.936	0.138	95.9
50/Lead	0.553	0.245	0.271	0.910	1.197	1.338	0.885	11.26
50/ADIPRENE®	0.531	0.119	0.134	0.915	1.695	1.822	1.480	7.98
50/VAMAC®	0.535	0.103	0.112	0.910	2.200	2.330	2.263	6.95
50 Durometer	0.534	0.100	0.110	0.909	2.255	2.306	2.589	6.63
40 Durometer	0.543	0.050	0.059	0.912	1.309	1.372	2.077	2.81

Table 2(b). El Centro input signal: V=0, H=200

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	H Base Displ (in)	H Fl 5 Displ (in)	Rel Base Displ (in)	Base Shear (k)
Fixed Base	0.588	0.836	1.909	1.874	2.028	2.816	0.137	69.6
50/Lead	0.581	0.282	0.355	1.822	2.688	2.871	1.455	13.68
50/ADIPRENE®	0.576	0.151	0.165	1.808	3.267	3.415	2.819	10.35
50/VAMAC®	0.562	0.130	0.147	1.809	3.002	3.140	3.000	7.92
50 Durometer	0.548	0.156	0.235	1.808	2.950	3.101	3.430	8.03
40 Durometer	0.558	0.069	0.069	1.820	1.850	1.905	2.607	2.90

Table 2(c). Taft input signal: V=0, H=350

	H Table Accel (g)	H Base Accel (g)	H Fl 5 Accel (g)	H Table Displ (in)	H Base Displ (in)	H Fl 5 Displ (in)	Rel Base Displ (in)	Base Shear (k)
Fixed Base	1.047	1.076	2.833	1.578	1.683	2.496	0.127	103.3
50/Lead	1.330	0.471	0.690	1.537	1.482	1.902	2.473	16.52
50/ADIPRENE®	1.283	0.133	0.193	1.520	1.336	1.533	2.685	10.47
50/VAMAC®	1.292	0.120	0.157	1.521	0.812	0.878	2.063	6.53
50 Durometer	1.287	0.210	0.220	1.523	0.755	0.819	2.011	6.22
40 Durometer	1.258	0.071	0.112	1.531	0.625	0.647	1.794	2.47

Table 2(d). Pacoima input signal: V=0, H=300

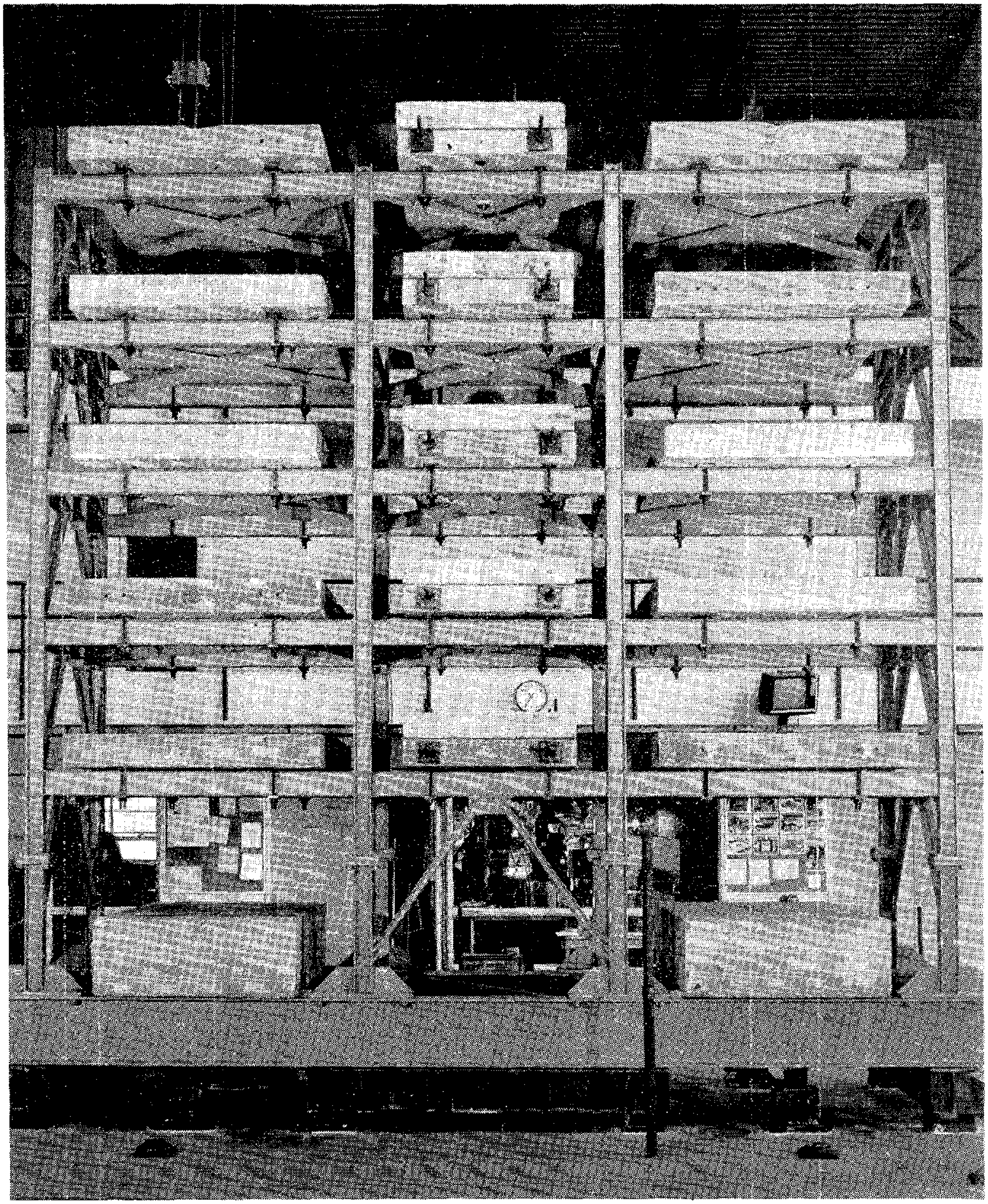


Figure 1 Five story, three bay one-third scale structural model used in base isolation experiments.

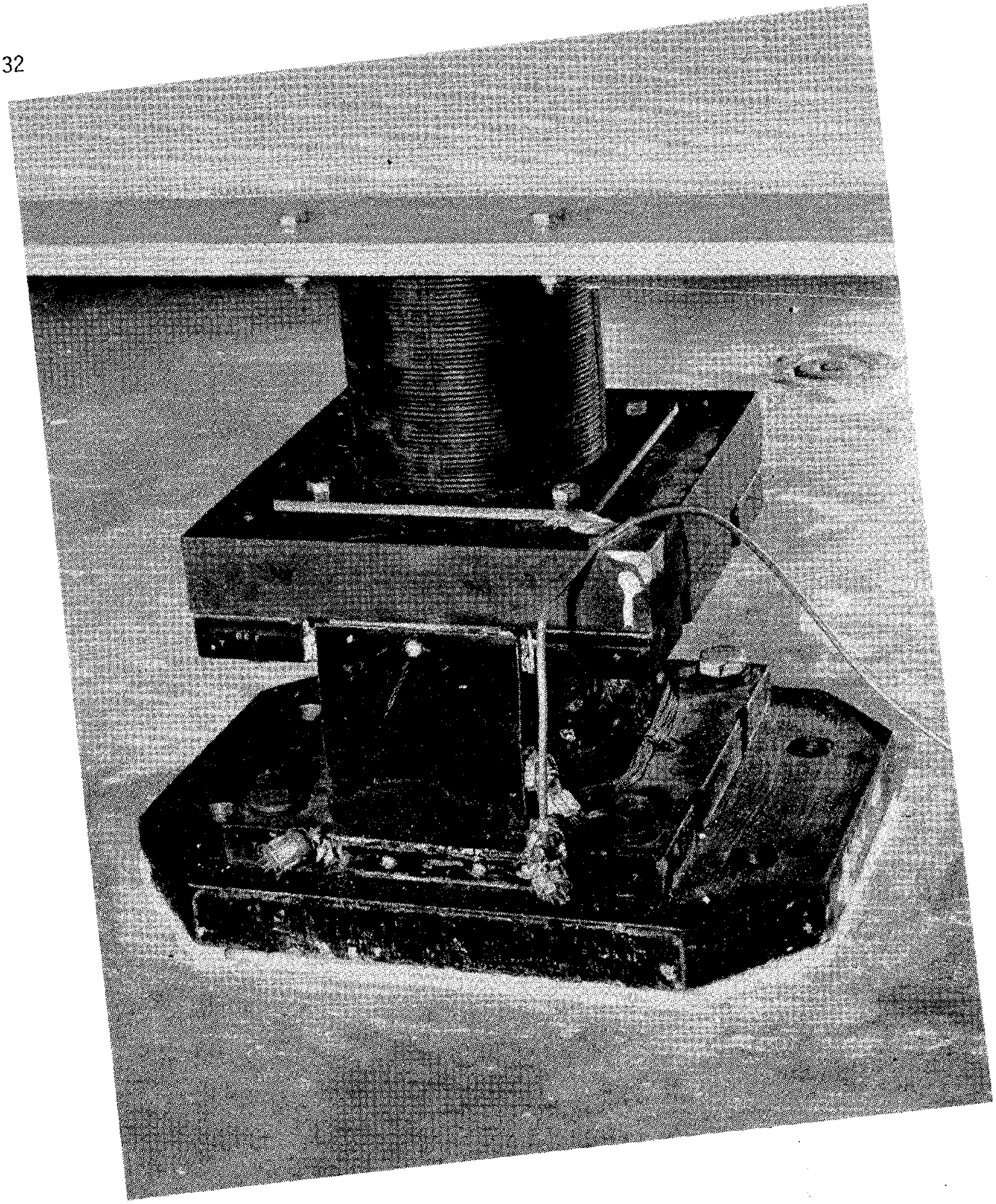


Figure 2 A bearing mounted on a load cell on the shaking table.

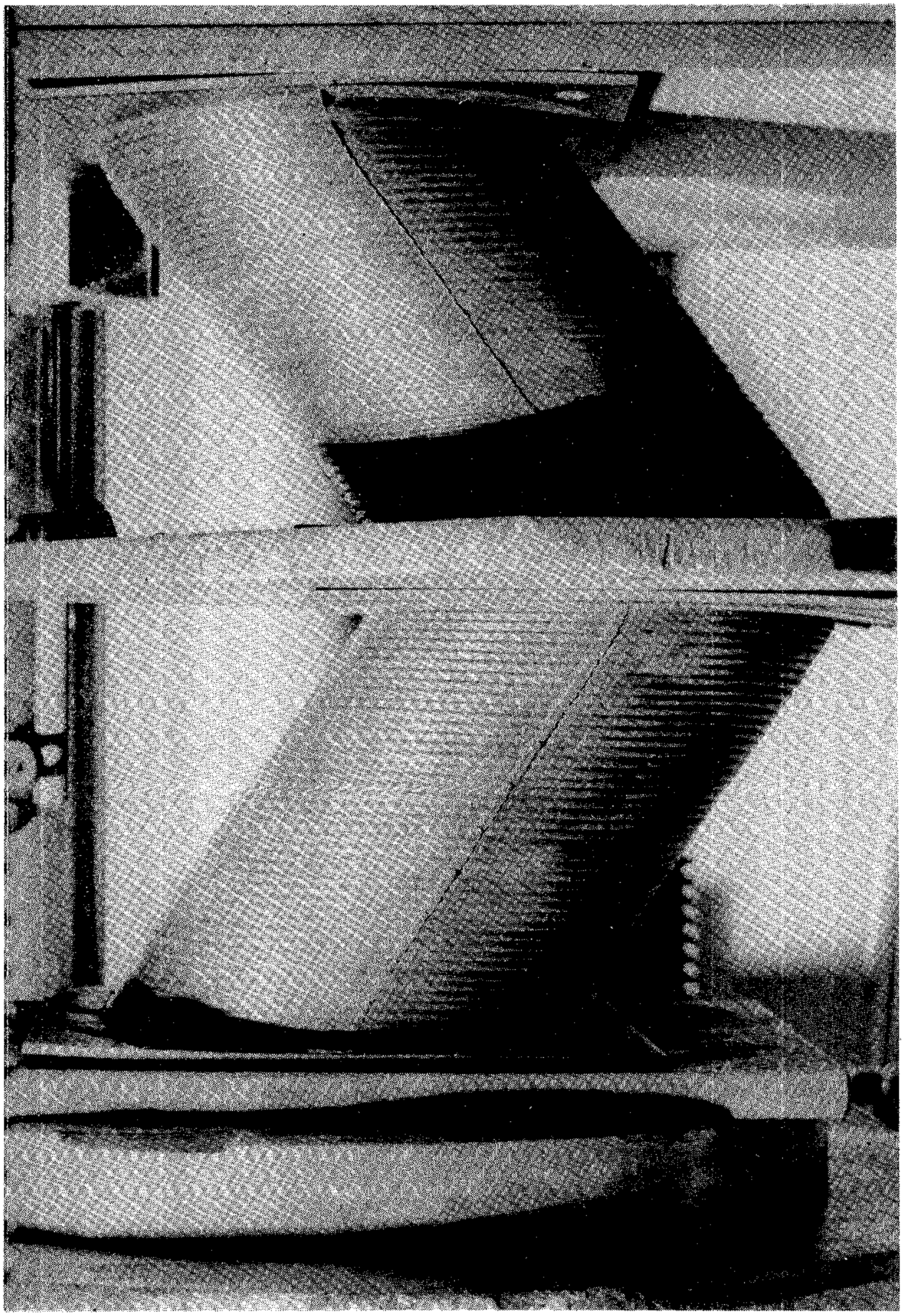


Figure 3 Static test of bearings under simultaneous vertical and horizontal load. Two bearings were tested simultaneously.

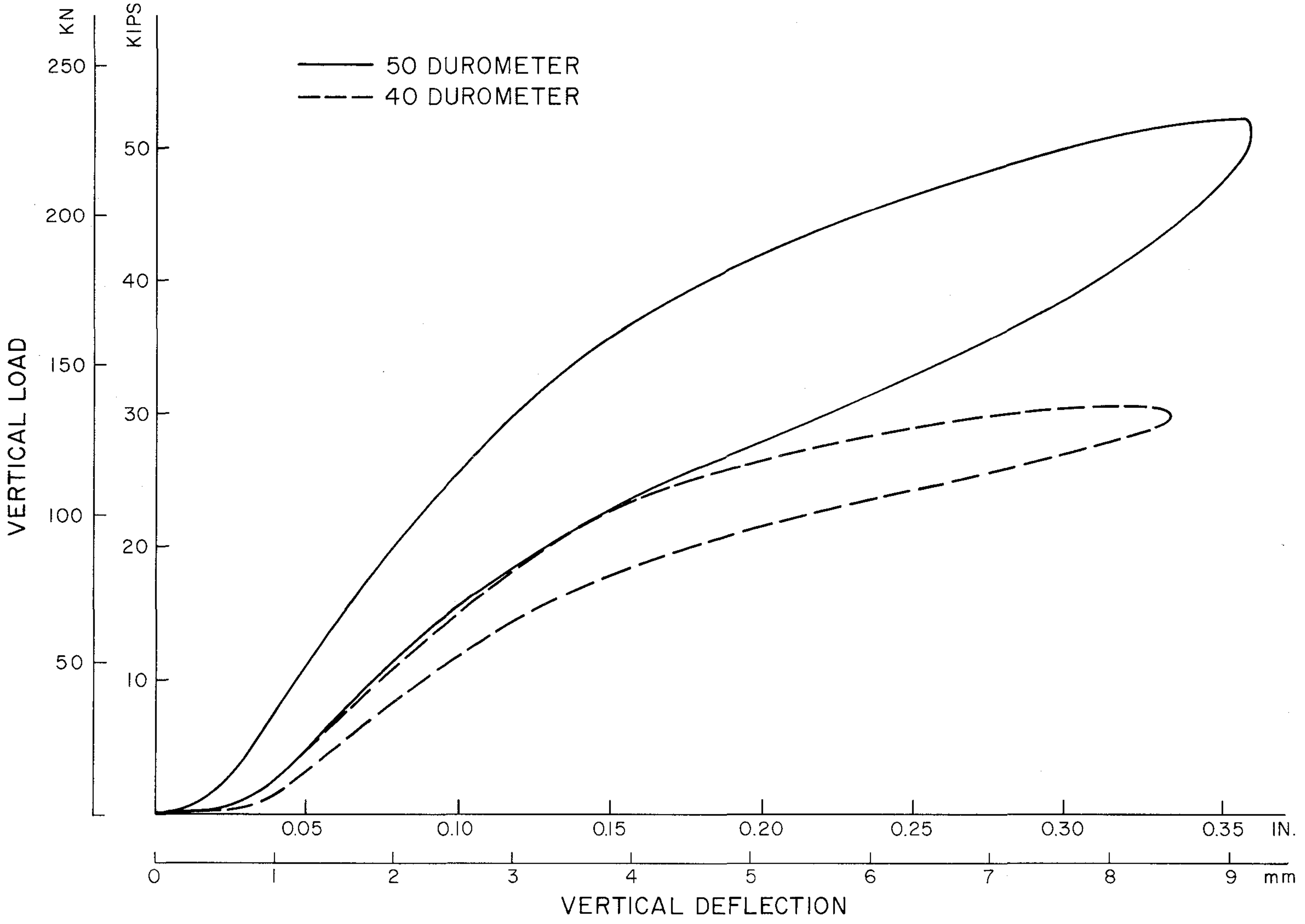


Figure 4 Static compression test of 50A and 40A durometer bearings. Two bearings were tested simultaneously.

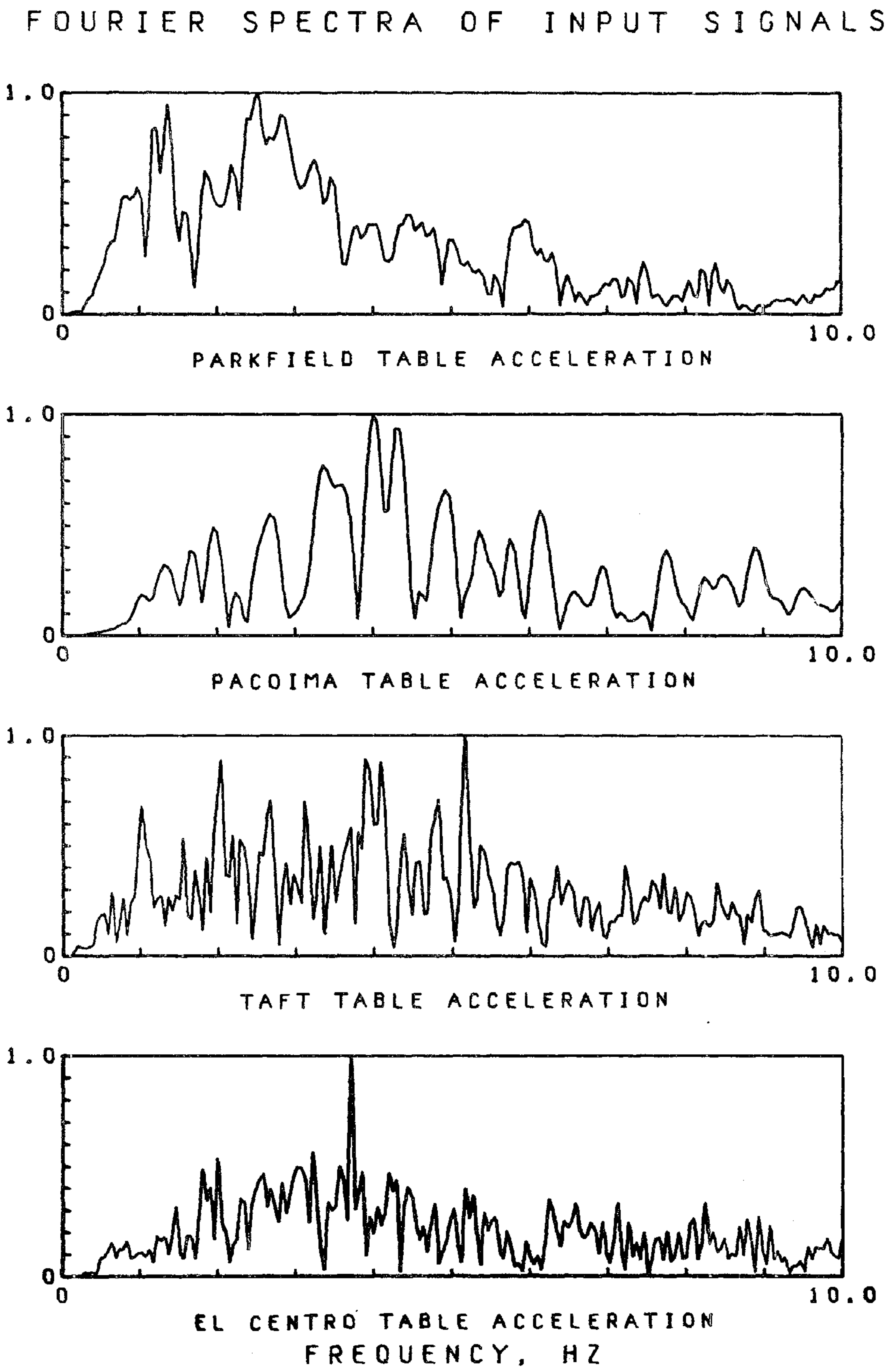


Figure 5 Fourier amplitude spectra of time-scaled simulated earthquake input signals.

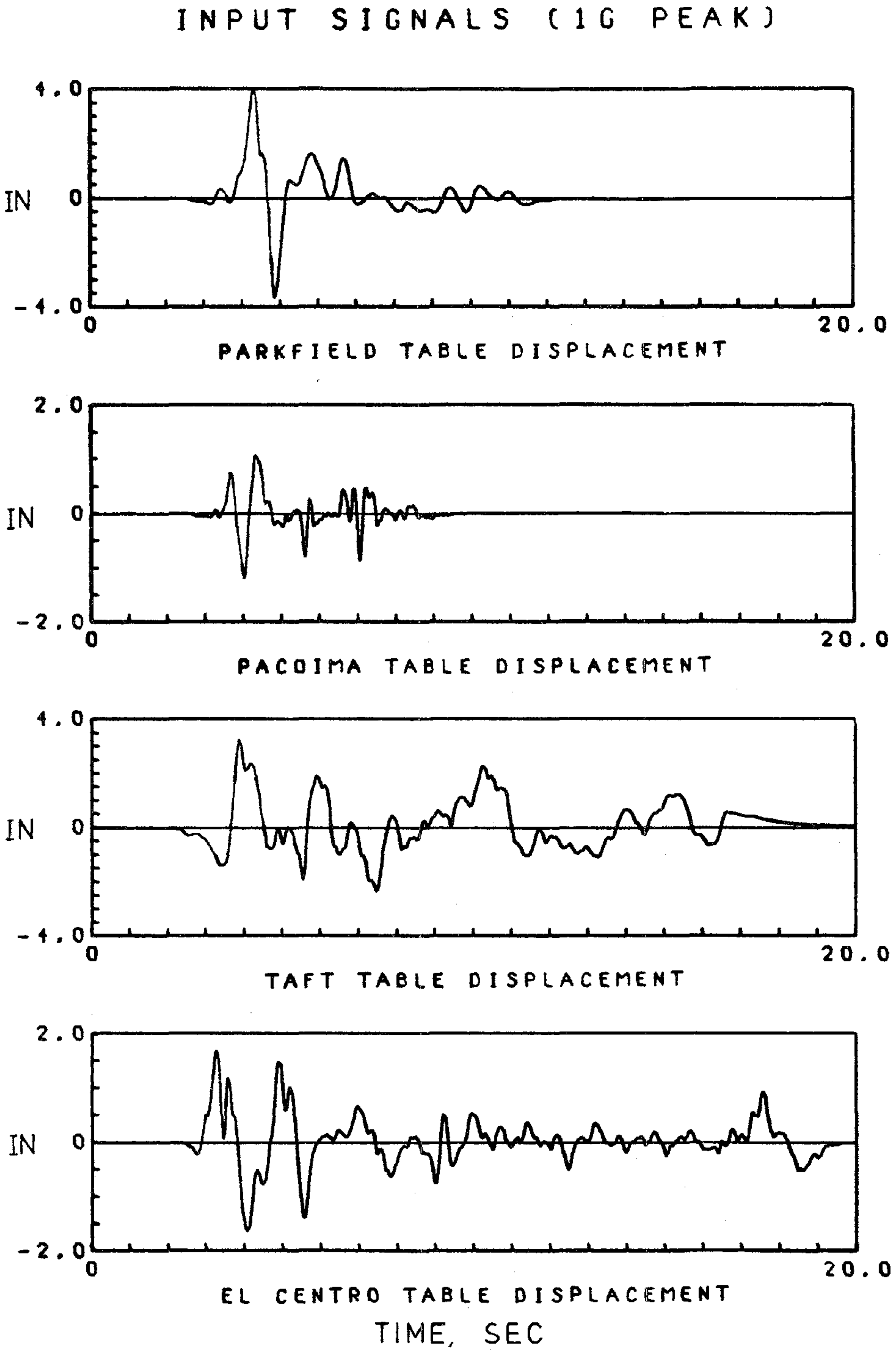


Figure 6 Displacement time histories of input signals.

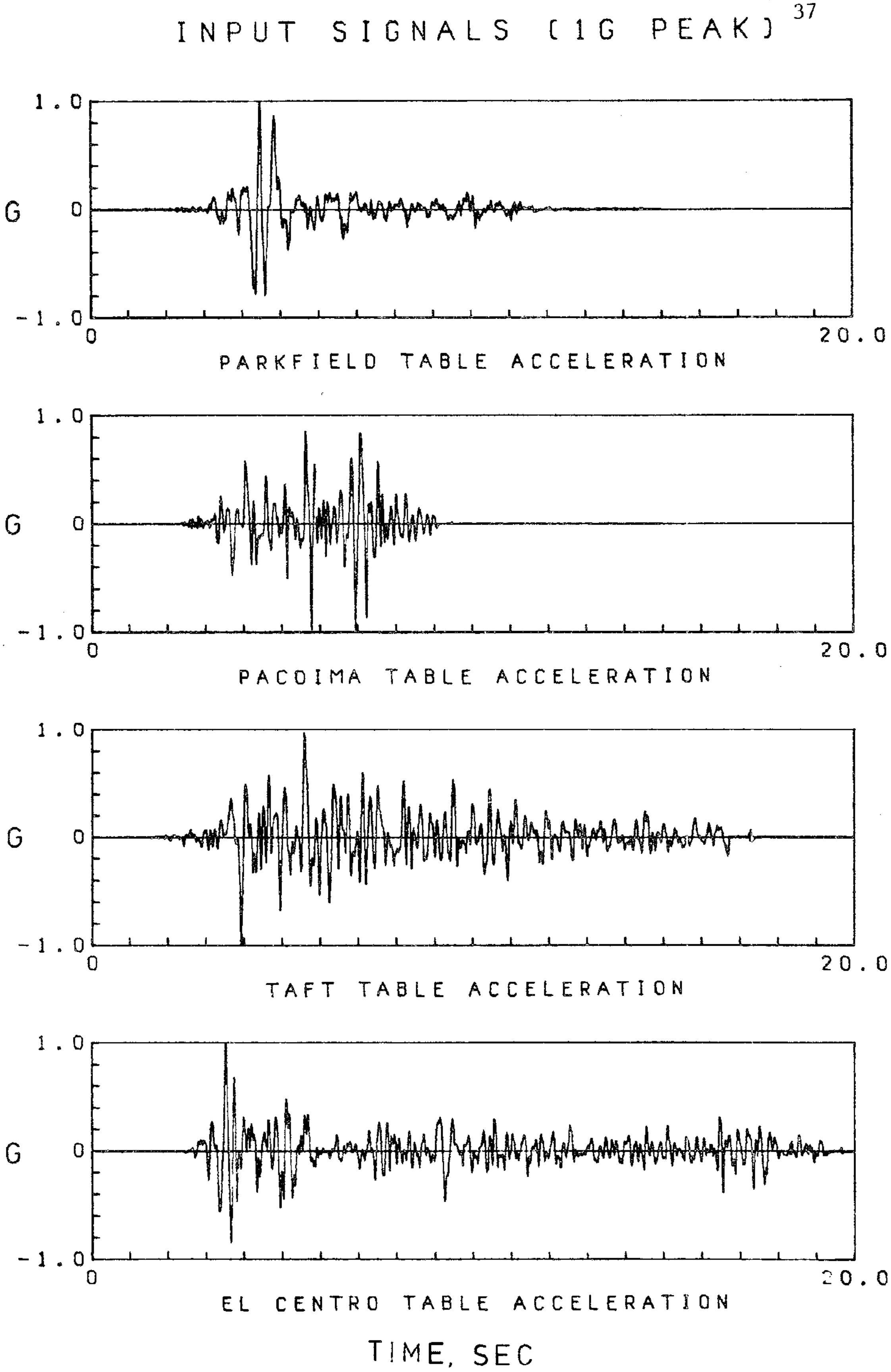


Figure 7 Acceleration time histories of input signals.

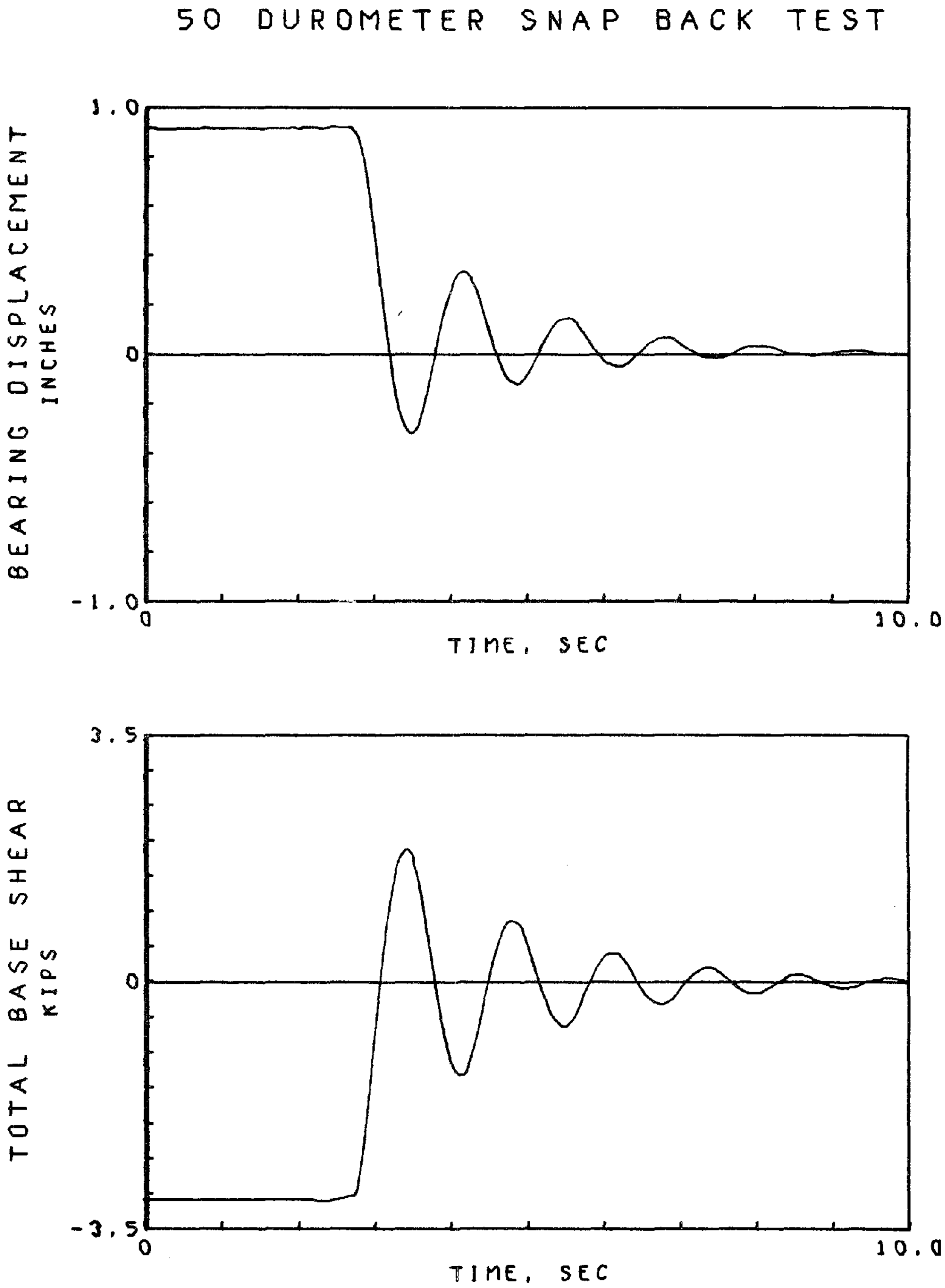


Figure 8 Pull-back test for 50A durometer bearings.

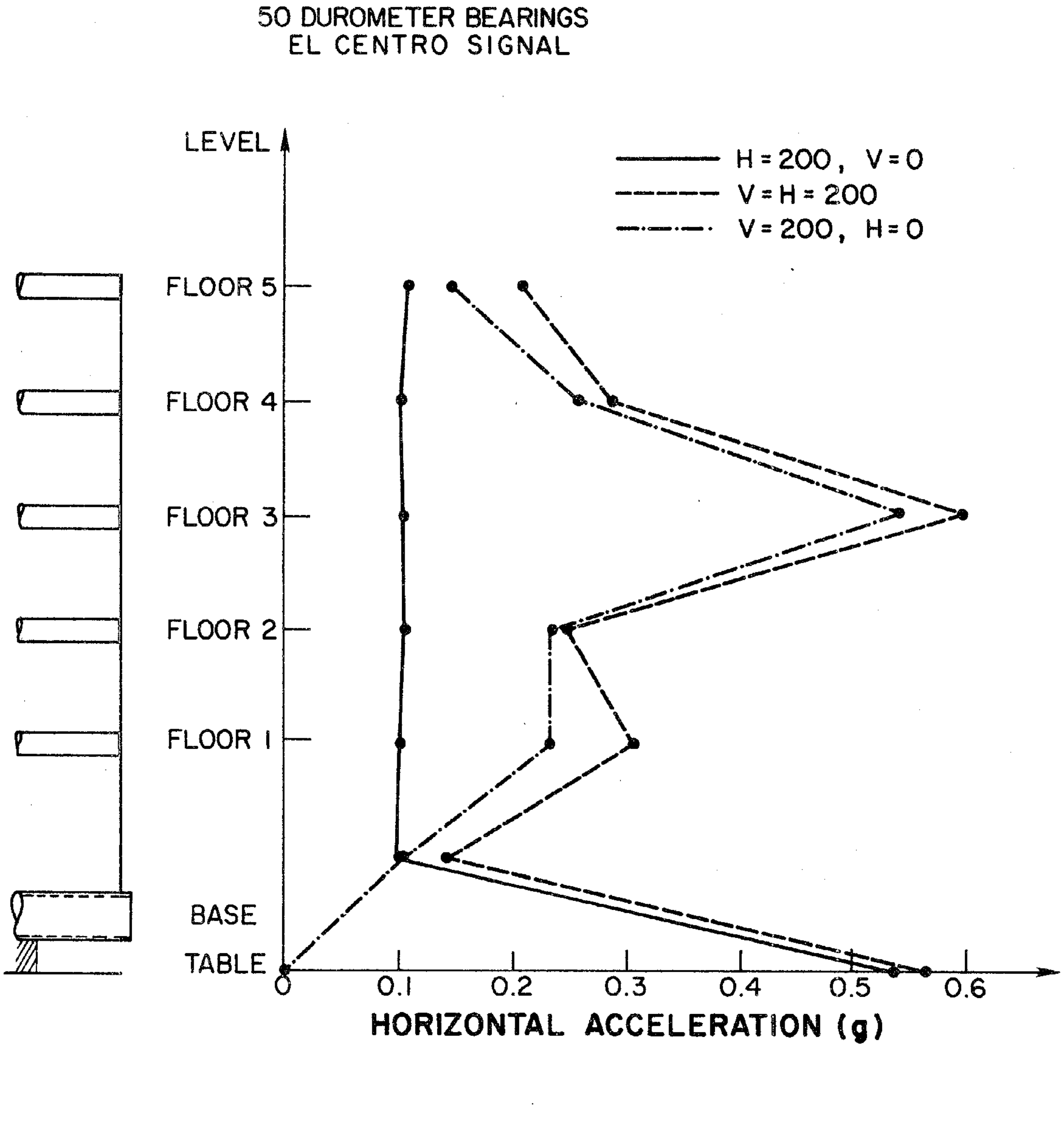


Figure 9 Horizontal frame accelerations for El Centro input signal including vertical excitation.

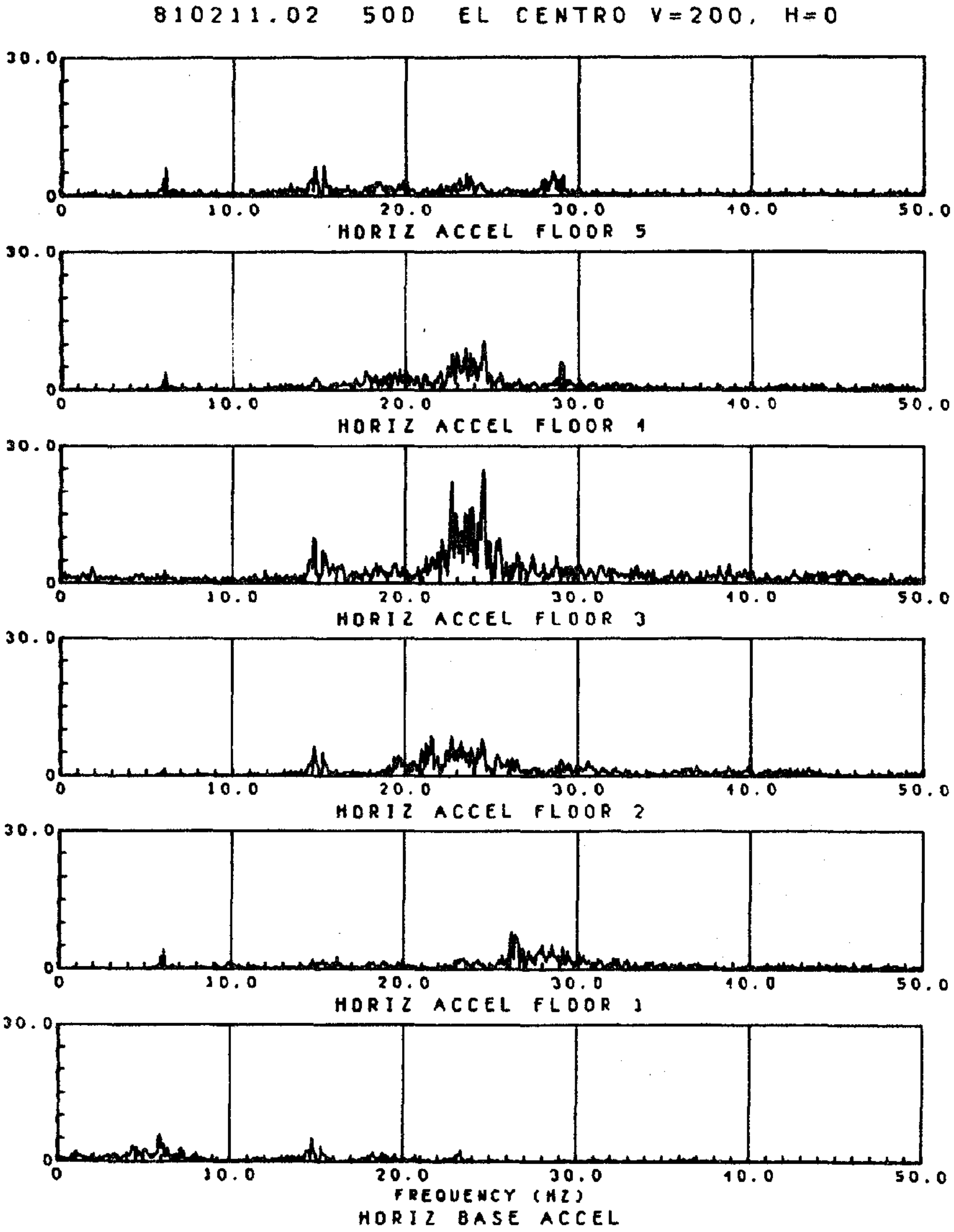


Figure 10 Fourier spectra of horizontal frame accelerations under vertical only excitation.

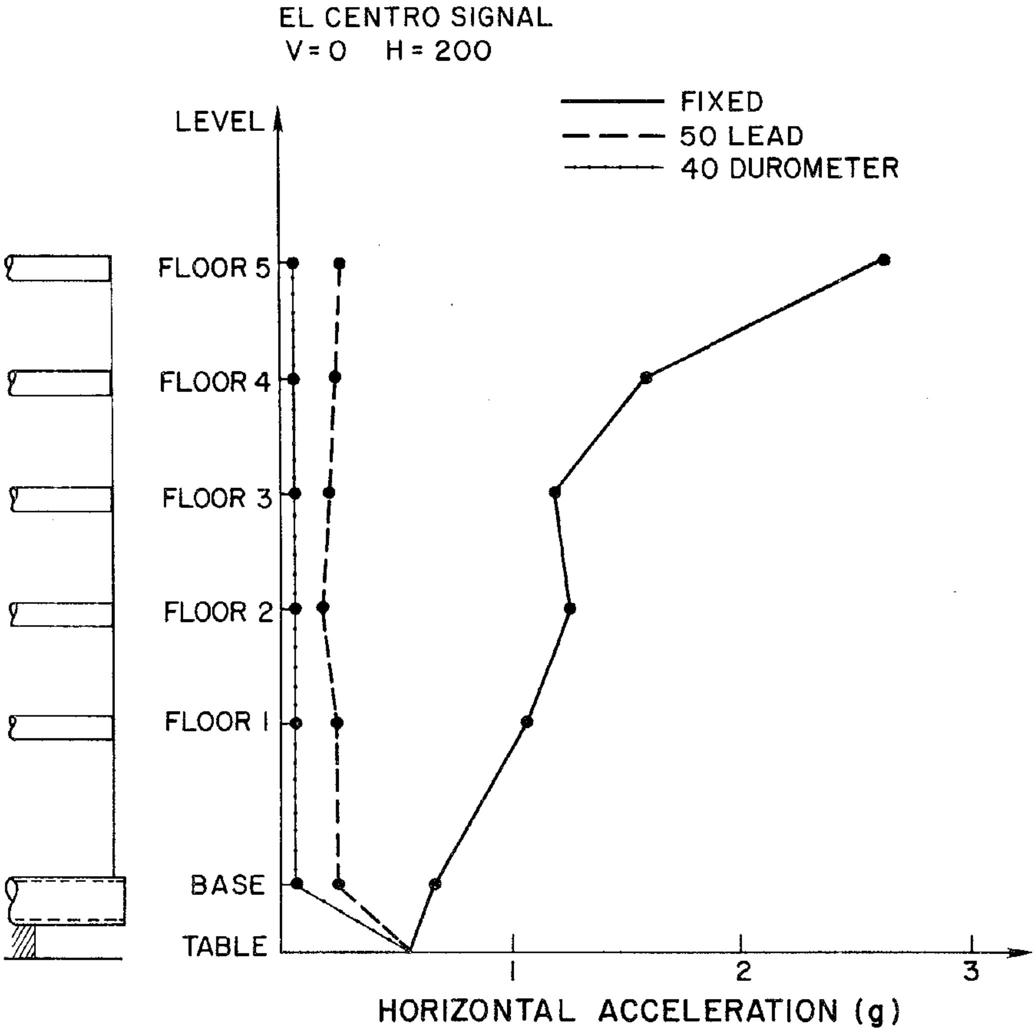


Figure 11 Frame accelerations for El Centro input signal showing fixed-base response.

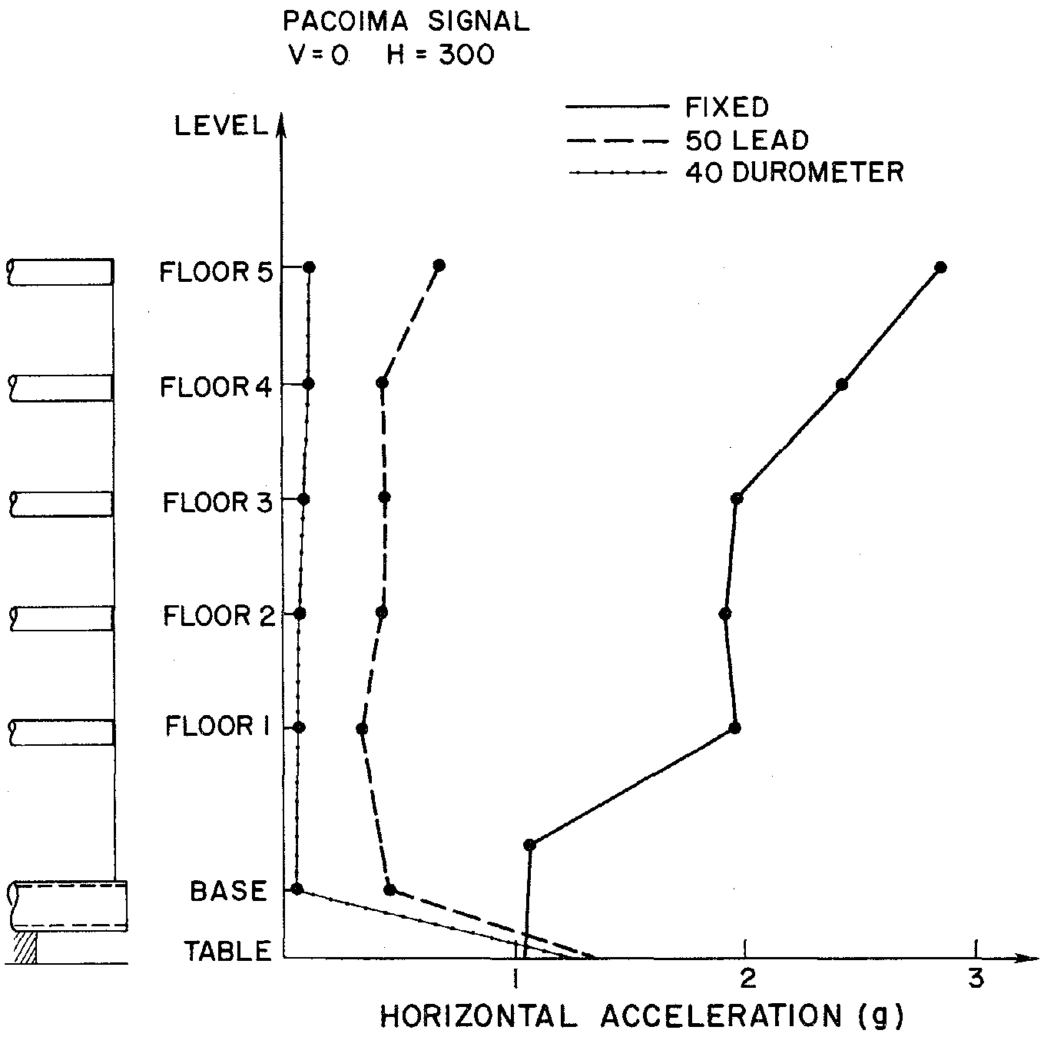


Figure 12 Frame accelerations for Pacoima Dam input signal showing fixed-base response.

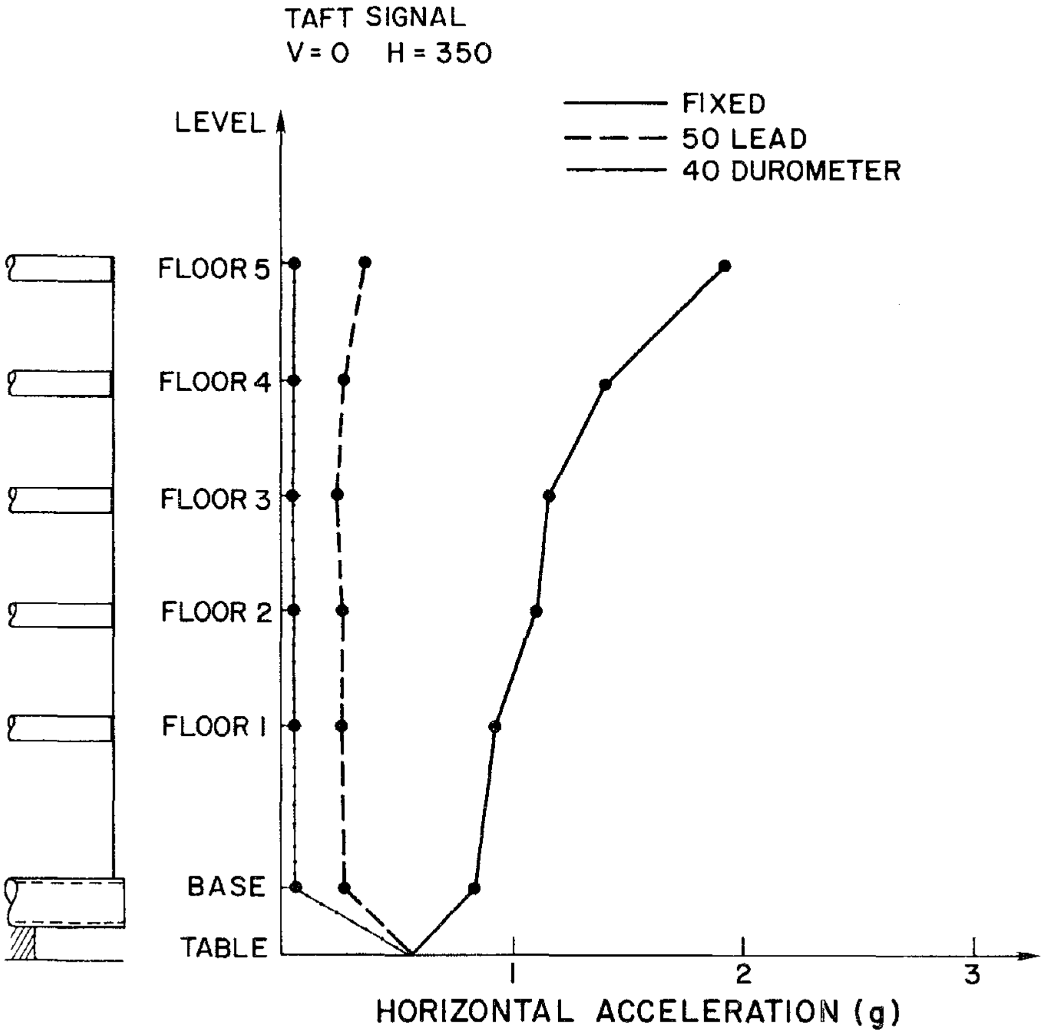


Figure 13 Frame accelerations for Taft input signal showing fixed-base response.

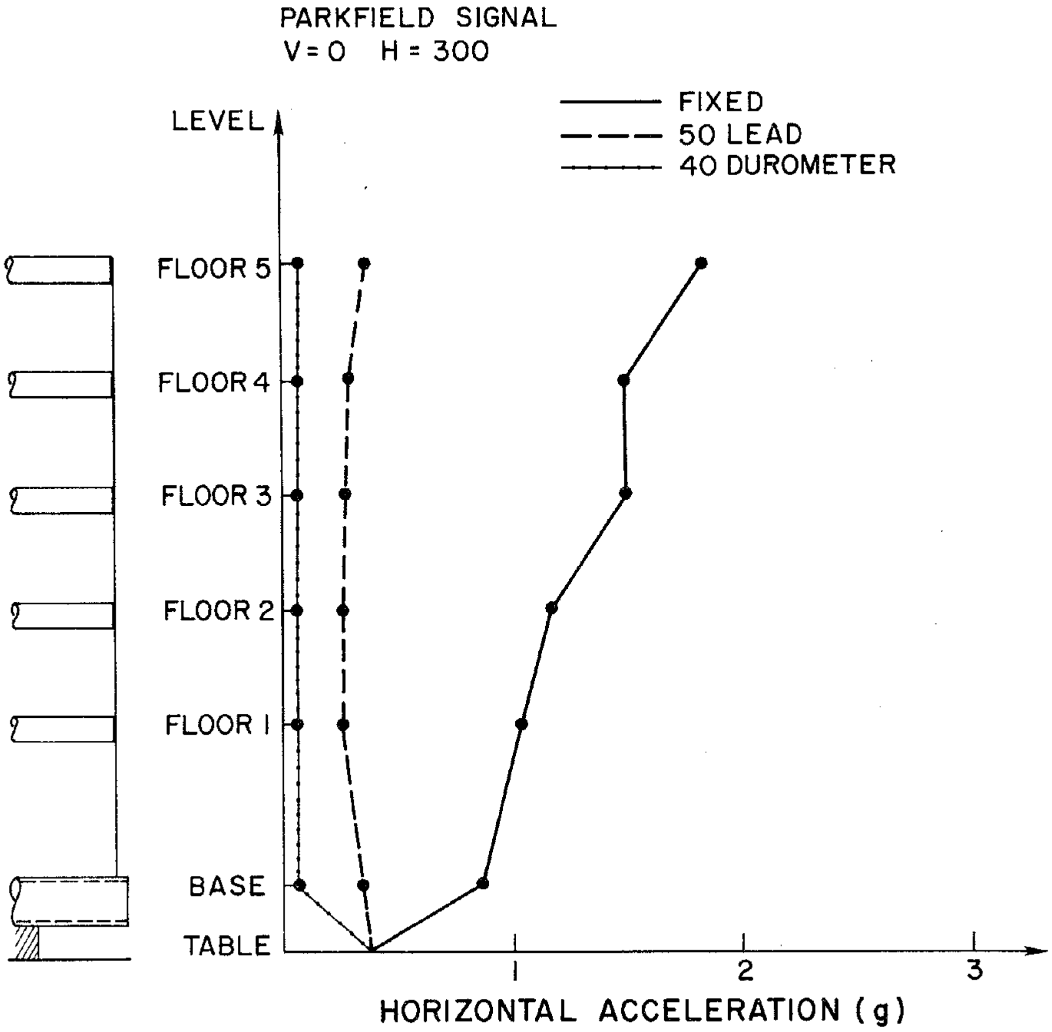


Figure 14 Frame accelerations for Parkfield input signal showing fixed-base response.

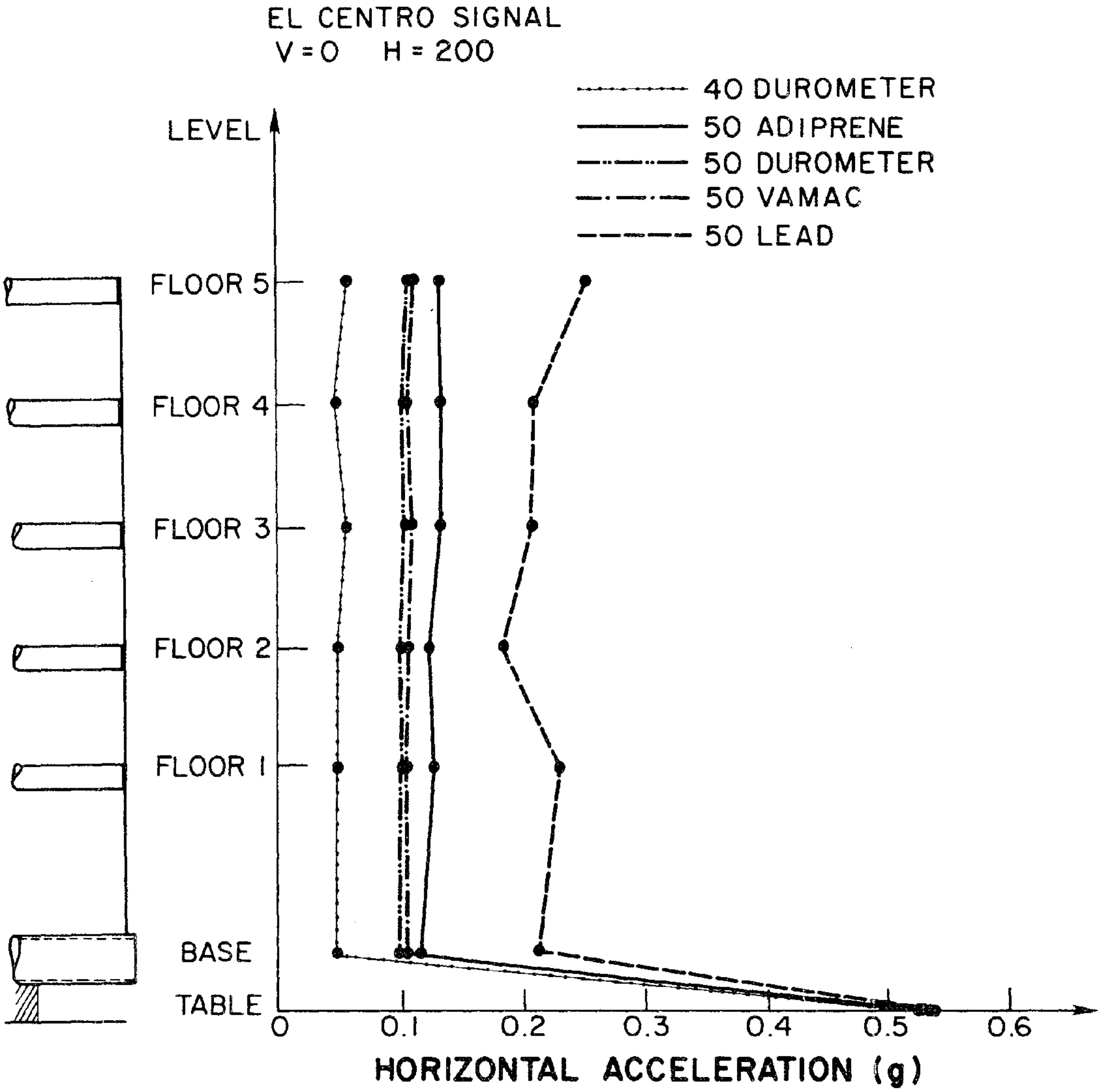


Figure 15 Frame accelerations for El Centro input signal, with different isolation conditions.

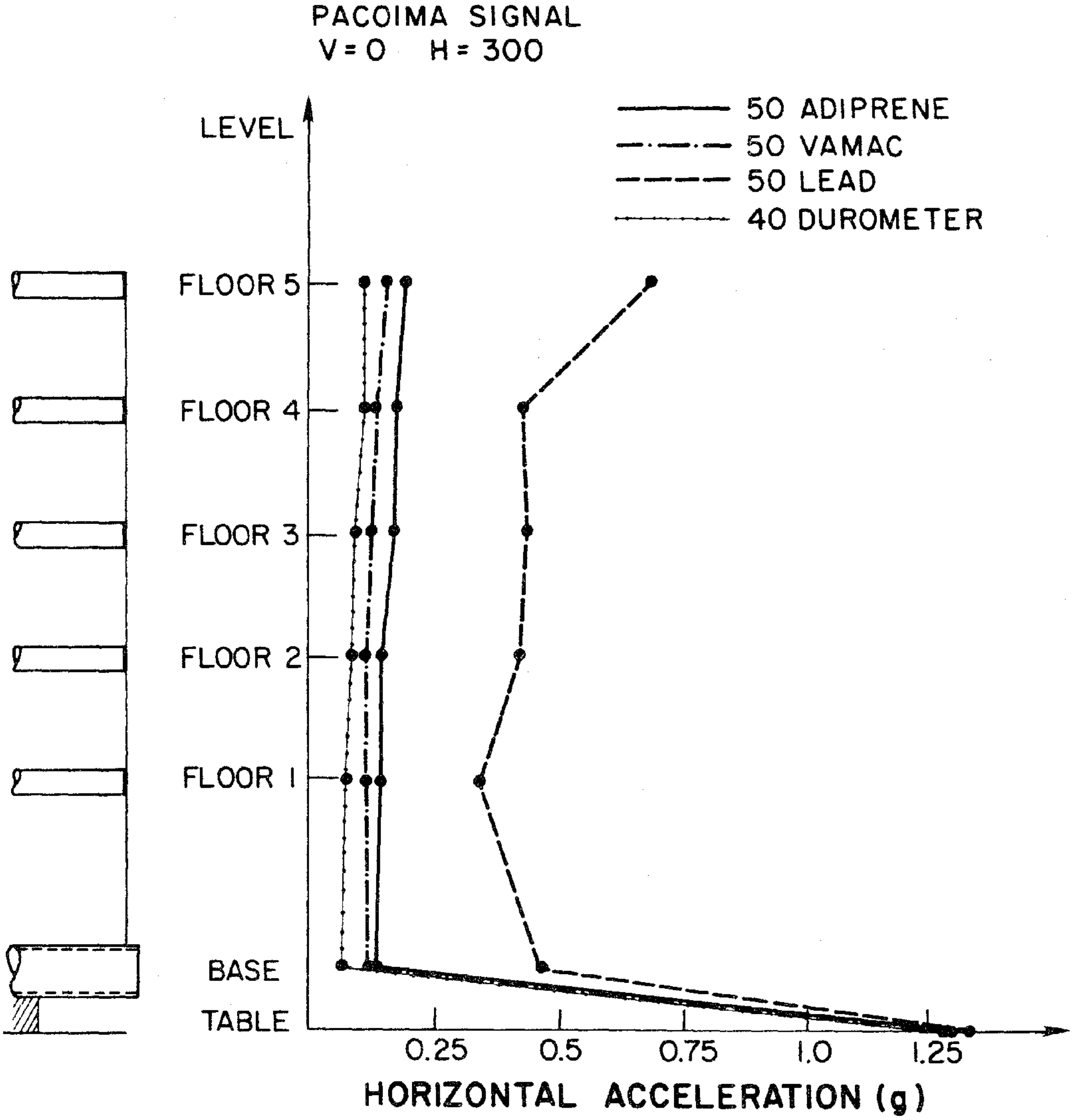


Figure 16 Frame accelerations for Pacoima Dam input signal, with different isolation conditions.

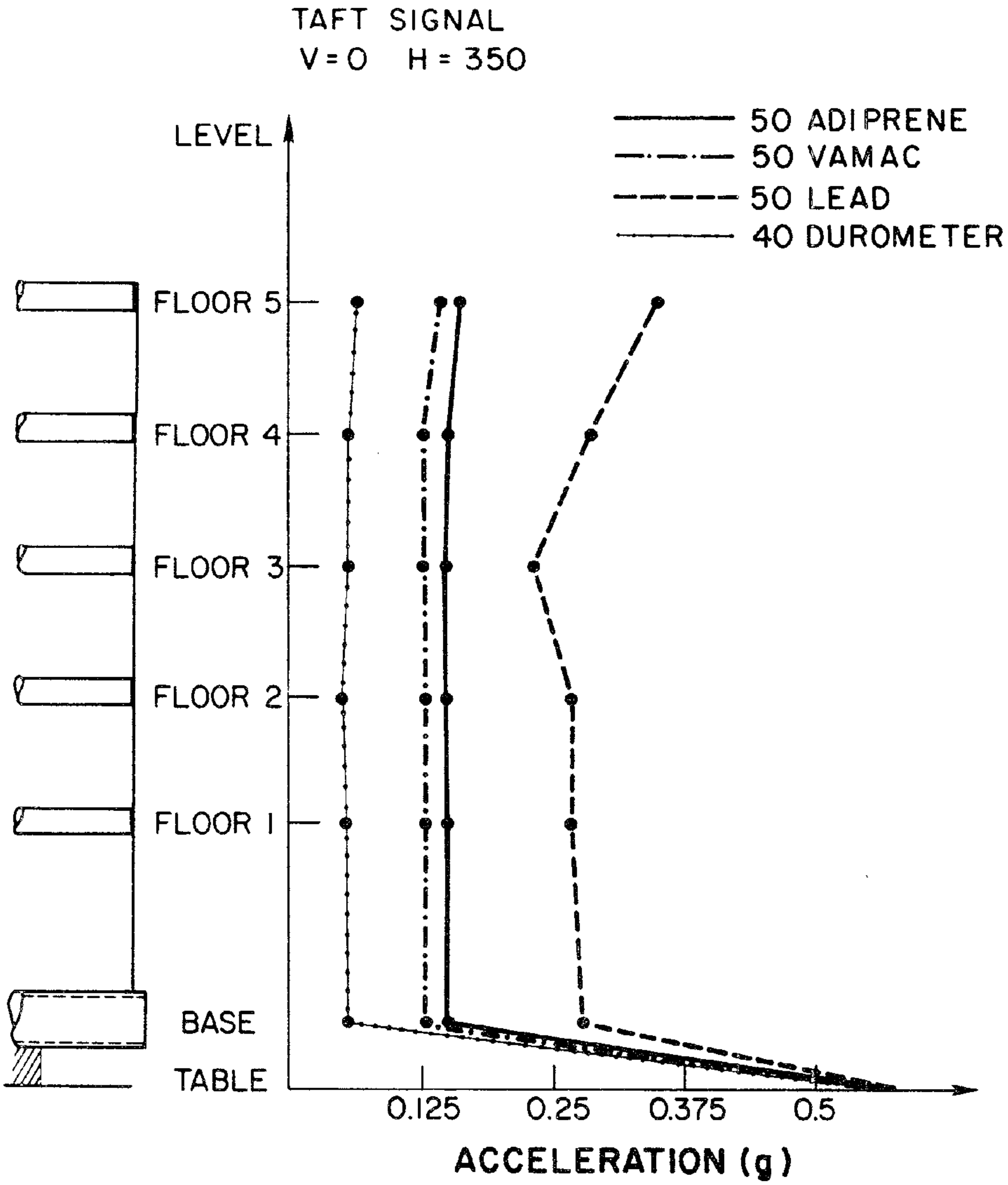


Figure 17 Frame accelerations for Taft input signal, with different isolation conditions.

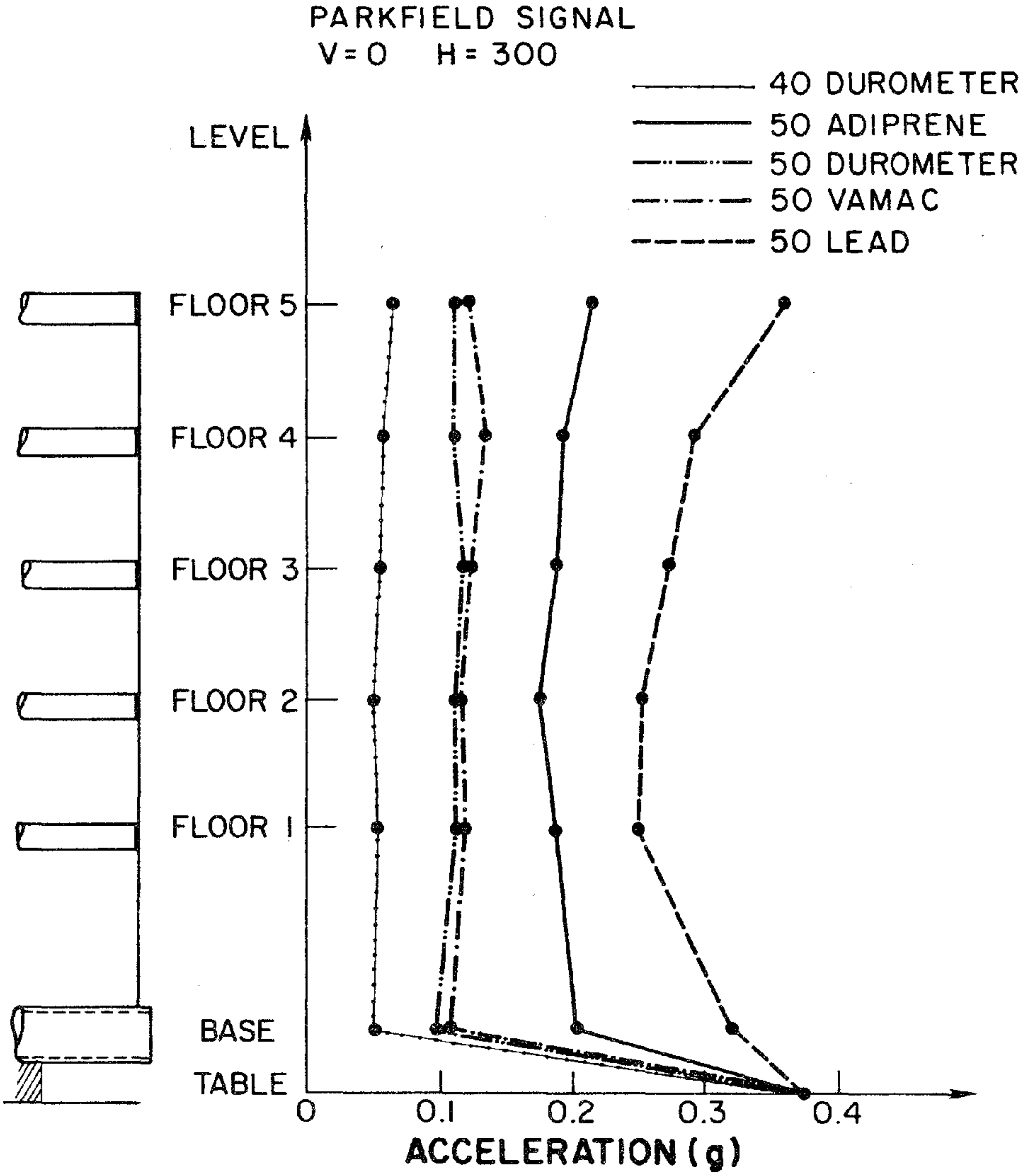


Figure 18 Frame accelerations for Parkfield input signal, with different isolation conditions.

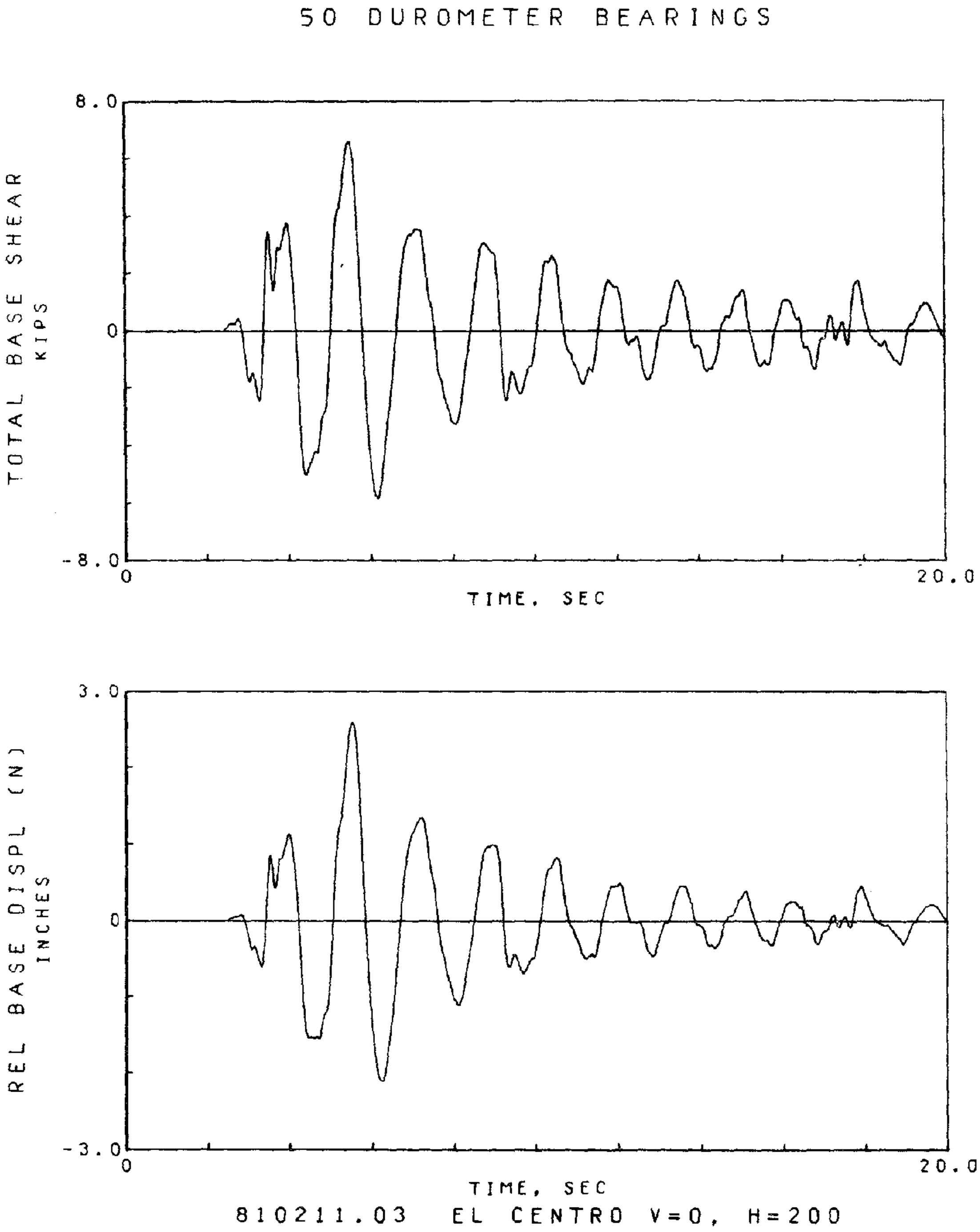


Figure 19 Time history records for 50A durometer bearings.

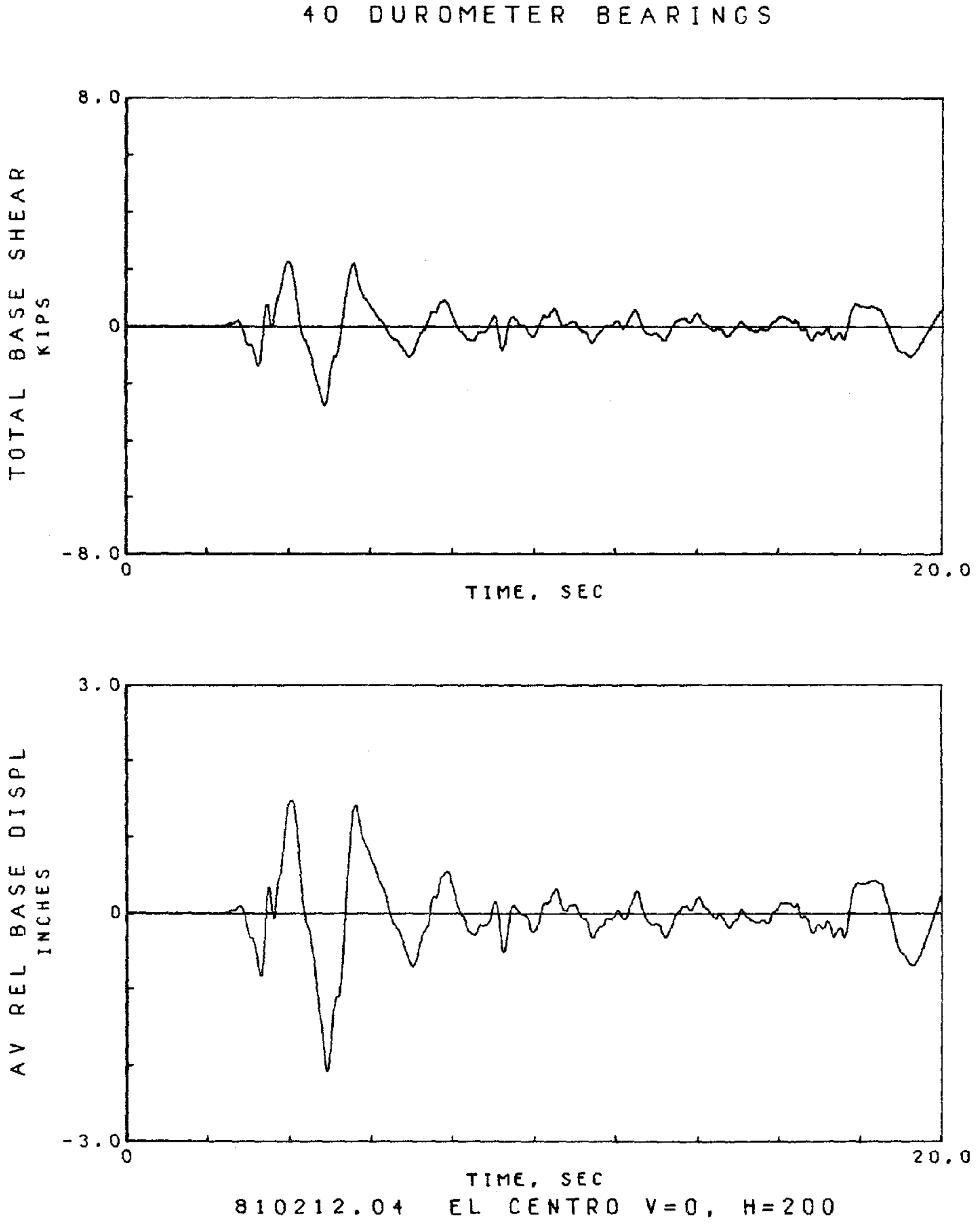


Figure 20 Time history records for 40A durometer bearings.

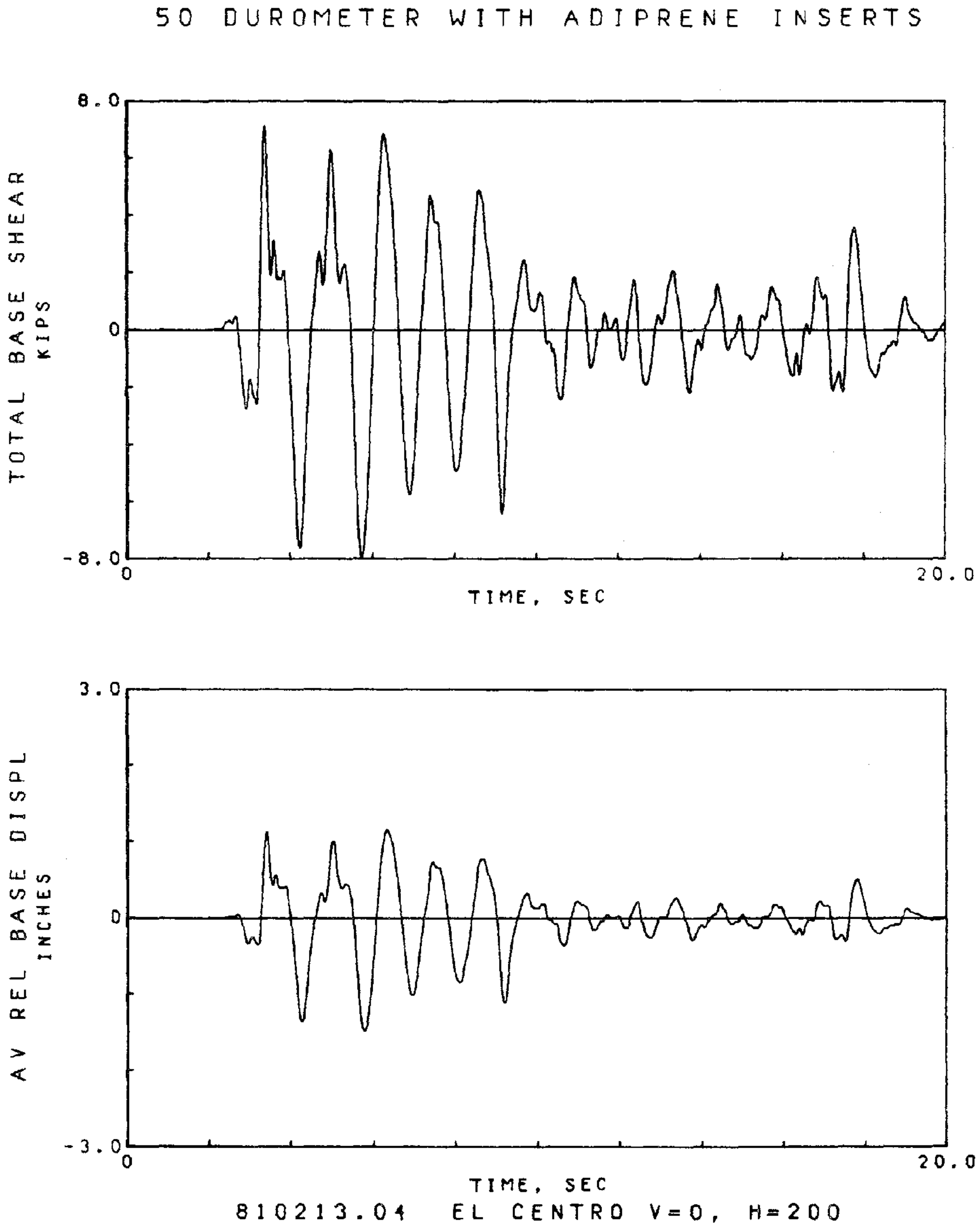


Figure 21 Time history records for 50A durometer bearings with ADIPRENE® inserts.

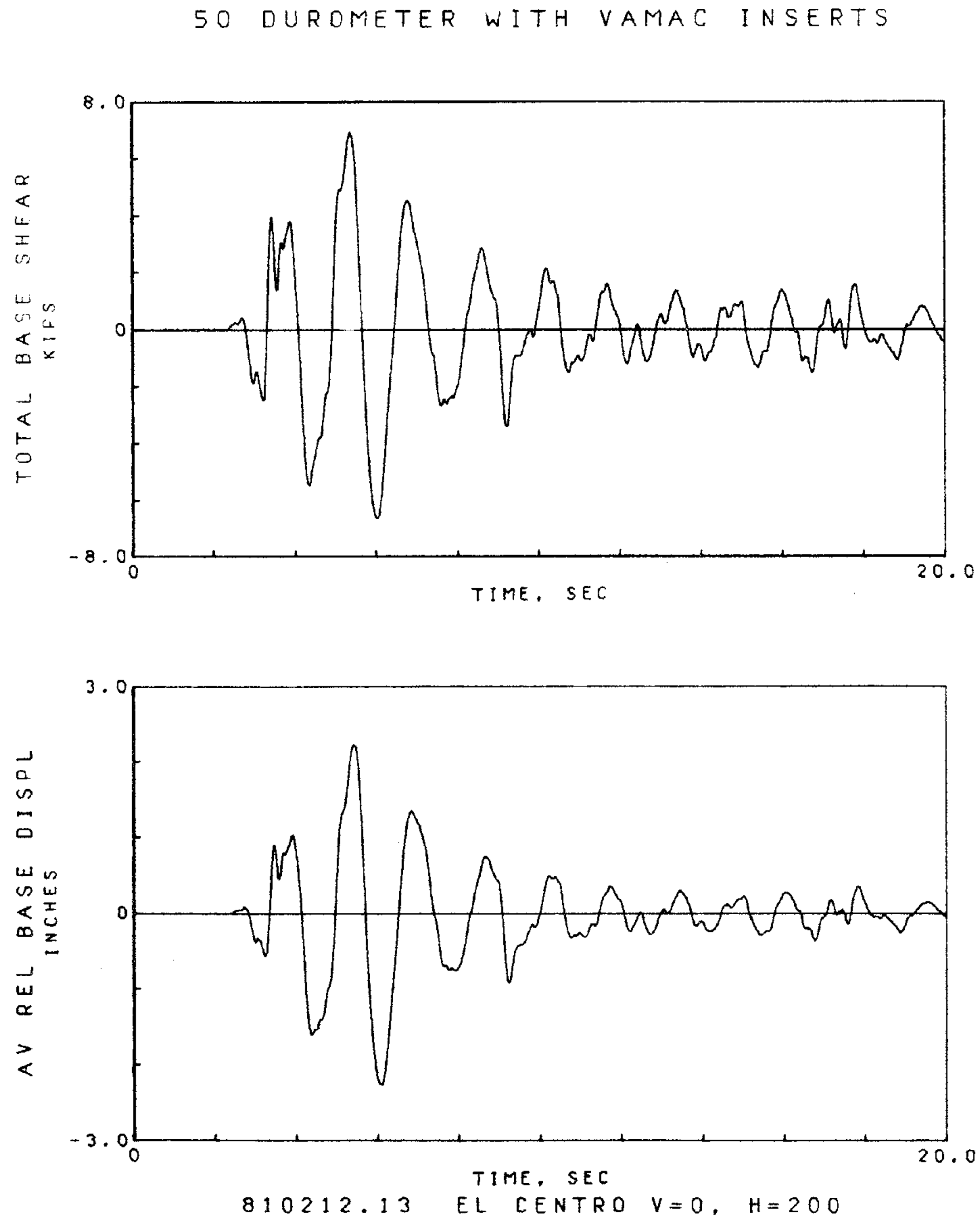


Figure 22 Time history records for 50A durometer bearings with VAMAC® inserts.

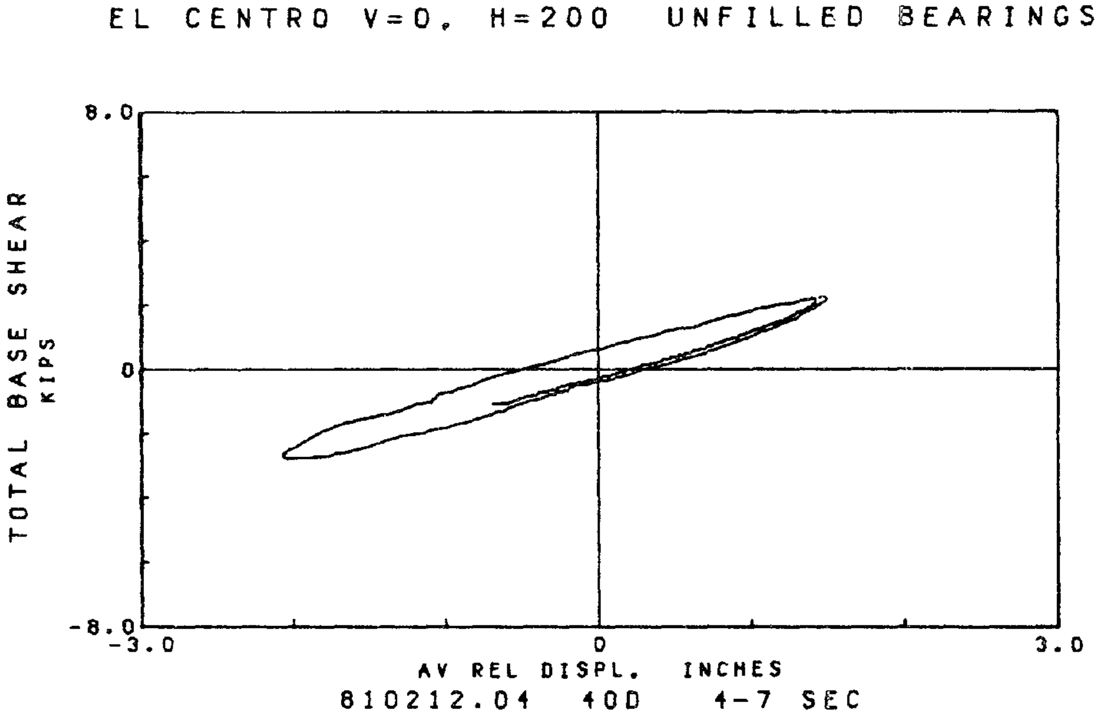


Figure 23 Hysteresis loops for 40D bearings, El Centro signal.

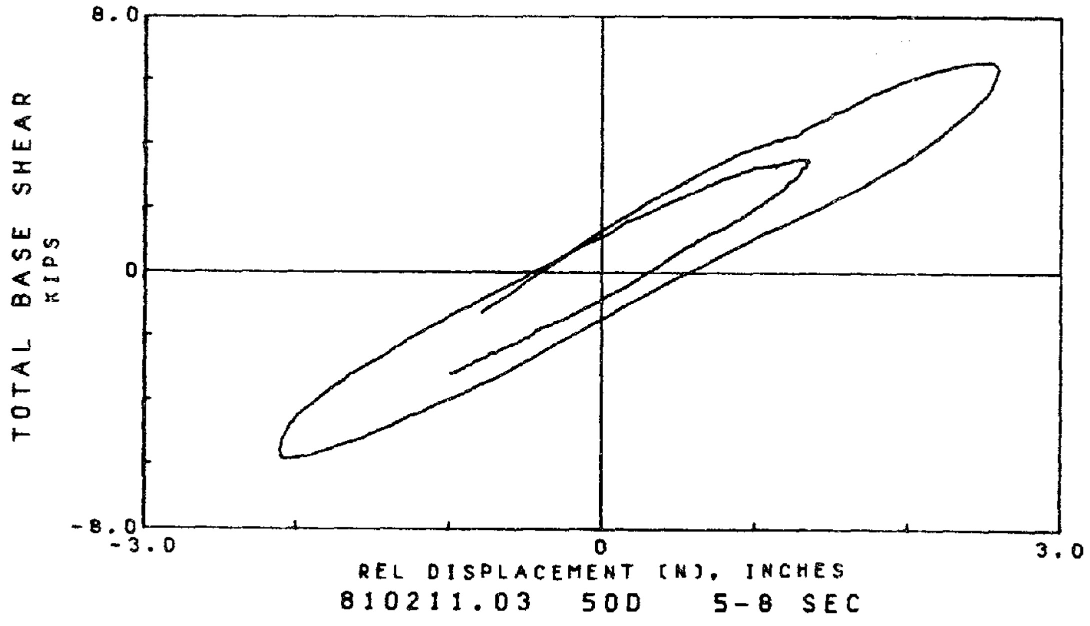


Figure 24 Hysteresis loops for 50D bearings, El Centro signal.

EL CENTRO V=0, H=200 DUPONT FILLED

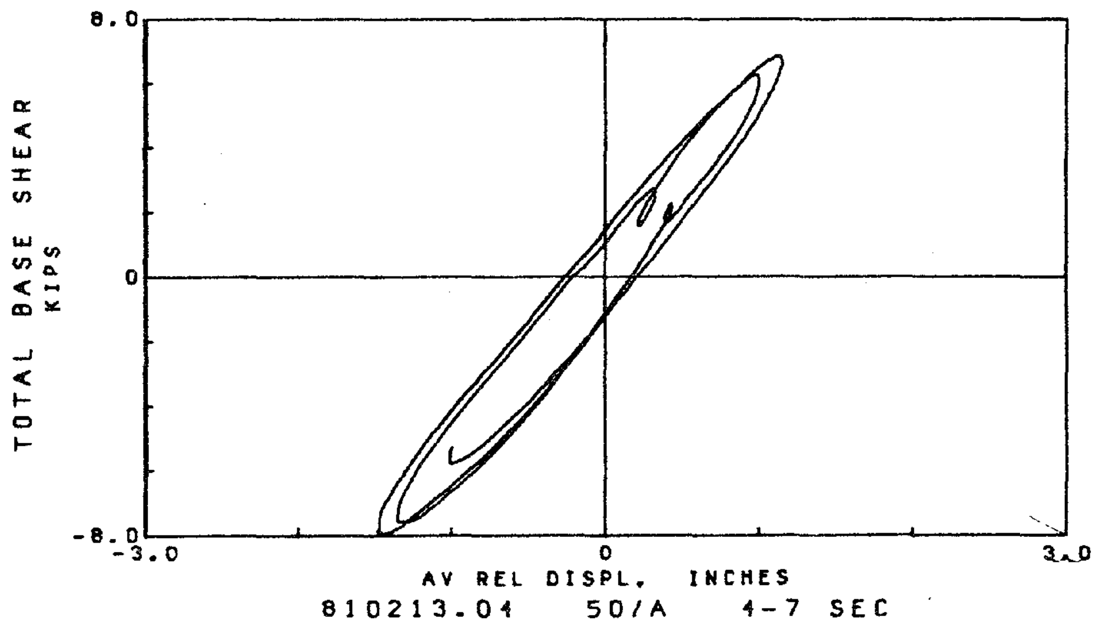


Figure 25 Hysteresis loops for 50D bearings with ADIPRENE® inserts, El Centro signal.

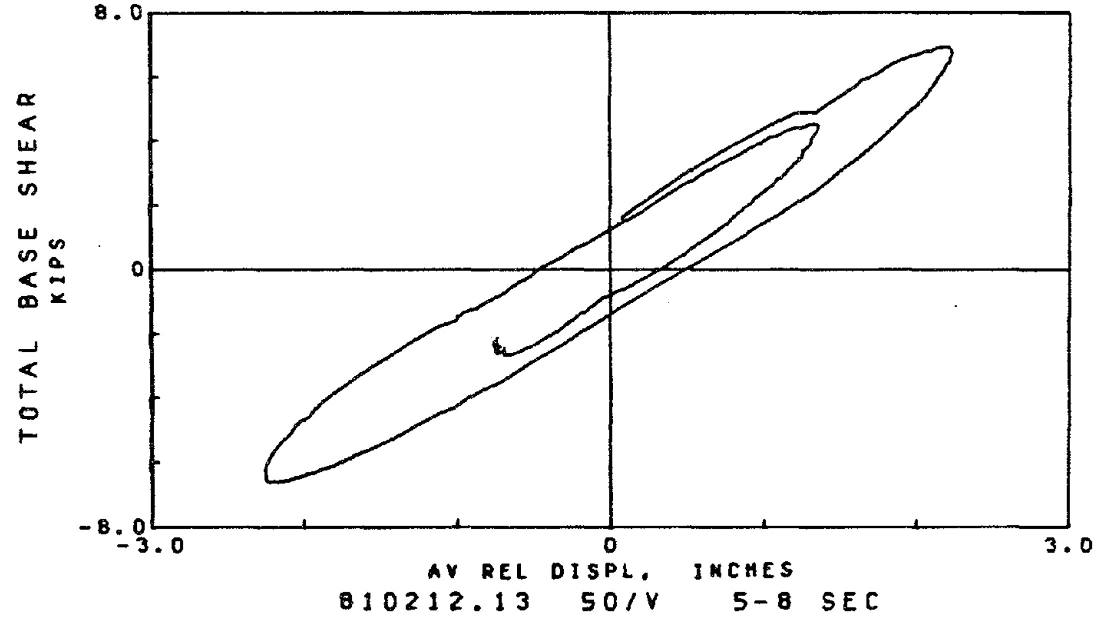


Figure 26 Hysteresis loops for 50D bearings with VAMAC® inserts, El Centro signal.

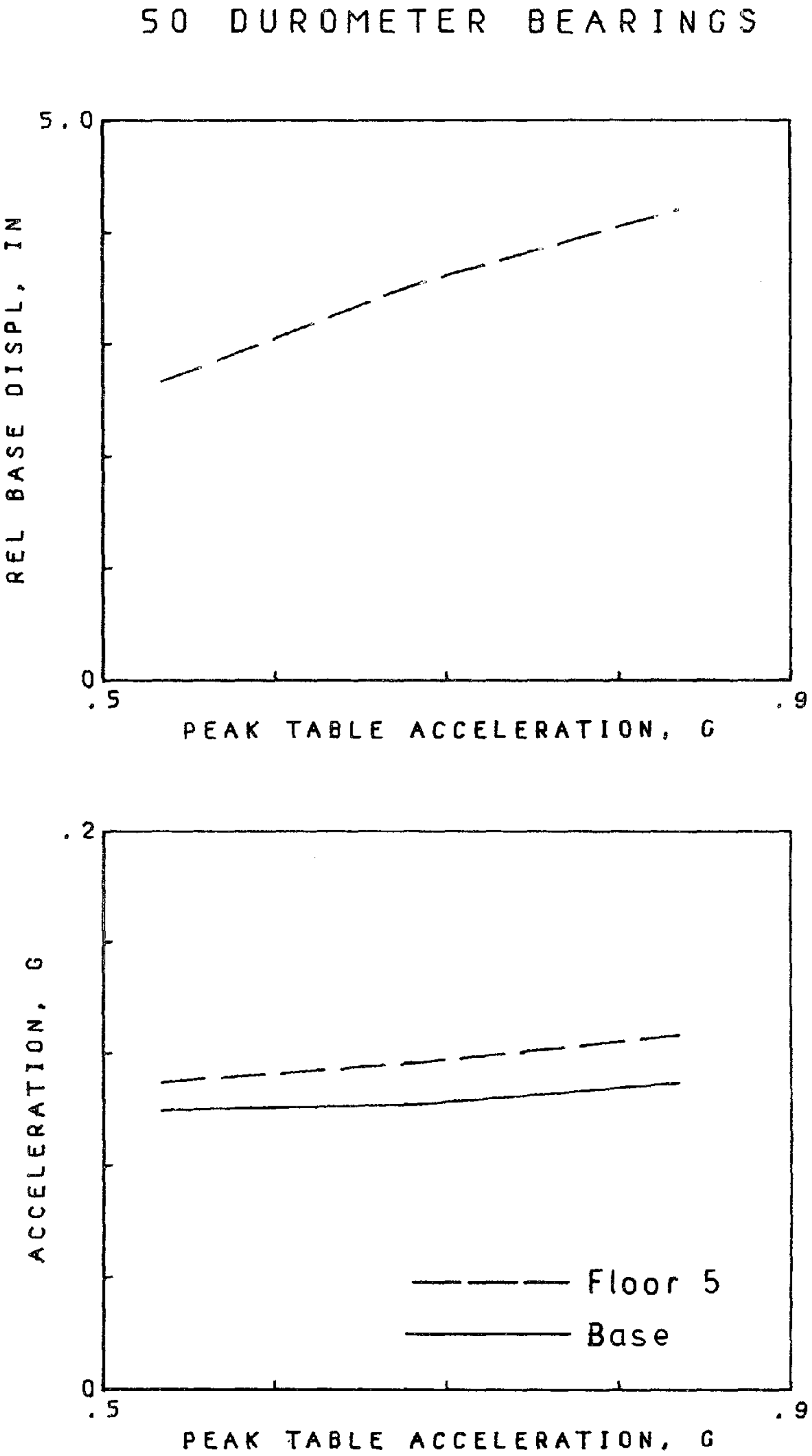
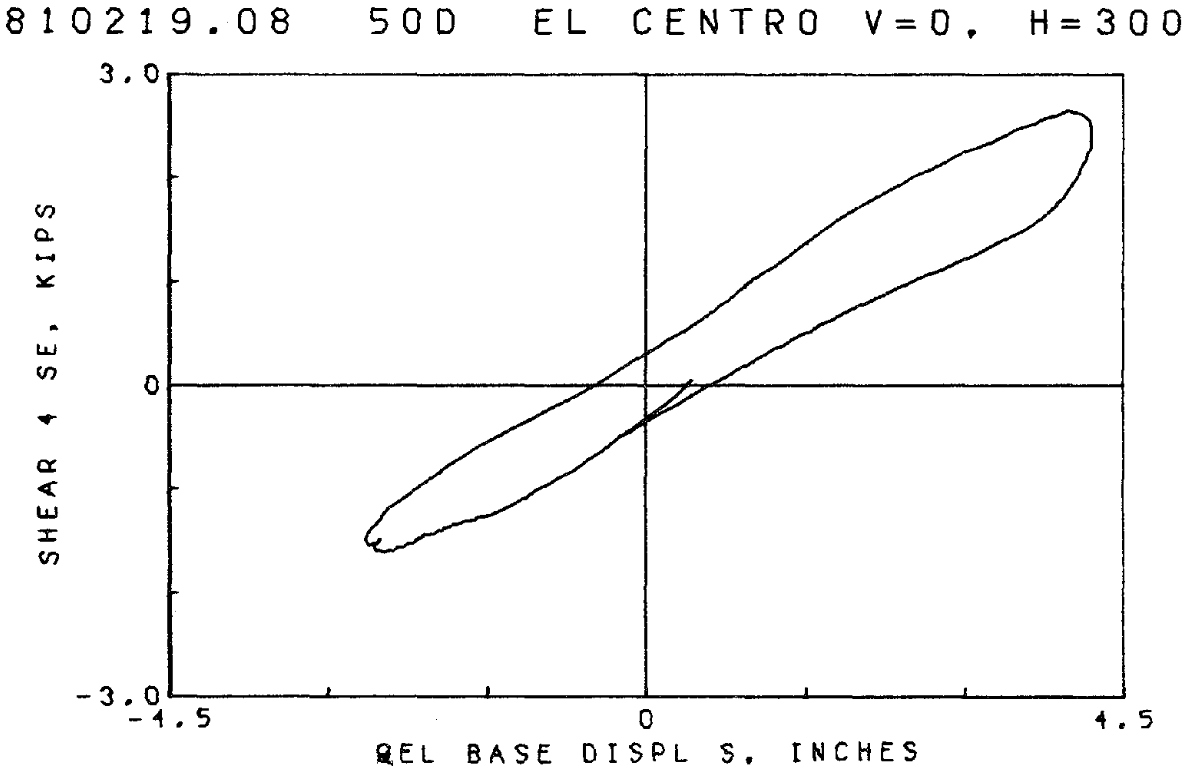
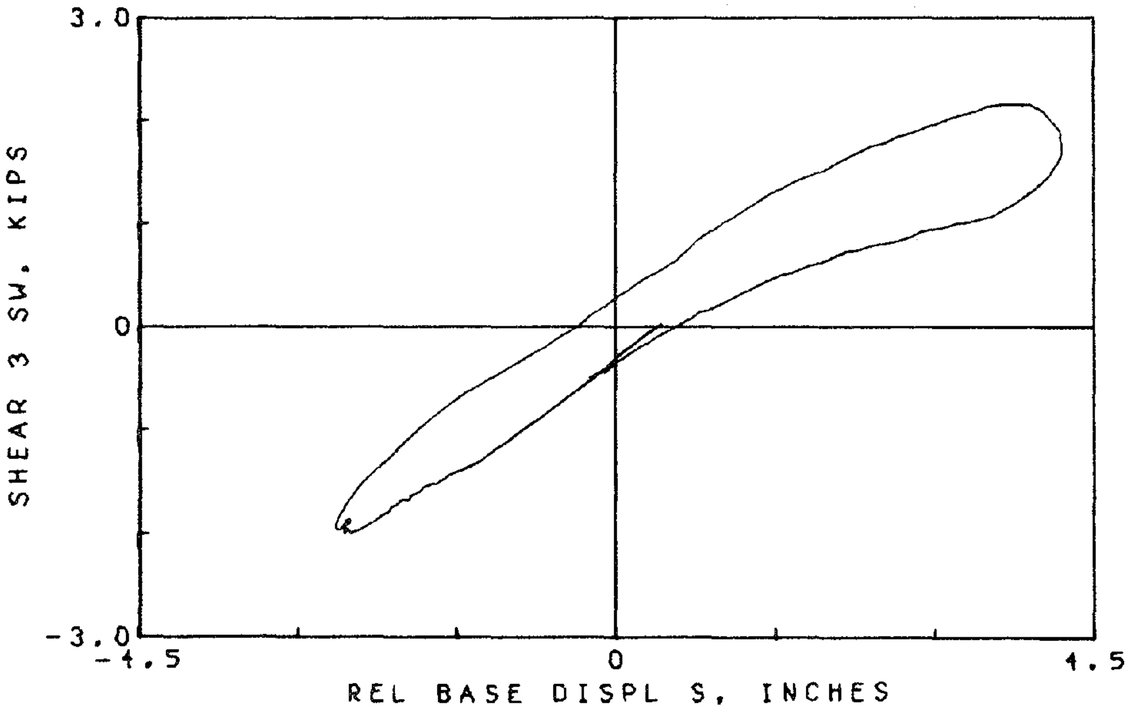


Figure 27 Relative base displacements and frame accelerations for 50D system under increasing peak acceleration.

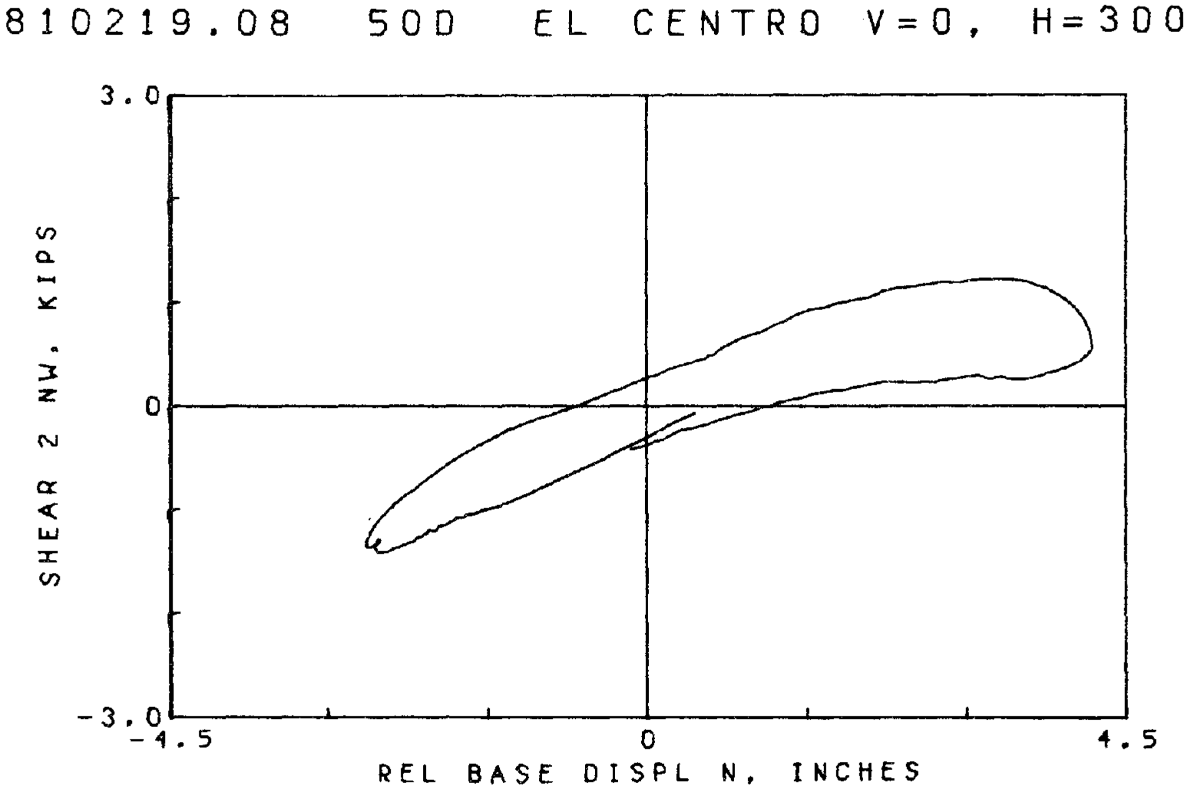


(a) Southeast bearing location.

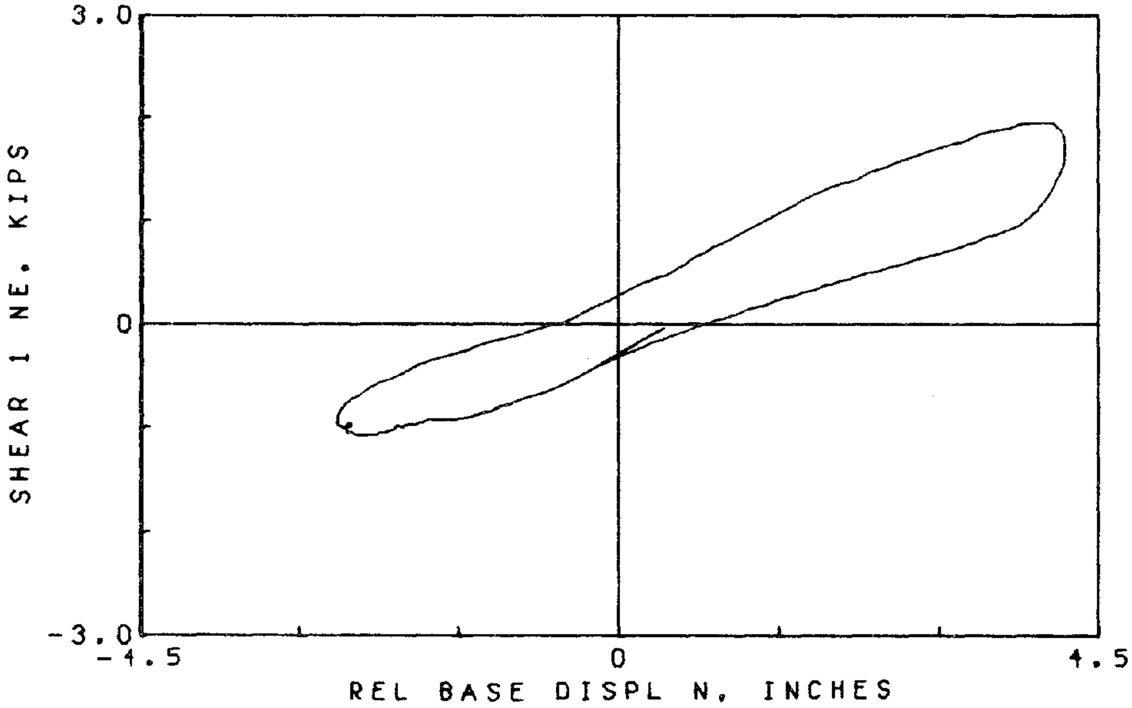


(b) Southwest bearing location.

Figure 28 Hysteresis loops for 50D bearings under largest El Centro signal, showing reduced stiffness and increased damping.



(c) Northwest bearing location.



(d) Northeast bearing location.

Figure 28 Hysteresis loops for 50D bearings under largest El Centro signal, showing reduced stiffness and increased damping.

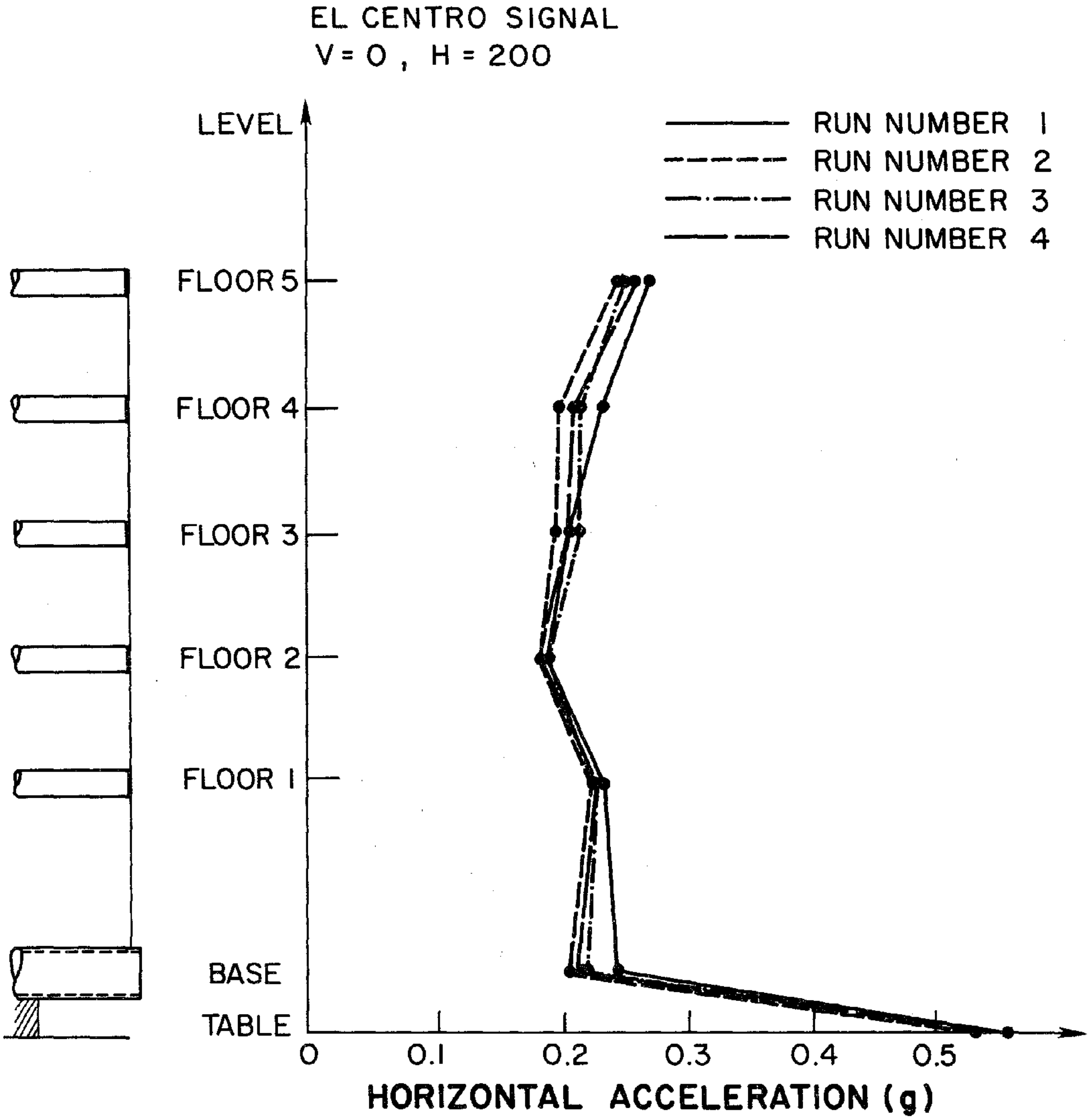


Figure 29 Frame acceleration for system with 50D bearings and two lead inserts, El Centro signal.

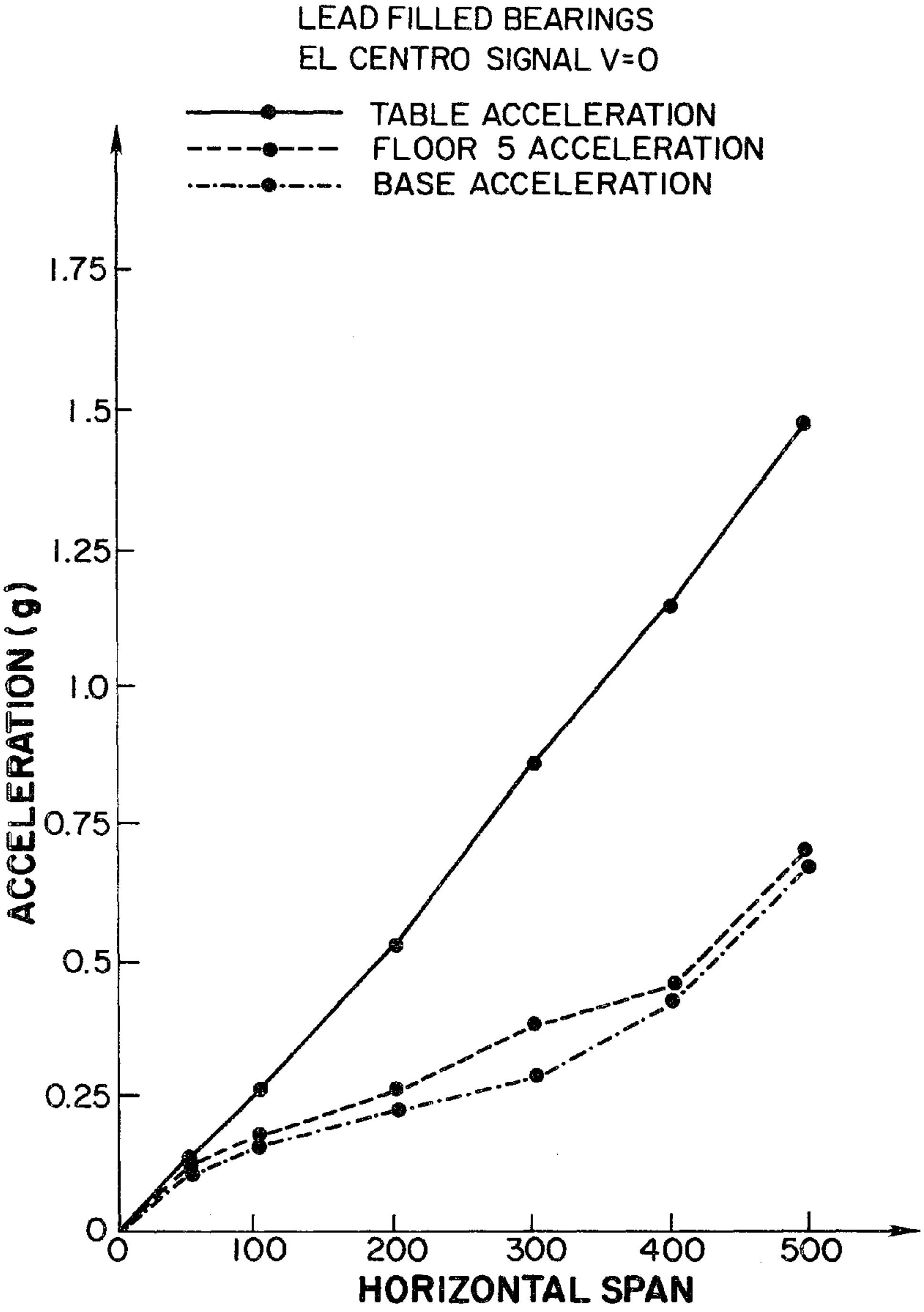


Figure 30 Nonlinear response with lead-filled bearings under increasing earthquake intensity.

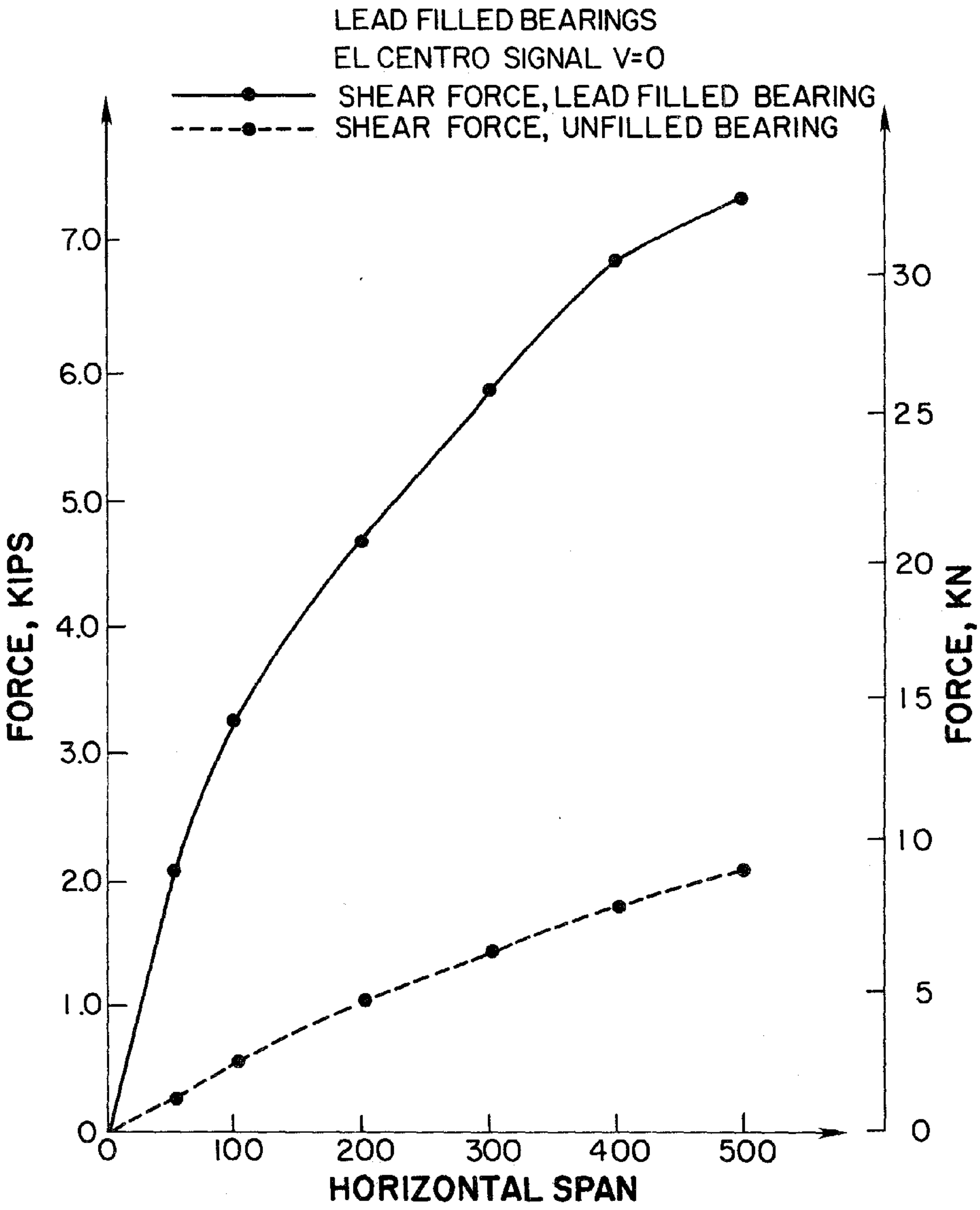


Figure 31 Forces in lead and in rubber under increasing earthquake intensity.

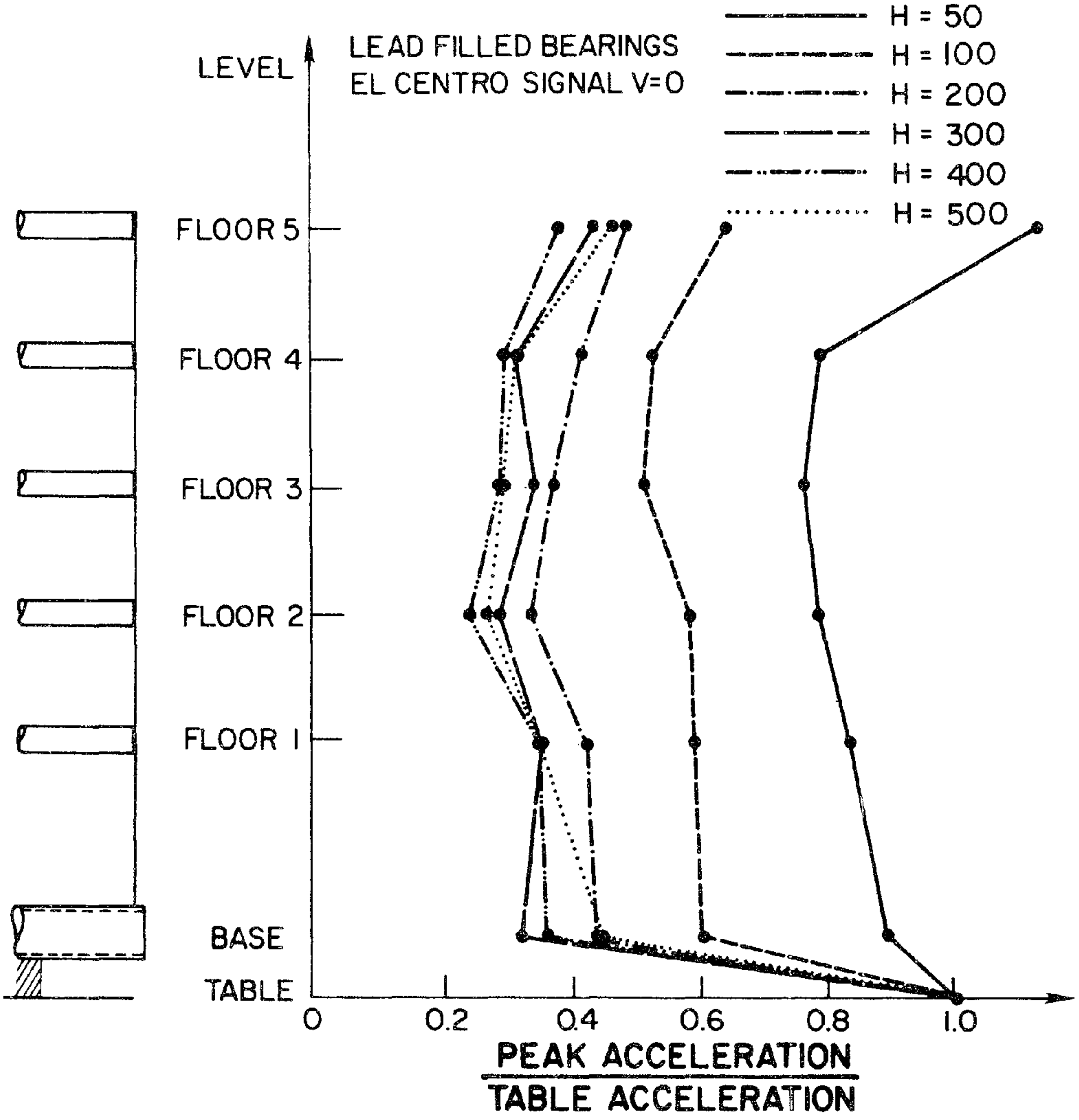


Figure 32 Normalized frame accelerations,
showing increased isolation under increased earthquake intensity.

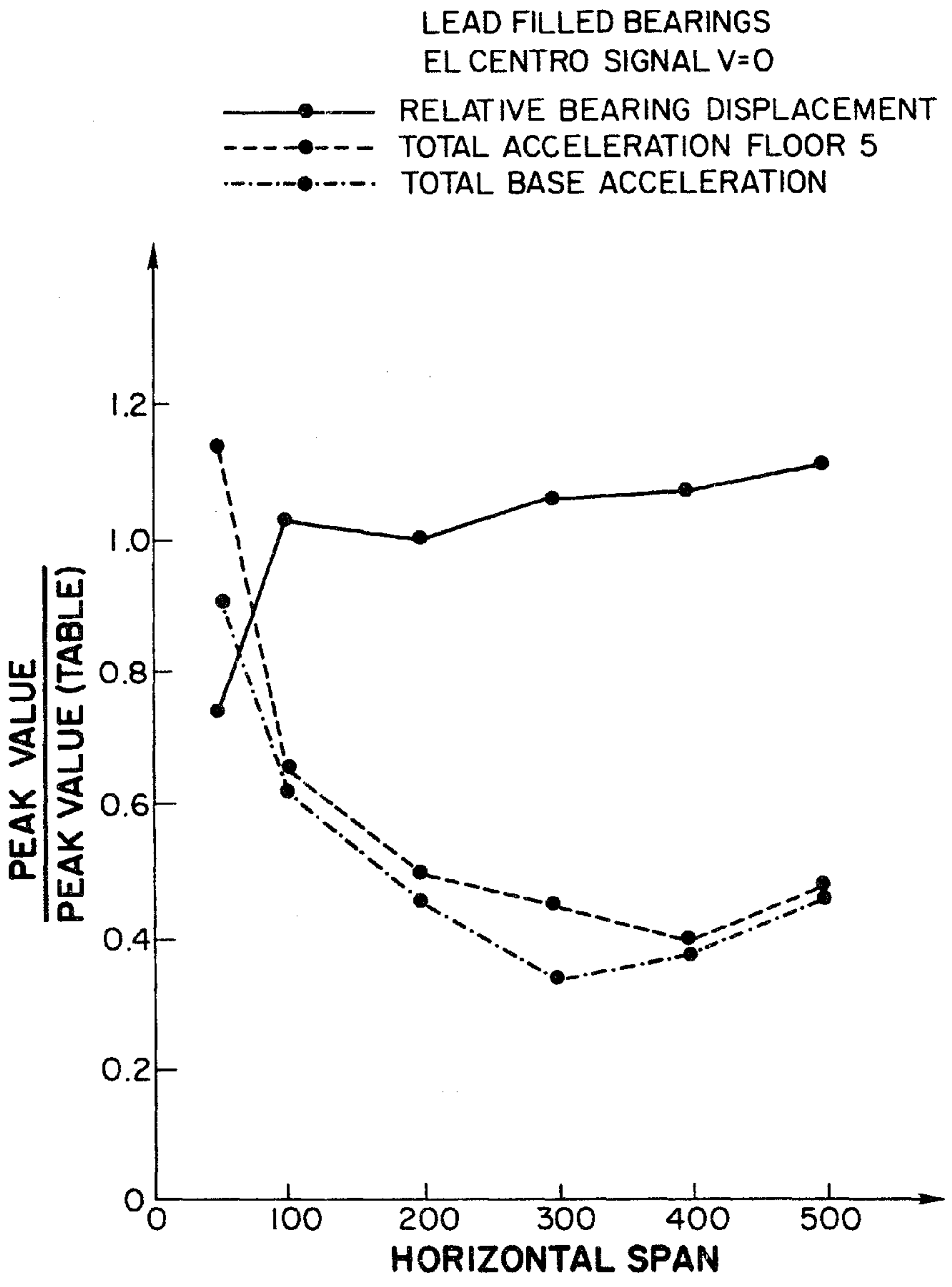


Figure 33 Normalized relative displacement, showing increased isolation under increased earthquake intensity.

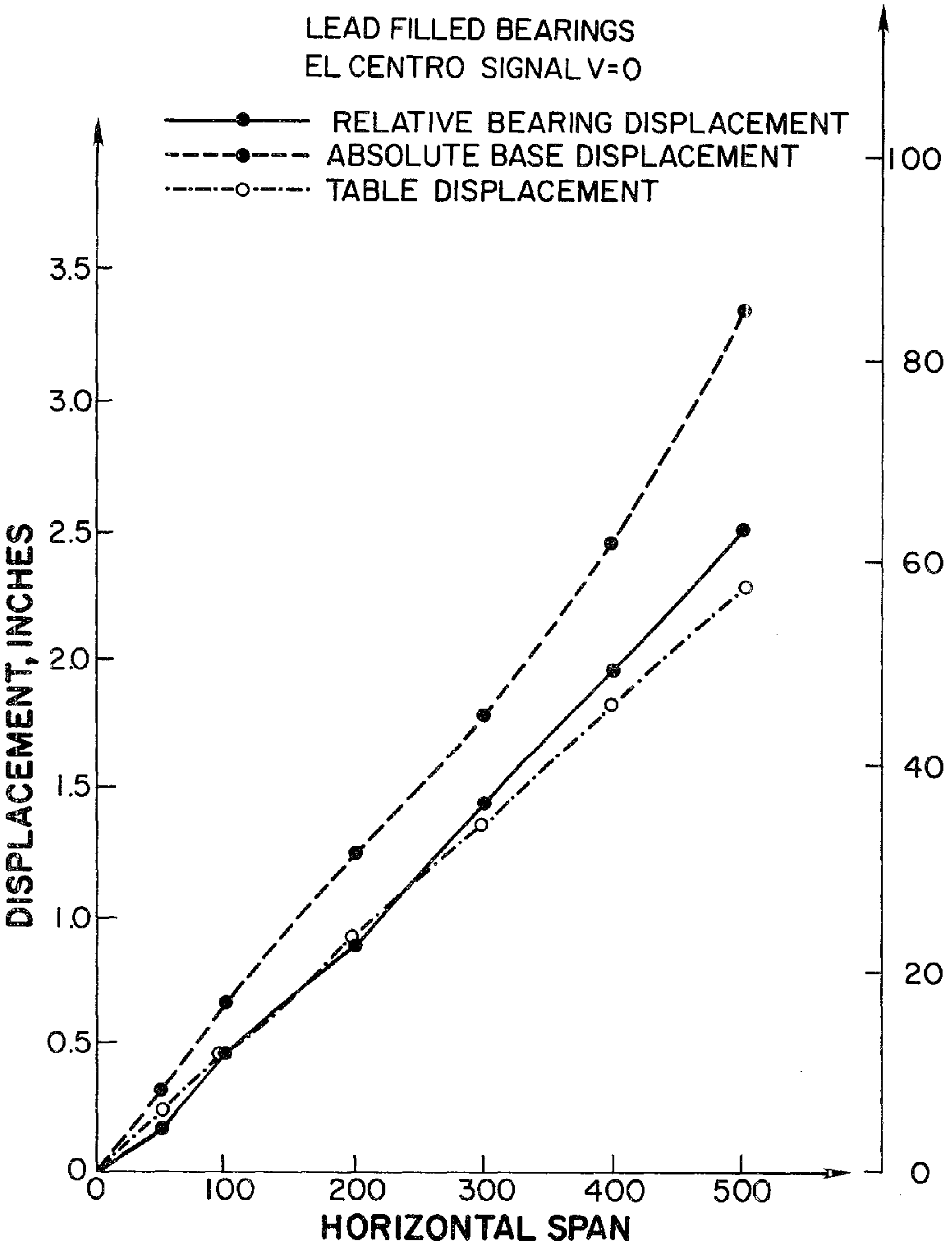


Figure 34 Relative displacement as a function of peak table displacement, under increasing earthquake intensity.

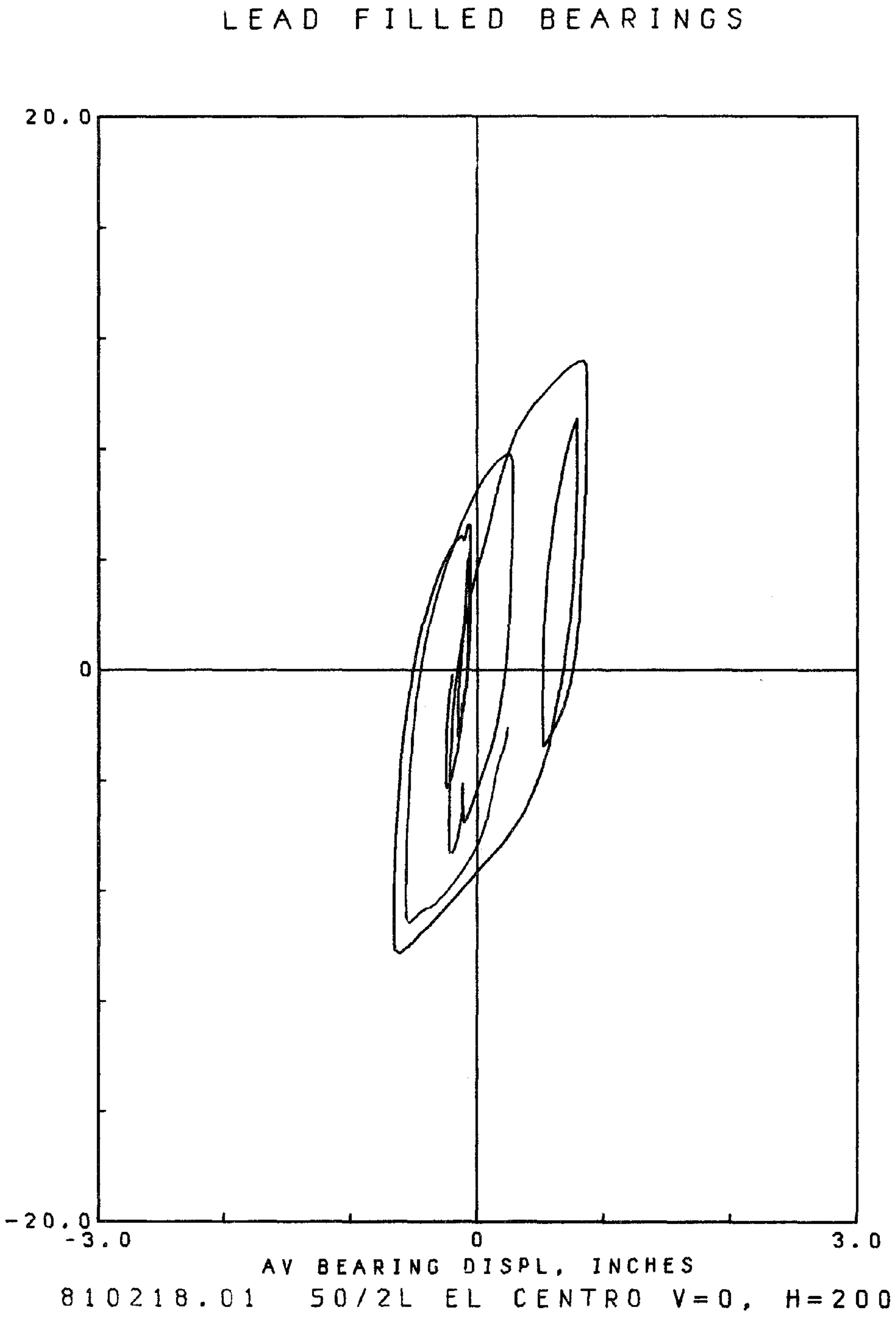


Figure 35 Hysteresis loops for isolation system with 50D bearings and two lead inserts, El Centro signal span 200.

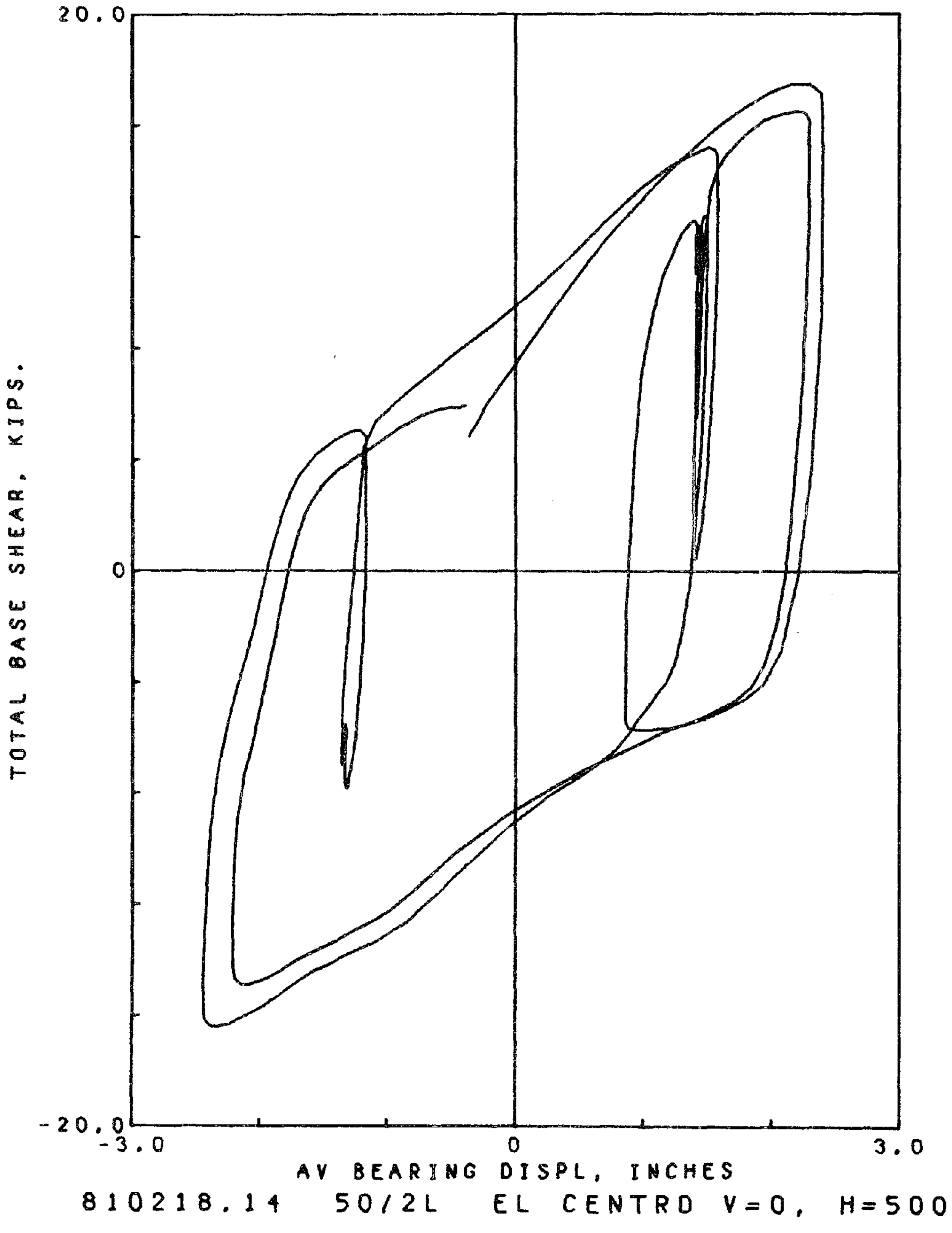


Figure 36 Hysteresis loop for isolation system with 50D bearings and two lead inserts.

LEAD FILLED BEARINGS

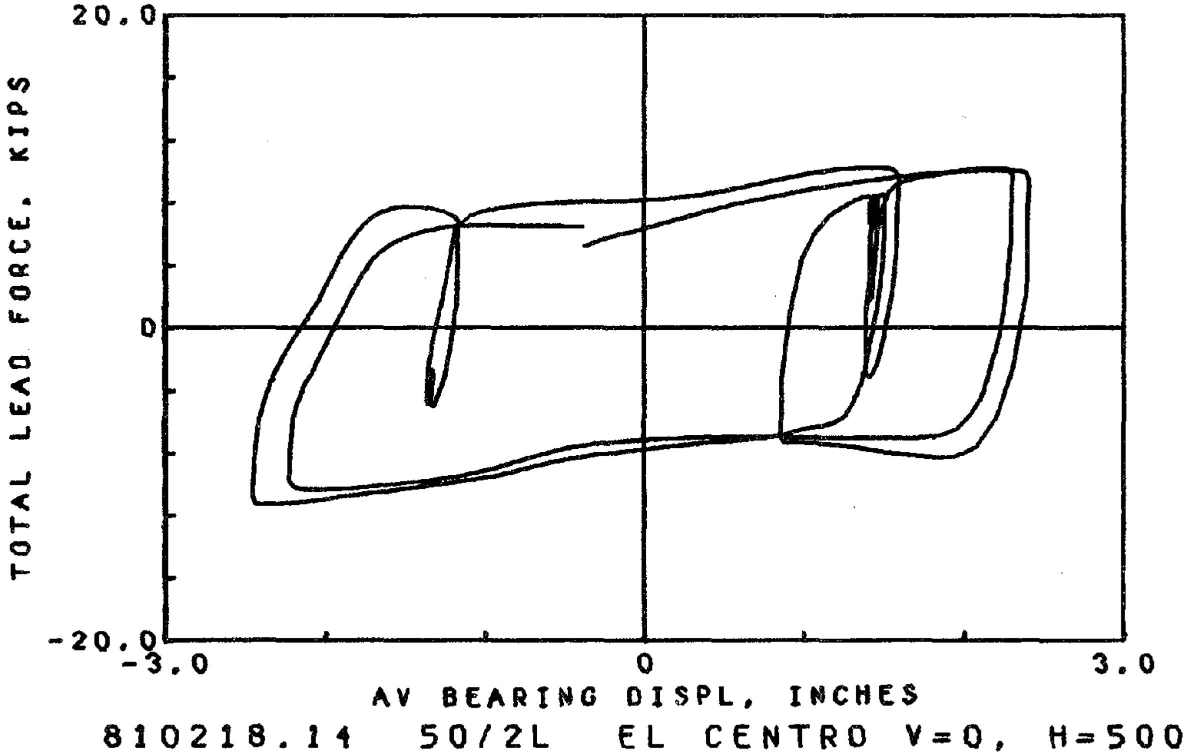


Figure 38 Lead force under El Centro signal span 500.

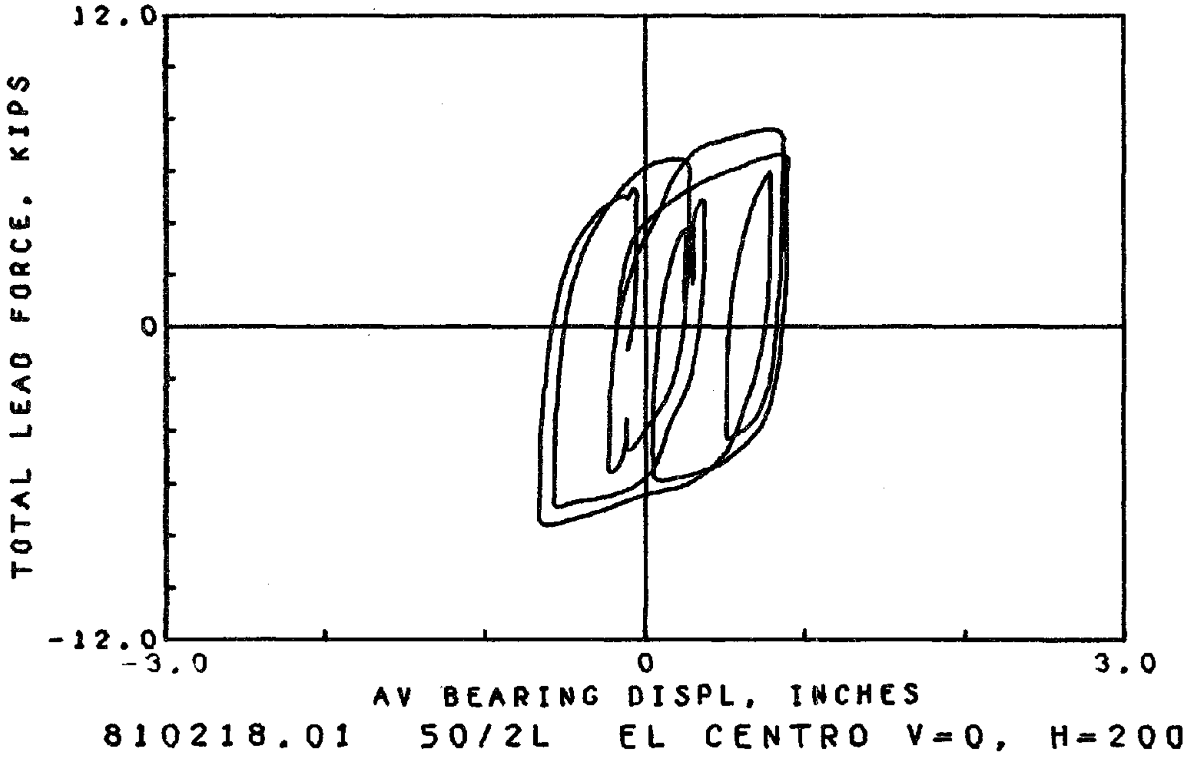
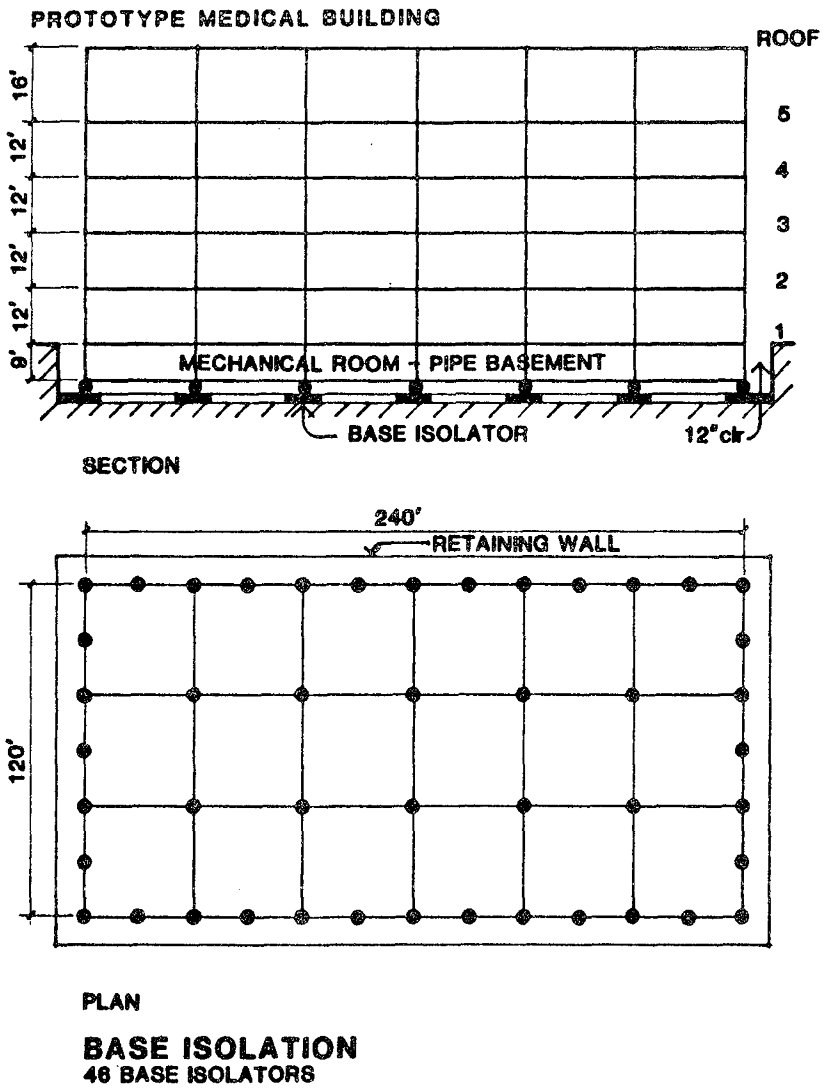


Figure 37 Lead force under El Centro signal span 200.



COST COMPARISON	ADD	DEDUCT
46 BASE ISOLATORS	$46000	
RETAINING WALL 720'x10'x$20	$144000	
BASEMENT SLAB SEPARATION 240'x120'x$2	$57000	
MISC. OTHER	$30000	
SEISMIC BRACING SHEAR WALLS 720'x73'x$3		$158000
FLOOR AND ROOF DIAPHRAMS, CONNECTIONS 240x120x7x$0.3		$60000
CEILING BRACING 240x120x7x$0.6		$88000
BRACING MECHANICAL AND ELECTRICAL COMPONENTS		$80000
	$277000	$384000

$ 384000
- $ 277000

SAVING : $ 107000 PLUS COST OF BRACING LOOSE EQUIPMENT

Figure 39 Cost comparison of medical building, with conventional construction and when isolated.

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