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Soil Structure Evaluation With Audiofrequency Vibrations[1]

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ABSTRACT

Young's moduli for soils measured with a vibrational technique varied with soil aggregate size, water content, texture, sensor-to-sample contact, and column handling. The magnitude of a Young's modulus varied from 10^7 dynes/cm^2 (147 psi) for nearly saturated columns to over 10^9 dynes/cm^2 for an air-dried, Na-saturated silt. The accuracy of the moduli measurements is in the order of 15% to 20%. The measured values compare favorably with others previously reported in the literature for undisturbed and reworked soil samples. The range of measured soil moduli, the repeatability of the measurements, the lack of restriction on sample size and the nondestructive nature of the technique indicate that this procedure may provide a useful measure for soil structure evaluation.

Additional Key Words for Indexing: **soil structure measurement, soil strength, soil elasticity.**

SOIL STRUCTURE is defined somewhat differently by various authors. Baver (1956, p. 123), states, "Soil structure is usually defined as the arrangement of the soil particles" (particles being either single or aggregates). Rose (1966, p. 109), recognizes some differences in the definition: "The concept of soil structure has been defined in various ways, in broadest terms as the arrangement of solid particles in the soil profile." In Agricultural Handbook 60, Richards (1954, p. 60), is found an emphasis of the aggregates which the soil particles form: "The arrangement of soil particles into crumbs or aggregates that are more or less water stable is an important aspect of soil structure." The Soil Survey Manual, Soil Survey Staff (1951, p. 225), also points out the presence of aggregates as a part of the definition of soil structure: "Soil structure refers to the aggregation of primary soil particles into compound particles, or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness." In Agricultural Handbook 316, Gill and Vanden Berg (1967, p. 304), it is recognized that factors other than geometric particle arrangement are important as far as describing soil structure is concerned: "The geometric arrangement of the solid material is generally called soil structure. Structure is an independent entity—the fortuitous arrangement of aggregates as influenced by total past history; therefore, structure will have to be measured or identified."

Soil structure is a characteristic that has eluded quantitative measurement. Perhaps this is because the concept associated with soil structure generally is more inclusive than just a geometric arrangement of particles. The concept includes kinds, shapes, and sizes of particles present, the manner in which particles are held together, the degree to which they are held together and, usually, the response of these groups of particles to some manipulation or probing of the soil. At some point this concept begins to overlap with another called soil strength as used in soil mechanics.

The term soil structure as hereafter used in this paper refers to the broadest concept given in the previous paragraph with the exclusion of soil response to major manipulation. The major factors considered while attempting to describe soil structure as just defined will be the nature of particle-to-particle contact and bonding, the degree of this bonding, and the effect that this bonding has on the transmission of small magnitude stresses through a mass of soil particles.

A common approach to the analysis of soil structure has been to consider as a model of the soil a system of uniform spherical particles. This emphasis on the particulate nature of soils has perhaps led to a model that is more complicated than necessary to adequately describe soil structure. The spherical particle model is complicated by different types of packing, different sized beads, and ultimately different shaped beads. This, even in its most complicated form, bears only a slight resemblance to a soil of highly irregular shaped and sized particles.

Considering the general problem of soil structure descriptions, one might ask—is it really the geometric arrangement of particles about which one should be concerned? If one could determine the response of a system of particles to an applied force, is it necessary to know the geometric arrangement of the components? If not, what must one know about the system of particles to provide the information about the soil's response to an external force?

An important shortcoming of the particular model is its failure to adequately consider the nature of the particle-to-particle contact within the soil. The particle-to-particle bonds or interactions will largely control the gross reaction of the collection of particles. Therefore, a model that would emphasize this bonding would be advantageous in describing soil structure.

First consider a simple particle-to-particle contact (Fig. 1*A*). In most cases of agricultural interest the particles will be held together by water at the point of contact. In addition, an organic or mineral cementing material may be present. As the amount of water between the particles changes, the forces holding the particles together would be expected to change and therefore the overall reaction of the particles to external forces would be expected to change. Any rigidity contributed by cementing materials or movement caused by slippage of particles past one another would also influence the reaction of the group of particles. This physical contact between these particles may be represented with a mechanical model of a spring and two dashpots in parallel (Fig. 1*B*). This type of model is that of a viscoelastic medium, one which exhibits both viscous and elastic properties. McMurdie (1963), and Waldron (1964) have shown that such a model does provide a

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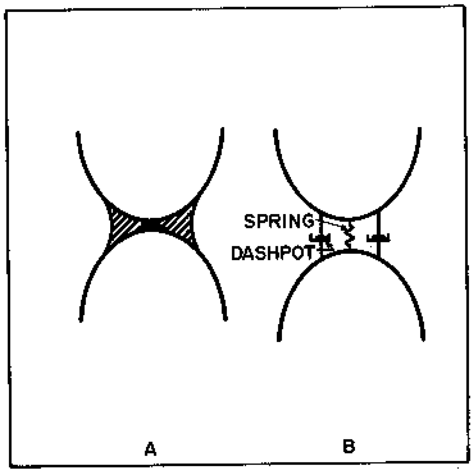

Fig. 1—Model representation of soil particle-to-particle contact.

satisfactory description of soil behavior in some creep tests. Kondner and Ho (1965a, 1965b) have used a viscoelastic model in stress relaxation tests on soil. This model for soil behavior appears even more desirable since descriptive parameters or "constants" for samples can be evaluated by nondestructive vibrational testing techniques which have been fully developed for viscoelastic or elastic material.

A vibrational test of a soil sample should provide a measure of particle-to-particle contact and bonding. In order for a pulse or one cycle of a vibrational wave to travel from one end of a sample to the other, the pulse must be transmitted from one particle to another via the contact between them. The amount of energy lost by a wave as it moves through a soil will be determined primarily by the losses that occur at each contact. The number of contacts and amount of cementation or bonding at each one will affect energy loss. The amount of energy loss that occurs at each junction will also depend upon wavelength. This can be reasoned by considering a system of uniform sized particles. If a vibration frequency is selected such that nodes (zero displacement) occur at every point of contact, less attenuation would be expected than for a different frequency that resulted in antinodes (maximum displacement) at points of contact. Each soil sample will have frequency transmission characteristics that will be determined by the sizes, arrangement, and type of contact of its component particles.

Each soil column, if it fits a viscoelastic or elastic model, will have a characteristic or resonant frequency which will be determined largely by those factors that are included in the concept of soil structure. From the resonant frequency for a soil column and its height and density, a Young's modulus for the soil can be calculated. By including a measure of the amount of attenuation (energy loss within the sample) at that resonant frequency, the elastic modulus can be converted to a viscoelastic or complex modulus. Either or both of these parameters for a particular soil condition should, therefore, provide an index for soil structure.

As early as 1936 Ishimoto and Iida (1936, 1937) used a vibrational technique to test a variety of soil materials. More recently, vibrational testing methods have been used on sand by Hall and Richart (1963), Hardin and Richart (1963) and on clay samples by Kondner (1961) and in direct field applications by Johnson (1965) and US Army Engineers (1963).

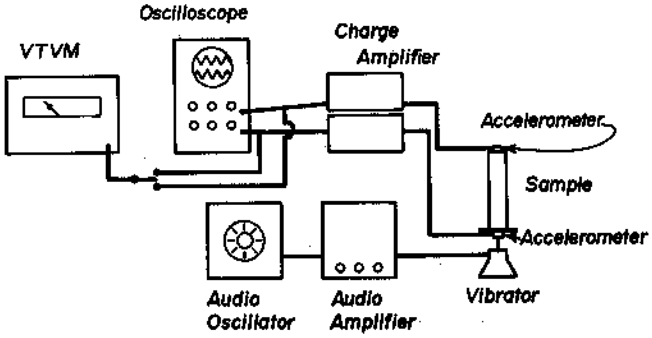

Fig. 2—Equipment and sample arrangement for elastic or viscoelastic modulus measurement.

The parameter most commonly measured with vibrational techniques is a "dynamic" modulus or a complex Young's modulus. A complex shear modulus can also be measured if shear waves rather than compressional ones are used. By using the equations of Ishimoto and Iida (1936) one can calculate a solid viscosity of a soil sample. A creep function, an attenuation constant and a mechanical impedance or a relaxation function as described by Eirich (1956) in his text on rheology are other parameters which can also be evaluated. Which, if any, of these parameters will provide the best description of the structure of an agricultural soil? This paper reports some laboratory vibrational measurements of complex Young's moduli and shear moduli of packed samples of various soils. Results obtained are used to evaluate the procedure for measuring soil structure.

PROCEDURE

The measurements reported in this paper are based upon the determination of a resonant frequency of a column with boundary conditions of a fixed bottom and a free top. Lee (1963) presented a complete theoretical development for this test procedure. Figure 2 is a schematic of the instruments and sample arrangement used for the measurements. Stevens (1966) has also used this procedure.

To obtain the resonant frequency of a sample, the column was placed on the supporting disk as diagrammed in Fig. 3. An accelerometer which was mounted on a circular metal plate was placed on top of the soil column. A circular sheet of sand paper was cemented to the bottom of the metal plate to promote contact with the soil. An electromagnetic vibrator (Ling Electronics Vibrator no. 201) was attached to the rod extending from the metal disk upon which the soil column is resting. (Trade name is for information only and does not indicate preference over other acceptable vibrators.) The bottom accelerometer was attached to this rod also. A 0.011-cm thick aluminum base plate upon which the soil column was mounted was clamped to the supporting disk. Ninety weight oil between the base plate and disk insured good acoustic contact. The output signals of the accelerometers at the bottom and top of the column were monitored on an oscillascope or with a vacuum tube volt meter (VTVM) as indicated in Fig. 2. Resonant frequency for the column was found by varying the output of the audio oscillator, Fig. 2, until the ratio of movement of the top of the column to that of its bottom was a maximum. In practice, the procedure used was to change the frequency of the audio oscillator in steps then vary the output

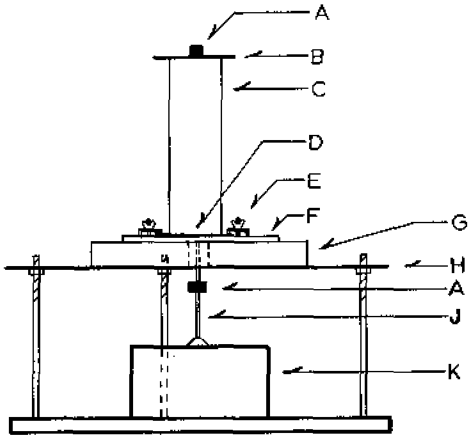

Fig. 3—Vibrational testing stand with soil column in place for resonant frequency measurement. Labels are: *A*—accelerometer; *B*—top contact plate; *C*—soil column; *D*—base plate; *E*—base plate clamp; *F*—support disk; *G*—support sponge; *H*—support platform; *J*—connecting rod; *K*—vibrator.

of the audio amplifier until a standard acceleration value (0.02 *g*) was obtained for the bottom of the column. The magnitude of the acceleration of the top of the column was then recorded. Near resonance the audio oscillator was tuned back and forth across the resonant frequency in order to obtain that frequency as precisely as possible.

In order to obtain measurements utilizing shear waves instead of compressional waves, a support apparatus slightly different from that in Fig. 3 was used. The metal disk that supported the soil column was held from beneath by a rod and bearing which allowed the disk to spin freely. Vibrations were imposed upon this disk by a rod inserted horizontally into its side and connected to a horizontally mounted electromagnetic vibrator. The amplitude of torsional vibrations was measured by accelerometers mounted a fixed distance from the central axis of the soil column. The accelerometers were mounted on the top metal contact plate and on the supporting disk and were positioned so to sense the torsional not compressional vibrations.

The quantities recorded for each sample measurement were (i) column height, (ii) column weight, (iii) column diameter, (iv) frequency of maximum amplitude ratio and (v) amplitude of acceleration of both bottom and top of the column. The amplitude ratio is defined as the ratio of the amplitude of movement of the top of the column to the amplitude of movement of its base when the column is vibrated sinusoidally under the boundary conditions of fixed bottom and free top.

The equation used to calculate the magnitude of the complex modulus for a soil sample as presented by Stevens (1966) is:

$$E^* = 16f^2L^2\,\rho\left(1 + \tan^2\left(\frac{x}{2}\right)\right)$$

$$\tan\frac{x}{2} = \frac{2}{\pi R_{\max}}$$

where E^* is the magnitude of the complex modulus, f is the frequency at maximum amplitude ratio or resonant frequency, L is column height and ρ is wet density of the column, $R_{\max}$ is the value of the maximum amplitude ratio, and x is called a loss angle. It is the angle by which strain lags stress during the vibrations at resonant frequency. The $\tan(x)$ is the ratio of the imaginary part (E'') to the real (E') part of the complex modulus when it is expressed as a complex number $E' + iE''$. The $\tan(x)$ is a measure of energy dissipation in the column.

Measured values of $R_{\max}$ ranged from 4 to about 30. The quantity $\tan^2(x/2)$ was less than 0.05 for all samples used. E^* could therefore be approximated by $E = 16f^2L^2\rho$, the elastic modulus, to within 5% or better for the measurements reported in this paper. The accuracy to which each of the terms in the equation for the complex modulus can be measured (with the exception of x) is 3% to 5%. If x is ignored, this provides a value for E^* with a possible accuracy of 15% to 20%. The range of resonant frequencies found for the soil columns was from 50 *Hz* to about 300 *Hz* for compressional vibrations and from 30 *Hz* to 200 *Hz* for torsional vibrations.

Six different soil materials were made into columns 6.1 cm in diameter and 15 to 30 cm high. The fine-textured samples were screened through a 0.5-mm screen. Sands were screened of organic matter larger than the sand particle size. Columns of the soils were formed in Saran Wrap lined split cylinders. After removal of the split cylinders each completed sample was, therefore, a soil column wrapped with Saran to maintain its shape. The Saran was presumed to have no influence on the soils or measurements. (Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the US Department of Agriculture.)

The frequency of maximum amplitude ratio was determined for the dry columns. Each was then wetted from the bottom to near saturation. The columns were permitted to dry slowly as water evaporated from the ends. Periodic vibrational measurements provided an elastic modulus for each sample at several different average water contents. These moduli were plotted as a function of average water content for each soil.

Shear modulus values were obtained by providing a torsional vibration at the bottom of the sample columns rather than compressional vibrations which were used for Young's modulus determination. Resonant frequency for torsional vibration was always lower than that for compressional resonant frequency and was unstable, particularly for wet columns.

To provide a measure of the repeatability possible with the technique, four replicate columns were made of Portneuf silt loam aggregates: (i) passing a 0.5-mm screen, (ii) passing a 2-mm screen but not a 1-mm screen, and (iii) a 1:1 mixture of (i) and (ii) by weight. The elastic modulus of each air-dry column was determined. Two columns of each set were then wetted and periodic measurements of elastic moduli attempted as the columns dried.

RESULTS AND DISCUSSION

Even at the low strength of the dry Portneuf aggregate columns, measureable differences in moduli were present. Attempts to measure the moduli as the columns were wetted and redried failed because, except for the less than 0.5-mm aggregates, the columns were too fragile to provide useable measurements without using excessive, time-consuming caution. There is a measureable difference among the dry replicate columns that elastic moduli indicate but bulk densities do not as shown in Fig. 4. Significant differences are present at the 5% level between the averages of the elastic moduli of the different aggregate combinations. Note that the elastic moduli order the columns differently and separate individual columns more than do bulk densities. The different order indicates that the finer aggregates tended to form a more rigid column than the mixed aggregates even though the mix had a higher bulk density.

Data shown in Fig. 5 illustrate the measured elastic moduli of seven different soil samples. The consolidated clay sample data in Fig. 5*B* are for a natural core of a silty clay subsoil (dry bulk density 1.55 to 1.60) taken from Ishimoto and Iida (1936) and presented here for com-

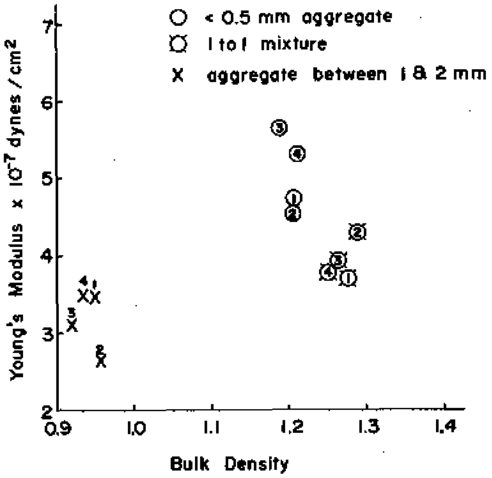

Fig. 4—Elastic modulus and bulk density of replicate air-dry Portneuf silt loam aggregate columns.

parison with those of the author. Their values probably approach the maximum moduli measured on unconfined uncemented soil material. A basic trend which has already been pointed out by Ishimoto and Iida (1936, 1937) and Stevens (1966) is evident. The elastic modulus of a soil increases as the soil dries, except for coarse sand the modulus of which does not change appreciably throughout the water content range.

The elastic modulus changes over a much wider range in some soils than in others. The differences among the sodium-saturated silt, the consolidated silty clay, and the clay columns in Fig. 5*B* illustrate this. Some other characteristics of each soil are evident from the curves shown. Near saturation the Na-saturated silt slakes and, therefore, has a very small modulus value. The laboratory-formed clay column on the other hand retains a larger modulus near saturation. As the soils dry, the Na-saturated silt and the consolidated silty clay column rapidly harden, as indicated by the slope of the lines connecting data points. The Na-silt column did not crack as it dried. The laboratory-formed clay column hardened less rapidly as it dried and horizontal cracks formed in spite of the long drying time (several weeks). The change in slope of the line at about 25% water for clay data points may indicate when the cracks became continuous enough to influence measurement.

The presence of horizontal (with column standing on one end) cracks in a column will have a major effect on measured values. In Fig. 5*A* are data from one of the Portneuf aggregate columns which was found to be in three separate pieces when examined. The first few data points from this column tend to parallel those of the other silt loam. After what was apparently the development of the major horizontal cracks, the modulus values by their irregularity reflected only the presence of cracks—not properties of soil.

Young's moduli were more consistent and varied over a wider range than did shear moduli. The shear moduli in Fig. 6 do show a difference between soil samples, however. It would seem that shear moduli might provide a good

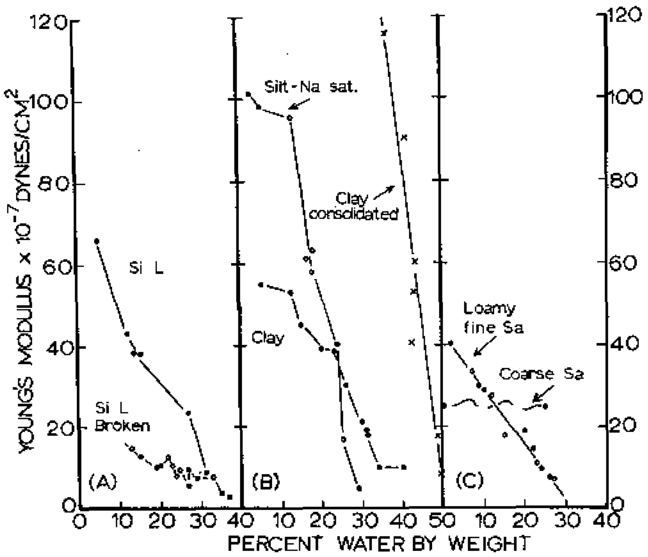

Fig. 5—Young's modulus vs. water content for soil columns. In section *A* (Si L) data were for a silt loam subsoil and the (Si L Broken) column was made from ½ mm Portneuf silt-loam aggregates. In section *B* the clay was from the B horizon of a soil collected in Idaho. (Silt-Na sat.) was a Na saturated silt from Nevada. In section *C* (Coarse Sa) was a washed (1 mm) sand and the loamy fine Sa was from Idaho. Data for undisturbed cores of a consolidated clay subsoil collected by Ishimoto and Iida (1936) were included (in section *B*) to provide a comparison with the reported measurements.

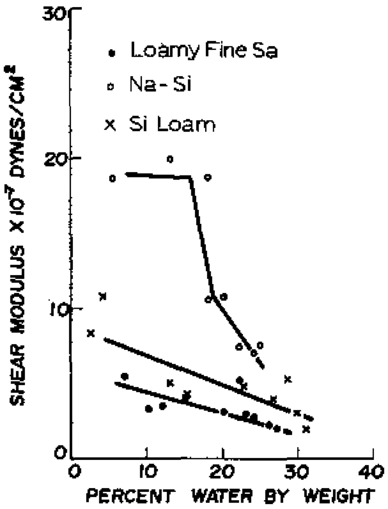

Fig. 6—Shear modulus vs. water content for disturbed soil columns.

numerical index for a soil's water stability. As a soil becomes saturated, if it slakes, it should lose much of its shear strength. Insufficient measurements were taken on near-saturated columns to test this idea.

It would seem as though the angle x or $\tan(x)$ of the complex modulus equation or the values of R_{max} should also provide a numerical separation of soils based upon the energy losses that occur within them during vibrational measurements. As shown in Table 1, however, values of R_{max} and x did not change consistently as the columns dried. It is suspected that the value of R_{max} was depend-

Table 1—Resonant frequency and loss angle for two laboratory packed soil columns

% water (dry wt. basis)	Resonant frequency (f) (Hz)	Amplitude ratio (R_{max})	Loss angle (x) (degrees)
	Silt loam		
31	71	14	5.2
29	121	9	8.1
16	160	13	5.6
12	175	13	5.6
7	222	23	3.2
	Loamy fine sand		
23	68	7	10.4
19	84	10	7.3
14	98	17	4.3
12	114	5	14.5
7	148	13	5.6
5	162	10	7.3

ent upon the nature of contact between the top accelerometer plate and the soil column. This contact was not repeatable for every measurement. As the soil columns dried the shape of the column top changed slightly and adhesion between the plate and soil column decreased considerably. If uniform or repeatable sensor contact could be established one should be able to use values of x or $\tan(x)$ to characterize energy loss within soil columns.

Aside from being an index for soil structure or stability, elastic moduli can be used to calculate other soil properties. If one analyzes soil cracking in terms of the rupture of an elastic medium by utilizing Griffith's (1920) cracking theory, the range of values of the elastic modulus of a soil provides part of the numerical information needed to calculate cracking parameters. Attempts to use elastic theory or some modification of it to describe soil behavior have been limited primarily to engineering applications such as Rostron (1967), US Army Engineers (1967), Johnson (1965), Ishimoto and Iida (1936), Hardin and Richart (1963), and Hall and Richart (1963).

Elastic theory must be restricted to conditions of small strain in any medium to which it is applied. For this reason it has been used successfully in engineering practice only where it is applied to highly compacted soils. In order to study mechanical behavior of soil in more detail and to determine the changes in structure and other properties that occur as force is applied to a compressible soil, more flexible theories of material behavior such as the viscoelasticity theory used or described by Eirich (1956), Kondner and Ho (1965a, 1965b), and Waldron (1964) will have to be used. If one is only interested in characterizing soil structure as a static property of a soil (in comparison to a soil mechanics characterization that is intended to describe a soil's response to a force), it appears that a simple elastic modulus for the soil will provide a useable index.

Throughout this paper the term modulus was used in preference to elastic "constant." The purpose of this deliberate omission of the word constant was to avoid the misconception that soil structure can be characterized by a single "constant" number. The structural properties of a soil change as any of a large number of factors change. The range of modulus values exhibited by a soil in various conditions and the manner in which the modulus changes with each controlling factor are therefore needed to characterize its structure.

CONCLUSIONS

Vibrational evaluation of soil structure has several advantages over previously used methods. Measured elastic moduli have a wide range of values (10^7 to over 10^9 dynes/cm^2 with a possible accuracy of 15%) which appear to be dependent upon those factors considered to determine soil structure-particle or aggregate size, bulk density, water content, and the presence or absence of cementing or stabilizing materials. Moduli for different textured soils change differently as water content of the samples decreases. Measured moduli compare favorably with those reported by other authors for undisturbed or compacted samples. Elastic moduli can be used to calculate other soil properties. There is relatively little restriction on sample size with this technique. Any cylindrical sample from 5 to 10 cm in diameter with height greater than diameter can be used. The same sample can be measured repeatedly at different water contents. This eliminates the need for large numbers of samples in any study of the change in structure or strength with water content. Undisturbed cores can be used as readily as disturbed columns.

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