THE APPLICATION OF GEOPHYSICAL METHODS TO GRADING AND OTHER HIGHWAY CONSTRUCTION PROBLEMS

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SYNOPSIS

For determining the presence and location of solid rock foundations, and for classifying soils and other underlying strata with respect to their relative degrees of compaction, the seismic method is more dependable than the electrical resistivity method and has an inherent advantage over all other methods now used, in that it measures directly the rigidity of the earth's crust A blasting cap or small charge of dynamite exploded at or under the surface of the ground becomes the center of a wave disturbance Sensitive microphone detectors placed at different distances from the shot pick up the disturbance successively and transmit the electric impulses to galvanometers which record them as light traces on a moving photographic film By means of an accurate timing mechanism the time of transit of the wave disturbance from the shot point to each detector is also indicated on the film, the speed of transit being indicative of the elastic character of the material traversed Data from a number of shots are plotted on a time-distance curve, and the relative rigidities of the underlying materials thereby classified The thickness of surface layers of soft material over denser layers of clay or shale are indicated, and likewise the depth to material of still greater rigidity, such as solid rock This geophysical method of exploration, which has long since passed the experimental stage in mining industries, should largely supercede the time-honored test pit and core drill for the shallow work of highway construction

In the planning and construction of highways the engineer is frequently confronted with the problem of determining the character of the subsurface materials that he must excavate and of those upon which he must build his bridges, underpasses and other structures Too often the cost of the test pits, core drillings or wash borings necessary to obtain this information is so great that only a meager amount of exploration is undertaken It was with the idea of bringing additional facilities into this field that the Bureau of Public Roads, about three years ago, undertook the application of geophysical methods of exploration to the relatively shallow determinations with which the highway engineer is concerned

Of the several physical principles which previously had been used in subsurface studies two were considered as being applicable to highway problems One of these methods of test, the electrical resistivity method, has already been used for some years with varying degrees of success by several state highway organizations in connection with grading operations, fills through swamps, and for determining the location and extent of gravel deposits and quarry material The other method, known as the seismic method, although used extensively for locating oil-bearing structures and in certain types of mining operations, has not been applied extensively to shallow determinations However, tests conducted by the Bureau over a period of two years indicate that for determining the presence and location of solid rock foundations and for classifying soils and other underlying strata with respect to their relative degrees of compaction, this method is more dependable and accurate than the electrical resistivity method

The electrical resistivity apparatus and method of application are illustrated in Figure 1 (Fig 4, Public Roads, June 1935), while Figure 2 is a photograph of a complete apparatus of a type recently developed and built by the

Bureau To determine the depth to rock or the depth to a change in material the usual procedure is to introduce an electric current of known strength into the ground through suitably placed electrodes and by means of intermediate electrodes to measure the average resistivity of a volume of earth comparable in dimensions to the spacing of the two intermediate electrodes By progressively increasing the electrode spacing and repeating the measurements, a curve is established which shows the relation of resistivity to electrode spacing (and indirectly to depth) From such data it is often possible to determine the approximate depth to solid rock or to any stratum of material having a definitely higher or a lower electrical resistivity than the topsoil

Under some conditions this method has been used successfully for classifying materials to be excavated and for locating deposits of gravel and quarry material for highway construction purposes It is particularly adapted to grading and other shallow operations because of the simplicity of the apparatus and the speed with which such tests can be carried out

Because there is not a definite or fixed relation between the resistivity of the materials in the earth's crust and their density or bearing power, this method of test is not infallible In many locations, under favorable conditions of moisture, the relation between resistivity and density is such as to render the method dependable in determining the depth to solid rock. It occasionally happens, however, that in other locations conditions are such that apparently no relation exists and, under these conditions, the resistivity method is of no use For example, in one instance the existence of a surface layer of volcanic ash and pumice of unusually high resistivity entirely obscured the presence of solid rock a few feet below In other instances porous or seamed rock containing considerable moisture has not been detected under topsoil of relatively high resistivity For this same reason, when employing the resistivity method of test in any territory it is necessary to obtain correlations with local well logs, core borings, open cuts or other available data and to use these data as the basis of interpretation of the resistivity curves

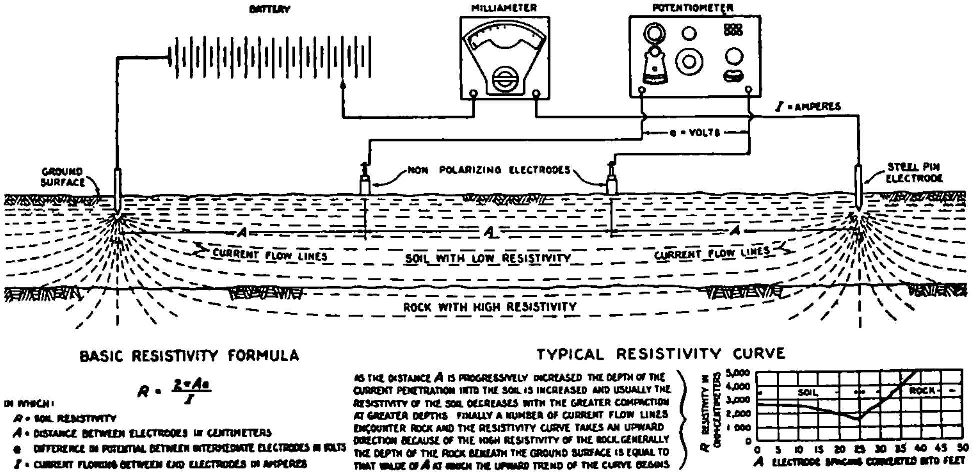

Figure 1. Arrangements of Apparatus for Measuring Electrical Resistivity

Extensive tests along the Skyline Drive in the Shenandoah National Park show

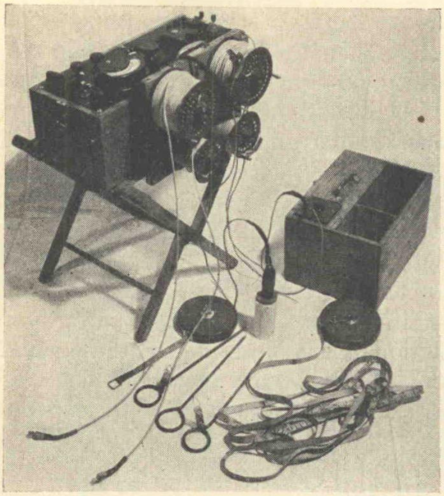

Figure 2

that in the majority of cases the resistivity method is well adapted to the general classification of materials of excavation in that territory. Similar success has been reported in the Ozark Mountains by the Missouri State Highway Commission.[1] On the other hand, satisfactory correlation could not be obtained by the Bureau in the Ranier National Park or near Portland, Oregon. Each locality presents a new set of conditions and the most reliable method of exploration can be determined only by preliminary experiments and correlations with known conditions.

The seismic method of exploration has an inherent advantage over all other methods in use at the present time in that it measures directly that property of the earth's crust with which the engineer is concerned, namely, rigidity. In using this method of test, advantage is taken of the wide difference between the elastic properties of plastic or granular material on the one hand and rigid or consolidated matter on the other. Non-rigid matter, such as sand, clay, or gravel, transmits wave disturbances at velocities of the general order of 1,000 to 6,000 ft. per sec. while rigid or elastic materials such as solid rock transmit wave disturbances at much higher velocities, generally of the order of 10,000 to 20,000 ft. per sec. In Figure 3 (Fig. 9, Public Roads, June 1935) is illustrated the method commonly used in making shallow depth determinations. A blasting cap or small charge of dynamite is exploded at or

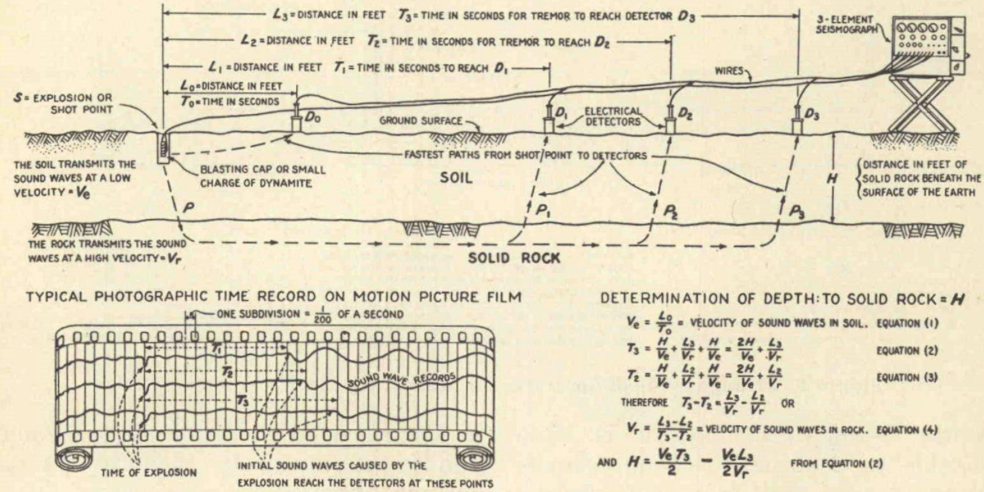

Figure 3. Sketch Showing Fundamental Principles of Seismograph Method

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[1] "The Earth Resistivity Method Applied to the Prediction of Materials in Excavation," by R. C. Schappler and F. C. Farnham. A paper presented at the meeting of the Mississippi Valley Conference of State Highway Departments, February 1933.

under the surface of the ground and becomes the center of a wave disturbance Sensitive microphonic detectors placed at different distances from the shot point pick up the disturbance successively and transmit the electric impulses to galvanometers which, in turn, record them as light traces on a moving photographic film By means of an accurate timing mechanism the time of transit of the wave disturbance from the shot point to each detector is also indicated on the film The speed of transit is indicative of the elastic character of the material traversed Data from a number of shots are plotted in the form of a time-distance curve (Fig 4) and from this curve it is possible to classify the underlying materials with respect to their relative rigidities The thickness of a surface layer of silt, muck, loam, or other soft material overlying a denser layer of clay, gravel or shale is indicated with surprising accuracy Likewise the depth to material of still greater rigidity, such as shale, cemented gravel or solid rock, is also determined

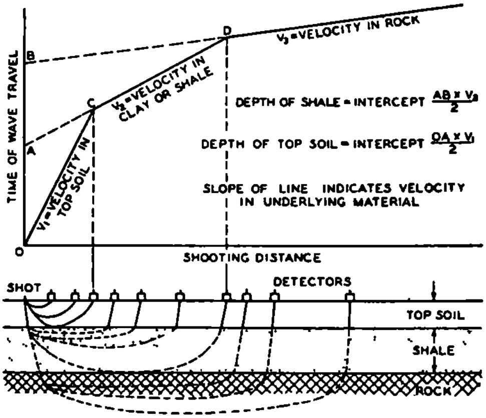

Figure 4. Time-Distance Curves from Which Soil Profile Determinations are Made

Numerous tests in and around Washington, D C, show satisfactory correlations with core borings at the same locations Some of these are shown in Figures 5 to 7 The position of the rock surface, as indicated by tests with the seismograph, is also shown on each diagram. In all cases the correlations are satisfactory when compared with the points at which cores begin to form in the seamed and weathered rock Because of the rather deep weathering of the rock in this region there is no sharp definition between soft and hard rock The hardness increases with the depth and cores usually begin to form at about the point where the rigidity and solidity of the rock is sufficient to transmit a high velocity wave

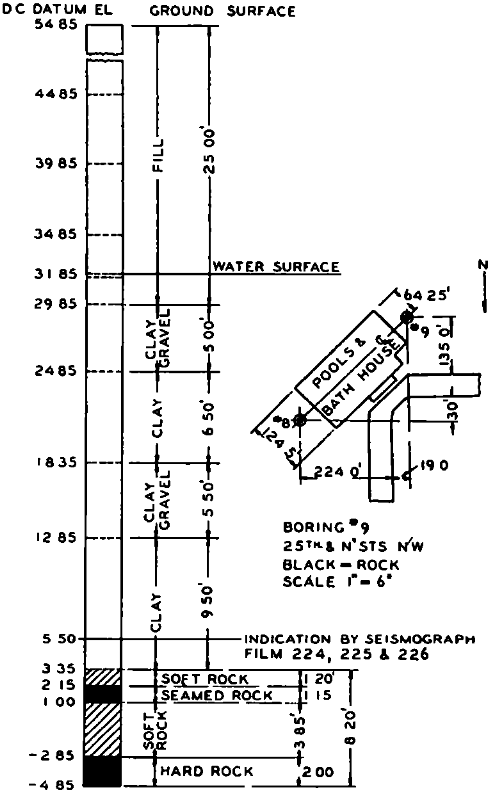

Figure 5

The value of subsurface studies to highway grading problems in mountainous regions has been indicated by tests in the Shenandoah National Park and more recently by rather extensive work in the

Bureau's districts 1 and 2 in California, Oregon and Washington National park and forest roads must frequently be built in extremely rugged territory where exact engineering data are necessary if a good balance of material is to be obtained This balance between excavation and fill is a matter of considerable importance and will depend upon the degree to which proper slopes can be predetermined A cut through solid rock will call for a perpendicular or near perpendicular slope, while a similar cut through sand or gravel will produce a much greater quantity of material because of the more liberal slopes required

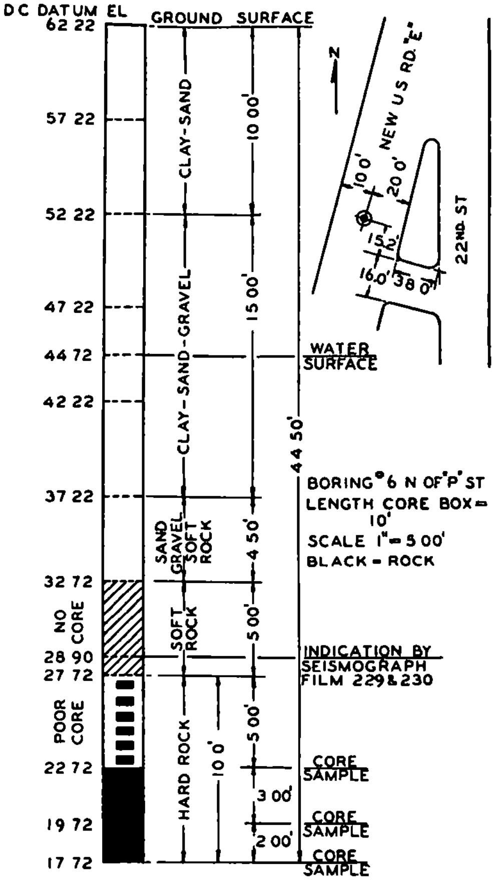

Figure 6

Wall footings and half bridges, often required on steep slopes to support the lower shoulder of the road, must be designed in accordance with the conditions of support available in the formation on which they are to be built These and many other conditions affect not only the design of the highway and its structures but also present perplexing problems to the contractor who is often called upon to base his bid upon little more than a guess as to what type of material he will encounter

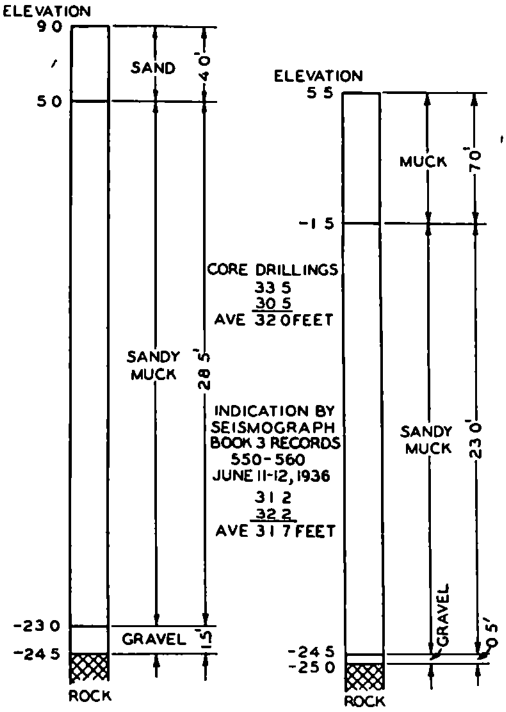

Figure 7. George Washington Memorial Highway Foundation Exploration for Bridge over Boundary Channel and Lee Boulevard Grade Separation. March 1936

The following instance is cited as an example of the need for subsurface studies prior to the design of a highway through rugged mountainous territory In one of the national forest highways now being constructed in the northwest a sharp hogback or ridge was encountered that would require either a tunnel or an open cut of approximately 100 feet depth The original design called for a tunnel as it was considered probable that so deep a cut would encounter solid rock Later, several test pits were dug in which nothing but soft material was encountered On the basis of this information the tunnel designs were abandoned and a cut decided upon This in turn called for rebalancing the line at additional engineering expense The cost of the test pits alone was approximately $800 The exploration of this huge ridge was one of the projects recently examined, and within the period of a few hours subsurface tests were made which indicated that the ridge was composed entirely of earth or other soft material to a depth far below the grade line Had it been possible to make these tests at the time of the preliminary survey much time, expense and uncertainty could have been avoided in arriving at a final and satisfactory design

In another instance a projected highway encountered a huge talus slide Information as to the depth of solid rock below the loose and sliding rock was necessary A day's work with the seismograph gave the desired information Many other similar examples could be given to show the value and importance of making subsurface studies at the time of the preliminary survey The results of such studies would be of great value to the engineer and, if made available to the contractors, would afford them a rational basis on which to bid, and also would help them in planning the work, building temporary roads and in the placing of camps and equipment

The question is often raised as to whether the apparatus and technique required for seismic studies can be successfully employed in the field by the type of personnel generally available In answer to this question it is only necessary to call attention to the fact that scores of such instruments have been and are at present being used to locate oil-bearing structures both in this and many other countries No particular difficulty has been encountered in obtaining operators for these instruments The work is interesting and young engineers are keen to learn the technique of operation and interpretation An intensive training period of a month, under the instruction of an experienced and competent engineer should be sufficient to fit a technical man for this type of work Suitable instruments, although as yet not fully standardized, can be obtained from instrument makers on specifications which the Bureau has developed No specific details of design are necessary so long as the instrument meets certain requirements as to sensitivity, speed of film, timing mechanism, etc

Geophysics has long since passed the trial or experimental stage in its application to the mining industry and there is no reason why it should be thought of as experimental for the more shallow work with which the highway engineer and builder is concerned He has only been slower in adopting it When its value is fully recognized by the highway fraternity it bids fair to supersede, to a large extent, the time honored test pit and core drill just as it has largely replaced the wild cat driller who blindly seeks for the hidden treasures of the earth

DISCUSSION ON GEOPHYSICAL METHODS

Dr Rudolf K Bernhard, *Consulting Engineer, Philadelphia, Highway Dynamics, a Practical Application of Artificial Vibration*:[1] Static highway investigations with more or less heavy loads and extensive borings do not always have efficient results They are also very expensive Hence a simple and cheap method of dynamic tests is described The new dynamic method avoids several disadvantages of the routine investigation, thus forming a useful supplement to the older methods and even replacing at times various static tests [2–4]

The fundamental principle of dynamic highway tests consists in the application of artificial vibration Artificial vibration may be excited by centrifugal forces, resulting from eccentrically supported rotating masses The reactions of the highway, including its superstructure, caused by these vibrations may be measured Their dynamic constants, such as amplitudes, phase-speeds, damping, reflection, and interference effects can then be investigated

Actual loads are seldom purely static Highway traffic causes dynamic loads and the foundations of buildings may be affected either by direct transmission of propagation waves or indirectly by vibrations of the whole structure Hence the imitation of actual field conditions requires the introduction of dynamic loads Furthermore the effect of insulating methods for damping, oscillations, such as the protection of structures against highway traffic vibrations by trenches can only be tested dynamically

Fundamental principle

This new method takes into account the experiences of well known *macro*seismic investigations Dealing with relatively small areas it may be called a *micro*seismic method In the geophysical field dynamic testing has been in use for quite a long time Macroseismic investigations are often carried out with artificial vibration excited by blasts or shots, which produce nonperiodic waves of rather complicated forms This microseismic method uses only artificial vibration of a periodic character having the form of a pure sine wave

The dynamic qualities, i e , bedding value, natural frequency of the highway surface and the subsoil, wave length, propagation speed, reflection, interference, and resonance effects caused by these artificial vibrations are measured All these dynamic qualities give a characteristic picture of the highway They allow us to draw important conclusions on the bearing capacity, the composition, and the compressibility of the subsoil and in certain cases on the formation, succession, or depth of various beds

The fundamental principle is very simple The highway under investigation is loaded in various places by alternating forces having a sine form Frequency and size of these forces can be changed Hence the soil must vibrate with forced and damped oscillations

The apparatus for exciting these alternating forces consists of a relatively small machine This machine has two discs eccentrically supported, the discs revolve in opposite directions and are

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[1] A more thorough treatment of this subject is to be published at a later date

[2] F P Ullrich Man-Made Earthquakes Engineering News Rec 1935, No 20

[3] A Hertwig, G Frueh and H Lorenz, Determination of important qualities of the soil by forced vibration in civil engineering Transactions of the German Society of Research in Soil Mechanics (Degebo) Berlin, 1933, No 1

[4] A Hertwig, Angenheister, R Koehler and A. Ramspeck, Application of dynamic soil investigation Transactions of the German Society of Research in Soil Mechanics (Degebo) Berlin, 1936, No 4

rotated by an electric motor Changing the eccentricity of the discs will change the amount of the centrifugal forces from about 1 to 4000 lb Changing the motor input will change the speed of revolution (hence the frequency of the exciting forces) from approximately 1 to 50 cycles per second All horizontal forces are neutralized in the body of the machine by the inverse rotation of the two discs Two external vertical forces alternating in a pure sine form remain, (Fig 1) The current supply (d c) for the motor consists of a small motor generator outfit mounted on a truck This truck transports the oscillator and all accessories

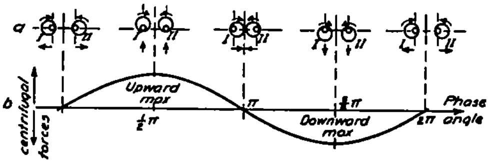

Figure 1 Exciting artificial vibration. (a) Position of the revolving masses during one revolution. (b) Corresponding centrifugal forces, alternating in a sine form.

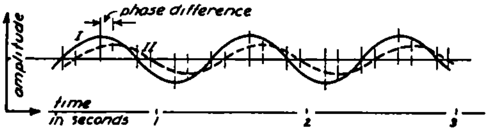

Figure 2. Amplitude-time curves recorded by two seismographs at various distances from the oscillator The seismograph, recording curve II, is further away from the oscillator, hence indicating a difference in phase in relation to curve I.

The power input of the oscillator motor is measured by a standardized wattmeter, the rotation speed (the frequency of the exciting forces) by a standardized tachometer

The propagation or phase speed of the forced oscillations can be determined by measuring the phase difference of two corresponding maxima or minima The time which is required by the wave, to move from a point on the oscillator to a point on the soil causes a phase difference in both sine curves plotted by the seismometers (Figs 2 and 3)[4] By moving the seismometers from point to point in such a manner that successive positions overlap, it is possible to plot closed profiles or contours with no danger of omitting salient points The evaluation of all results can be done in the office

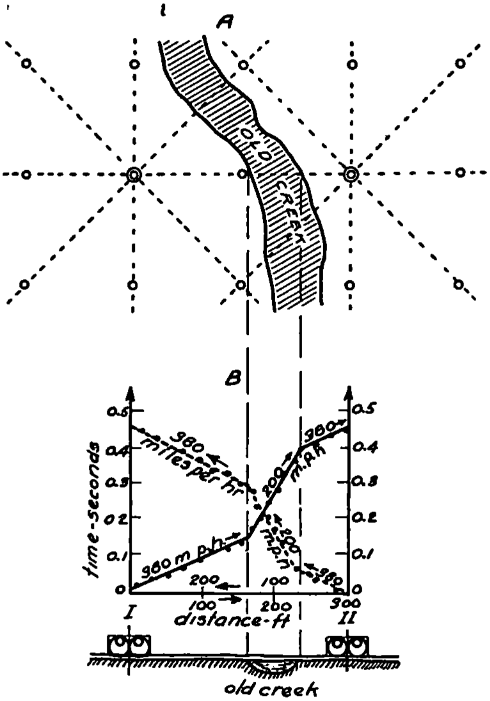

Figure 3. Static method. o o o borings. Dynamic method· --------- measuring points for seismographs. I and II position of oscillator.

A Comparison of soil investigation with oscillator and borings. Dynamic method gives closed and overlapping profiles on dotted lines. With borings old creek might easily be missed

B Subsoil investigation with phase-speed curves on strata including an old creek, corresponding to Fig. 3A. The old creek is marshy and has a low rigidity, hence causing a smaller phase speed. ——— speed curve measured with oscillator at point I. --------- speed curve with oscillator at point II.

Bearing capacity of the subsoil

Highway research may include the investigation of the quality (bearing capacity) or the formation of the subsoil (succession of beds)

As already mentioned the quality of the soil depends on its dynamic constants Determining the natural frequency of the oscillator with the soil, (the resonance point) one of these relations will be indicated A higher frequency shows a higher bearing capacity For example soft marshland is very elastic, has a low natural frequency and hence poor bearing capacity, sharp sand is relatively rigid, corresponding to a high natural frequency and good bearing capacity

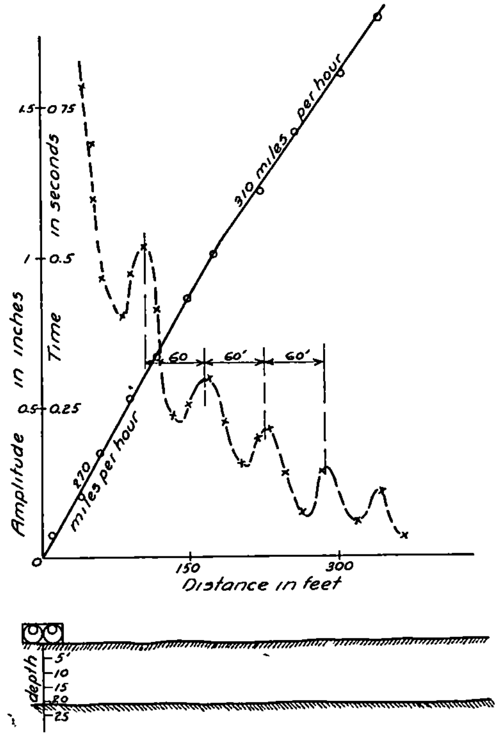

Figure 4. Investigation with amplitude-distance curve (x------- x ------- x) and time-distance curve (o ——— o ——— o) on stratified soil. The distance of the maxima (60′) and the change in speed (270 to 310 miles per hour) indicates the second stratum

The phase speed shows a similar relation to the bearing capacity of the subsoil A loose sand strata has a low speed, a dense sandstone a high speed, indicating a bad or good bearing capacity respectively

Formation of the subsoil

A highway under investigation might be planned over an old creek of marshy material not visible to the eye (Fig 3) Closed profiles are obtained by measuring from point I to point II with the oscillator in I and from point II to point I with the oscillator in II Hence the slightest lack of homogeneity easily missed with borings, will show up twice The time distance curve in Fig 3 shows the result The change in speed from 380 to 200 and back to 380 miles per hour indicates clearly the presence of the old creek The natural position of the soil is not disturbed nor is any damage done to the surface by this investigation

Another important test is the determination of the succession of various beds The length of the elastic wave depends on the frequency Decreasing the frequency of the exciting vibration will increase the wave length, and will show the qualities of strata at greater depths With a frequency of 35 cycles per second strata may be investigated to a depth of about 10 ft, with a frequency of 15 cycles per second to a depth of approximately 60 ft In Fig 4 two speed curves are plotted, the speed curve of 270 miles per hour where the oscillator ran at a high frequency indicates the upper stratum, the curve of 310 miles per hour at a lower frequency shows the second bed[4] This proves that the lower stratum with its higher speed is more rigid

At the same time the existence of various strata will appear in the amplitude-distance curves (Fig 4) Their presence may be noted by observing the maximum and minimum points on the curves These maxima or minima are the result of the previously mentioned interference effect. The distance of maxima or minima allows the determination of the depth of the bed with the help of simple formulae[1]

Improving the subsoil

Vibrating the subsoil in its natural frequency has a very effective densifying result A similar principle is often used to densify concrete mixtures Friction between minute earth elements plays the most important part during compression Ramming or rolling the soil effects only the surface since the coefficient of starting friction is acting and prevents deeper penetration of the compression on account of some sort of self locking effect Vibrating the soil in its natural frequency suspends the minute particles in a kind of floating equilibrium In this case the coefficient of sliding friction is acting which is relatively smaller The densifying effect with artificial vibration reaches strata of more than 8 ft in depth

Vibrating a new highway fill to densify it is much more effective than any other methods, especially for materials with low binding qualities and low water ratio The best check on any soil improvements consists in the measurement of the phase speed The higher speed indicates greater rigidity Figure 5 demonstrates the difference in speed between a recent fill and cut where the soil is still in its virgin condition[4]

This artificial improvement of the soil is very effective in foundation work for highways, where ground with insufficient bearing capacity is encountered The allowable bearing pressure can be raised, thus saving the expense of a higher superstructure

By observing the settlement curves during the oscillation, conclusions can be drawn as to how the highway will behave under traffic causing vibrations or impacts

Thickness of the concrete surface

Furthermore, the improvement of highway surfaces can be studied The required thickness of highway concrete is determinable, again by measuring the phase speed Usually the concrete is more rigid than the subsurface, thus having a higher propagation speed Any subsoil having a higher speed than the concrete is in itself strong enough and needs but a very thin surface just thick enough to prevent moisture penetration A big difference in speed between concrete surface and subsoil indicates that both parts are vibrating separately, the adja-

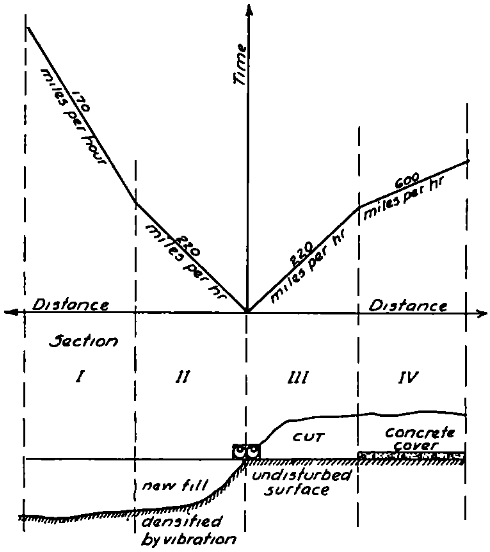

Figure 5. Investigation of a new highway with phase-speed curves. The lowest speed indicates the new fill (section I); artificial vibration densified this fill (section II) to the same rigidity as the undisturbed surface of the cut (section III), the concrete cover (section IV) improved the surface again considerably The speed ratio between the various sections is 170 220 220 600 miles per hour

cent surfaces acting as a slide plane In this case the concrete must be thick and must be reinforced to prevent cracks through vibration, Fig 5 (Section III and IV), shows the results of speed measurements on a highway surface with and without concrete It proves clearly that the speed of 220 miles per hour without the concrete is considerably smaller than the speed of 600 miles per hour with the concrete Hence the effective gain in rigidity, including the influence of various intermediate lower bases, can be checked easily

Conclusions

This new method has been used for several years with ever increasing success in the United States and Europe Being still in the development stage nothing can be said yet as to how important this method may become in this particular connection or in related engineering fields It must be borne in mind, that it cannot replace the old methods in all cases It is, however, already a useful help for all kinds of highway investigation problems, supplementing the old standard static tests

Acknowledgment The author wishes to express appreciation to Prof Hertwig, Dr Lorenz and Dr Ramspeck for advice.

Mr L W Teller, *U S. Bureau of Public Roads* I should like to comment on two points in connection with Dr Bernhard's discussion One is that in connection with sub-surface exploration, it is very often the case that it is pioneer work in rough country and it is difficult to get into such regions with apparatus that is of any considerable mass or weight

The second is that in connection with the work of Mr Shepard which Mr Moore described, we have been interested in the time of arrival of the first shock and not in the form of the wave after that point The moment of arrival of the first tremor is not difficult to obtain and the complicated wave form that follows is of no particular interest in the work that we have been doing

Dr Bernhard. The machine for inducing artificial vibration (the oscillator) can be built very small and therefore easily transported on pack animals or by trucks wherever the oscillator is required

It is true that the time of arrival of the first shock might be sufficient to get *one* single result However having a continuous wave of a sine form, as many amplitudes may be used as desired, in other words any number of trials may be used to check each other

It might be mentioned that it is very difficult to build instruments which indicate steep wave fronts correctly, such as those caused by blasts, on the other hand it is very easy to build apparatus which will record a sine form wave absolutely accurately. Another advantage is that a blast only endures a very brief moment while the artificial vibration can be extended hours so that it is not difficult at all to adjust the instruments Furthermore tests can be repeated with exactly the same amplitudes and frequencies as often as desired which is almost impossible with blasts

Mr J A Buchanan, *U S Bureau of Public Roads*· I note that Dr Bernhard describes his induced vibrations as having the form of a true sine curve I question this although it may make no real difference so long as he gets faithful reproductions of consecutive vibrations "When the weights are travelling upward they are moving against the influence of gravity and in going downward the influence of gravity is added Does not this difference of 2 g result in a modified or unbalanced sine curve?" It may be that the instruments and technique of curve analysis are insensitive to this difference, particularly after the vibrations have traversed a considerable mass of earth, but I question the true sine nature of the phenomenon

Dr Bernhard. Centrifugal forces excited by the oscillator itself are completely independent of the force of gravity and therefore may be used in any direction Any modification of the sine form in soil curves has not yet been detected The gravity component (dead weight) has merely the effect of varying the position of the datum line

SURFACE-CHEMICAL FACTORS INFLUENCING THE ENGINEERING PROPERTIES OF SOILS *

By Hans F Winterkorn, *Research Assistant Professor, University of Missouri*

At the 1935 meeting of the Highway Research Board Professor Krynine stated the desirability of expressing the influence of various exchange ions on the engineering properties of soils in the common engineering terms and indices Today we are able to present such data The soils tested were as follows

(1) Cecil Clay· red subsoil developed under lateritic weathering from gneiss, with an appreciable amount of mica in its larger-sized fractions and most probably also in the clay and colloid fraction Iron and alumina are present in the crystal structure as adsorbed ions and in the form of hydrous oxides The soil contains practically no organic matter Base exchange capacity of extracted clay, 13 milliequivalents per gram

(2) Hagerstown Clay: reddish brown, sandy clay subsoil, developed from chert free limestone under podsolic type of weathering, modified by presence of limestone Base exchange capacity of extracted clay about 60 milliequivalents per gram

(3) Putnam Silt Loam: grey-brown silty clay subsoil of mixed glacial and loessial origin Developed by podsolic type of weathering Base exchange capacity of extracted clay 67 milliequivalents per gram

Preparation of the Homoionic Soils Nine samples of each of the three soils were furnished for test, one representing the natural soil The other eight samples were prepared from the natural soil by satisfying its base exchange capacity with a particular ion The eight ionic species were hydrogen (H+), sodium (Na+), potassium (K+), magnesium (Mg++), calcium (Ca++), barium (Ba++), aluminium (Al+++), and the ferric ion (Fe+++) The number of positive charges, +, ++, or +++, denotes the positive valence of the particular ionic species

The method of satisfying the base exchange capacity of the soil was as follows.

Air-dried samples were placed in percolators and each sample was treated with one of the chloride solutions, KCl, NaCl, $FeCl_3$, etc , and hydrochloric acid For the K, Mg, Ca, Ba and Fe soils, 0 1 normal chloride solutions were used as leachates For the Al soil aluminium sulfate was used as the leachate In the preparation of the H soil, 1/50 normal hydrochloric acid alone was used as the leachate There is little tendency for HCl of this low strength to dissolve the colloids

Leaching was continued until the leachate had the same concentration as the

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* Abstract of a report on a cooperative study of the Bureau of Public Roads, the Missouri State Highway Department and the Missouri Agricultural Experiment Station The complete report will be published in Public Roads.