Sediment Transportation Research

By HANS ALBERT EINSTEIN

SOIL erosion and sedimentation are two of the most powerful tools that nature has used in shaping this earth. Whole mountain ranges have been removed, new territories have been built by this instrument during geologic times and are still being built today. Both air and water act as carriers and both will. in time, step up their action enormously. It is usually during dust storms and floods that nature reaches deep into our daily lives and makes us conscious of the power involved. These are the times of catastrophe, when the engineer is powerless against the forces of nature. When these catastrophies occur frequently and especially when they cause loss of lives and property, the problem is generally recognized and placed in the hands of the engineer for study and counteraction. Only limited success has been achieved in many cases because our knowledge of the fundamental action, *i.e.*, the movement of sediment by fluid motion, is still very limited. For this reason, the engineer is still forced to rely upon his intuition rather than upon a sound theory.

TRANSPORTATION BY AIR

When air is the carrier, we are able to observe the movement in action. We can watch the wind pick up particles on an unprotected soil and lift them up to a considerable height. We can see whole clouds of particles being moved great distances without ever being allowed to touch the ground. These particles are held in suspension by the turbulence of the air. The turbulence appears as an irregular boiling movement superimposed on the main flow and constantly keeps the air-particle mixture well mixed. We can observe, then, how particles are settled out in places where the wind velocity is reduced and we can especially see a very efficient sorting of the moving particles, depositing coarse sand in one place, fine sand in another, while the still finer particles move as dust for great distances until they finally are deposited in some quiet spot. The wind will carry these fine particles for miles and miles in a short time, while the coarse sand is moved only a short distance. Wherever sand accumulates it begins to move slowly, creeping along the ground. If the depth of the loose sand increases, the characteristic ripples and waves are formed which will grow to the size of dunes if sufficient sand is available. (See *Fig. 1*). Dunes will slowly migrate in the direction of the wind, burying everything they encounter.

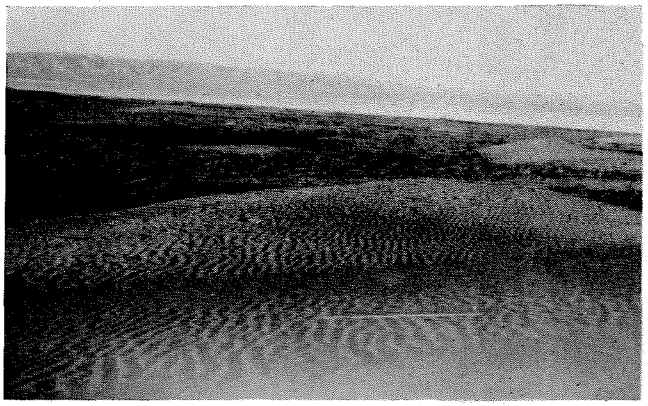

FIG. 1. Sand dunes showing characteristic ripples.

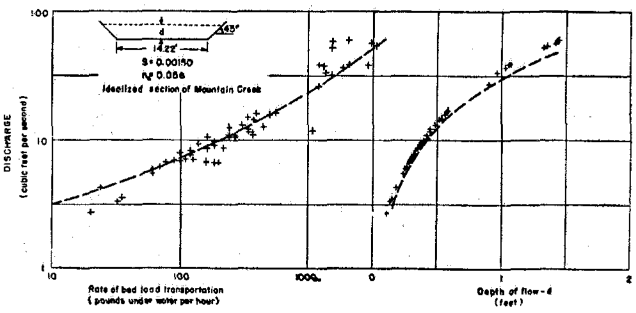

FIG. 2. Measured bed-load transportation and water depth in Mountain Creek compared with theoretical values. Crosses indicate measurements; the curves indicate theoretical values.

Entrainment of particles by moving air is very common; it can be observed in all its phases in one's own backyard as well as on the desert. Still, very little systematic knowledge is available about it. Quantitative studies of any kind that would allow the prediction of sand movement are especially rare. The obvious reason for the lack of systematic information is the difficulty of measuring and recording the steadily changing moving force of the wind.

TRANSPORTATION BY WATER

The movement of water, on the other hand, is restricted to certain channels. It is much more regular and predictable, and, in general, better known. It is, therefore, understandable that the movement of solid particles entrained by water is more thoroughly investigated than in the case of air. The following remarks will be restricted to water entrainment and transportation, but it may be understood that many of the principles involved hold for air as well.

Practical sediment problems in a river can be studied with any hope of success only if the entire watershed is considered. The term, watershed, as used here includes all the area and the streams in this area that will contribute runoff to a given river section. The term, sediment, includes all solid particles that come in contact with a moving fluid and are heavier than the volume of fluid they displace. Sediment settles in the fluid, in our case, water, and the settling velocity of a given particle in still water is one of its most important characteristics. The settling velocity depends on the size, shape, and specific gravity of the particle, and to some extent on the temperature of the water. By far the greatest range of variability is found in the grain size. In the following discussion sediment may be described either by its grain size or its settling velocity, with the fine sediment having low settling velocity and the coarse sediment high velocity.

BASIC FACTS OF TRANSPORTATION

One of the main assumptions usually made in studying sedimentation problems is the independence of the moving grains; that is, the presence or movement of one grain will not directly affect the movement of another grain. This fact makes sediment movement accessible to treatment by statistical methods. It may not be assumed, however, that the presence of sediment in water will not affect the flow. To find the effect of the total sediment load on the flow as a whole is one of the main problems. Let us consider the watershed above a given observation point or section on a river. According to the assumption

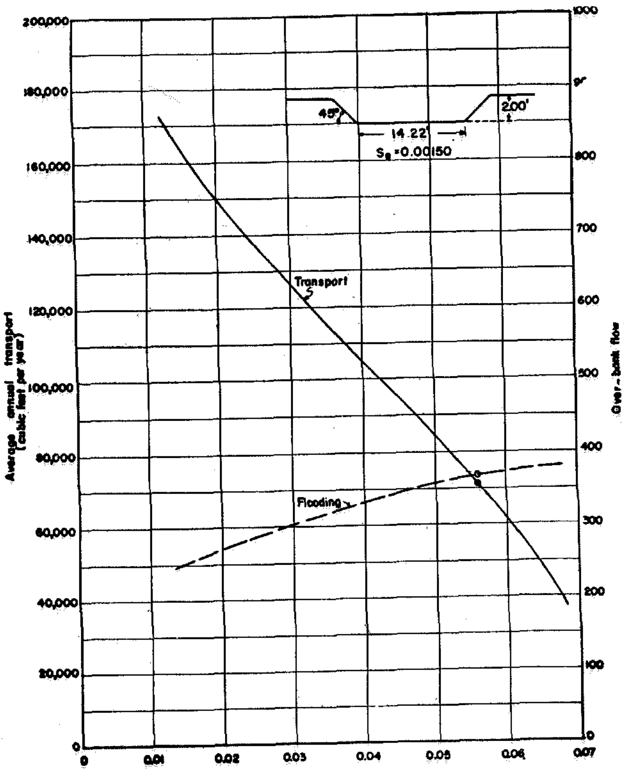

FIG. 3. Average annual transport of bed load in Mountain Creek for various roughnesses of the banks.

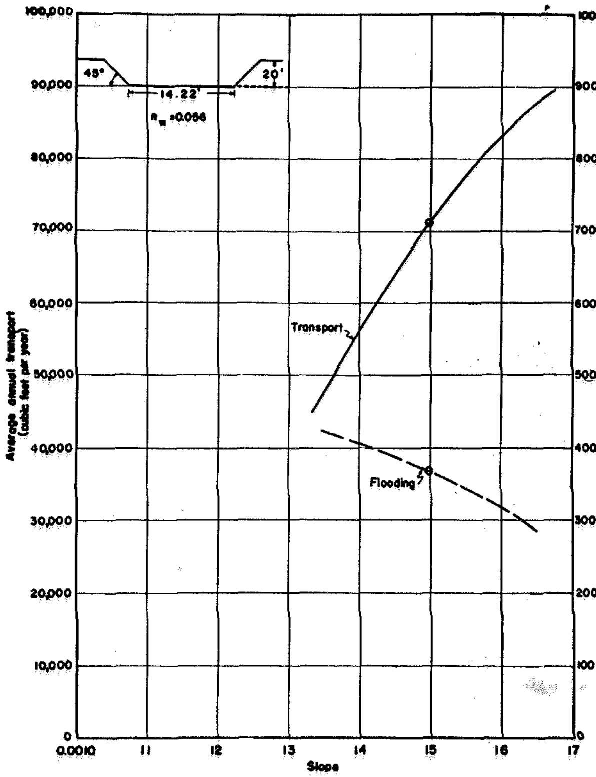

FIG. 4. Average annual transport of bed load in Mountain Creek for various slopes.

of independent motion, the movement of the different grain sizes can be studied independently, once the influence of total load on the flow is known. (This influence is usually of the order of a correction.) The finest grains, that is, clay and fine silt, will never be settled out in the river system because the flow velocities are everywhere sufficient to keep them in suspension. The particles are picked up by the water somewhere in the watershed, *e.g.*, on the stream banks, and, once in movement, they will move with about the average water velocity until they pass the observation point. The rate at which the finest particles arrive at the section depends only upon the rate with which they are eroded in the watershed. Erosion again is influenced in a certain watershed by many factors, such as distribution and intensities of rain, dampness of the ground, vegetal cover, temperature, and size of rain drops. The rate of erosion, and with it this fine load, can definitely not be expected to be a direct function of the discharge in our cross section. All attempts to find this relationship for different rivers have failed. Only a general tendency is found for concentration to be higher with higher discharges, especially in large watersheds. The total amount of these fine particles in a river, which is "washed" straight through the system without being temporarily deposited in the river channels, has been called the wash load. (1)* A certain regularity is found often in the pattern followed by the sediment load as the flood goes through its different stages. Where such a pattern exists, it is possible to apply the unit graph method (2), which can be used to good advantage for the interpolation of the concentration between measurements especially in smaller sized watersheds.

These remarks about wash load make it clear that the rate of wash load in a stretch of a river cannot be influenced by any structural protective and training work in the river itself. However, it can also be seen that erosion control measures in the watershed have an immediate and full effect on this part of the load. For the same reasons the wash load has no effect whatsoever on the stream bed. A change of the rate with which this material is moving down the stream system will not give rise to a change in either cross section or profile of the stream. Its presence only becomes significant when the flow of the water is retarded sufficiently to allow deposition as in reservoirs and on flood plains or when the water is used for domestic and irrigation purposes. It is also clear now that the rates of investments and total amounts of this material that are moved in a certain river system can only be determined by a continuous sampling program which may be aided by certain short-cuts as the above-mentioned unit graph method.

The coarse particles within the stream load behave entirely differently. Their motion is slow and intermittent, and they usually take years for the same travel from their origin in the watershed down to the reference section, which the wash load covers during a single flood. Instead of being in suspension, these particles move essentially along the bottom. They do not move continuously, but are settled out on the bed for longer or shorter periods.

In reaches where the stream has less transporting power, these particles are deposited in great numbers and cover the whole bed. There the stream flows over a bed consisting of its own sediment only, and it becomes what is usually called a graded stream. The sediment particles which are moved over this bed are continuously exchanged for particles in the bed, and there is no distinction between the moving particles and the bed. They are equivalent in every respect and the movement of these particles can be interpreted as the movement of bed material. This type of sediment movement is of the greatest importance to the river engineers because there exists a definite relationship between the flow of the stream and its transporting capacity, and the stream bed

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*See Bibliography, Page 17.

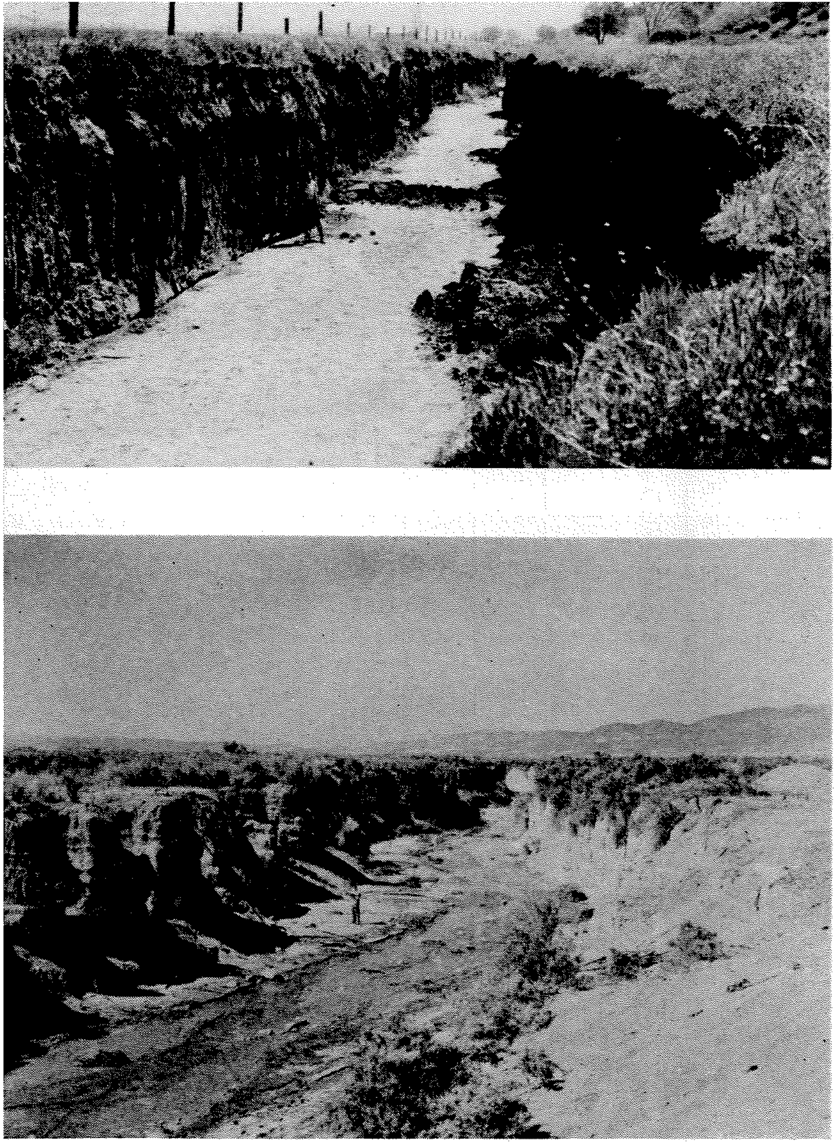

FIG. 5. Views of canyons formed by rapidly eroding streams.

can only be stable if the rate at which sediment is supplied from upstream equals this transporting capacity. Any difference between the capacity and the incoming rate has to be taken care of by scour or deposition on the bed.

These basic facts have very important consequences in the natural river. Below a graded stretch of a river the rate of bed material movement is a function of the discharge. Short term deviations of the incoming sediment load from the load that the stream can carry are fully counteracted by temporary deposition or scour on the bed, without permanent change to the latter and its flow characteristics. Systematic deviations in one direction, however, will gradually change the hydraulic characteristics of the stretch by modification of the cross section or the profile and will, gradually, adapt the carrying capacity of the stretch to the average incoming load. The carrying capacity of an undisturbed graded stretch of a river will, therefore, allow a rather close estimate of the average sediment production in the watershed above for coarse material.

THE TRANSPORTATION LAW

During the last century, a theory has been proposed by Dubois which interpreted the movement of bed material as a laminar motion of the bed. The resulting tractive force formula for transportation of bed material had two constants which varied with the bed material and flow conditions and which had to be determined empirically in each case. The extreme variability of these constants made the formula almost worthless and gave rise to the development of new formulas based on different principles in recent years. A very attractive approach has been tried by Shields (3), who based the development of his formula on the principles of dimensional analysis only. Unfortunately, this method in itself is not sufficient because the problem contains too many variables for the number of equations available. A recent method described by the author (4) which bases the rate of movement not only on the average flow but also on the turbulent fluctuations, seems to have more chance of success. At least it eliminates all "variable constants" and reduces a multitude of conditions into a well-defined single curve.

But no matter which equation is used, the relationship between the flow and transportation exists and can be determined. This has been done for a great range of conditions during past years. The next step is the application of the equation of transportation to the natural river. Systematic studies were made by the Soil Conservation Service on this problem during recent years by simultaneously measuring transportation and flow conditions in rivers and by subsequent analysis of the data under application of the above mentioned transportation laws. Good agreement has been found between the measured and the calculated values for transportation and water depth in terms of discharge as shown in *Fig. 2* for Mountain Creek. This good agreement over a considerable range of conditions proves both the transportation law and the method of application to be correct (5).

APPLICATION

Fig. 2 shows distinctly that the movement of bed material is a function of discharge and that the sequence of discharges is unimportant. The annual transportation through a cross section of the river can, therefore, be calculated, based on the duration curve of the flow. The duration curve itself has the great advantage of being very similar for different streams and it can be derived rather accurately for any stream from records of similar streams. Based on such a duration curve, the annual total transport and the duration of overbank flow has been calculated and plotted in *Figs. 3 and 4* for varying bank roughness and varying average slope respectively in the case of the above mentioned Mountain Creek. The curves of *Fig. 2* are plotted for the actual section where the roughness of the banks is $m_w = 0.056$, the slope $s = 0.00150$, moving a total bed load of 71,000 cubic feet per year. By comparison of *Figs. 3 and 4* it can be seen directly how the stable slope will change if the average annual load changes. For example, a load increase from 71,000 to 90,000 cubic feet per year would increase the slope from 0.0015 to 0.00168. *Fig. 3* shows that this increase can be avoided, for example, by smoothing out the banks. If the small brush surface with a roughness factor $n_w = 0.056$ is smoothed by a growth of grass with $n_w = 0.047$, the increased load can be moved without any change of slope.

Many other graphs of this kind could be shown for the same section describing the influence of some other factors on the transporting capacity which enable the engineer to predict the behavior of a bed-load carrying stream section. Today the analytical method of determining the carrying capacity of streams which underlies these graphs has been proved applicable to small streams and large ones with coarse bed material. The proof by

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or vane, which is immersed in the fluid tested; hence the vibrations of the reed are transmitted to the vane. The reed and vane assembly is supported within the cell by ribbon or torsion type bearings located just below the reed member of the assembly. The free or upper end of the reed carries a magnetic coil over a permanent magnet, thus inducing a current which is registered on the indicator dial and which varies with the amplitude of *the period of vibration of the reed. With this* arrangement it is apparent that increasing resistance to vibration in the vane will increase the amplitude of vibration in the reed (assuming constant voltage and frequency of the exciter current) and thus generate more current from the magnetic field, which is registered by the indicator. Resistance to vibration in the vane is provided by the inertia resulting from the density of the fluid in which the vane is immersed. Theoretically, and apparently in practice, viscosity of the fluid is a negligible factor because the period of vibration of the vane is too small to exert any appreciable shear.

THE FUTURE OF MUD ENGINEERING

Development of other instruments like the gravimeter has been held up for the duration, but their usefulness has manifold possibilities in the future. Mud preparation and its chemical control are comparatively new and offer a fertile field for future improvement. Not only are varied fluids needed for specific applications but new treatments may be found. A great deal of fundamental work is necessary, as demonstrated by the comparatively little known about the common clays and the mechanics of treatments of their water suspensions.

As time goes on, and as drilling goes deeper past the present record, which is 600 feet short of three miles, mud treatment and control will be more and more helpful. Drilling must continue at an accelerated pace, for although more fields are found, they are smaller in reserves. Thus since the targets are smaller the firing must be greater and more accurate.

The Engineer and Postwar Planning

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neutrality legislation and we were determined not to be provoked into war, but the isolationists would not foresee that the decision was not ultimately in our control. Actually even they were unwilling to accept the conditions Japan and Germany would have imposed upon us. They should have abandoned their isolationism after Pearl Harbor—and many did. Yet it appears that there are still enough of them left to make both major political parties afraid to take an unequivocal stand in favor of joint force to oppose aggression. The pattern of thought on postwar planning is not now significantly different from that following World War I. It does not appear, therefore, that the present war will be the last.

Reluctant though one may be to accept the implication of such action, it seems wise in our postwar planning to recognize that seriously destructive wars occur about once per generation and that as time goes on they become more extensive and more destructive. The action in starting now to prepare for World War III seems realistic and sensible. The disheartening effect of planning in the midst of one war for the one to follow in about 30 years is somewhat relieved by the knowledge that most postwar planning is for peace.

The engineer is amused by some of the imaginative predictions that some advertisers are making. He knows that extravagant claims cannot be fulfilled, that unfair advantage is being taken of the fact that non-technical people have recently heard more than usual about the usefulness of science. But the engineer knows also that the war has given tremendous acceleration to many developments such as jet and rocket propulsion, the combustion gas turbine, welding processes, electrical communication, electronic heating, X-ray inspection, plastics, and to almost every other scientific process and product.

Although winning the war is still the primary purpose of engineers, they know that the first day of peace will see most of them return to projects abandoned a few years ago and to planning new peacetime projects not believed necessary or economical before the war. Their efforts will be demanded by civilians almost as urgently as they are now needed by war and it will be difficult to explain to potential buyers why their postponed wants cannot be fulfilled immediately. Conversion of war production was remarkably rapid and complete but, very fortunately and in spite of the misguided isolationists, it started long before we were actually at war. Because it started so early many people do not realize how long the process of conversion actually required nor do they realize that the conversion was planned years before it was started.

Reconversion to peacetime production probably will not proceed as rapidly as did conversion to war goods production since reconversion will not be of such vital importance to survival and its costs will have to be borne to a larger extent by private capital. Because it will proceed more slowly, it should start earlier. The indefiniteness of V-Day makes it difficult to know just when reconversion should start but it is probable that those who have not already at least started to plan reconversion will find postwar competition extremely hard to meet.

The importance of starting reconversion as early as possible is attested by the recent agreement of the War Production Board, the War and Navy Departments, and of the War Manpower Commission to permit the manufacture of civilian goods hitherto prohibited or restricted in the plants of companies which have labor and machinery not needed in the war effort.

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field measurements is still missing for large streams with fine bed material.

Often conditions are too complicated for analytical treatment. Irregular shaped cross sections or profiles, confluence of streams or temporary deposition of bed material are some of the complicating factors. In these cases the direct analytical method may be supported by model studies which can give quantitative results for transportation problems if they are based on the rules given by the laws of transportation (6). Model studies of such sediment problems have been performed using either sediment of the same or of different specific gravity in model and prototype.

The analytic determination of the transporting power of different stream sections gives the engineer a tool to predict the future development of streams with a movable bed. *Figs. 5a and 5b* show the canyons into which two small streams developed when their transporting power exceeded the available sediment supply. Thousands of acres of the most valuable valley lands are made unusable for agricultural purposes by similar developments. Hundreds of thousands of dollars are spent every year to prevent and repair damages to our communication systems due to channel cutting. But just as much or more damage is caused by streams flowing in channels with insufficient transporting capacity. When the transporting capacity is insufficient the stream channels fill up, flooding adjacent land which may include roads and residential sections. Accompanying this flooding will be a deposit of sediment. In their economical importance the direct sediment damages are often surpassed by the indirect damage. If a stream is cutting as shown in *Fig. 5*, all tributaries and side ditches will cut, too. The whole water table under the remaining areas will be lowered and the soil dried out. Channel filling will bring a raised water table and in humid regions extensive swamp conditions can be expected, with all their consequences.

The analytical method of calculating a bed-load carrying stream is being developed by the Soil Conservation Service for its own needs in finding appropriate means and methods for the stabilization of such streams. The same method can be used to study any bed-load carrying stream from the standpoint of flood control and channel stabilization. It is to be hoped that after this war the scientific treatment of such problems will find a greater development, based on the work that has been done and that is still being done within the research organization of the Soil Conservation Service.

(1) *"A Distinction Between Bed-Load and Suspended Load in Natural Streams,"* by H. A. Einstein, A. G. Anderson, and J. W. Johnson. Transactions, American Geophysical Union, 1940, paragraph II, p. 628.

(2) *"Distribution Graphs of Suspended Matter Concentration,"* by Joe W. Johnson. Proceedings, American Soc. Civ. Eng. Vol. 68, No. 10, October, 1942.

(3) *"Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung,"* by A. Shields, Mitt. der Preussischen Versuchsanstalt fur Wasserban und Schiffbau, Berlin, 1936.

(4) *"Formulas for the Transportation of Bed-Load,"* by H. A. Einstein, Trans. Amer. Soc. Civ. Eng. Vol. 107, 1942, pp. 561-573.

(5) *"Bed-Load Transportation in Mountain Creek,"* by H. A. Einstein, unpublished report of the Soil Conservation Service, Greenville, S.C. November, 1942.

(6) *"Conformity Between Model and Prototype,"* A symposium. Discussion by H. A. Einstein, Proc. Am. Soc. Civ. Eng. Vol. 69, No. 4, pp. 531-535, April, 1943.

ALUMNI NEWS

ANNUAL JUNE BANQUET

In normal times, Commencement Day in June is the date set for the annual Alumni Banquet. The Class of 1944 which, in peacetime, would have graduated in June, received their degrees in February and have now scattered to all parts of the world. However, the alumni selected the traditional month for their annual reunion, and on June 22, 170 alumni assembled in Pasadena.

In the absence of the commencement exercises, the alumni were conducted on a tour through the new wind tunnel now under construction in Pasadena. The group then gathered at the Meteorologist Mess Hall on the campus (the Athenaeum facilities were not available due to shortage of help) for the banquet. Late reservations exceeded the capacity of the hall, and 21 alumni found it necessary to hold their banquet at the campus coffee shop.

The election of officers resulted as follows:

President	Harry K. Farrar '27
Vice-President	Earle Burt '15
Secretary	Victor V. Veysey '36
Treasurer	Karl Hegardt '32

Members of the Board: Joe Lewis, '41; J. Stanley Johnson, '33; and Frank Weigand, '27. Board Members to continue in office are Grice Axtman and Donald S. Clark. Grice Axtman and Joe Lewis have joined the Military Service and Frank Weigand has resigned, making new appointments necessary. Paul Hammond, Wendell Miller and Charles Varney are to fill these offices. Ernst Maag, ex-president, will be retained, according to the revised by-laws, to attend board meetings in an advisory capacity.

Mr. Maag, as retiring president, presided at the dinner, and introduced Mr. Farrar, the new president. Mr. Farrar called on representatives from the reunion classes for short talks. Virgil Morse, '24, told of his search for the Soil Conservation Laboratory, which was mentioned in the directions to the mess hall. Upon inquiring the location of the laboratory from someone on the campus, he was directed to the Mudd Building.

News of members of the reunion classes which was given at the banquet may be found listed among the Personals.

At the close of the banquet, the men adjourned to a lecture room in Arms Building to hear Lawrence G. Fenner, '30, and Mark Serrurier, '26, discuss informally some of the interesting problems of the wind-tunnel project.

SAN FRANCISCO CHAPTER

Due to wartime conditions and transportation difficulties the usual bi-monthly meetings were temporarily discontinued during the past year. However, a few alumni have been regular attendants at the Monday noon luncheons at the Fraternity Club at the Palace Hotel in San Francisco.

A preliminary poll indicated that a good attendance of Tech men and their wives could be expected for the fifth annual Sports Day and picnic at Howard Vesper's home at "Cactus Rock" in Oakland. In spite of gasoline rationing an attendance of 33 alumni and their wives enjoyed a very pleasant afternoon on Sunday, May 28.

Absence of the younger set was noticeable in that very little enthusiasm could be stirred up for the usual softball game between the "old" grads and the "young" grads. Lack of a suitable playing field was a contributing factor but it was evident that most alumni were more interested in Howard's well-equipped play room where several lively games of ping pong and pin ball were held.

This served to whet the appetites of those present and everyone enjoyed the picnic supper served in the patio. News of other alumni was passed along and a community "sing" was held in front of the outdoor fireplace. The following alumni were present:

Kenneth B. Anderson	'24	Hilmer E. Larson	'27
Lawrence W. Baldwin	'35	Donald F. Morrell	'24
Marshall A. Baldwin	'27	D. S. Nichols	'28
Robert B. Bowman	'26	D. J. Pompeo	'26
Edward Dorresten	'24	Lee W. Ralston	'27
Howard Fisher	'27	Ted Vermeulen	'36
Dave G. Harries, Jr.	'23	Howard G. Vesper	'22
Alex J. Hazzard	'30	Gordon K. Woods	'42
Maurice T. Jones	'26		

A short business meeting was held, during which Howard Fisher, the outgoing president, gave the report of the nominating committee. The following officers were elected for the coming year:

Alex J. Hazzard, '30	President
Marshall A. Baldwin, '27	Vice-President
Maurice T. Jones, '26	Secretary-Treasurer

Some colored slides of last year's swimming party at Bob Bowman's pool were shown. Bob announced that the next swimming party would be held on September 3, and invited all alumni and their ladies to be his guests on that day. Bob has constructed a lovely swimming