DYNAMIC RESPONSE OF A 20 FT X 20 FT SHAKING TABLE

by

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SYNOPSIS

A 20 ft x 20 ft shaking table that can move in one horizontal direction and the vertical direction is described along with its associated electro-hydraulic drive and electronic control system. The dynamic performance of the shaking table is illustrated first by means of frequency response functions,and then by the accuracy to which the table can simulate a given earthquake motion.

SHAKING TABLE AND ASSOCIATED SYSTEMS

An earthquake simulator laboratory has been constructed at the University of California's Richmond Field Station. The central feature of the laboratory is a shaking table with plan dimensions of 20 ft x 20 ft. The shaking table has one horizontal and the vertical degrees of freedom. It may be used to subject structures weighing up to 100 kips to motion of about twice the intensity of the N-S component of the El Centro (1940) earthquake in its horizontal direction of motion, and simultaneously, to vertical motion about twice the intensity of the vertical component of the same earthquake. The main purpose of the shaking table is to study nonlinear behavior in test specimens vibrating at amplitudes large enough to cause inelastic deformations(1).

The shaking table is constructed from a combination of reinforced and prestressed concrete. Structurally, it may be considered as a 1 ft thick 20 ft square plate. The plate is stiffened by heavy central transverse ribs that are 1 ft wide and extend 1 ft 9 in below the bottom surface of the plate, and by lighter diagonal ribs that are also 1 ft wide and extend 4 in below the bottom surface of the table. The hydraulic actuators that drive the table horizontally are attached to the table by means of one of the transverse ribs. The vertical actuators, as well as test structures, are attached to the table by means of prestressing rods located in 2 in diameter pipes that run vertically through the table on a 3 ft square grid. The table weighs 100 kips and is shown in Fig. 1(a).

Structures can cause large bending moments in the table while sitting on the table between tests or during testing. The design moment of the table is 50 kip ft/ft and its free-free natural frequency is 24 cps. The shaking table was designed (2) to have a natural frequency greater than

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20 cps so that it would behave essentially as a rigid body in the typical operating frequency range of 0-10 cps. A concrete table was selected primarily on the basis of cost. However, a concrete table was considered to have a secondary advantage over a steel table, namely, higher damping capacity and a lack of local modes of vibration both of which result in quieter operation. The largest shaking table in the world (3), located at the Ministry of Science and Technology's National Disaster Prevention Agency in Japan, is constructed from welded steel plate. The Japanese table is 15 m x 15 m, making it approximately four times the plan area of the facility at the University of California.

The shaking table is driven horizontally by three 50 kip hydraulic actuators, one of which is shown in Fig. 1(b), and vertically by four 25 kip hydraulic actuators, one of which is shown in Fig. 1(c). The actuators have swivel joints at both ends so that they rotate about the foundation swivel joints as the table moves. The total length of each horizontal actuator, including swivel joints, is 10 ft 6 in, and the total length of each vertical actuator is 8 ft 8 in. The length of the actuators help to decouple the vertical and horizontal motions of the table, and further decoupling is accomplished by electronic means. The actuators are located in a pit beneath the shaking table as shown in Fig. 2.

The horizontal actuators are equipped with 200 gpm servo-valves and the vertical actuators with 90 gpm servo-valves. The flow rate of the servo-valves limits the maximum velocities in the horizontal and vertical directions to 25 in/sec and 15 in/sec respectively. The strokes are 12 in ($\pm$ 6 in) for the horizontal actuators and 4 in ($\pm$ 2 in) for the vertical actuators. However, the horizontal actuators are being limited to displacements of $\pm$ 5 in to improve the resolution of table motion in the horizontal direction.

In operation, the air in the pit within the foundation and beneath the shaking table is pressurized so the total dead weight of the table and the test structure is balanced by the difference in air pressure between the air in the pit and the air above the shaking table. The pit entrance is sealed by two air tight doors that provide a lock chamber and thus access to the pit while the air in the pit is pressurized. The 1 ft gap between the shaking table and the interior foundation walls is sealed by a 24 in wide strip of vinyl covered nylon fabric. The fabric, in its inflated position, can be seen in Fig. 1(a). A differential air pressure of 1.55 psi is required to balance the dead weight of the shaking table alone; the maximum air pressure is not expected to exceed 4 psi.

Because the dead weight of the table and test structure are balanced by air pressure, the vertical actuators only have to supply the forces required to accelerate the table vertically. Thus, the four vertical actuators can accelerate the unladened table up to a maximum acceleration of 1 g vertically. The three horizontal actuators can accelerate the table up to a maximum acceleration of about 1.5 g horizontally.

At frequencies lower than 1 cps, the intensity of motion that the table can undergo is limited by the actuator strokes. At intermediate frequencies from 1 to 4 cps, the intensity of motion is limited by the maximum actuator velocities. At frequencies greater than 4 cps, the intensity of motion is limited first by the maximum accelerations and then by the frequency response characteristics of the shaking table drive system. These limitations for both horizontal and vertical motions are illustrated in Fig. 3.

Oil, at an operating pressure of 3,000 psi, is supplied to the actuators by four 80 gallons per minute variable volume pumps, each of which is driven by a 120 HP electric motor. Accumulators that can double the peak instantaneous flow rates are installed in the main oil line, but even so, the oil supply is not sufficient to permit maximum horizontal and vertical table velocities simultaneously. It is assumed unlikely that the maximum horizontal and vertical velocities in an earthquake record would occur simultaneously.

The actuator forces are reacted by a massive foundation, which is a reinforced concrete structure in the form of an open box with 5 ft thick sides. The outside dimensions of the box are 32 x 32 x 15 ft, and the inside dimensions are 22 x 22 x 10 ft. The shaking table forms a closure for the box; the top of the shaking table being flush with the top of the foundation walls which in turn are flush with the floor slab of the building housing the shaking table, see also Fig. 1(a). The foundation weighs 1,580 kips.

The vertical actuators do not have sufficient force capacity to resist the overturning forces that would be generated by the largest structures that are envisioned for testing on the table. Currently (1972), the table is operating under an active stabilization system (4), to evaluate the effectiveness of this system in resisting overturning forces. One of the objectives in the development of the 20 ft x 20 ft shaking table has been to study the problems associated with such shaking tables, and in particular, to assess the relative merits of active and passive stabilization techniques (4). It is planned to install a passive stabilization system for the shaking table that will have a larger overturning moment capacity than the active stabilization system in the near future.

The electronic control system for the shaking table, which was supplied by MTS Systems Corporation, Minneapolis, Minnesota, who also supplied the hydraulic actuators, is based on controlling five degrees of freedom of the shaking table (5). The sixth degree of freedom, translation perpendicular to the direction of the horizontal translational degree of freedom, is controlled by a sliding mechanism. Transducers are installed in each actuator to measure displacements and forces. From the displacement signals, feedback signals representing the average horizontal and vertical displacement, the pitch, roll and yaw (or twist) are derived on the assumption that the table is a rigid body. Corresponding force signals are also derived that are used to supplement the primary displacement feedback signals. Normally the pitch, roll and yaw command signals are zero, and the horizontal and vertical command signals represent translational displacement time histories of an earthquake record.

Earthquake motions are recorded and stored normally in the form of acceleration-time histories. A mini-computer, whose prime function is the collection of data during a test (6), is used to integrate the acceleration time history to obtain a velocity-time history which in turn is integrated to obtain a displacement-time history. The time histories are then checked to see that the maximum velocity and maximum displacement do not exceed the performance limits of the shaking table. If they do, a base line correction is made to the original acceleration-time history and the procedure is repeated.

After satisfactory displacement-time histories are available for both the horizontal and vertical command signals, they are fed via a digital-to-analog converter to an analog tape recorder. The command signals are stored on the analog tape recorder until they are required for a test, and at that time they are fed from the tape recorder to the control system.

DYNAMIC PERFORMANCE OF THE SHAKING TABLE

Frequency response functions for vertical and horizontal motions of the shaking table are shown in Figs. 4(a) and 4(b) respectively. The gain factors exhibit varying degrees of flatness and peaking because the control settings were different for each frequency response measurement. The control system is quite sensitive to gain settings of the primary loops in the translational degrees of freedom, and to the amount of force stabilization in the pitch degree of freedom. A particular frequency response could be improved slightly by searching for an optimum control setting. However, since such adjustments will be difficult to perform with a test structure on the shaking table, the curves should be regarded as typical.

The phase factors of Figs. 4(a) and 4(b) show that the frequency at which the excitation lags the response by 90° is about 8 cps for both vertical and horizontal motions. These frequencies are normally the fundamental resonant frequencies of the particular degrees of freedom associated with the frequency response curves. In electro-hydraulic systems, the fundamental resonant frequency is referred to as the oil column resonant frequency because the most flexible element in the spring associated with the resonant frequency is the compressibility of the oil in the actuator. However, the oil column resonant frequencies of the 20 ft x 20 ft shaking table have been established to be 15 cps for vertical motion and 16 cps for horizontal motion. The reason the 90° phase lag frequency occurs at a frequency that is just greater than half the oil column resonant frequency is being investigated. The electronic control system, which was developed specifically for this shaking table, is being checked carefully, and the effects of foundation transmissibility on the control system are also being studied.

The foundation transmissibility functions have been established by operating the table under harmonic motion of constant acceleration amplitude and varying frequency. The transmissibility functions for vertical and horizontal motions are shown in Figs. 5(a) and 5(b) respectively. The gain factors show that at frequencies below 10 cps the soil stiffness is predominant in reacting actuator forces, while at frequencies above 20 cps, the inertia mass of the foundation becomes predominant in reacting the actuator forces. At frequencies between 10 and 20 cps, there is a transition zone where soil stiffness and foundation inertia are combining to react the actuator forces.

In the vertical direction of motion the ratio of foundation acceleration to table acceleration reaches 4% at a frequency of 24 cps. At 24 cps the ratio appears to be rapidly approaching its limiting value of 6.3%, which is the ratio of table weight to foundation weight. The ratio of foundation acceleration to table acceleration for horizontal motion reaches the limit of 6.3% at 25 cps and will probably exceed this value because the actuator forces are applied in a plane above the center of gravity of the foundation, see Fig. 2. Thus the foundation pitches as well as translates under the action of the horizontal actuators. The foundation acceleration measurements for Fig. 5(b) were made at the level of the horizontal actuators. The phase lag in the foundation transmissibility function for vertical motion reaches 90° at about 8.5 cps and tends to a limit of 130° with increasing frequencies. In the horizontal direction of motion the phase factor reaches a limit of about 60° at 12 cps.

The overall dynamic performance of the shaking table can probably be judged most easily by the accuracy to which the shaking table can reproduce a given earthquake record. The displacement-time history of the N-S component of the El Centro (1940) earthquake was obtained by the techniques described above and fed as the horizontal command signal to the shaking table control console. The earthquake acceleration-time history and its derived displacement-time history are compared with the actual displacement and acceleration-time histories of the shaking table motions during a simulation of the horizontal component of the El Centro earthquake in Fig. 6. The shaking table follows the displacement command with sufficient accuracy that the table acceleration is a good replica of the El Centro earthquake acceleration.

CONCLUSION

A 20 ft x 20 ft 100 kip shaking table that can move in one horizontal direction and the vertical direction has been shown capable of reproducing motions which are good replicas of prescribed strong-motion earthquakes.

ACKNOWLEDGMENT

The shaking table facility was developed with the financial support of the National Science Foundation.

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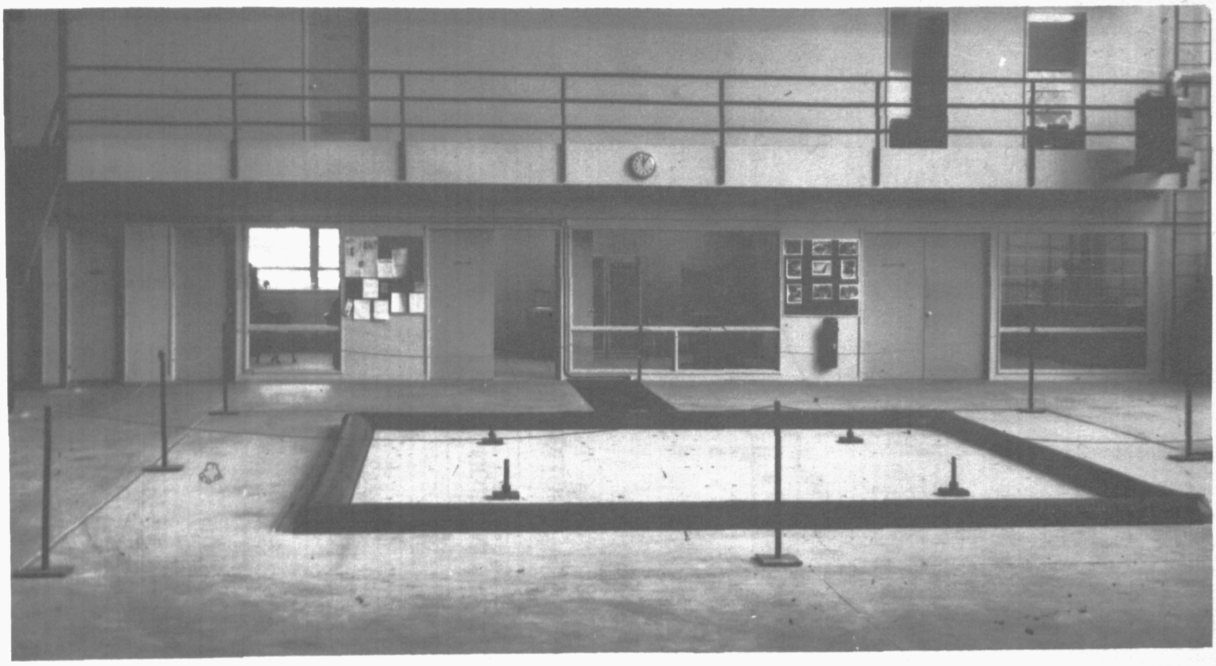


FIG. 1(a) above, THE SHAKING TABLE

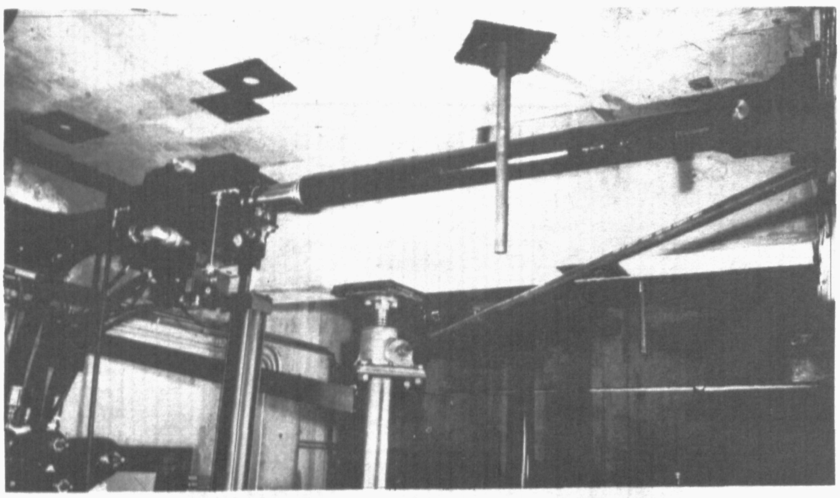
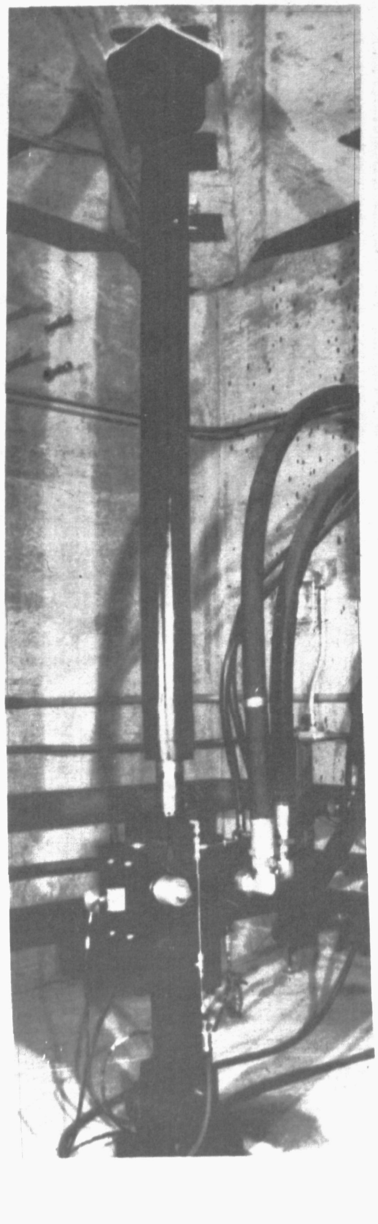


FIG. 1(b) above, A HORIZONTAL ACTUATOR

FIG. 1(c) right, A VERTICAL ACTUATOR



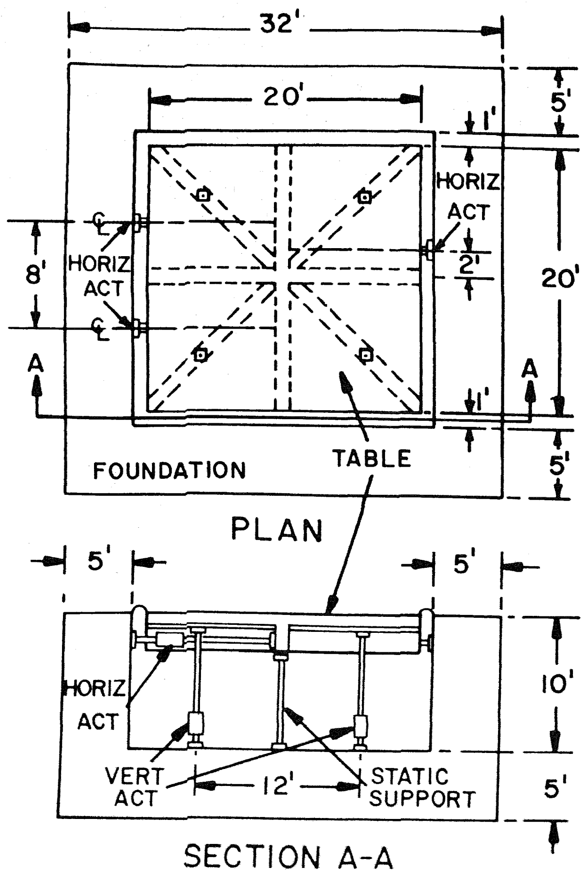


FIG 2 ACTUATOR LOCATIONS

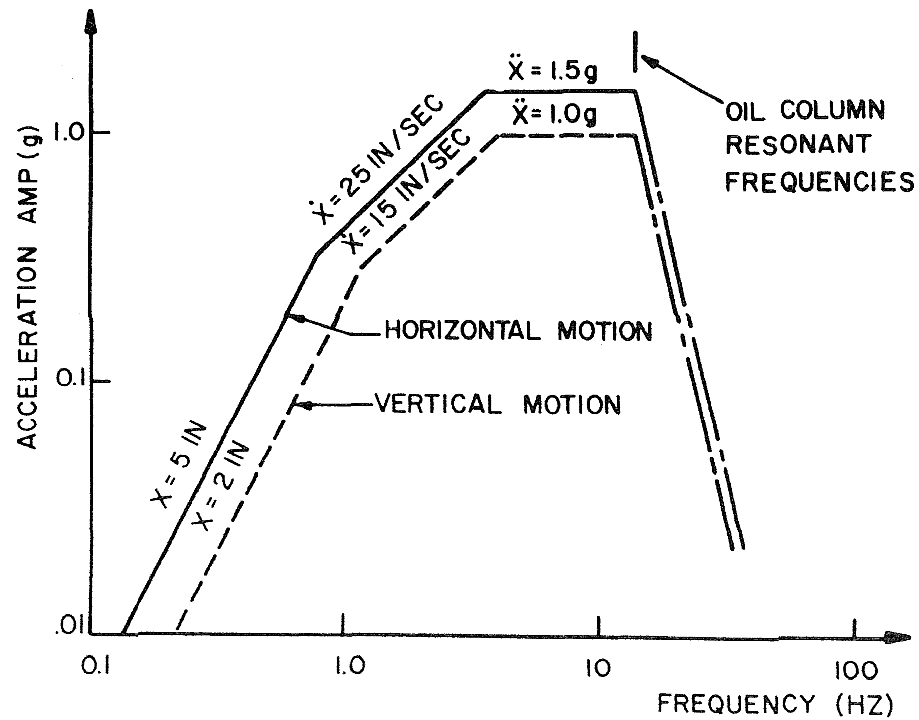


FIG 3 LIMITATIONS ON DYNAMIC PERFORMANCE

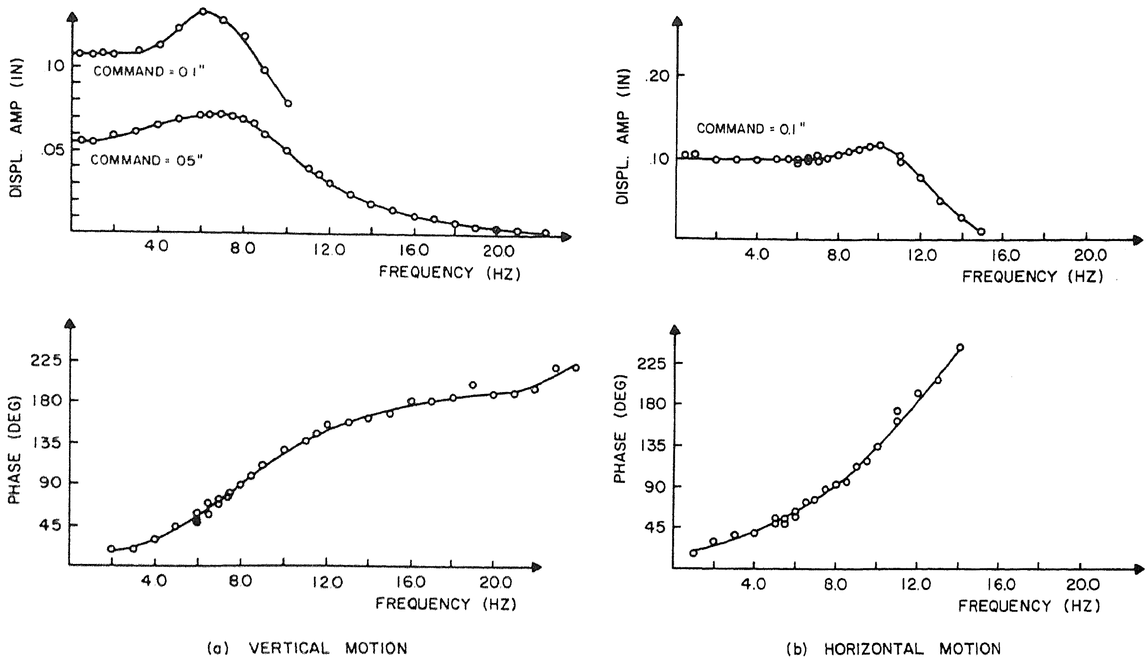


FIG. 4 TRANSLATIONAL FREQUENCY RESPONSES

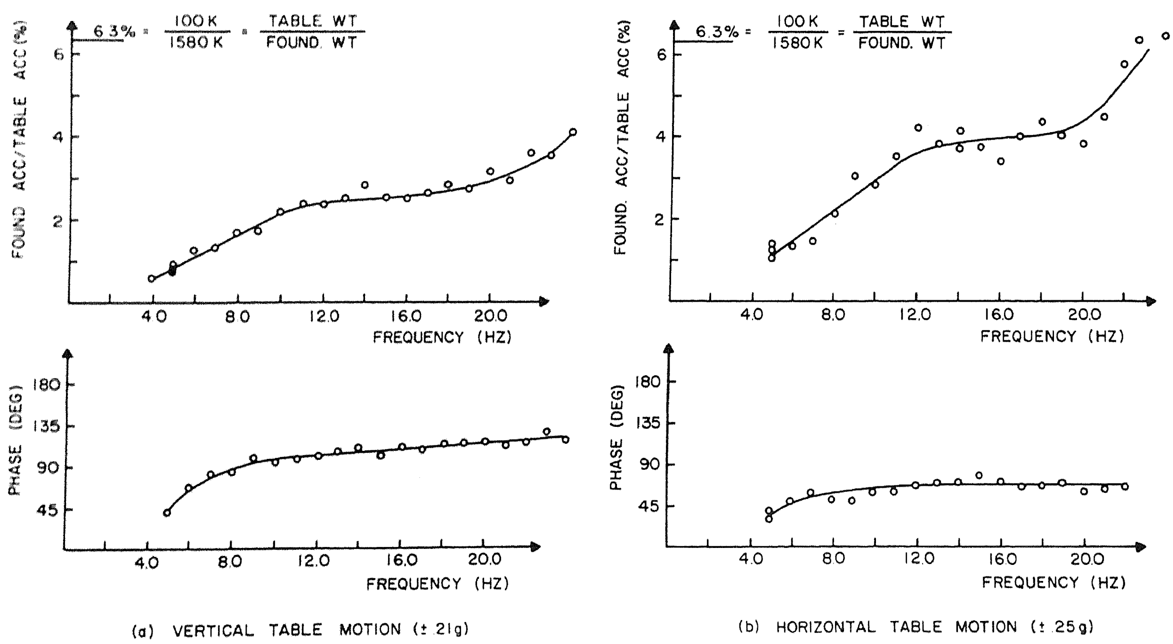
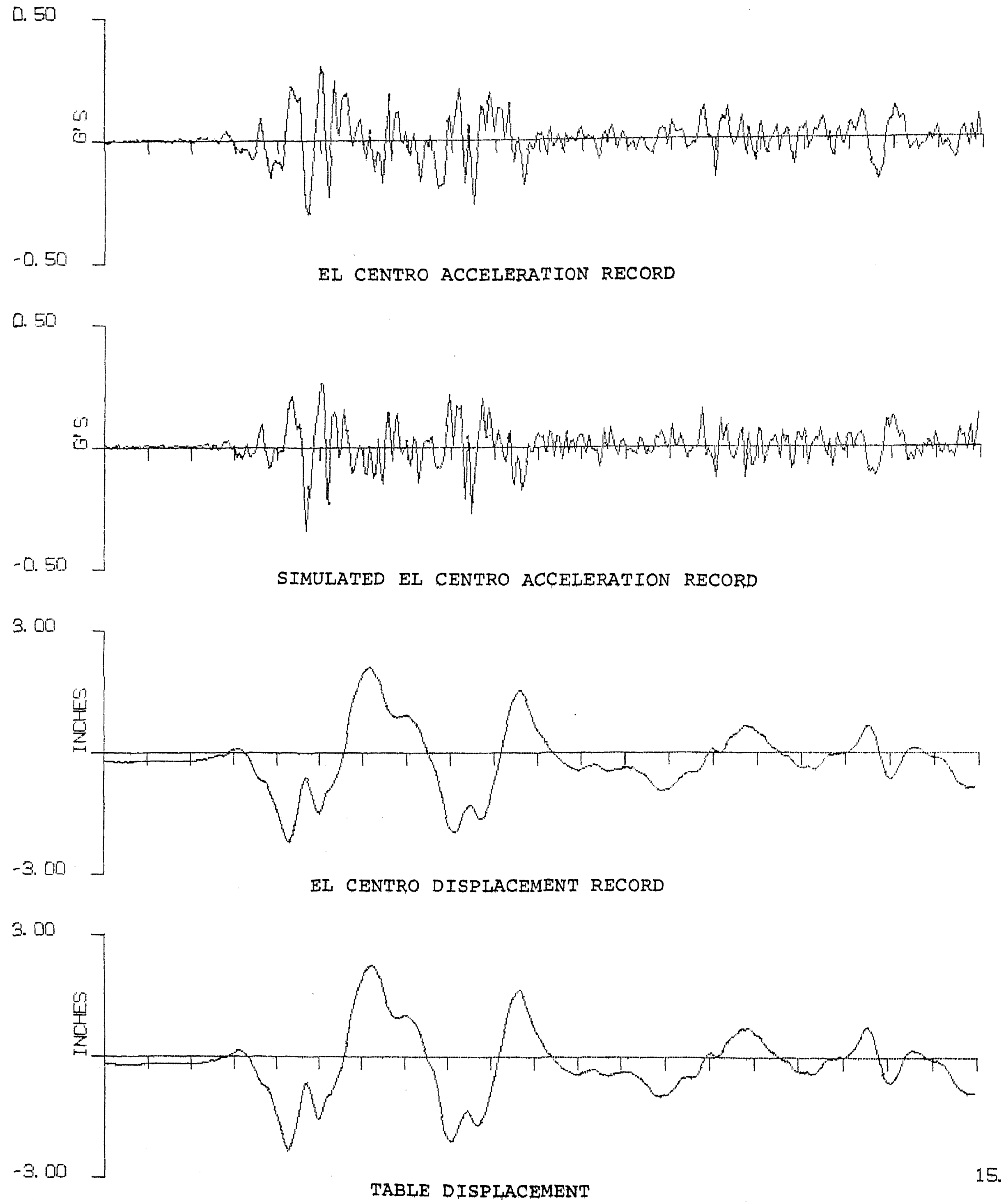


FIG. 5 FOUNDATION TRANSMISSIBILITIES



FIG, 6 SIMULATION OF EL CENTRO EARTHQUAKE