Nuclear Moisture—Density Measurements in Construction Control

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INTRODUCTION

Soil strength is determined to a large extent by the soil's density. A soil compacted to a relatively high degree of density will have high relative strength resulting not only from the densification process but also from restriction of loss of strength brought about by reduced moisture absorption. The strengths of base course materials and asphalt surfaces are also affected to a large extent by the material's degree of compaction.

Specifications for highway embankments, earth dams, subgrades, and bases usually stipulate a minimum density that must be attained during construction. Since soil density in turn is dependent on moisture content, this latter value should also be specified. Even though compacting moisture content may not be specified for many routine jobs, sound engineering practice dictates that close control should be exercised over it at all times.

Moisture and density control requires field tests during the construction operation. Control testing must be keyed to modern construction techniques wherein a large number of tests can be performed with a minimum amount of shut down time on the part of the contractor. Conventional methods of measuring field density and moisture content have in the past been tedious, requiring up to several hours to produce reliable results and thereby eliminating any possibility of producing test data in quantity. As a result, it generally becomes necessary to perform just one or two tests on a compaction lift and then to assume that these results are representative of a large area. The inspector is faced with the problem of using short cut methods wherever possible to meet the demands on his time. Short cut testing methods themselves often introduce errors that may be large.

Recent developments in the field of nuclear physics have resulted in an instrument which gives reliable results in very short periods of time. These instruments are quite costly and require that the engineer understand a few of the basic principles of nuclear engineering. The instruments, however, can be operated efficiently with just a nominal amount of training on the part of the operator.

The Joint Highway Research Project has undertaken a study wherein several nuclear instruments will be evaluated. This research is sponsored jointly by the Bureau of Public Roads and the Indiana State Highway Commission. At the completion of this study the instruments will be turned over to the Bureau of Materials and Tests for use on routine construction. As part of this overall study, a review of available literature has been made.

USES AND ADVANTAGES OF THE INSTRUMENT

The nuclear moisture-density measuring instrument is designed to overcome the difficulties mentioned in previous paragraphs and has the added advantage of being non-destructive in its operation. The instrument is a comparatively recent innovation; a great amount of investigational work is still in progress to adapt and improve it for all conditions encountered in practice. Nevertheless, several authorities employ the instrument for routine control of compaction of embankments, subgrades, subbases, and bases. Nuclear testing has also been used to a limited extent for control testing on earth-fill dams.

The instrument can be used as a preliminary investigation tool to determine the degree of density of natural soils on new highway routes. It is useful for evaluating seasonal moisture and density variations. Determination of the density and moisture content of a pavement foundation after the pavement has been in use for a period of time will often reveal the effects of traffic and climatic changes on the pavement structure. The nuclear moisture-density instrument permits measurement of density and moisture content without the cumbersome practice of direct sampling. This applies similarly to investigations of pavements which have been distressed. The versatility of the instrument will no doubt make it a most useful adjunct to a highway materials laboratory if the instrument's reliability is improved so that it can be accepted without hesitation.

The principal advantage of the nuclear moisture-density instrument lies in its portability and speed of operation. The major shortcomings of conventional methods are eliminated in that with the nuclear device testing in a specific spot can be accomplished in a matter of minutes for a complete test, and for ordinary checking, in no more than two minutes.

This then represents a significant step in permitting continuous control over large areas with minimum time and cost, and with maximum efficiency of operation.

HISTORY OF DEVELOPMENT

The first attempts in the United States to measure soil moisture and density by means of isotopes for engineering purposes were made at Cornell University for the Civil Aeronautics Administration* (2, 21, 28).† By 1952 the research team at Cornell reported successful nuclear measurement of the moisture content of thin layers of soil. These methods, however, were not accurate enough to replace existing tests (sand cone density, oven dried moisture content, etc.).

Interest in nuclear techniques also developed in Europe. By 1955 the minimum standard requirements of this type of equipment were established by U. S. and European scientists. From about 1955 to the present, refinements in instrumentation, by introducing Geiger-Muller detector tubes and scintillation detectors, have been the major fields of developments. The theory of scintillation detectors was clarified by S. E. Roy and H. F. Winterkorn in 1957 (24).

With the advent of transistors, instrumentation reached the stage where self-contained portable equipment made the versatility of these instruments a practical proposition.

In 1956 Pocock (19), from the Michigan State Highway Department, and in 1957 Roy and Winterkorn from Princeton University (24) developed the minimum mathematical and practical design requirements that the nuclear moisture-density apparatus must satisfy for successful performance.

Most of the early work dealt with development of depth probes. These probes, inserted in holes drilled into embankments, in general were not suitable for routine control testing. They permitted, however, study of seasonal changes of moisture and density since tubes could be placed in the holes and periodic measurements could be made through the tube walls with little difficulty.

Instruments have now been developed which can be placed directly on the surface to measure moisture and density. Commercial instruments of this type have been on the market for about five years; many construction agencies now use this type of nuclear equipment as a

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* Now Federal Aviation Agency.

† Numbers in parenthesis refer to reference numbers in bibliography at the end of this paper.

replacement for the conventional density and moisture techniques of construction control.

Accurate statistical detection of low intensities of gamma rays for unit weight determination and slow neutrons in the moisture measurements proved to be the main problems in the development of the instrument. From 1950 to the present various investigators experimented with the use of different radioactive sources. Pieper, Yates, Belcher (21, 28, 2) placed Indium and Rhodium foils in the soil at various distances away from the radioactive source which was placed in a hole drilled in the soil. The radioactivity of the foils then provided data for a calibration curve for the soil moisture meter.

Various isotope sources with strengths from 250 to 10 millicuries were studied by a number of research workers. Ra-Be has been established generally as the most suitable neutron source. Improved probes were produced, but it was not until Gardner and Kirkham (11) introduced BF_3 gas filled slow neutron detector tubes that significant accuracy was reported. The introduction of photo-multiplier detector tubes in scintillation techniques appears to have introduced considerable accuracy into instruments that was not possible in earlier models.

Carlton (6) employed a Cobalt 60 source, separating the source and detector by a thickness of lead thus employing a back-scatter technique for measurement of soil density. Significant deviation from a linear relationship between count rate and wet density was found.

Some modern instruments use Ra-Be as their radiation source. Since its half-life is 1620 years, variation due to change in radiation characteristics over long periods is minimized. It is apparent that suitability of various sources must still be evaluated.

PRINCIPLES OF OPERATION

The nuclear moisture-density apparatus as used in highway construction generally consists of two surface probes, one for measuring the unit weight of the soil and the other for measuring in-place moisture content. A scaler or counter which records the data is coupled to the detector. Moisture content and density are then determined from a calibration chart.

Fig. 1 shows a nuclear moisture-density meter including surface and depth probes and scaler. The surface gauges are shown on the left of Fig. 1 while the depth probes are shown on the right of the figure. The depth probes, when used, are lowered into holes drilled into the embankment to the required depth, and the readings are read on the portable scaler. For the surface gauges it is merely necessary to set

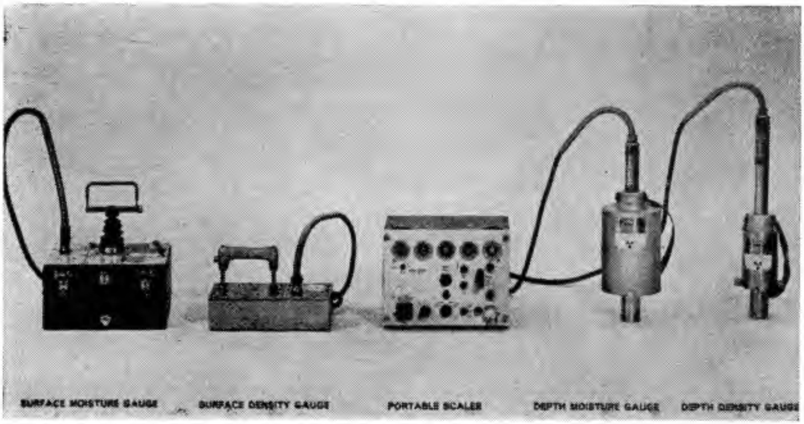

Fig. 1.

these on relatively flat surfaces; moisture and density values are determined for the upper layer of the soil or other construction materials.

The nuclear moisture-density instruments employ a radioactive source

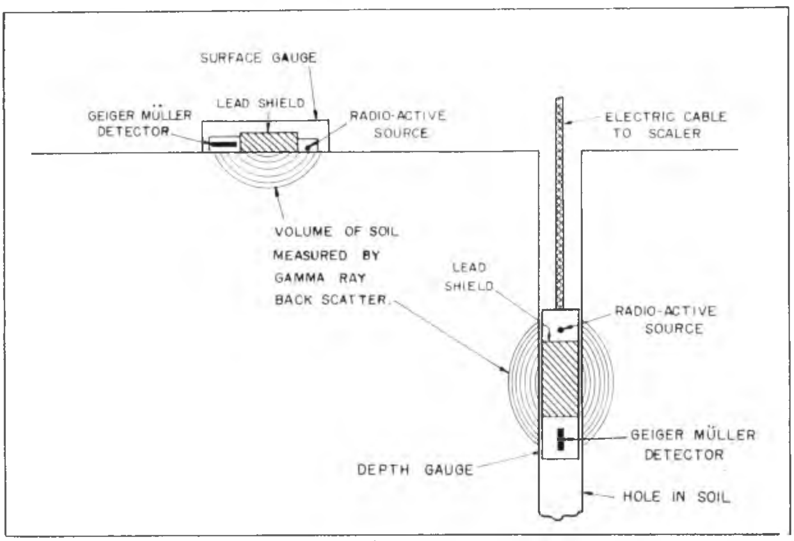

Fig. 2.

of low intensity and a detector which is placed close to it. Fig. 2 illustrates in diagrammatic form the depth and surface density gauges. It is to be noted that the density of some volume of the soil surrounding the probes is measured and that the resulting density will be an average value for all the material within the zone of influence. This in the past has been to the disadvantage of the instrument since it has not been possible to measure moisture content and density of relatively thin layers. The zone of influence for the density meter is dependent upon the distance between the source and detector.

For density probes the radioactive source is either Cobalt 60, Cesium 137, or Radium-Beryllium and the detecting device is generally a Geiger-Muller detector. Moisture probes generally contain a Radium-Beryllium Source and their detecting device is a Boron-Trifluoride tube.

Fig. 3 illustrates a surface nuclear moisture-density meter in use. This particular device is well adapted to construction control, is sturdy,

Fig. 3.

and has given reasonably accurate results for most materials. The surface gauge measures moisture content and density for a layer of soil at the surface. Surface gauges eliminate the necessity for drilling holes as is the case for depth probes. Depth probes, however, are available which can be used with the scaler shown in Fig. 3.

Fig. 4 is a diagrammatic sketch illustrating a gauge which contains both the density and moisture probes in a single case (19). This instrument offers the advantage of reducing the amount of required

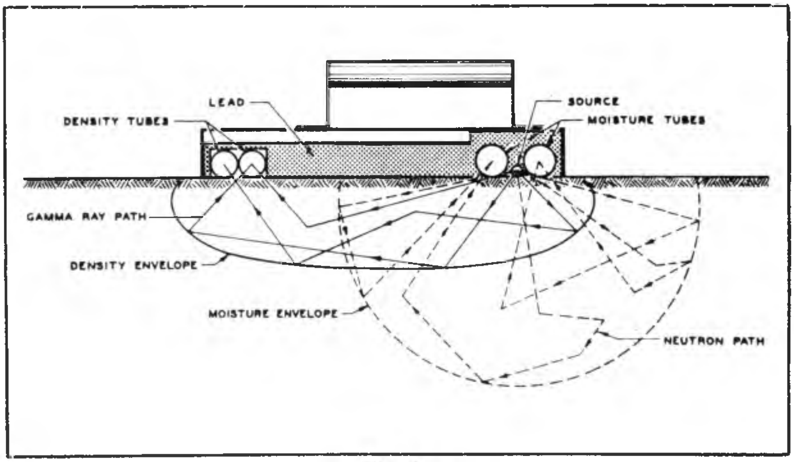

Fig. 4.

equipment but in addition it permits measurement of both moisture and density at a specific spot within a short period of time. This particular instrument was developed at the Michigan State Highway Department (19); a similar instrument is available commercially from the Union of South Africa (22).

As shown in Fig. 4, the radioactive source is placed at one end of the gauge and the density detector is placed at the other end. The moisture detector is situated close to the source. The source in this case radiates gamma particles and neutrons as indicated by the arrows; by the "back-scattering" phenomena they eventually strike the detector. These "strikes" are transformed into electrical impulses which are amplified through a preamplifier attached to the Geiger Counter and transmitted along a coaxial cable to the scaler. The recording on the scaler is calibrated against unit weight of the soil.

Moisture measurements accomplished by the instrument illustrated in Fig. 4 are made using the same radioactive source as for the density measurement. The moisture measurement is based upon neutron moderation which in turn is a function of the amount of hydrogen in the soil water mixture. Since the principal source of hydrogen in inorganic soils is water, the moisture content of the soil can be determined.

It is pertinent to note that the back-scatter occurs in a volume that is dependent upon the distance between the density detector tube and source. The unit weight measured then is an average value representative of this volume below the gauge.

Depth of density measurement is dependent upon the distance between the source and detector tube. Carey and Reynolds (4) suggested the possibility of measuring density at various depths by adjusting the distance between the source and tube. This has been accomplished on one instrument. It has been found that the depth of measurement is dependent, to some extent, upon the density which is measured as well as distance from the source of the detector.

Fig. 5 illustrates the effect of wet density on effective depth of measurement (22). It is to be seen that for a wet density of 150 lbs.

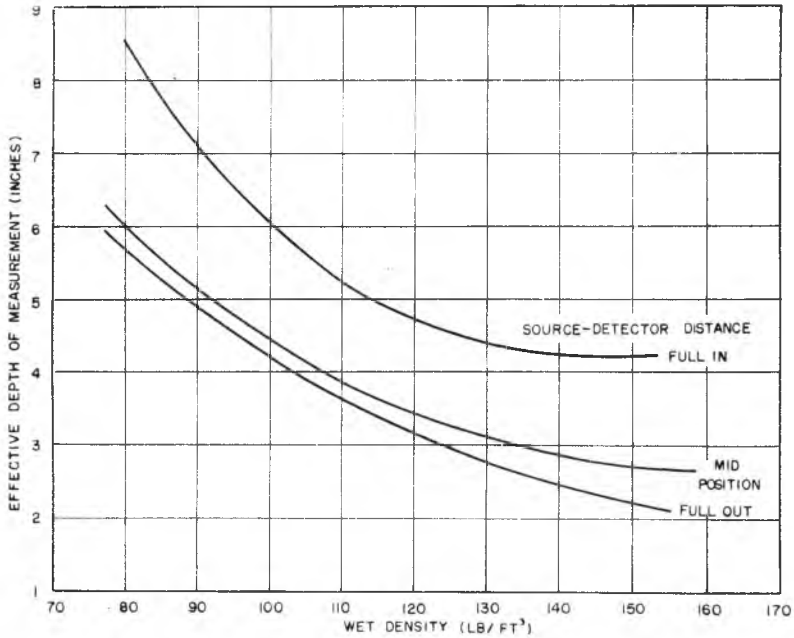

Fig. 5.

per cu. ft. the effective depth of measurement varies from a little over 2 inches up to about 4¼ inches. The effective depth of measurement for an extremely light material (80 lbs. per cu. ft.) varies from 5¾ inches to 8½ inches. Thus it can be said that density measurements made in clay-like soils are for a depth of 4 to 5 inches whereas for asphaltic surfaces and base courses the effective depth of measurement varies between 2 and 4 inches. This characteristic of the instrument has interesting possibilities particularly in light of measuring density of asphaltic surfaces for control purposes.

Nuclear instruments are generally calibrated to measure moisture content in weight per cu. ft. of soil. The count is recorded on the scaler and the weight per cu. ft. is obtained from the calibration curve; the moisture content is then calculated using weight relationships.

It is important to note that data obtained from the nuclear moisture-density meter are subject to the same statistical laws which effect measurement of moisture and density using conventional techniques. It is fortunate that the variation within the range of data obtained by the instrument is of the order of 0.5 to about 2 per cent. This variation is well within the limits of accuracy established for conventional techniques of testing.

CALIBRATION OF NUCLEAR INSTRUMENT

Data obtained from the nuclear instrument are in terms of counts per unit of time. Therefore the instrument must be calibrated against materials having known densities. In addition, like other conventional apparatus the instrument must be calibrated regularly. Calibration is perhaps the most complicated phase of its use.

Calibration is usually accomplished by fabricating standards having densities over the range expected in practice. Regular checks must be made to insure that the field data are accurate. Most instruments, which are available on the market, have been calibrated at the factory, but it is wise for any testing agency to check these calibrations against their own materials.

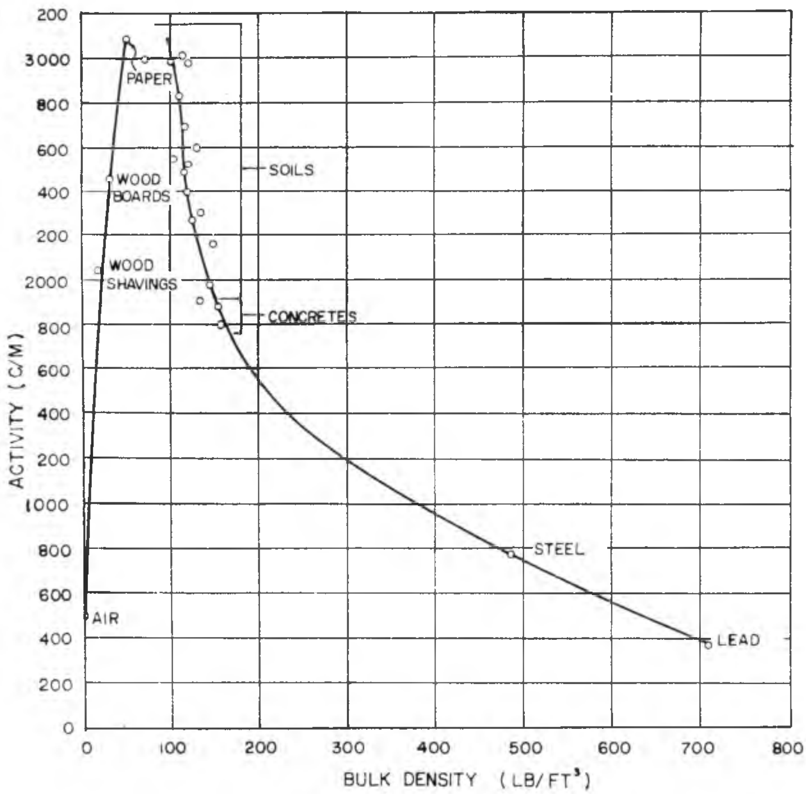

Fig. 6.

Fig. 6 illustrates data obtained from several materials (22). These range from a high value of lead having a unit weight of over 705 lbs. per cu. ft. down to the density of air. The portion of the calibration curve of interest to the engineer lies between that of concrete having a unit weight of about 150 lbs. per cu. ft. down to a value as low as 90 lbs. per cu. ft. for a clay-like soil. The curves in Fig. 7 represent

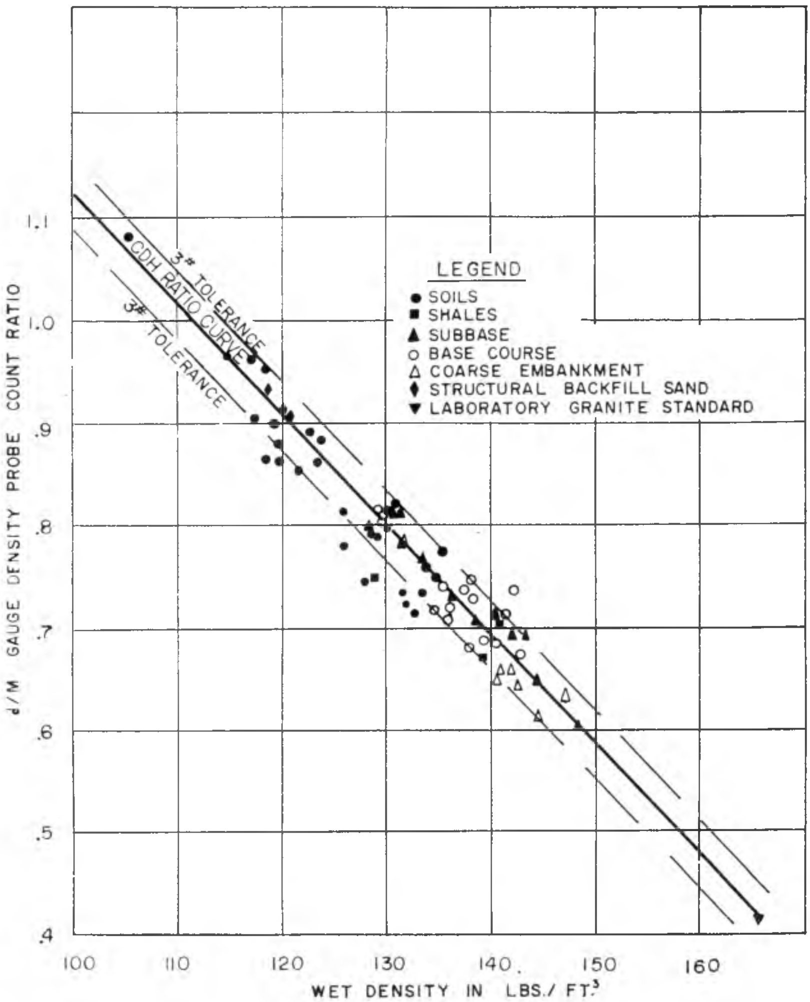

Fig. 7.

calibration data for density (7). Calibration curves for moisture content of soil can be obtained in a similar manner. Moisture determinations, however, depend to some extent upon plasticity of the soil. This is illustrated in Fig. 8 (22). Since moisture content as determined

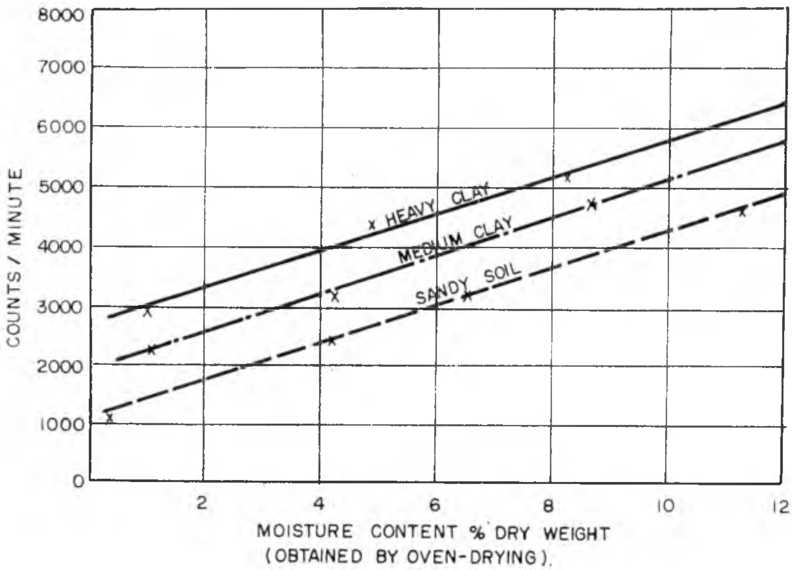

Fig. 8.

by the nuclear meter is dependent upon soil type it becomes necessary to obtain calibration curves for various soil types in order to obtain accurate calibration data.

Referring to Fig. 7, it can be observed that the points are clustered about the calibration curve and that the maximum variation is generally within ± 3 lbs. per cu. ft. For most practical control problems this variation is not detrimental. This is particularly true in control of large embankments and earth dam structures. However, this variation may be significant from the standpoint of controlling density of subgrades.

Data in the literature indicate that with careful calibration and close control of the measurements in the field it is possible to measure density with less variation than that indicated in Fig. 7. It should be noted however that some variation does exist and that it must be taken into account when evaluating field test data.

CONCLUSION

A large amount of research has gone into the development of the nuclear moisture-density instrument. Recent advances in transistorizing the instrument have resulted in compact, easily portable gauges that can be used with a nominal amount of training. The engineer, however, must be aware of the principle that soil is a complex material and that since nucleonics in itself is a complicated subject, it has not as yet been possible to produce a simple piece of nuclear equipment which will measure the desired properties of soils under all conditions that might exist. Much development work remains to be done. However, with proper precautions and careful interpretation of results the instrument can be accepted at the present time as a useful tool.

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