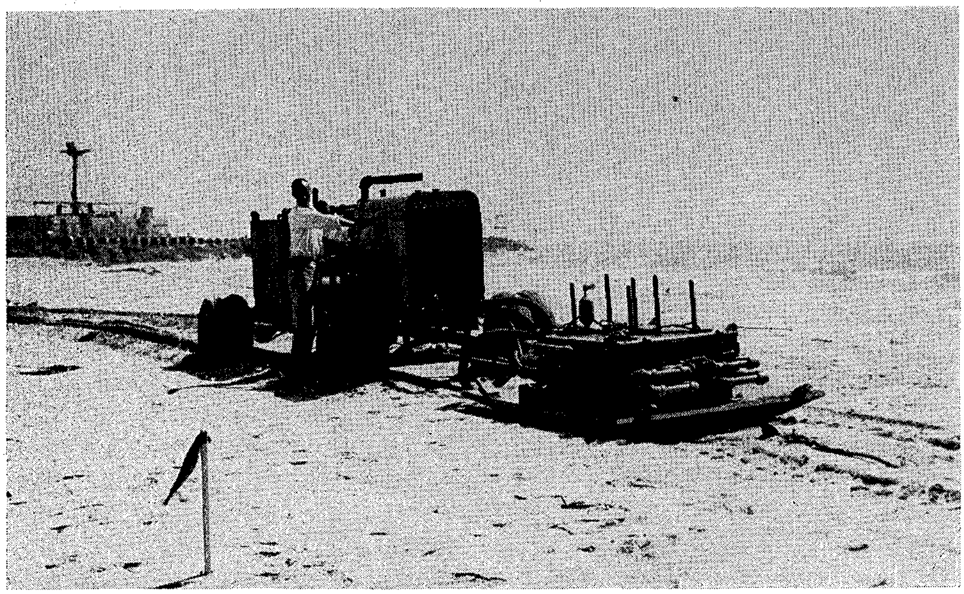


Vibrator, designed by Caltech engineers for compacting soil, is tested by the Navy at Port Hueneme, Calif. Trailer hauls vibrator, which is at right.

SOIL COMPACTION BY VIBRATION

Basic research produces a highly practical machine to compact soil for airfields

by FREDERICK J. CONVERSE

As AIRPLANES GROW larger, wheel loads get heavier and tire pressures become higher. The problem of constructing runways for handling planes on the ground therefore becomes increasingly greater. To obtain a firm foundation, the soil below the runway pavement must be compacted to a high density to considerable depths. At the present time the soil is compacted by very heavy rollers or "super compactors" working over many thin layers of soil until thicknesses up to two, three, or even four feet are compacted into a hard base on which to place the pavement.

The heaviest "super compactors" weigh up to 400,000 pounds. There is a definite need for a lighter machine which will obtain the required densities in a shorter time. Vibration compaction appears to offer a solution. However, attempts to develop such a machine in the past have not been very successful. Much of the trouble seems to have come from a lack of basic knowledge of the laws governing the compaction of soil by vibration. The engineers for the armed forces are keenly aware of this need, and it was through their sponsorship that a team of engineers at the California Institute of Technology was given the opportunity to study the problem.

From September 1948 to March 1950 the study was sponsored by the Department of the Army, Engineer Research and Development Laboratories, Fort Belvoir, Virginia. This was primarily a basic research project. The principal objective of the investigation was the development of a method for calculating the resonant frequency of the entire system in terms of the vibrator loads and dimensions and certain elastic constants of the soil. The complete system, which includes the vibration mechanism and the soil being vibrated, is called the vibrator-soil mass.

Resonant frequency means that the natural frequency of the vibrator-soil mass is the same as the frequency of rotation of the vibrator eccentrics. Since maximum dynamic displacements occur at the resonant frequency, it was anticipated that operation at such a frequency would produce maximum compaction of the soil. A second objective was to measure the degree of compaction and depth to which the soil could be compacted.

The problem was attacked from two angles. The first was purely theoretical and required certain simplifying assumptions as to the character of the soil in order to make the mathematics at all possible of solution. The second was experimental, and involved tests in a pit 10 feet square and 6 feet deep filled with sand.

A solution was obtained from the theoretical studies, which pointed the way toward the development of an empirical formula from the field tests.

The field tests were made by placing a vertical oscillator on circular steel plates of various diameters and running it at frequencies varying from about 7 cycles per second to 30 cycles per second. Dynamic forces from 300 pounds to 1200 pounds were used in these tests, and the dead load of vibrator and plates varied over about the same range.

In these tests the frequency was gradually increased and the resonant frequency was assumed to have been reached when the rate of settlement was a maximum. The resonant frequency was easily recognized by observing the violence of the oscillation. No difficulty was experienced in determining the resonant frequency to within half a cycle per second.

Factors found to affect the resonant frequency were: magnitude of the dynamic force, weight of the oscillator, size of the base plate, density of the soil, and shearing modulus of the soil. A formula involving these variables was developed as a result of the tests and the resonant frequencies predicted by this equation agreed closely with all values determined experimentally, including several observations made on a compact beach sand, using base plates 19 and 45 inches in diameter.

How much compaction?

The best speed at which to run the vibrator having been determined, the next problem was to find out how much compaction resulted and how deep the increased density extended below the surface. This was accomplished by measuring in-place densities before and after vibration by means of a penetrometer, or drive rod, calibrated to measure densities in terms of the number of blows of a standard weight falling through a standard height.

The results of these tests indicated that very excellent densities were obtained to depths of at least one and one-half times the width of the surface plate.

Based on the results of this work, the Institute undertook the design and testing of a large vibrator for the U. S. Navy Civil Engineering Research and Evaluation Laboratory, Port Hueneme, California. It was anticipated that this larger unit would provide data for checking the theory of resonance in the range of machines of practical size.

Newly-designed vibrator

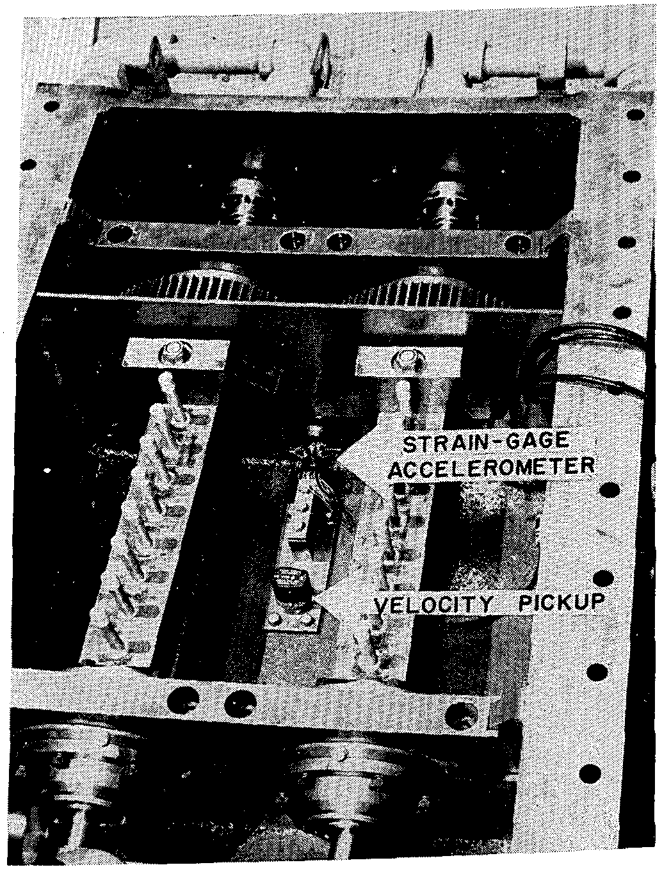
The new vibrator was designed with a base area of 15 square feet and a maximum weight of 6.6 tons, of which 2 tons were in the form of removable plates. This machine produces vertical dynamic forces by means of two oppositely-rotating shafts carrying eccentric weights. By this means the horizontal components of the centrifugal forces are balanced out and the vertical components are additive. At 720 revolutions per minute (12 cycles per second) the unit has a maximum dynamic force of 7.5 tons.

The photograph at the right is a view looking down into the vibrator, with the shafts and connecting gears visible. The design calls for nine removable eccentric weights on each shaft, held in place by stud bolts. Each eccentric weighs 18.3 pounds and its center of gravity is 3.05 inches from the center of the shaft. The studs provide an additional unbalance of 6.65 inch pounds. This arrangement permits nine different dynamic forces to be developed at any speed. A pair of the eccentrics are visible at the far end of the eccentric box, the rest having been removed. The photograph also shows a velocity pickup and an accelerometer, part of the vibration measuring equipment used in testing.

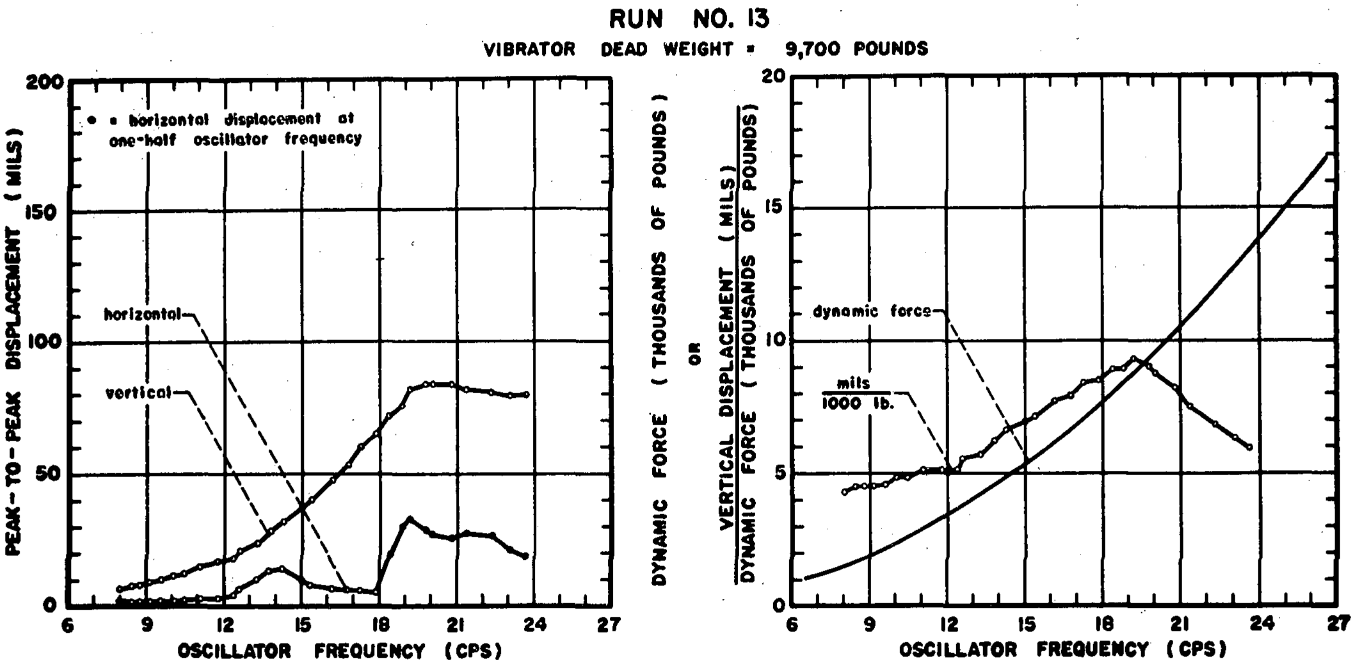
The shafts are driven by four hydraulic gear motors with oil as the fluid. Two of the motors are visible at the bottom of the photograph. There are two similar motors on the opposite ends of the shafts.

The vibrator and trailer assembly are shown in the picture on p. 12. The vibrator is at the right, on the sled type base plate, and the trailer is at the left, carrying the engine, the pumps and the oil storage tank. Power is supplied by a Chrysler engine driving two Vickers vane type double pumps through a two to one reduction gear. At 1200 revolutions per minute and 1000 pounds per square inch these pumps deliver 131 gallons per minute and require 70 hp. to drive them. Actually the pressures developed during the tests were less than one-third of the maximum and the power required was correspondingly lower.

The first field tests were designed to determine the resonant frequency of the vibrator-soil mass under various conditions of dynamic force and weight of vibrator, and to compare these results with the theoretical predictions. To do this the vibrator was kept in one spot and operated through a range of speeds, while the dead weight of the oscillator and the number of eccentric weights were varied. The amplitude of the oscillations, both vertical and horizontal, the frequencies, resonant point, and the pipe line pressures, were obtained by means of electronic recording equipment.



The new vibrator—as seen from above



Typical results are shown in the chart above. At the left is shown the total displacement at various values of oscillator frequency. The curves show both vertical and horizontal movements. Resonance occurs at the maximum peak-to-peak displacement. The sharpness of the peak is somewhat masked by the fact that displacement also varies with dynamic force, and dynamic force varies with frequency. To overcome this difficulty the curves at the right were plotted. This figure shows how the dynamic force varies with frequency. The other curve was obtained by dividing each displacement value by the corresponding dynamic force in 1000 pounds. This gives equivalent displacement per 1000 pounds of dynamic force. The resonant point is sharply defined in this later curve.

The results of these tests checked very closely with the theoretical predictions based on the tests with the small oscillator, and indicate that the smaller unit modeled the larger one very satisfactorily.

A further check on the theoretical approach exists in the results of experiments by Professor Adrian Pauw on the behavior of heavy concrete blocks under vibratory loading. These results are included in a thesis entitled "A Rational Design Procedure for Machine Foundations," presented as partial fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering at the California Institute of Technology. Professor Pauw worked on the compaction project while developing his thesis, and his contributions to the theory have been especially important.

The effectiveness of the machine as a compactor was determined by towing it along the beach and recording densities of the sand both before and after the machine had passed. The values of density in pounds per cubic foot were converted into percent of the maximum obtainable by the standard laboratory compaction procedure for comparison with the requirements of engineering practice. In this procedure the soil is compacted in a 1/30 cubic foot cylinder by 25 blows of a ten pound hammer falling 18 inches on each of three layers. The soil is compacted at different moisture contents and its dry density is found to vary with moisture. At a certain moisture content the density is a maximum. This density is called "maximum density of the soil." Ninety-five per cent of maximum indicates excellent compaction. In these tests values close to or even above 95% were obtained to a depth of five feet. This is especially remarkable because the sand contained only about 3% moisture, while 13% is required for maximum compaction by standard laboratory methods. The density in the field was actually approximately 100% of the value obtainable in the laboratory at the same moisture.

The theory and the testing to date have all been on granular material, specifically sand. New theoretical considerations will have to be developed for use with other types of soil. The effects of cohesion, and the manner of variation of the modulus of elasticity of cohesive soil with depth are two important variables affecting resonance and damping, about which little is known. During the coming year an attempt will be made to modify the theory used in the studies of granular soils to include these variables. Both theoretical and experimental work will be carried on simultaneously.

The members of the Institute staff contributing to the project are Professors Converse, Director; Housner; Hollander; and Martel. Special mention should be made of the work of Mr. Delbert Hausmann, class of '48, who has been project engineer throughout the entire program. Professor Adrian Pauw of Rice Institute and Professor Patrick Quinlan of University College, Cork, Ireland, contributed heavily during their residence as graduate students at the Institute. Professor Walter Johnson of Pasadena City College assisted in the mechanical design of the large vibrator.