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# STATIC AND DYNAMIC SOIL COMPACTION

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## SYNOPSIS

**This paper** describes an investigation on soil compaction as part of a more comprehensive study on "Dynamic Properties of Soils," sponsored by the New Jersey State Highway Department, the Bureau of Public Roads, and Rutgers University. Methods to produce and measure compaction effects are discussed; laboratory and field experiments have been performed, and static and dynamic compaction efficiencies compared. The results indicate that for certain soils, in particular soils used often as highway subbases, dynamic compaction can produce higher densities and reach deeper strata than static compaction.

● The concept of soil as engineering material is only a few decades old. Though the foundations of most of our buildings, in particular our highways, are based on soil, rather little is known about the static characteristics and still less about the dynamic characteristics of soils.

Soil compaction to improve the load-bearing capacity becomes of primary importance whenever necessary to prevent failure of the structure supported by the soil.

### PURPOSE

The general purpose of the research project discussed in this paper was to (1) obtain a comparison of compaction effects on confined and nonconfined soils due to static loads, dynamic loads, and a combination of both; and (2) determine efficiency factors referring to static and dynamic compaction methods, or both, for confined and nonconfined soils.

The increasing interest can be deduced from the numerous papers published on these topics (*1* to *5*) in particular, during the last years (*6* to *8*).

### ORGANIZATION

A Joint Highway Research Committee consisting of members of the three sponsoring organizations, that is, the New Jersey State Highway Department, the U. S. Bureau of Public Roads, and Rutgers University, together with one member of Princeton University, authorized as one of their projects an investigation on "Compaction and Dynamic Properties of Soils."[1]

This investigation is based on suggestions made by the author in 1937 to the New Jersey State Highway Department and presented again in 1946 as a modified four-year program (*9*) to the committee. Actual work on the project started in 1947.

Eight unpublished reports (*10* to *17*) have been submitted so far to the committee and three published papers (*18* to *20*) preceded and emanated from this work. In this discussion, an attempt is made to summarize some of the results. The project has been subdivided into two parts: applied and fundamental research or, as indicated by the title of the project, first, "Compaction of Soils," and second, "Dynamic Properties of Soils."[2] This report is limited to the first part only, that is, mainly to the engineering aspect in-

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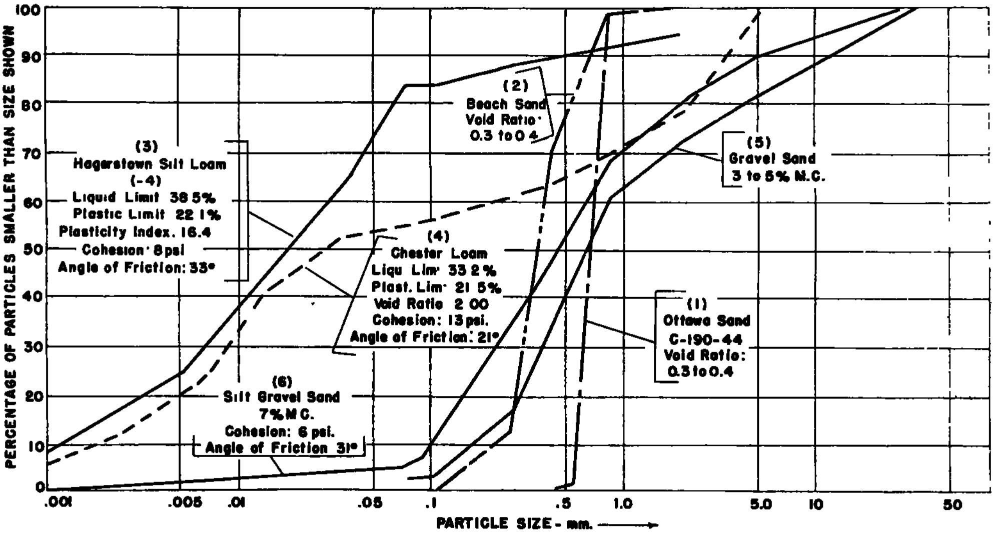
[1] The other projects authorized under the same sponsorship are: Engineering Soil Map and Soil Testing, Pavement Roughness and Performance, and Frost Reaction of Soils.

[2] Topics referring to the second part of the project, that is, "Dynamic Properties," are for example: critical frequencies, moduli of elasticity (Young, shear, bulk), characteristic waves (longitudinal, transverse, surface), damping, attenuation, pressure transfer, and density determinations. Investigations of this type are in the pilot stage.

cluding possible applications of dynamic compaction methods. The project, so far as "Soil Compaction" is concerned, comprises the following periods: (1) study and development of methods to measure and to produce compaction effects (first year); (2) compaction in the laboratory of noncohesive and cohesive soils with various moisture contents confined in three types of containers increasing successively in size, that is, first in small size containers with 4-in. diameter, second in medium size containers with 25.75-in. diameter, third in a large size container consisting of a concrete basin with a soil volume of 24 by 11 by 4 ft. (second and third year); and (3) compaction in the field of nonconfined soils by means of commercially avilable compactors (fourth year).



| Clay 0-.005 | Silt | Sand | Sand | Gravel | |
|---|---|---|---|---|---|
| Colloids 0-.001 | .005 - .05 | Fine .05-.25 | Coarse .25- 2.0 | 2.0- 4.76 | 4.76- 76.2 |

Figure 1. Grain-size accumulation curves.

Static-compaction experiments with sheepsfoot and heavy rollers, and dynamic compaction experiments with rammers or hydraulic investigations could not be made. Furthermore, studies covering cost ratios comparing static- and dynamic-compaction methods have been excluded.

GENERAL TEST PROCEDURE

1. *Preparations:* Distribution of soil as loosely as possible.

2. *Before Compaction:* Determination of soil surface profiles and average soil densities.

3. *During Compaction:* Determination of displacement amplitudes on the surface and pressure transfer below the surface of the soil at various depths during static or dynamic compaction.

4. *After Compaction:* Determination of soil surface settlements and soil densities at various depths after static or dynamic compaction.

Only a few pertinent data obtained during these four stages could be presented in this paper.

SOILS INVESTIGATED

Six types of soils have been investigated so far. Their characteristic data are combined in Figure 1.

*Ottawa Sand:* A standard sand (ASTM Standard: C190-44) was chosen for its uniform grain size and form. This synthetic sand has been selected with the thought in mind to have a basic reference in connection with results obtained by other investigations and was used for small-scale laboratory experiments only.

*Beach Sand:* A substitute for Ottawa sand had to be found for the concrete basin, since the price for filling the basin with Ottawa sand would have been too expensive. Samples of four different beach sands from the New Jersey coastline were collected and analyzed: from Seaside Heights, Manasquan Beach, Sea Girt, and Beach Haven.

All beach sands showed sufficient similarity with respect to grain size as compared with Ottawa sand. Beach sand from Seaside Heights was finally selected mainly because it was readily available.

Both sands, i.e. Ottawa and from Seaside Heights, have a void ratio between 0.30 to 0.40.

*Gravel Sand:* A gravel sand (slightly cohesive) was dumped over the top soil by trucks to an average height of 3.5 ft. This sand served as subbase for Route 4 (near Toms River, N. J.) and for the field experiments described later. The moisture content varied from 3 to 6 percent. For simplicity's sake, this sand has been designated as "dry" in the report. Grain-size distribution and moisture-density relation do not deviate very much from Ottawa and Beach sand; hence, to a certain extent, a comparison of the results obtained for the three soils might be permissible.

*Silt Gravel Sand:* A cohesive gravel sand with silt inclusions had been dumped several months before tests could be made by heavy dispersing equipment (Euclids). This sand served as subbase for Route S-49 (near Wildwood, N. J.) and for the field experiments described later.

A significant difference between the gravel sand and the silt-gravel sand was the silt content and the higher Proctor density of the latter.

The moisture content of the silt gravel sand during the experiments was approximately 7 percent. Results of triaxial shear tests indicated a cohesiveness of 6 psi and an angle of friction of 31 deg. for the silt-gravel sand in contrast to the gravel sand which had a slight cohesiveness only.

*Chester Loam (minus 4 material):* A Chester loam was selected in order to produce characteristic compaction effects whcih differ substantially from those of any type of less cohesive soils and was used for small scale experiments only. The initial void ratio of the Chester loam is approximately 2. All tests carried out so far have been made with a moisture content of 10 to 15 percent of the dry weight.

*Hagerstown Soil:* A cohesive soil, Hagerstown silt loam (minus-4 material), more readily obtainable than Chester loam, was used in the 25.75-in-diameter containers. The Hagerstown silt loam grain-size accumulation curve does not deviate substantially from the Chester loam as far as colloidal and silt particles are concerned. Additional constants of the Hagerstown silt loam are: liquid limit 38.5 percent, plastic limit 22.1 percent, and plasticity index 16.4 percent.

For the Hagerstown silt loam, 5-percent, 19-percent, and 23-percent moisture contents were investigated. A moisture content of 23 percent lies 0.9 percent above the Plastic Limit. Higher moisture contents have not been tested, due to difficulties in handling the soil. The various moisture contents were obtained by weighing the required amount of soil and water separately and mixing both thoroughly in small batches.

These time-consuming procedures required a complete drying for noncohesive soils and new samples for cohesive soils for each test and explain why only a restricted number of moisture-content variations have been tested so far.

## METHODS TO MEASURE COMPACTION EFFECTS

Purpose of the measuring methods is a determination of compaction effects due to static or dynamic loads.

A study of existing measuring devices at the beginning of the project, in 1947, indicated that adequate and reasonably priced methods, fulfilling all requirements, were not available at that time. Since then most of the developed instrumentation has been published in various papers (*18*, *19*, *20*) so that a detailed description can be omitted.

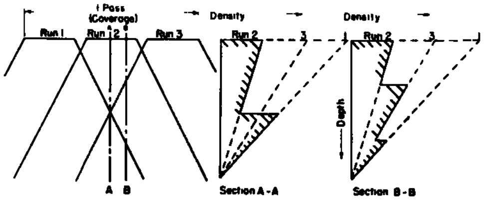
*Soil Density:* Compaction effects can be determined most advantageously by measuring soil density. The standard sand-cone method[3] offered one possibility.

[3] AASHO Desig. T 147-49. Disturbed Sample Method.

One of the difficulties inherent to any spot-check procedure, such as the sand-cone method, is demonstrated schematically in Figure 2. A variation in soil density with increasing soil depth is shown for one pass (complete coverage) indicating the overlapping effect of three adjacent runs. Assumed are two sections, one along the vertical A-A and a second along the vertical B-B. The results for both sections, that is soil density versus soil depth, produce rather different profiles.

Hence, it is not surprising that a minor, often unavoidable, deviation of the location of the spot checks from the vertical, that is a shift from the vertical A-A to B-B, introduces inconsistent results. (Slight straddling of a compaction machine on the surface has similar effects.)

Another reason for the often erratic density readings, for example in the silt-gravel sand investigated, was the formation of mortar-like clusters, due to a mixture of shell-residue (calcareous cemeting agent), sand, and water. Hence, many of the readings, hitting accidentally these densified spots, had to be discarded.



A-A, B-B Vertical lines along which soil densities are measured

**Figure 2. Change in soil density versus depth profiles due to overlapping effects of adjacent runs of compactors.**

Similar phenomena became obvious when evaluating the pressure-cell records.

A soil-density-determination method integrating over a larger distance, that is, measuring the average soil density between two points automatically, for example 3 ft. apart or more, would avoid some of these difficulties. Pilot tests with radioactive isotopes (*19*) have been started and are now being continued under the sponsorship of the Research Council of Rutgers University.

Finally, the sand-cone method, besides being a disturbed sample and rather time-consuming procedure, cannot be used for dry, noncohesive sands.

### *Surface Settlement, Surface Displacement-Amplitudes and Pressure Transfer*

Three other methods could be applied: First, the time-honored measurement of surface settlement by level and rod observations before and after compaction; second, the recording of displacement amplitudes on the surface by means of vibrographs; and third, the pressure transfer below the surface by means of pressure cells (the last two methods during compaction).

It must be understood that all three methods cannot replace direct density measurements, since they yield results which are not necessarily proportional to the soil density. They produce, however, rather valuable supplementary information with respect to compaction effects.

*Surface Settlement:* Surface settlements observed by rod and level have several disadvantages. They can only be made before and after compaction and not during the compaction procedure. Furthermore, no continuous and automatic recording is possible. Hence, a deflectometer was developed for experiments with soils confined in containers to continuously record the settlement, including penetration effects, which reached peak values in the order of 5 in. The settlement of a plate contacting the soil could be transmitted via a spring-loaded string-and-pulley arrangement to a potentiometer. The output of this potentiometer, consisting of a circular slide-wire resistance, was fed into an oscillograph.

*Displacement Amplitudes:* A vibrograph (Fig. 3) recording unidirectional displacement, velocity, acceleration, and jerk (*20*) (change of acceleration) has been developed with the primary objective of investigating soil-surface displacement amplitudes. The pickup unit of this vibrograph, essentially an electromechanical device, responds to linear motions only; the recorder unit, comprising an electro-optical device, is a modified standard galvanometer-oscillograph. The motion of the pickup unit is transmitted by means of a differential transformer via an amplifier to the recorder unit.

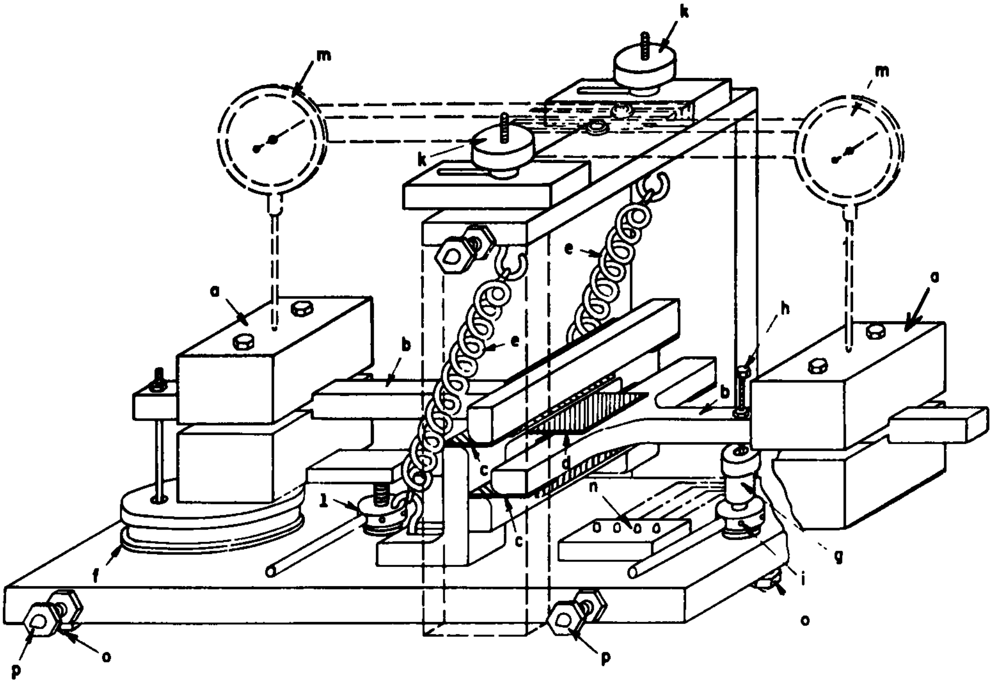
Hence, displacements on top of the vibrating soil or pavement in a vertical or any horizontal direction can be recorded. (A similar device would be adequate to obtain a continuous and permanent record of riding comfort in a vehicle, or road roughness, or of road profiles.)

SPECIFICATIONS FOR VIBROGRAPH

Displacement-Amplitude Range: 0.0001 to 0.1 in.

Frequency Range: 1 cps. to 100 cps.

*Pressure Transfer:* In order to determine compaction effects (pressure transfer) without disturbing the soil, pressure cells had to be developed which record pressure changes in the interior of the soil in any desired direction. In order not to disturb the continuity of the soil significantly, the pressure cells have been made as small as possible. The outside dimensions could be reduced to 1 in. diameter and 2 in. height. Their output, due to the rather small pressure changes in the soil of 0.001 lb. and less, must be recorded, requiring a high sensitivity. Each cell comprises a small linear-differential transformer enclosed in a cylindrical lucite housing. An interchangeable, pressure-sensitive, copper-beryllium membrane, 0.003 to 0.01 in. thick, deflects proportionally to the outside soil pressure and transmits its minute motion to the core of the transformer. No physical connection between membrane and transformer exists which otherwise might cause a disturbing restoring force, particularly in case of very small pressure changes. The natural frequency of the vibrating system is about 120 cps., permitting linear outputs up to 60 cps.



| | |
|---|---|
| a | ADJUSTABLE WEIGHTS |
| b | MOVABLE ARMS |
| c | CROSS LEAF JOINTS |
| d | COUPLING LEAF |
| e | SUSPENSION SPRINGS |
| f | DASHPOT |
| g | DIFFERENTIAL TRANSFORMER |
| h | COARSE ADJUSTMENT FOR TRANSFORMER |
| i | FINE ADJUSTMENT FOR TRANSFORMER |
| k | ADJUSTMENT FOR SPRINGS |
| l | DIFFERENTIAL SCREW FOR CALIBRATION |
| m | DIALS FOR CALIBRATION (DETACHABLE) |
| n | CONTACTS FOR TRANSMITTER CABLE |
| o | SUPPORTS FOR VERTICAL DISPLACEMENT |
| p | SUPPORTS FOR HORIZONTAL DISPLACEMENT |

**Figure 3. Pick-up unit for unidirectional displacement, velocity, acceleration, and jerk.**

Attempts to use resistance-wire gauges were not successful, mainly because of difficulties when interchanging the pressure sensitive elements to adapt the cell for various pressure ranges. In Figure 4, a positive X-ograph (*19*) print of Beach Sand after compaction is represented. Compaction was produced by dropping a Proctor hammer 15 times from a height of 12 in. at the center of the 3.11-in. thick sample. Embedded in the soil is a pressure cell and four aluminum foils. The deformation of the aluminum foils and the sinking of the pressure cell for more than 1 in. after compaction is clearly visible. The upper foil broke during compaction due to excessive strain. The streaks of light bending around the pressure cell are caused by irregularities when sand is poured into the container.

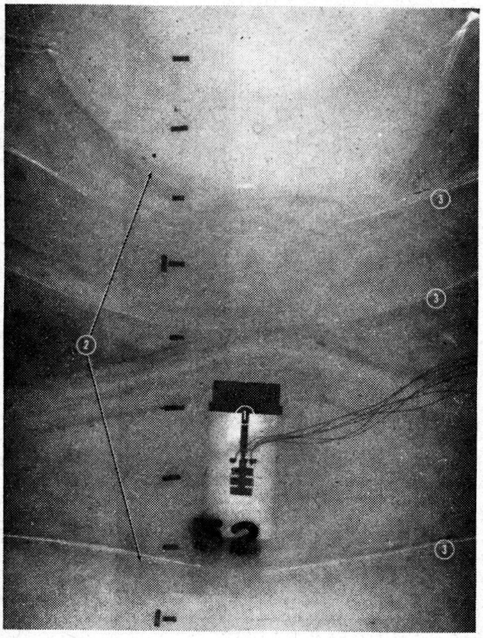


**Figure 4. Radiograph of pressure cell after compaction of beach sand confined in container; 1, pressure cell; 2, lead markers every inch; 3, aluminum foils.**

To supplement the regular pressure cells, several cells were adapted to measure hydrostatic pressures. A fine sieve over the top of the cells, covering the sensitive diaphragm, prevented contact between soil and membrane and permitted water pressure only to be transmitted.

Finally, a pressure-cell holder has been developed in order to insert each cell with the same initial contact pressure between cell bottom and underlying soil, particularly at larger depths. Erratic pressure-cell outputs at the beginning of the experiments showed the necessity of making the initial pressure independent of the operator.

### SPECIFICATIONS FOR PRESSURE CELLS

Pressure Range: 0.001 to 10 lb.
Frequency Range: 0 to 60 cps.

### CALIBRATION OF METHODS TO MEASURE COMPACTION EFFECTS

For static and dynamic calibration, a vibration table has been built (Fig. 5). A platform, supported by eight vertical and four horizontal springs, can be excited to controlled mechanical vibrations of sinusoidal characteristics. Displacement amplitudes, ranging from 0.0001 to 13 in., and frequencies ranging up to 60 cps. are observed by means of a micrometer microscope illuminated by a stroboscope (*21*).

Vibrographs and pressure cells can be subjected to these vibrations when attached to the platform and their output calibrated against the readings of the above-mentioned optical, inertialess measuring device. The platform was excited to vibrations by a three-mass, space oscillator. Oscillator, platform, and the above-mentioned suspension of the platform present a six-degrees-of-freedom system; hence, three linear motions (in the X, Y, and Z directions) and three rotational motions (around the X, Y, and Z axes) could be reproduced.

The oscillator consists mainly of three eccentrically supported weights, rotatable around three parallel shafts. Rotational speed, eccentricity, and phase angle of these three weights can be adjusted automatically and remotely while the machine is operating. Thus sinusoidal force vectors or moment vectors of the desired frequency, magnitude, direction, and action line, can be excited and any required cycling sequence can be set up, changing from motions in one into two or three planes.

The space oscillator was used also to drive the experimental compactor, as shown later. A detailed analysis of this oscillator has been published (*18*).

## METHODS TO PRODUCE COMPACTION EFFECTS

The following photographs represent some of the various static and dynamic compactors available during the experiments:

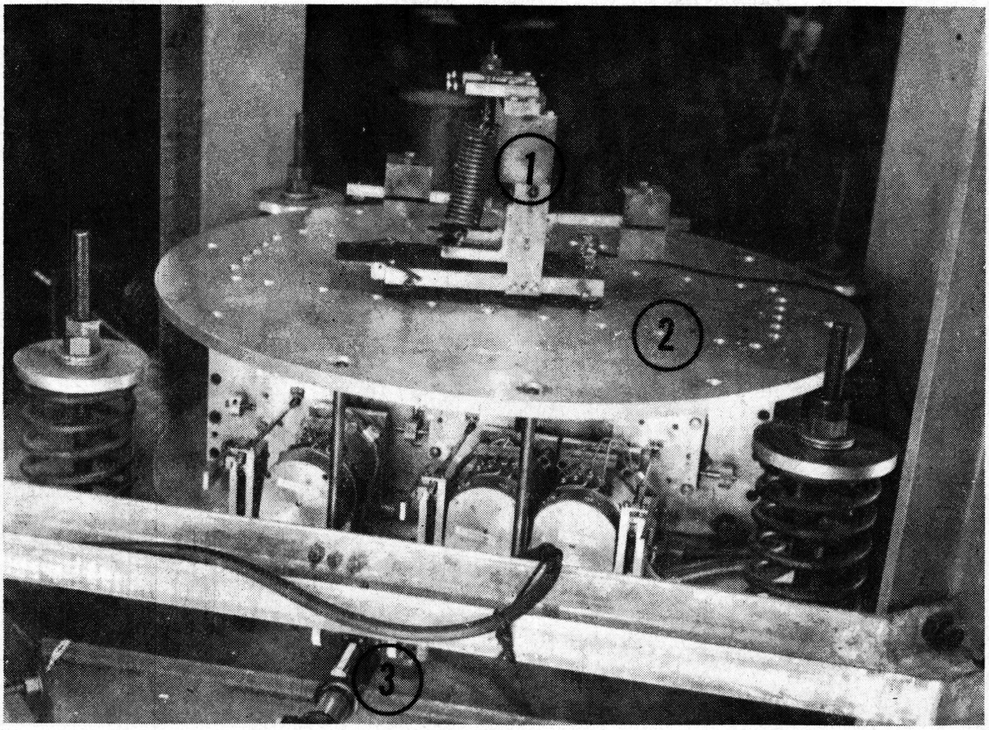


Figure 5. Calibration of vibrograph on vibration table. 1, vibrograph; 2, space oscillator; 3, optical control.

### *Static Loads*

Static loads were produced by rollers, tractors, or by dynamic compactors with their dynamic compaction unit not operating.

*Roller:* Figure 6 shows a roller-tractor combination, the roller being supported by nine wobble-wheels, equipped with pneumatic tires.

SPECIFICATION FOR THE ROLLER:

Overall length: 6 ft.
Width: 5 ft.
Contact pressure: 225 lb. per in. of width
Total weight: 14,500 lb.

*Tractor:* Figure 7 is a photograph of a tractor passing over a mound of loosely distributed soil.

SPECIFICATIONS FOR TRACTOR

Overall:
  Length—127 in.
  Width—81 in.
  Total Weight—14,000 lb.
  Drive—70 hp. diesel engine
  Compaction velocity—1.5 ft. per sec.

Tracks:
  Center-to-center width—63 in.
  Tread width—16 in.
  Length track on ground—67 in.
  Ground contact—2144 sq. in.

### *Dynamic Loads*

The types of dynamic soil compactors moving on the soil surface may be subdivided according to the following general characteristics:

#### *Contact Areas*

(1) The contact area of the compactor base on the soil is moving (rotating) and consists of rollers, tires, or caterpillar treads.

(2) The contact area forms essentially a flat surface which is lifted from the soil during part of the upward stroke of the dynamic force vector.

**Figure 6.** Static compaction with roller, rear-end view. (Five wobble wheels at rear end, four wobble wheels at front end.)

*Compacting Action*

(3) Static—Preload consisting of fixed dead weight or additional weights, rigidly or seismically supported from the compacting base.

(4) Dynamic—Transmitted force vector has quasisinusoidal or impact characteristics.

(5) Static and dynamic—Combination of static and dynamic loads, acting simultaneously or consecutively.

*Forward Motion*

(6) Compaction unit is self-propelled (leap-frog motion) by tilting the dynamic force vector

(7) Compaction unit is pulled by separate unit (tractor, truck, jeep, etc.)

*Dynamic Force Vector*

(8) Sinusoidal force vector is produced by two-mass oscillator with vector fixed or adjustable in magnitude and direction.

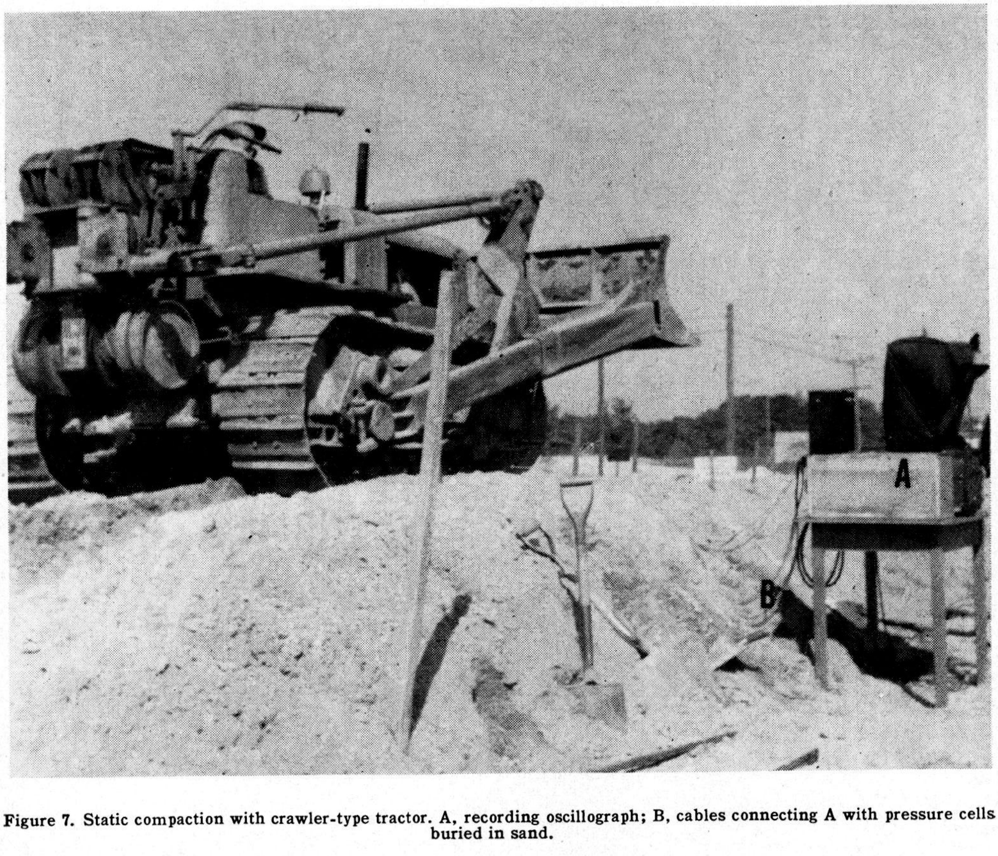
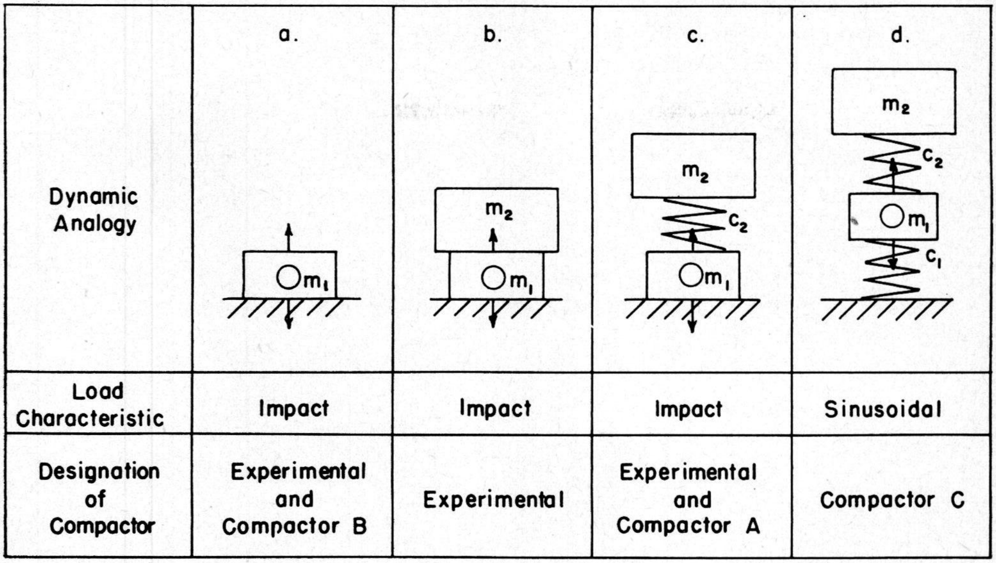


**Figure 7.** Static compaction with crawler-type tractor. A, recording oscillograph; B, cables connecting A with pressure cells buried in sand.



| | a. | b. | c. | d. |
|---|---|---|---|---|
| Dynamic Analogy | | | | |
| Load Characteristic | Impact | Impact | Impact | Sinusoidal |
| Designation of Compactor | Experimental and Compactor B | Experimental | Experimental and Compactor A | Compactor C |

$m_1$ - Mass of mechanical oscillator

$m_2$ - Mass of nonvibrating weights (static preload)

$c_1$ - Springs supporting $m_1$

$c_2$ - Springs supporting $m_2$

**Figure 8.** Dynamic analogies for soil compactors (spring- and mass-action of soil omitted).

(9) Sinusoidal force vector is produced by three-mass oscillator with vector fixed or adjustable in magnitude, direction, and action line.

(10) Frequency of dynamic force vector dependent upon or independent of forward motion of compaction unit.

*Transportability*

(11) Compaction unit can be pulled on highways or has to be loaded on vehicles.

### AVAILABLE DYNAMIC SOIL COMPACTORS

In Figure 8, the dynamic analogies of the four dynamic soil compactors, used during the experiments, are outlined and the corresponding load characteristics and designations indicated.

*Experimental Compactor:* The experimental compactor is shown in Figure 9. Primary purpose is its use for experimentation. Significant features are the manual or remote control of the dynamic force vector over a large range of frequencies, magnitudes, directions, action lines, and of sinusoidal or impact characteristics, and finally, its self-propulsion.

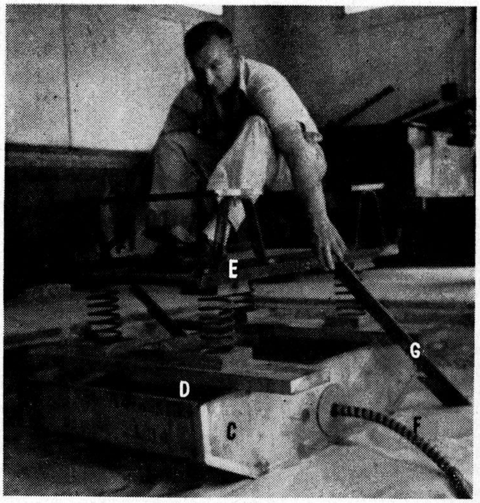


**Figure 9.** Experimental compactor compacting beach sand confined in basin (self-propelling and steered by operator). C, base; D, three-mass oscillator; E, seismically supported platg form for additional weights; F, flexible shaft to drivin-motor; G, steering paddles.

This self-propulsion is produced by tilting the exciting force vector to either side of the vertical. The vertical force component must be large enough to cause "bouncing" or "impact" while the horizontal force vector takes care of the horizontal motion. Both actions occur simultaneously during part of the upward stroke of the compacting base.

A shift in position of the action line of the force vector below the center of gravity of the vibrating system (*17*, *18*) improves the hill-climbing capacity and reduces the washboard effect (permanent wave) on the compacted soil surface. Figure 10 represents the experimental compactor without surcharge climbing up an incline of 20 deg. by self-propulsion.

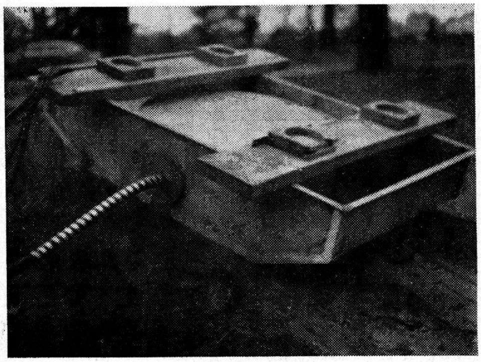


**Figure 10. Experimental compactor climbing 20-deg. slope of Hagerstown silt loam.**

Various surcharges could be added, either rigidly or seismically supported from the compacting base.

SPECIFICATIONS FOR EXPERIMENTAL COMPACTOR

Total Weight—1500 lb. (including used surcharge of 1150 lb.)
Compaction Velocity—1.0 ft. per sec. (self-propelled)
Drive—5 hp. motor or jeep power takeoff
Contact Area—1024 sq. in.
Max. Unbalance—70 in.-lb.
Dynamic Force—4,500 lb. at 25 cps.

*Compactor A:* The compactor is represented in Figure 11. Primary purpose is its use as a confined-area compactor. Significant features are its self-propulsion and impact characteristic, produced in a similar manner as previously described for the experimental compactor, however, using a tiltable two-mass oscillator.

SPECIFICATIONS FOR COMPACTOR A

Total weight—3300 lb.
Contact area—1440 sq. in.
Compaction velocity—0.3 ft. per sec. (self-propelled)
Drive—10 hp. diesel engine (seismically supported from base)
Total unbalance—62 in.-lb.
Dynamic force—4,000 lb. at 25 cps.

*Compactor B:* The compactor is shown in Figure 12. Primary purpose is its use for compaction of gravel subbases under Macadam roads and placing of screenings. Significant feature is its 12-ft-wide compaction area and self-contained crawler unit.

SPECIFICATIONS FOR COMPACTOR B

Overall:
  Width—12 ft. 6 in.
  Inside distance between crawlers—9 ft.
  Width of track—12 in.
  Length of track on ground—47 in.
  Compaction velocity—0.5 ft. per sec. (self-propelled)
  Total weight—8000 lb.
  Engine power—60 hp. at 2000 rpm.

Vibrating Shoes:
  Number of vibrating shoes—6 (each equipped with one two-mass oscillator)
  Overall shoe dimensions—20 by 25 in.
  Surface contact area of each shoe—306 sq. in.
  Total weight of each shoe assembly—290 lb.
  Unbalance in each vibrating shoe—35 in-lb.
  Maximum vibration frequency—46 cps.
  Dynamic force—5,700 lb. per shoe at 40 cps.

*Compactor C:* The compactor is represented in Figure 13. Primary purpose is its use as a nonconfined-area compactor. Significant features are the heavy static loads totaling 25,000 lb. and transmission of static and dynamic loads to the soil via pneumatic tires.

Compactor C is a machine which permits a comparison between dynamic and static

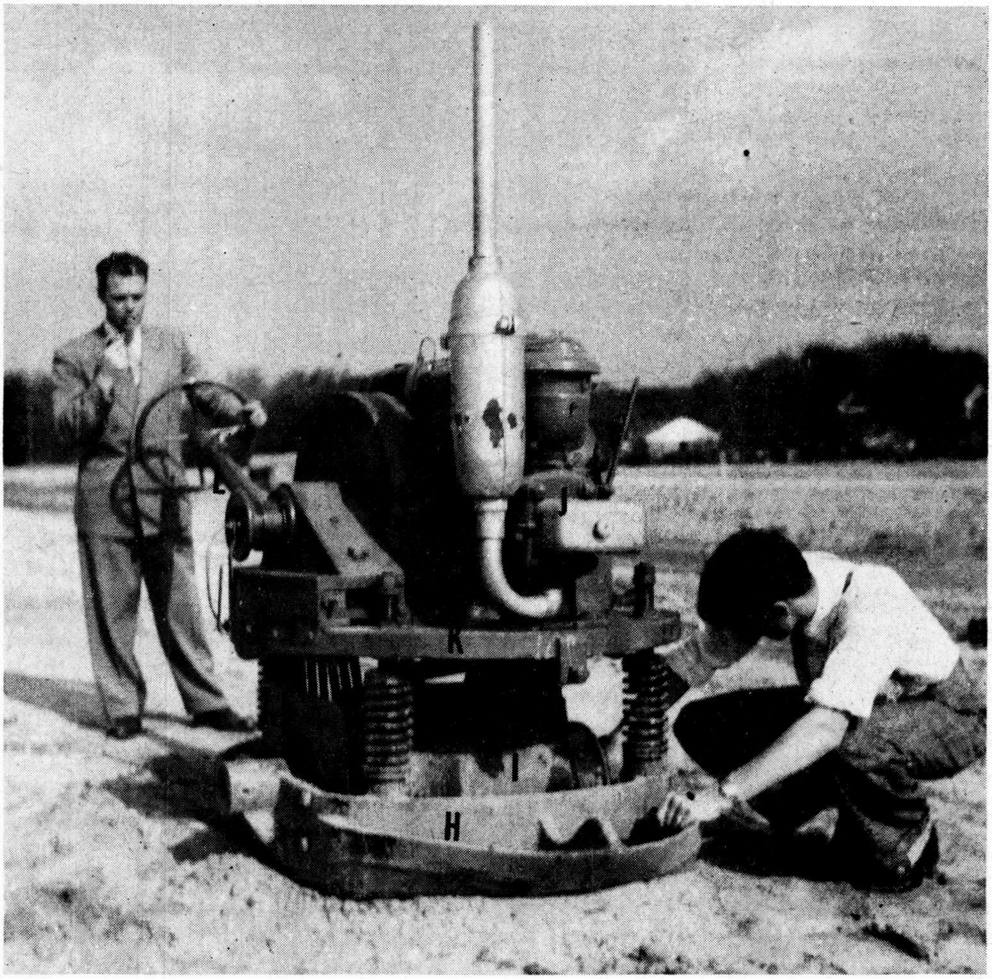


**Figure 11.** Dynamic compaction with compactor A. H, base; I, two-mass oscillator; J, diesel motor to drive I; K, seismically supported platform for J; L, steering column.

compaction by either operating or not operating the independently driven oscillator unit.

### SPECIFICATIONS FOR COMPACTOR C

Total weight loaded—27,760 lb.
Total weight empty—12,500 lb.
Overall length—15 ft.
Overall width—8 ft. 9 in.
Number of tires—4 size—12:00 x 20 14 ply
Tire pressure—75 psi.
Number of springs—16
Engine power—40 hp. to drive two-mass oscillator
Total unbalance (two wts.)—625 in.-lb.
Vibration frequency—17.5 cps. (max.)
Dynamic force—20,000 lb. at 17.5 cps.

### EXPERIMENTS WITH CONFINED SOILS

*Purpose:* Purpose of the confined-soil experiments was fourfold: (1) to check the response of the developed instruments recording settlement, pressure transfer and displacement amplitude; (2) to collect data for various ratios of static to dynamic load; (3) to be able to interchange soils with respect to cohesiveness, grain-size distribution, and void ratio; and (4) to be able to vary the

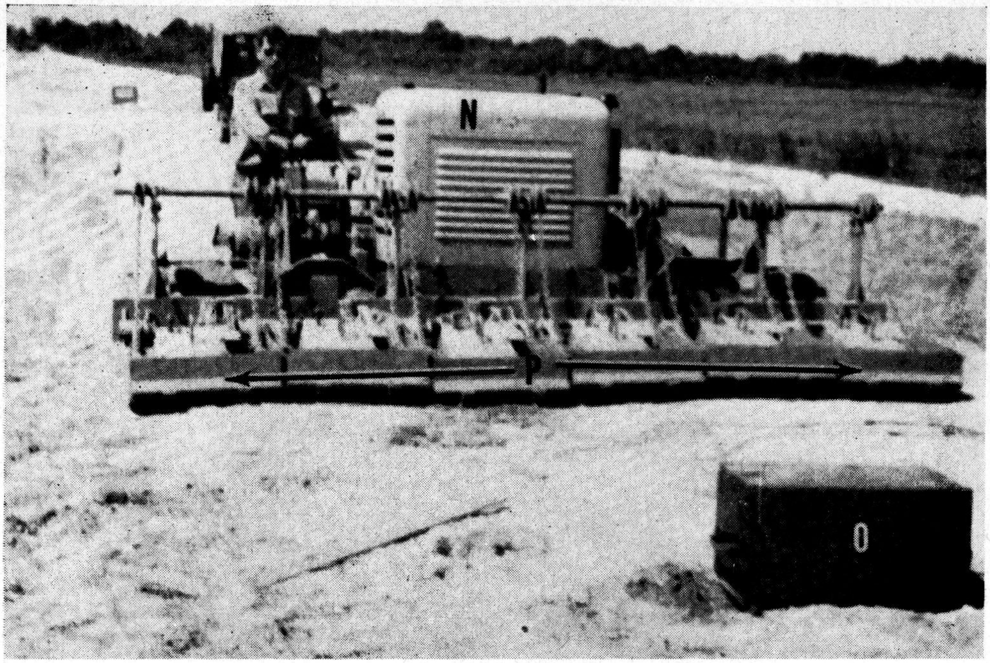


Figure 12. Dynamic compaction with Compactor B for nonconfined areas. N, gasoline engine; O, vibrograph; P, vibrating shoes.

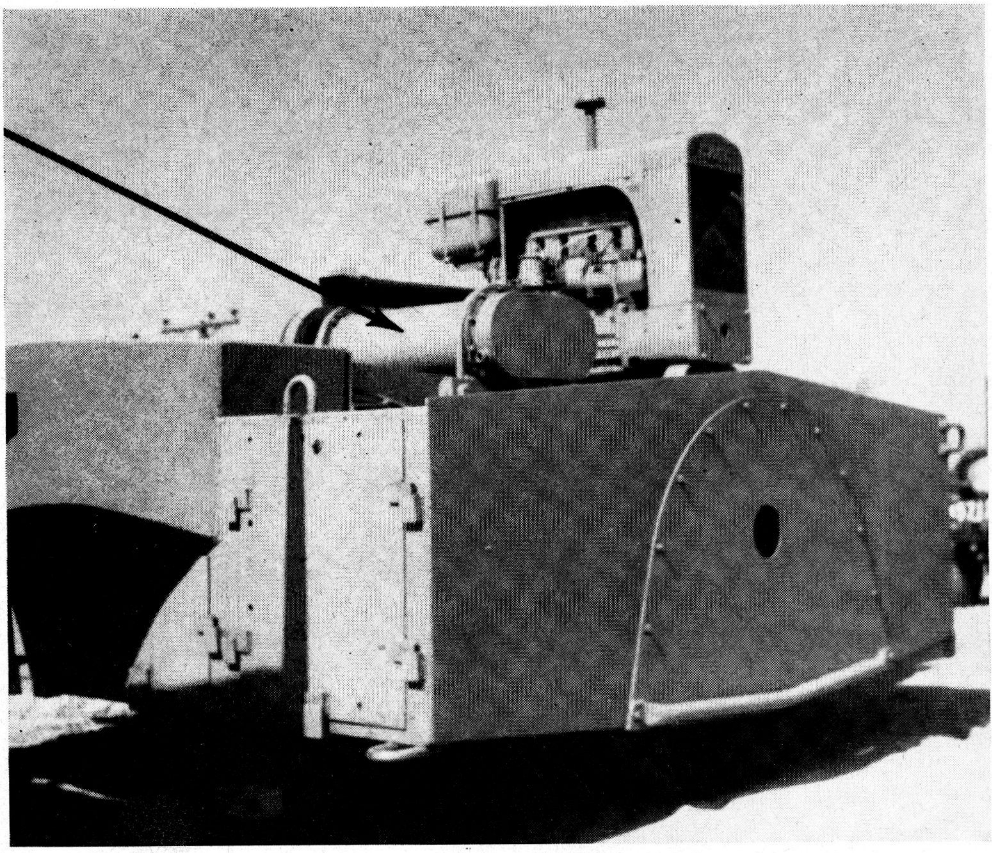


Figure 13. Dynamic compaction with Compactor C for nonconfined areas. Arrow points to mechanical two-mass oscillator.

consistency of the soil with respect to moisture content at constant temperature.

*Advantages:* The advantages of the experiments in containers are the controllable conditions for the numerous variables mentioned above.

*Disadvantages:* A disadvantage is the unavoidable disturbing influence of the walls of the containers, such as, friction, elasticity, vibrations, particularly in case of steep wave fronts due to impact loads.

For the confined-soil experiments, three types of containers, successively increasing in size were used: (1) 4-in. diameter containers (Proctor molds), (2) 25.75-in.-diameter containers, and (3) a concrete basin, 24 ft. long, 11 ft. wide, and 5 ft. deep.

This successive increase in container size was selected deliberately, gaining experience before each following step.

*Four-Inch-Diameter Container:* As a standard container, a Proctor mold (inside diameter 4 in., height 6.16 in.) was selected. Main reason for selecting this mold in the first tests was to obtain a connecting link between soil reactions in standardized containers and soils in larger units or for nonconfined soils.

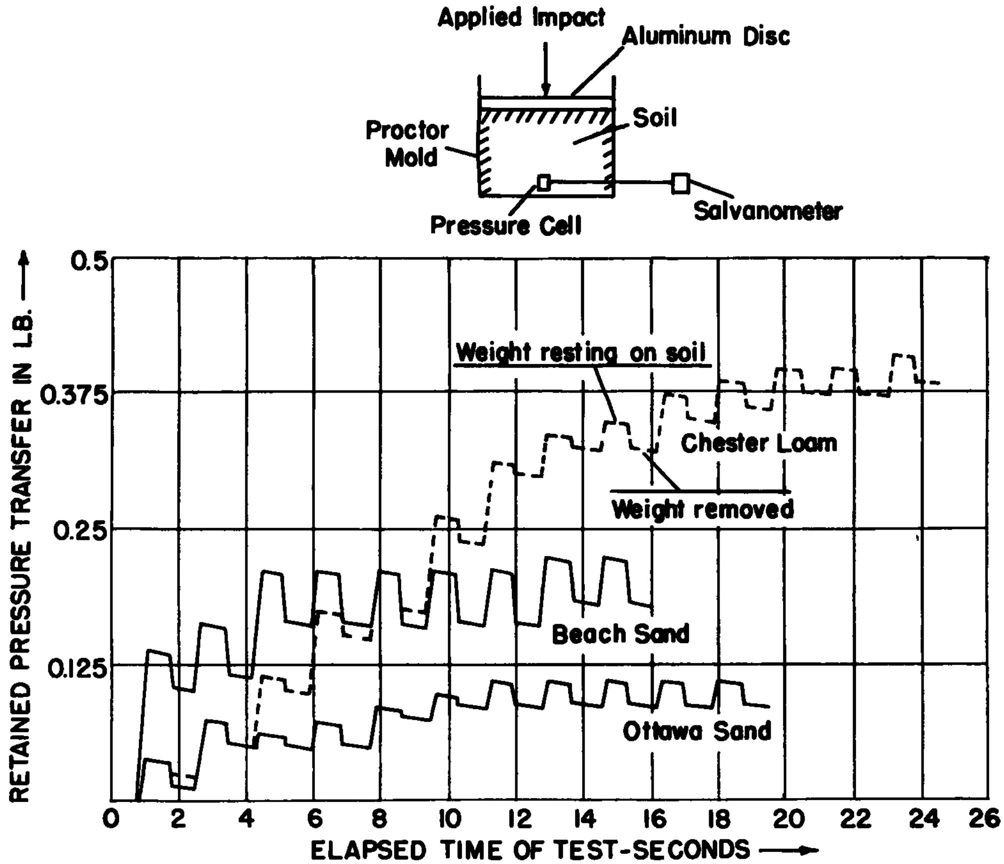


**Figure 14.** Dynamic compaction of cohesive and noncohesive soils confined in 4-in.-diameter Proctor mold. Pressure transfer versus time. Impact of 66 in.-lb. every 1.7 sec.

Figure 14 summarizes some results of dynamic-compaction tests in this container for Ottawa sand, Beach sand, and Chester loam, produced by successive impacts of 66 in.-lb. every 1.7 sec. The three step-shaped curves do not include the transient pressure transfer due to a steep wave front following each impact blow. A coincidence observed between the two sands under static conditions holds true under impact loads only for the initial stages. The Chester loam indicates a substantially different characteristic.

*25.75-Inch-Diameter Container:* The general setup for this container is shown in Figure 15. Numerous experiments had to be carried out to determine the most expedient loading conditions, details of which will be omitted. The following types of loads were found to yield consistent results.

Static and dynamic loads were transmitted to the soils by means of an 18- by 18- by $\frac{5}{8}$ in. aluminum plate (contact area 324 sq. in.). A total maximum of 650 lb. was selected for the two types of loads. Any higher load tended to produce excessive penetration effects of the contact plate under higher moisture content (shear failure of the soil surface).

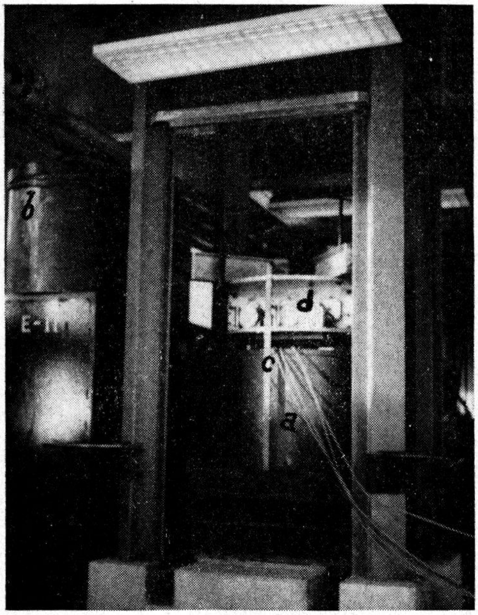


Figure 15. Dynamic compaction of soils with various moisture contents confined in 25.75-in.-diameter container. a, soil container; b, water tank to saturate soil in *a*; c, water gauge; d, space oscillator.

*Static Loads*—The static load consisted of the constant weight of the oscillator (350 lb.) and additional variable loads ranging from 0 to 300 lb. This variable load was produced by slowly filling with water (or emptying) slowly a graduated tank placed on top of the oscillator.

*Dynamic Loads*—The dynamic loads were induced by the previously described three-mass oscillator. A sinusoidal, vertical force vector of ±300 lb. was superimposed on the static load. The frequency of the force vector has been varied from 10 to 30 cps. To prevent tilting of the contact plate, the oscillator housing was guided by four rubber-wheel casters, barely touching four vertical steel columns.

*Non-Cohesive Soils*—The variation in moisture contents of the sands was limited to three cases: dry, capillary saturated (approximately 5.5 percent moisture content) and fully saturated (approximately 25 percent moisture content).

Full saturation of the sands was achieved by syphoning water from a tank standing at a higher level than the soil container. This tank had to be filled 24 hr. before draining to permit the water to obtain room temperature. The water entered the soil sample slowly through a valve at the bottom of the container up to full saturation.

Retained water, called capillary saturation in this report, was produced by reversing the procedure, that is, draining slowly the fully saturated soil through valves at the bottom of the soil container.

A glass gauge (burette) indicated the water level during the experiments.

*Cohesive Soils*: Figure 16 represents an oscillograph record, produced by five pressure cells located at various depths in a Hagerstown silt-loam sample and subjected to dynamic loads of ± 300 lb. at a frequency increasing from 10 to 30 cps. Five traces are produced by pressure cells, the lowest trace by a hydrostatic pressure cell. The sixth trace (top) is the output of the settlement recorder previously described. The transmission of the exciting sinusoidal force vector with increasing amplitudes in the range of the significant frequency at about 19 cps. visible in all six images. Similar, much-more-complex phenomena referring to significant frequencies have been observed for nonconfined soils.

For an evaluation of all oscillograph records, the magnification factor (sensitivity) for each individual trace has to be considered.

Figure 17 shows frequency versus settlement curves for Hagerstown silt loam with 5-, 19-, and 23-percent moisture contents. A typical shape, similar to resonance curves, is

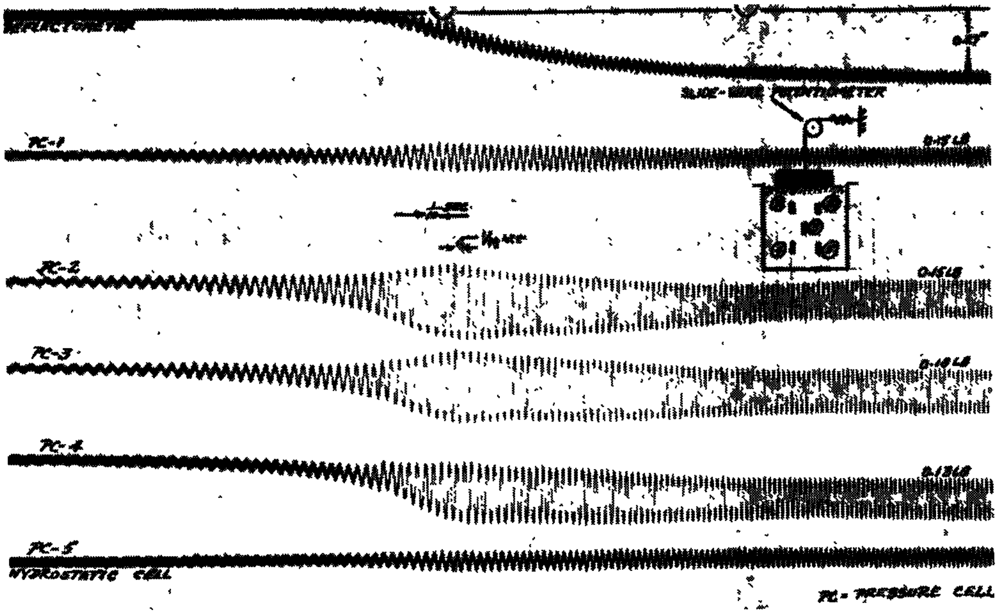


Figure 16. Dynamic compaction of Hagerstown silt loam with 19 percent moisture content confined in 25.75-in.-diameter container. Settlement and pressure transfer versus time record. Compaction frequency 10 to 30 cps. Exciter force: ±300 lb.

noticeable, indicating again the existence of a significant frequency of the vibratory-oscillator–soil-container system. Similar phenomena have been reported by other investigators. (*1*, *2*, *4*). The maximum settlement of approximately 1.5 in. is reached at the highest moisture contents of 23 percent and lies substantially below the values obtained for fully saturated Ottawa sand (5 in.) and fully saturated Beach sand (4 in.) under similar conditions.

It must be kept in mind, however, that all compaction values referring to both sands include a certain amount of penetration effect due mainly to shear failure, while the values for the Hagerstown Silt Loam are due largely to settlement only. Furthermore, the significant frequency has decreased, as compared for the two noncohesive soils, Ottawa and Beach sands. Finally, a decrease in significant frequency from approximately 19 cps. to 15 cps. seems to be combined with an increase in moisture contents from 5 to 23 percent.

Figure 18 combines the settlement-frequency response curves for three soils, cohesive and noncohesive, at their lowest moisture content. Again, the striking similarity to resonance curves and, furthermore, a drop in significant frequency and of maximum settlement values with increase in cohesive characteristic could be generally observed. The significant frequencies at about 22 cps. for both sands and at 19 cps. for Hagerstown silt loam are almost identical with natural frequencies as reported for nonconfined medium sand (dry) at 22 cps. and for clay sand at 20.7 cps. (*1*, *2*).

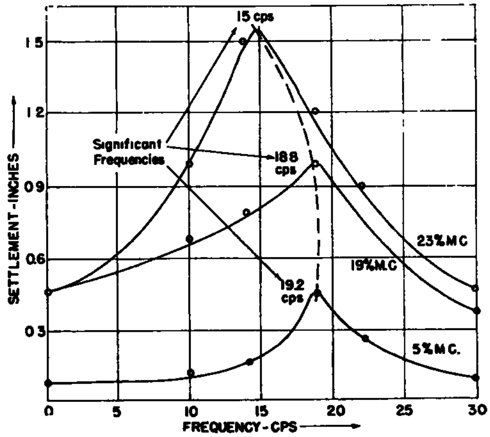


Figure 17. Dynamic compaction of Hagerstown silt loam with various moisture contents confined in 25.75-in.-diameter container. Settlement versus frequency response.

Figure 19 represents time versus settlement curves for dry, capillary saturated, and fully

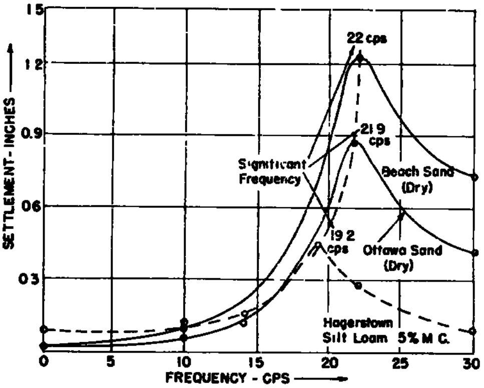


**Figure 18. Dynamic compaction of cohesive and noncohesive soils confined in 25.75-in.-diameter container. Settlement versus frequency response.**

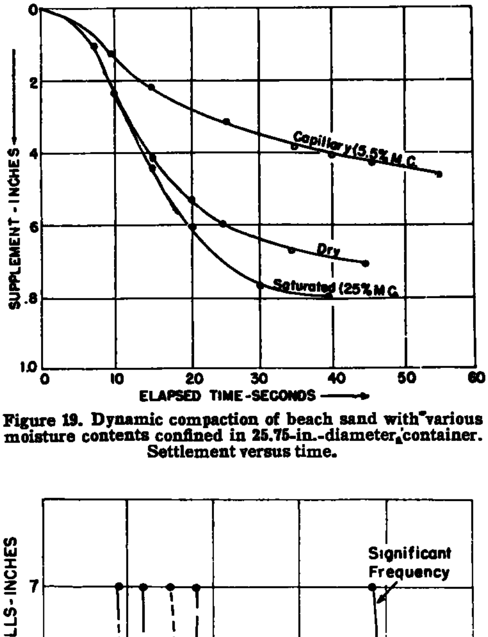


**Figure 19. Dynamic compaction of beach sand with various moisture contents confined in 25.75-in.-diameter container. Settlement versus time.**

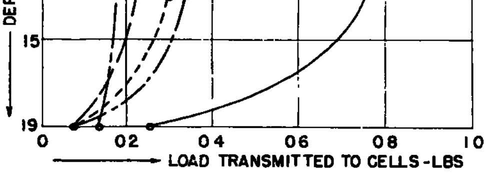


**Figure 20. Static and dynamic compaction of Hagerstown silt loam with 23 percent moisture contents confined in 25.75-in.-diameter container. Pressure transfer versus soil depth at various compaction frequencies.**

saturated Beach sand at 30 cps. The time axis (X) is extended until a quasidynamic equilibrium is reached. This time varied from about 40 to 60 sec. A comparison with the corresponding Ottawa-sand curves indicated a pronounced resemblance. Noteworthy is that only at exciter frequencies above 20 cps. does Beach sand indicate more settlement for dry than for capillary saturated (5.5 percent M.C.) conditions.

The tendency of the two settlement curves, first for capillary-saturated sand and second for dry sand, to reverse their relative position at higher compaction frequencies might be explained tentatively as follows:

At higher frequencies, that is, in and above the significant frequency range, the capillary tension is not broken, thus producing an increased shear resistance and preventing further settlement effectively.

Figure 20 shows pressure transfer (in pounds) versus soil depth at various frequencies for Hagerstown silt loam of 23 percent moisture content. The pressure transmission for dynamic loads is higher than for static loads (0 cps.) in particular at the significant frequency of 19 cps. This difference in pressure transmission decreases with depth, approaching zero transmissibility, regardless of the frequency, at larger depth. The maximum pressure transfer occurs at about 12 in. depth, with a tendency to smaller values in the uppermost crust under certain conditions (*19*).

*Basin:* Main purposes of the tests in the basin were to: (1) simulate as closely as possible actual field conditions in confined areas, such as might occur in excavations of trenches, bridge abutments, foundations, where self-propulsion is advantageous; (2) study self-propulsion velocities, hill-climbing capacity, and washboard effects due to static and dynamic compaction; and (3) gain experience as how to insert pressure cells at larger depths, in particular under difficult conditions, for example in dry, noncohesive sands.

In the latter case, a post-hole digger, driven from a jeep by means of its rear-end power takeoff, and acting as a sand pump (Fig. 21) was used to lower a 10-in.-diameter steel tube. This arrangement permitted the insertion of pressure cells at various depths with the developed cell holder, simultaneously withdrawing the tube slowly.

After each series of compaction experiments, the soil has been de-densified with the same equipment, omitting however the steel tube (Fig. 22).

Figure 23 represents a comparison of average surface settlements in the basin versus the number of passes for a 400-lb. roller and two confined-area compactors, the experimental machine and Compactor A.

It will be noticed that neither machine produced any appreciable settlement after the second or third pass. The total settlement obtained by Compactor A was almost twice as large as that under the experimental compactor, due mainly to the higher capacity of Compactor A as used in these tests. However, it is difficult to compare directly the efficiencies of both dynamic compactors as regards settlement because of different contact areas, propagation velocities, weights, force vectors, and operating frequencies of each machine.

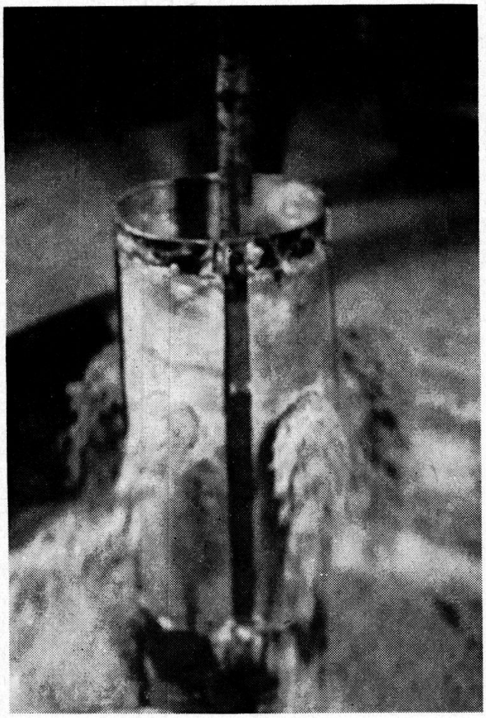


**Figure 21. Lowering tube to insert pressure cells in beach sand. Sand pump ejecting soil.**

Specific efficiency ratios are discussed later.

RESULTS FOR CONFINED SOILS

The results of laboratory experiments with cohesive and noncohesive soils confined in the three containers can be summarized as follows:

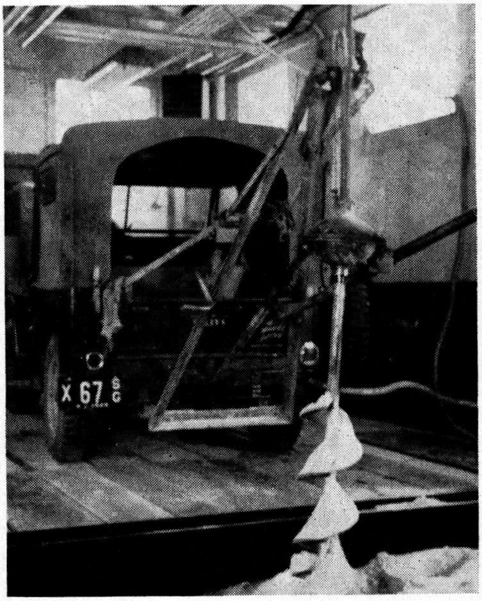


**Figure 22. De-densification of compacted beach sand confined in basin. Post-hole digger driven from jeep (rear-end power take-off).**

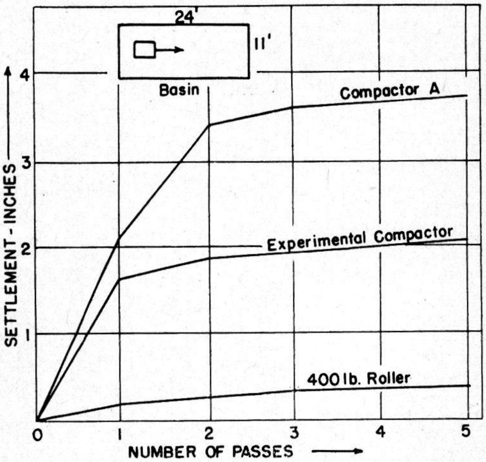


**Figure 23. Static and dynamic compaction of dry beach sand confined in basin produced by various compactors. Settlement versus number of passes.**

1. The developed types of measuring de-

vices, referring to settlement and displacement-amplitude records on the surface and pressure transfer records below the surface of the soil, yielded rather consistent and reproducible results.

2. The data obtained, first for the two noncohesive soils, Ottawa and Beach sands, and second for the two cohesive soils, Chester loam and Hagerstown silt loam coincided rather closely for each group respectively. However, the static and dynamic compaction effects of the first group differed substantially from the second group.

3. For both groups, a significant frequency exists for any particular combination of the vibrating soil-compactor-container system, which causes the optimum settlement. Dynamic loads, exerted at this significant frequency, produced pressure transfer reaching deeper strata than equivalent static loads.

4. This significant frequency for Ottawa and Beach sands and Hagerstown silt loam was below 30 cps. The largest settlements, including penetration, were observed for high moisture contents, that is fully saturated for Ottawa and Beach sands and 23 percent moisture content for Hagerstown silt loam.

5. The two confined-area compactors achieved large settlements when operating as impact compactors and when combined with static (seismically supported) surcharges.

## EXPERIMENTS ON NONCONFINED SOILS

*Purpose:* Purpose of the nonconfined soil experiments was twofold: (1) To determine the static and dynamic compaction effects on deeper strata, not possible in containers, and (2) To compare the efficiency of various static and dynamic compaction methods with nonconfined-area compactors under actual field conditions.

*Advantages:* The advantages of all field experiments is that the disturbing influence of the confining container walls is avoided.

*Disadvantages:* The disadvantages of field experiments are that most of the numerous variables, particularly moisture content and homogeneity of the soil, cannot be controlled. Hence, laboratory and field tests must supplement each other as is the case for many investigations of similar character.

Two types of experiments were performed: first, on a highway subbase with the concrete pavement in place, and second, on a highway subbase without the pavement.

### *Highway Subbase with Concrete Pavement*

The experiments were restricted to the recording of vertical displacement-amplitudes on top of the pavement and of pressure transfer at various depths below the subbase surface. Furthermore, no compaction tests were made.

Three types of semitrailer trucks, with rear-axle loads of 18,000 lb., 28,000 lb., and 32,000 lb. could be made available (the 32,000-lb. trailer equipped with two rear axles, the two other trailers with one rear axle).

All vehicles passed the measuring points with their nearest wheels at a 40-in. horizontal distance. The maximum obtainable speed had to be confined to 20 mph. due to a restriction in starting length. The concrete pavement was 8 in. thick, the subbase approximately 10 in. thick and consisted of slightly cohesive gravel-sand.

One characteristic diagram is reproduced in Figure 24 for the semitrailer truck with a 28,000-lb. single rear trailer axle passing at a speed of 20 mph. Again, when comparing the individual traces, the various amplification factors have to be considered. Of special interest are: (1) the pronounced phase difference, that is the time lag in the range of 0.04 sec. between deflection of the pavement (vibrograph output) and pressure-cell reaction; (2) the small load release (upward excursion) as indicated by the pressure-cell records in contrast to the vibrograph traces; and (3) the characteristic head and tail waves (wake) of the pavement, that is, up and downward deflections of the pavement before and after the vehicles have passed the vibrograph—the head and tail waves were probably distorted due to the interaction of transverse joints in the pavement.

Figure 25 indicates the result of pressure-cell records plotted on semilogarithmic paper. An approximately logarithmic attenuation of pressure transfer with increasing depths, about one decade per 6 in., becomes rather obvious.

The 32,000-lb. load distributed on two axles transferred less pressure than the 28,000-lb. single axle. Due to limitation in vehicle speed (20 mph.) no critical velocity response could be established.

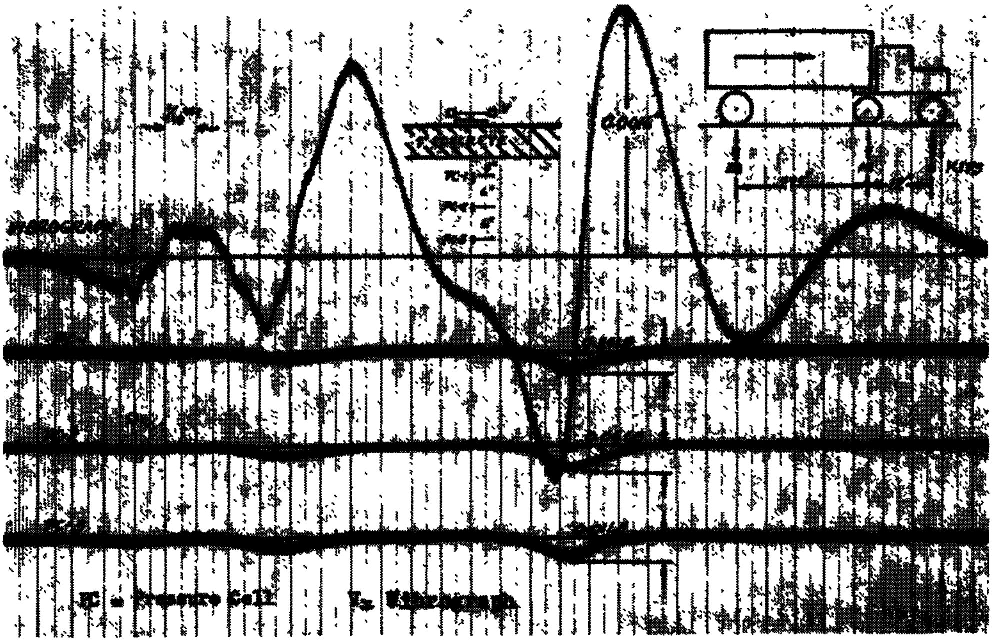


Figure 24. Vertical surface displacement and pressure transfer versus time. Records produced by semitrailer truck with 28,000-lb. single rear trailer axle passing at 20 mph. over 8-in.-concrete highway slab on slightly cohesive gravel sand as subbase.

HIGHWAY SUBBASE WITHOUT PAVEMENT

Only two types of subbases have been investigated so far; a fill of slightly cohesive gravel sand approximately 3.5 ft. high, and a fill of cohesive silt gravel sand about 7 ft. high. Both types of soils represent typical examples of subgrade material often used under New Jersey highways.

*Soil Surface Pattern:* The smoothness of the soil surface after compaction is of significance insofar as special operations may be required to flatten out rough surfaces, for example, before placing the final cover on the compacted subsoil.

The rough surface pattern (Fig. 26) after static compaction of the slightly cohesive gravel sand with the wobble-wheel roller, indicates a considerable transverse motion of the uppermost sand crust.

A difference between the rough surface before compaction and the smooth surface after dynamic compaction with Compactor B on a cohesive, silt-gravel sand is demonstrated in Figure 27.

*Oscillograph Records:* The following figures

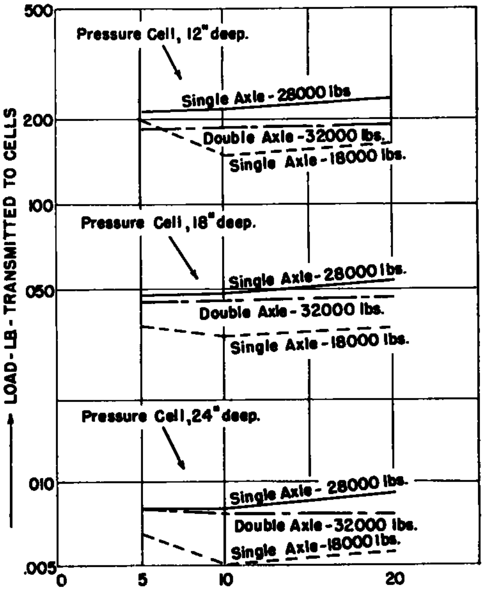


Figure 25. Pressure transfer versus velocity produced by various vehicles passing over 8-in.-concrete slab on slightly cohesive gravel sand as subbase.

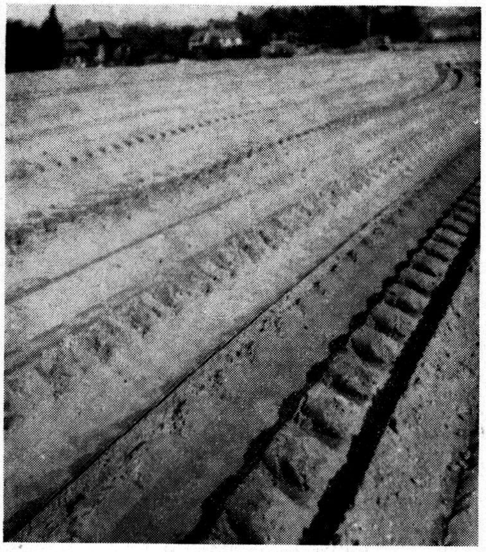


Figure 26. Soil surface pattern after static compaction with wobble-wheel roller of dry, nonconfined, slightly cohesive gravel sand.

are pressure-cell and vibrograph records obtained in nonconfined soils and produced by the four dynamic compactors. When comparing the various traces of these records the magnification factor of each individual pickup unit has to be taken into account, as mentioned before.

Figure 28 represents an oscillograph record of the transmitted pressure produced by the stationary experimental compactor and picked up by four pressure cells buried in a vertical line at 1, 2, 3, and 4 ft. below the compactor base.

Short trains of sinusoidal pressure waves follow regularly after a period of 0.065 sec., corresponding to the operating frequency of 15.5 cps. of the experimental compactor. The identical reproduction of each impact, reduced in amplitude with increasing depth, and the dying out of the sinusoidal wave trains between each impact, becomes obvious.

A corresponding record, however, produced by Compactor A is shown in Figure 29. The

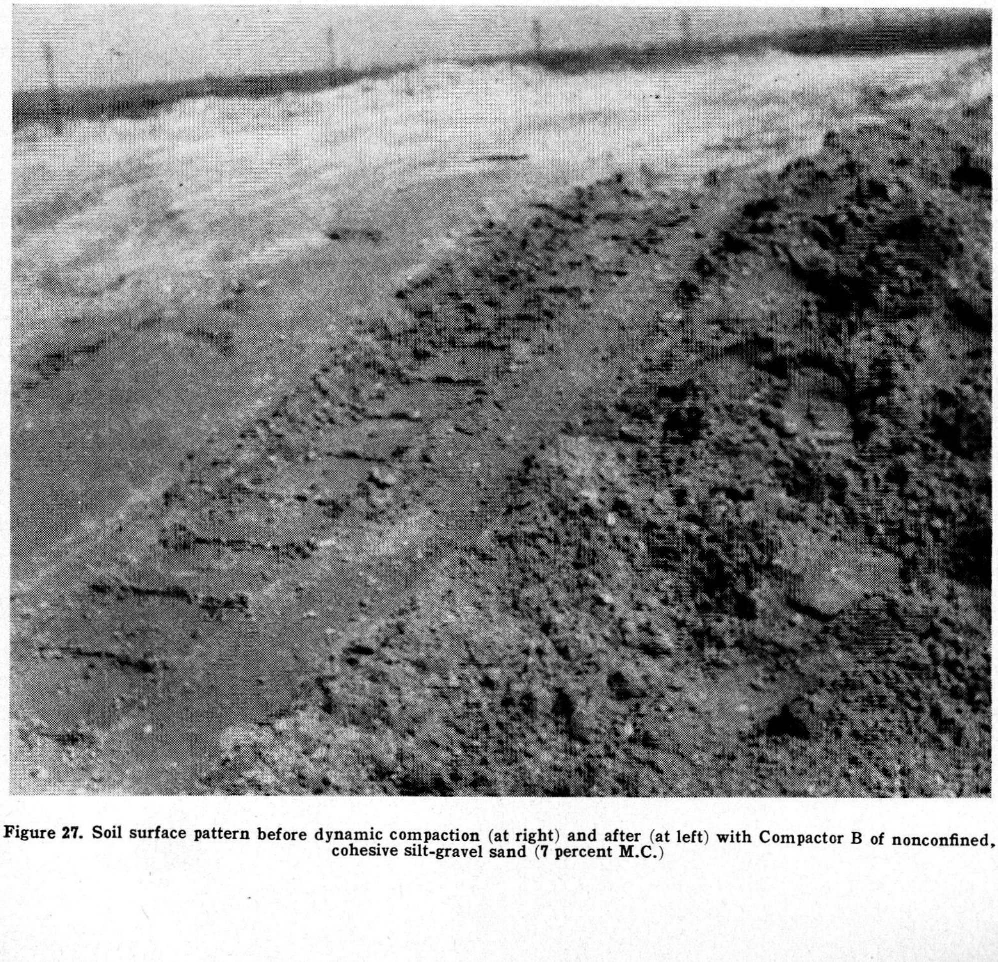


Figure 27. Soil surface pattern before dynamic compaction (at right) and after (at left) with Compactor B of nonconfined, cohesive silt-gravel sand (7 percent M.C.)

trace of a seismometer (B), located 10 ft. away from the compactor, is added. Due to the increased time scale all conclusions drawn from the pressure-cell traces of the previous record (Fig. 28) becomes substantially clearer. The seismometer, however, shows a different pattern, caused mainly by attenuation and reflection phenomena.

Records produced by dynamic compaction with the stationary Compactor B, operating with all six shoes, are indicated in Figure 30. The upper trace represents the output of a pressure cell (PC 1) buried 1 ft. below one of the shoes closest to the center of the machine, and the lower trace is the output of a seismograph (B) at 10 ft. from this shoe.

The pressure cell (upper trace) shows a strong impact blow with a frequency of approximately 10 cps., probably excited by the impact of the shoe directly over the cell. Since the operating frequency of Compactor B was 30 cps., only every third cycle was effective and produced an impact blow. This was due mainly to the lack of static preload over the shoes.

The seismometer records indicate a rather complex, strongly attenuated wave form containing much higher frequencies due to the excitation by six shoes, all operating with the same frequency, however, out of phase.

Two records represented in Figures 31 and 32 are traces of three pressure cells (PC 1, PC 16, and PC 10), buried at 1-, 2-, and 3-ft. depths below the surface.

The difference between the two records is that in the first case (Fig. 31) Compactor C passed over the cells without the oscillator unit operating, and in the second case (Fig. 32) with the oscillator unit operating at 17.5 cps. Compactor C is the only machine tested so far where such a direct comparison between static and dynamic compaction can be attempted.

Noteworthy is a small amount of retained pressure on the cells after the tractor has passed over the cells (see also Fig. 14). Finally, the energy attenuation with increasing depth can be readily seen, when taking the magnification factors for each trace into account.

Another possible comparison between static and dynamic action would have been to run the machine, first fully loaded with the oscillator not operating, and second to run the machine partially loaded with the oscillator operating. The partially removed dead weight for dynamic compaction should be equal to the root mean square of the sinusoidal force vector, or in other words, the total contact pressure exerted on the soil ought to be equal in both cases. This idealize comparison, however, was not possible since Compactor C does not operate satisfactorily under no-load or partially loaded conditions on this particular soil.

From these two records, it becomes obvious that the combination of static and dynamic compaction produces larger pressure transfer amplitudes than the static compaction, that is sinusoidal pressure transfer waves of 17.5 cps.—operating frequency of the oscillator unit (Fig. 32) are superimposed to the rather smooth static compaction traces (Fig. 31). The ratios of maximum dynamic plus static to maximum static pressure-transfer amplitudes are:

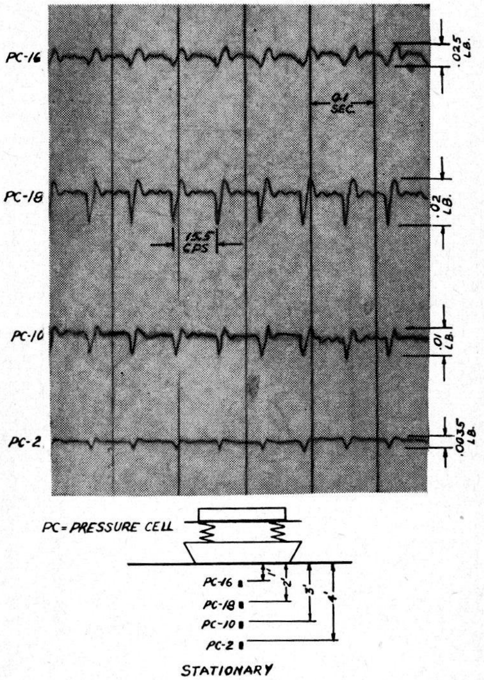


Figure 28. Dynamic compaction of non-confined, cohesive silt-gravel sand (7 per cent M.C.). Pressure transfer versus time record. Produced by experimental compactor.

at 1-ft. depth: 6.9/5.65 or 1.22
at 2-ft. depth: 4.0/3.70 or 1.08
at 3-ft. depth: 1.25/1.00 or 1.25

These ratios did not change significantly with increase in depth.

### RESULTS FOR NONCONFINED SOILS

The results of field experiments with various non-confined soils can be summarized as follows:

1. As stated previously for confined soils, the developed measuring devices yielded rather consistent and reproducible results.

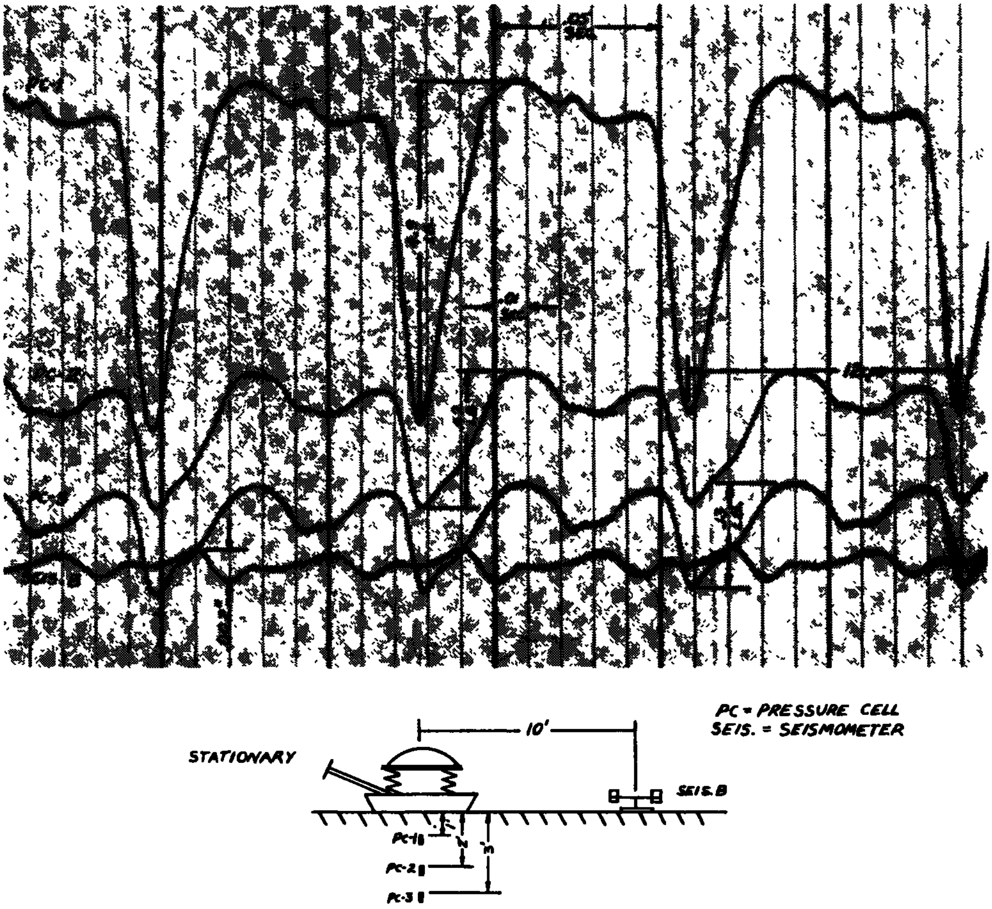


**Figure 29. Dynamic compaction of nonconfined, cohesive silt-gravel sand (7 per cent M.C.). Pressure transfer and vertical surface displacement versus time record. Produced by Compactor A.**

2. These results coincide in many cases with the values obtained for confined soils, that is dynamic-impact compaction combined with static preload produces larger compaction effects and reaches deeper strata than static compaction alone.

3. Significant frequencies of the vibrating compactor-soil system are in the range from 20 to 30 cps.

4. Dynamic compaction with flat contact areas achieved, in many cases, the smoothest surface pattern, reducing additional operation after compaction as well as breaking through the surface due to shear failure of the soil.

5. The overall efficiency of the dynamic compactors available could be improved upon, particularly by making them adjustable to and operatable in the significant frequency ranges of the vibrating compactor-soil system.

In analyzing the experiments, an attempt is made to cross match some of the results obtained with the various static or dynamic compaction methods.

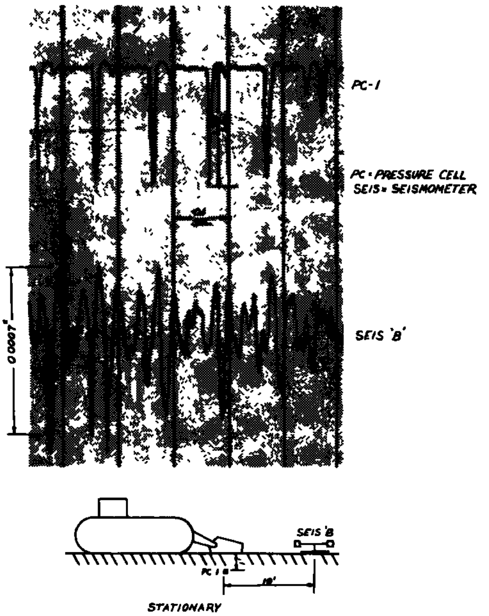


Figure 30. Dynamic compaction of non-confined, cohesive silt-gravel sand (7 percent M.C.). Pressure Transfer and vertical surface displacement versus time record. Produced by Compactor B.

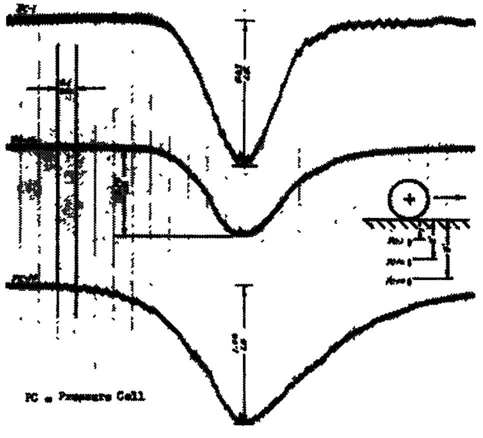


Figure 31. Static compaction of nonconfined, cohesive silt-gravel sand (7 percent M.C.). Pressure transfer versus time. Record produced by Compactor C with oscillator unit not operating.

## CONFINED SOILS

Fig. 33 combines in one graph a few pertinent results referring to settlements of confined soils. All settlements were obtained at their respective significant frequencies. The peak settlement values, including penetration effects, become obvious, that is for fully saturated Ottawa sand the value of 5.1 in., the not substantially smaller amount of 4 in. for fully saturated Beach sand, and the still considerable settlement of 1.5 in. for Hagerstown silt loam with 23 percent

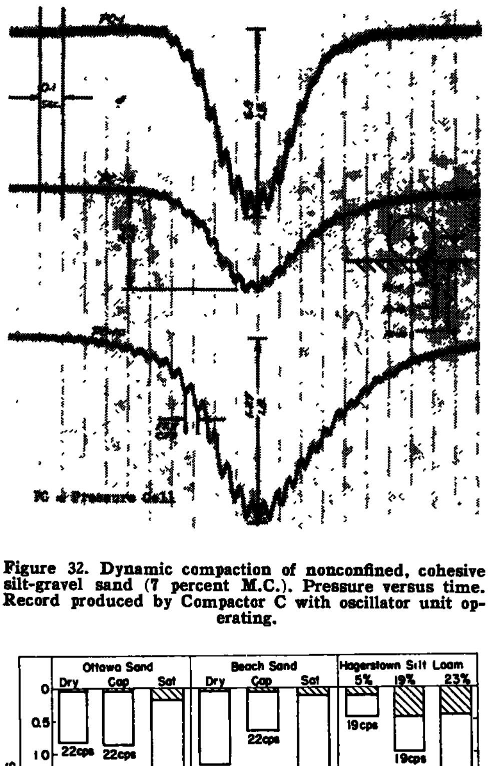


Figure 32. Dynamic compaction of nonconfined, cohesive silt-gravel sand (7 percent M.C.). Pressure versus time. Record produced by Compactor C with oscillator unit operating.

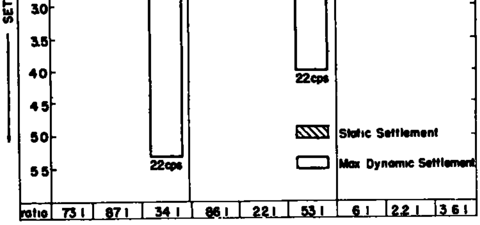


Figure 33. Static and dynamic settlement of cohesive and noncohesive soils with various moisture contents confined in 25.75-in.-diameter container. Dynamic settlement produced at significant compaction frequency.

moisture contents; hence, all three settlements were obtained at maximum moisture contents.

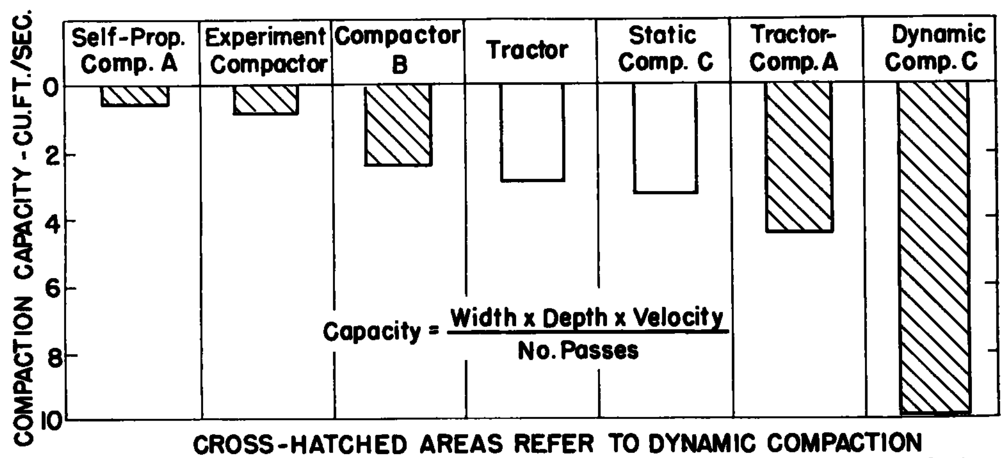


Figure 34. Compaction capacity in cu. ft. per sec. for various static and dynamic compactors obtained on nonconfined, cohesive silt-gravel sand (7 percent M.C.).

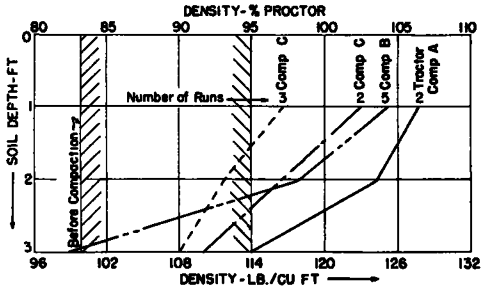


Figure 35. Static and dynamic compaction of nonconfined, cohesive silt-gravel sand (7 percent M.C.) produced by various compactors. Soil depth versus density.

Of special interest are the maximum ratios of dynamic to static settlement for capillary saturated Ottawa sand (87:1) and for dry Beach sand (86:1). Similar and higher ratios up to 140 have been reported by other investigators (1, 2, 4).

### NONCONFINED SOILS

Corresponding cross-matching charts are made for analysing some results obtained from nonconfined soils. The following sequence is maintained and abbreviations used for the various compactors: (1) experimental compactor (self-propelled, dynamic), (2) static Compactor C (tractor-drawn), (3) tractor (static), (4) Compactor A (self-propelled, dynamic), (5) dynamic Compactor C (tractor-drawn, static and dynamic), (6) Compactor B (predominantly dynamic), and (7) tractor-Compactor A (static and dynamic).

In all but one case, where the first pass was plotted throughout, that number of passes was selected after which no appreciable improvement by any number of additional passes could be produced.

### COMPACTION IN CUBIC FEET PER SECOND

In Fig. 34, the compaction capacity in cubic feet per second of all seven compaction methods is evaluated based on: (1) width of compaction (feet) (2) compaction velocity (feet per second) (3) minimum number of passes to produce 95 percent Proctor, and (4) depth of compaction (feet for 95 percent Proctor).

In this chart, the maximum effective depth was restricted to 2 ft. in order to be on the safe side, discarding the fact that in some cases three feet and more could be effectively compacted. From the economic point of view, this comparison chart seems to represent the most important result.

Figure 34 shows that the deliberately selected sequence in which the seven methods are arranged in this cross-matching chart follows a steady increase in compaction capacity with the minimum value for the self-propelled Compactor A, and the maximum value for the tractor-drawn dynamic Compactor C.

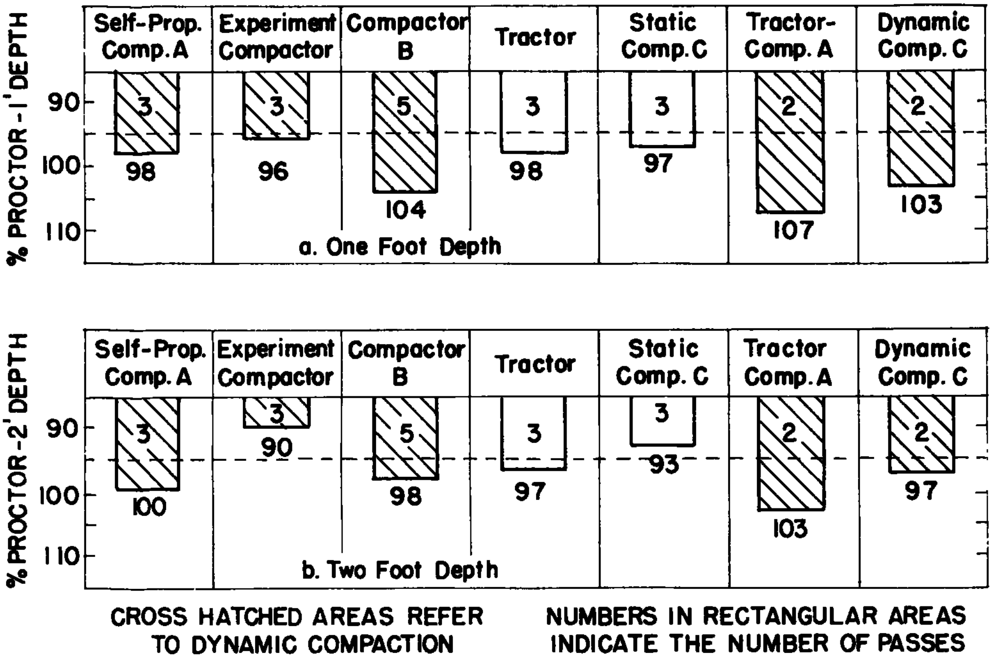


**Figure 36.** Static and dynamic compaction of nonconfined, cohesive silt-gravel sand (7 percent M.C.) produced by various compactors at 1-ft. and 2-ft. depth.

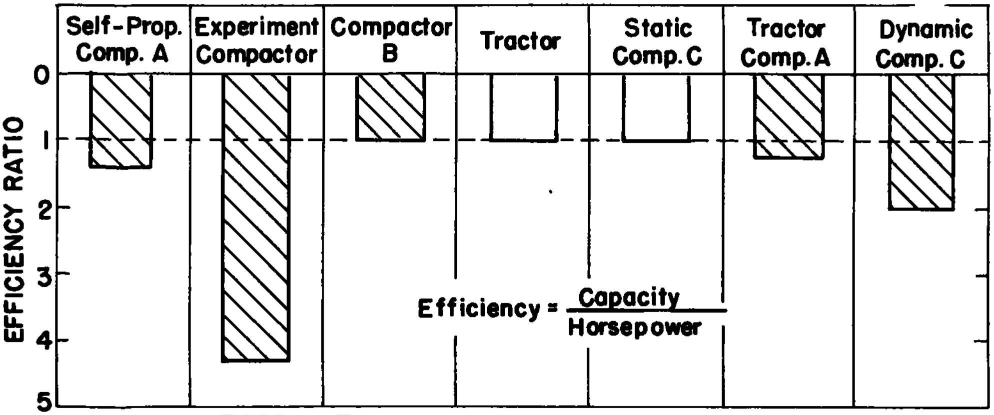


**Figure 37.** Efficiency based on the ratio of compaction capacity over horsepower for various static and dynamic compactors obtained on nonconfined, cohesive silt-gravel sand (7 percent M.C.).

### DENSITY

In Figures 35 and 36, the soil densities obtained with the seven compaction methods are compared.

The density profiles in Figure 35 are shown to a soil depth of 3 ft., while in Figure 36 the densities are repeated, however, for the sake of clarity separated into two figures, Figure 36*a* at 1-ft. depth and Figure 36*b* at 2-ft. depth.

In these two charts, no densities in the uppermost strata, that is at less than 1 ft., are plotted. It was found that measurements in this region are particularly erratic, one reason being that horizontal, transverse displacements of the soil are often predominant. Under certain conditions, even a loosening (de-densification) of the upper crust might take place.

Significant results are:

1. The substantial gain in density obtained by dynamic compaction becomes obvious when comparing dynamic Compactor C with static Compactor C (Figs. 35, 36a and 36b).
2. Of all compactors, the tractor Compactor A produced the maximum density (Figs. 35 and 36).
3. At 1-ft. depth, a Proctor density of 95 percent was obtained by all compaction methods (Figs. 35 and 36a).
4. At 2-ft. depth, all but the static Compactor C and the experimental compactor reached this goal. The light weight of the experimental machine presents a handicap in this comparison.
5. At 3-ft. depth, only the tractor Compactor A produced 95 percent density (Fig. 35). The strong impact action of Compactor A, combined with the static effect of the tractor, appears to have been the best combination in this series of compaction experiments.

## EFFICIENCY RATIOS

In any comparison of the seven compaction methods for nonconfined areas, some of the compactors are at a serious disadvantage, for example the experimental compactor, due to its light weight, while other compactors are favored, for example, Compactor C, due to large weight.

To obtain better comparison values, taking into account to a certain extent these various advantages and disadvantages, an attempt is made to derive some kind of efficiency factors. It must be clearly understood that these efficiency ratios are set up only for the sake of comparison. For this purpose, the rather controversial assumptions have been made that compaction velocity, effected soil depth (95 percent Proctor density), weight, and the number of passes follow a linear relationship.

### *Efficiency Ratios Based on Total Horsepower*

In Figure 37, the efficiency ratios based on the total horsepower of each compaction unit are evaluated by dividing the compaction capacity by the total horsepower. For this crossmatching system, the experimental compactor shows the highest efficiency, while the tractor (static), static Compactor C and Compactor B (predominantly dynamic) produce the efficiency ratio of one.

Dynamic Compactor C is, as in all previous cases, more effective than the static.

No comparison charts including costs, such as capital investment, depreciation, operation, etc. are presented. It is obvious that, for example, a heavy machine does not cost twice as much to operate as a machine of half the weight.

## CONCLUSIONS

The following conclusions may be drawn, keeping in mind that most of the compaction experiments in the field were restricted to rather dry, gravelly sands.

### *Depth of Dynamic Compaction*

Combined static and dynamic loads compact deeper strata more effectively than static compaction or than dynamic compaction alone.

In many cases, loose soils poured in a single layer of 3.5-ft. depth, have been compacted dynamically to more than 95 percent Proctor density down to two and often down to three feet and deeper.

### *Change in Depth of Layers*

Hence a change in construction methods by increasing the height of individual layers to 2 ft. and more ought to be considered, which, under certain conditions, will lead to a substantial saving in time and money.

This increase in pouring depth, however, may require a modification in hauling and dispersing equipment, mainly to prevent breaking through the loose soil surface of heavy, tire-equipped tractors.

### *Change of Specifications*

Since dynamic compaction is, in many cases, particularly for cohesionless and slightly cohesive soils, if not more efficient, at least equivalent to static compaction, the suggestion is made to omit in subsoil specifications a designation of any method of compaction, for example by static rollers. Thus, revised specifications might be confined to the required amount of compaction only; in other words, leave the choice of the compaction method to the contractor.

### *Methods of Dynamic Compaction*

*Compaction of Confined Areas*—For compaction of confined areas, such as may occur in excavation of trenches, bridge abutments, foundations, etc., self-propelled dynamic compactors are advisable.

For these confined-area compactors the following characteristics are advantageous:

Operating frequency: Dynamic force vector in the range of 15 to 40 cps. adjustable to the critical frequency of the vibrating system: compactor-soil.

Compaction speed, direction and magnitude of dynamic force vector: Force vector tiltable in the range of ±45 deg. from the vertical and large enough to lift the compactor base from the soil in order to produce strong impact blows and to make the unit self-propelling.

Action line of dynamic force vector: Force vector acting below the center of gravity of the compaction unit to reduce digging-in and washboard effects and to improve the hill-climbing capacity. This may be achieved, for example, with a mechanical three-mass oscillator.

*Compaction of Nonconfined Areas*—For compaction of nonconfined areas, such as subsoils under highways and airfields, gravel under railroad tracks and for earth dams, fills, etc., self-propelling units are not advisable due to the low compaction speed obtainable.

Modified crawler-type tractors or rubber tired vehicles with multiple wheels transmitting static preloads can be combined with a mechanical two-mass oscillator producing dynamic compaction. Such a combination permits three types of compaction, that is, static, dynamic, or both, and the selection of that ratio which is the most effective for the particular soil to be compacted.

The following characteristics for nonconfined-area compactors are advantageous:

Operating frequency: same as for confined-area compactors.

Compaction speed, direction and magnitude of dynamic force vector: The compaction speed is governed by the speeds available for the tractor. Hence the force vector can remain vertical at all times.

The magnitude of the force vector depends upon the type of dynamic compacting action, that is, whether sinusoidal or impact characteristics are desired.

Action Line of Dynamic Force Vector: The force vector may act through the center of gravity of the compacting unit.

Surcharge: The surcharge or static compaction is governed by the weight of the machines and, if necessary, by additional weights, preferably seismically supported above the compaction base. Crawler treads rather than rubber tires or rollers allow for the best maneuverability under most adverse soil surface conditions.

In both cases, the maximum contact pressure must not exceed the breaking through pressure on the soil surface due to shear failure.

*Limitations of Dynamic Compaction*—The investigations carried out so far did not include a determination of the limits to dynamic compaction methods. A number of soils exist, for example, soils with high elastic, cohesive, and viscosity characteristics which are not compactable by static or dynamic loads.

## ACKNOWLEDGMENT

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Finally, the writer is greatly indebted to the Research Council and the College of Engineering of Rutgers University, in particular to E. Easton, dean of the College of Engineering and J. J. Slade, director of the

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## APPENDIX

### GLOSSARY OF TERMS AS USED IN THIS REPORT

Attenuation: Dying out (decay) or transfer of forces due to energy dissipation.

Capillary Saturation: Saturation obtained by draining water from fully saturated soil through openings at bottom of container.

Centrifugal Force Vector: Sinusoidal force (lb.) produced by mechanical oscillator.

Cohesion: C as evaluated from the Mohr's circle by Coulomb's formula:

$$\tau = C + \sigma_n \tan \phi$$

where $\tau$ = shear stress (psi.)
$\sigma_n$ = effective normal unit pressure (psi.)
$\tan \phi$ = coefficient of internal friction

Consolidation: Gradual compression of soil by non artificial means.

Compaction capacity: Compaction of soil volume (cu. ft.) per unit of time (sec).

Compaction: Increase in soil density by mechanical means.

Compaction velocity: Velocity (ft. per sec.) with which complete compaction unit is moving.

Confined Area Compactor: Machine built primarily to compact soils in confined areas such as trenches, bridge abutments, machine foundations, etc.

Contact Area: Total area between compactor base and soil being in contact during compacting action.

Coverage: See "Pass".

Critical Frequency: Frequencies (cps.) at which maxima of the displacement amplitudes, or energy (pressure) transfer amplitudes occur.

Decompaction: Decrease in soil density (dedensification).

Energy Transfer: Forces excited by loads on soil surface and transmitted through soil to pressure cells.

Full Saturation: Saturation obtained by water entering through bottom of container up to soil surface.

Grauser: Transverse rib attached to crawler.

Impact Compaction: Transmitted pressure to soil surface follows discontinuous pattern. During part of the upward motion of compactor, contact between compactor base and soil is broken, causing impact blow at beginning of downward motion.

Magnification Factor: Sensitivity factor with which excursion of record traced by instrument has to be multiplied to obtain quantitative values—(for pressure cells: lbs., for Vibrograph: inches).

Moisture Content: See water content

Nonconfined-Area Compactor: Machine built primarily to compact soils in nonconfined areas, such as subsoils of highways, airfields, dams, etc.

Optimum Moisture Content: Moisture content producing peak of curve obtained from plotting dry unit weight (lb. per cu. ft.) of soil versus moisture content in percent of dry weight according to AASHO T-9949.

Pass: Complete coverage of definite soil area by compactor without touching same area twice.

Penetration: Drop in elevation of soil surface due to shear failure.

Preload: Static loads produced by weights rigidly or seismically supported.

Pressure Cell: Unit to pick up energy transfer below the surface of the soil, produced by loads acting on the surface of the soil.

Proctor Density: Soil density obtained by standard laboratory method AASHO T-9949 in Proctor mold.

Run: Continuous motion of compactor in one direction only.

Seismograph: See "Vibrograph".

Seismic Support: Mass (heavy) supported on springs (weak) so that mass remains almost at rest when free end of springs is subjected to sinusoidal motion at operating frequency.

Self-Propulsion: Compactor is not supported by wheels and moves in small leaps without being pulled by independent and separate power unit.

Sensitivity: See "Magnification factor".

Settlement: Drop in elevation of soil surface.

Significant Density or Settlement: That density or settlement which does not increase significantly by any additional passes of compactor.

Sinusoidal Compaction: Transmitted pressure to soil surface follows quasi-sinusoidal (continuous) pattern. Contact area between compactor base and soil is not broken.

Spring Characteristic: Increase in load versus increase in deflection of spring—(not constant for soils).

Surcharge: See "Preload."

Three-Mass Oscillator: Mechanical unit to produce sinusoidal, unidirectional or two-directional force vectors through point not necessarily coinciding with center of oscillator by means of three unbalanced rotating masses.

Two-Mass Oscillator: Mechanical unit to produce sinusoidal, unidirectional force vectors with action line through center of gravity of oscillator by means of two unbalanced rotating masses.

Vibrograph: Unit to pick up vertical or horizontal displacement amplitudes on surface of soil, produced by loads acting on surface of soil.

Void Ratio: Ratio of volume of voids to volume of solids.

Water content: Ratio expressed as percentage of weight of water in given soil mass to dry weight of solid particles.

## DISCUSSION

D. P. Krynine, *Consulting Engineer*—The majority of persons participating in the activities of the Highway Research Board are familiar with the laboratory procedures and certainly can appreciate the large amount of time and energy spent by the author of this paper and his coworkers in the instrumentation side of the project. The reading public often looks first at the results of the research; and in this way the design and construction of new research instruments often remains not duly appreciated. Certainly this should not be the case with this paper.

As to the field and laboratory research as such, the author's program was ambitious, but due to different unfavorable circumstances could not be materialized to its fullest extent. As the author states, for example, he could not investigate throoughly enough compaction with heavy rollers. Otherwise the results obtained in the research are interesting enough and should be recorded by highway engineers. Without discussing the merits of the paper, the writer of this discussion wishes to point to some questionable items only, hoping that his remarks will be considered as constructive criticisms:

Combined static and dynamic loads compact deeper strata more effectively than static or dynamic loads separately. Application of static loads on large distances is economically prohibitive, and this result has academic interest only.

At the present time the 12-in. lifts are all what the contractors desire; the 24-in. lifts would be possibly difficult to handle as the author states himself in his conclusions.

Not all specifications require a particular method of compaction in the field.

The criterion of good compaction is not the density of the compacted fill, but its shearing strength which oppposes possible changes of shape caused by traffic and other wear of the riding surface. The shearing strength and density are not necessarily proportional.

The author of the paper states that he has in view the study of different other phases of soil dynamics. The writer of this discussion wholeheartedly greets this intention but desires only that in presenting the results of their studies the author or authors of corresponding papers use plain language with full explanation of terms. In the province of soil vibrations we are now in the same situation as we were 15 years ago with respect to ionization, base exchange and other similar concepts that then seemed to be obscure but now are entirely clear.

R. K. Bernhard, *Closure*—The field of soil dynamics covers such a large area and so little research has been done in this field that only a few topics could be covered by the restricted number of experiments carried out so far. Hence, the author fully agrees with Krynine's highly appreciated discussion and would like to emphasize that the investigation can be considered as pilot study only.

In particular, a knowledge of the basic dynamic soil characteristics, such as moduli of elasticity, damping, energy dissipation and the relation between shear strength and density, are of primary importance. Since elasticity and damping are in all probability nonlinear functions, the fundamental question of forming an adequate theoretical model or dynamic analogy of the vibrating mass-soil system including the effect of dispersion presents substantial mathematical difficulties. The writer would be satisfied if his paper succeeds in creating an interest to study these questions more in detail.