FIG. 1. Concrete channel in orange grove near Pasadena. The channel had adequate capacity to carry the water flow but it could not carry the extremely heavy sediment flow.

SEDIMENT TRANSPORTATION RESEARCH

at California Institute of Technology

By VITO A. VANONI

WHEN the Soil Conservation Service (SCS) was established in 1935 as a bureau of the United States Department of Agriculture, the need for research in soil erosion control was recognized and projects were established to study the basic problems involved. Among the projects established was the one at the California Institute of Technology, which was assigned to the study of the basic hydraulics and mechanics of soil conservation problems. One of the most important research problems undertaken by the project was the study of sediment transportation. The data and results reported below were obtained in this study.

CONSERVATION OF FARM LAND

The SCS is concerned primarily with conserving moisture and controlling erosion on agricultural lands. In general, these objectives are accomplished by (1) encouraging the rainfall to percolate into the soil so as to be available for crop use, and (2) controlling the part of the rain that cannot be absorbed in such a manner that a minimum amount of valuable soil is carried away by the flow. It is easy to see that these two objectives are compatible since the more water is stored in the soil, the less is the flow available to transport soil from the land. Much of the effort of the Soil Conservation Service has gone into finding practical methods of attaining these objectives so that the soil can be protected while, at the same time, yielding a return to the farmer that will enable him to operate profitably. This has been done by modifying tillage practices, installing systems of flood channels, and, in some cases, by actually planting different crops or even by discontinuing farming, on critical pieces of land. The widely used practice of farming on the contour or across the slope instead of up and down the slope has its main value in encouraging infiltration by providing small depressions which can store rainfall, thus giving the water more time to percolate into the soil. The practice of terracing merely provides a drainage system by which the runoff can be discharged from the land without causing serious erosion. Terraces are shallow ditches placed on a relatively flat grade which carry the runoff flow to a terrace outlet channel which conducts the flow down the slope and finally into a stream. Drainage networks, including terraces or other channels as well as the main rivers, involve handling of sediment-laden waters. The control of systems of this kind is as much a problem of sediment transportation as it is one of handling water. As a matter of fact, the handling of clear water alone can be accomplished without difficulty by established methods, but the problem of passing the sediment load is still unsolved. *Fig. 1* illustrates the failure of a concrete storm channel in an orange grove near Pasadena. The channel was adequate to handle the water runoff, but it could not discharge the extremely heavy sediment load and, therefore, was filled with sediment. The storm waters then flooded the orange grove depositing coarse material that must be removed if permanent damage to the trees is to be avoided. Damage due to sedimentation as illustrated in the figure is less spectacular than erosion damage but it can be very destructive. Very often the sediment that is deposited where it is not wanted has been removed from where it is needed and damage is done to both the giver and the receiver.

Fig. 2 shows a large gully in southern California and illustrates another type of erosion that must be combated. In this particular case if the gully is allowed to continue uncontrolled, it will ultimately widen and deepen further and destroy valuable land. In order to determine the best type of control measure to apply, it is necessary to be able to predict just how the gully would react to various treatments. The objective of sediment transportation studies is to obtain knowledge that can be applied to this type of control problem. When it is possible to determine in advance how a particular stream will act, *e.g.*, whether it will deepen, widen, or fill up under given conditions of treatment, then it will be a relatively simple matter to determine the best course of treatment to follow. Sedimentation damage, as illustrated in *Fig. 1* and damage due to stream bank erosion occur with practically every major storm. Much of it can probably be avoided by the development and use of more effective and more reliable stream control methods. It is expected that new basic knowledge of sediment transportation will contribute materially to these developments.

SUSPENDED LOADS

Sediment transportation has been studied experimentally by many investigators. However, practically all of this work has dealt with the so-called bed load or the coarse material which is transported near the bed of the stream and very little work has been devoted to the so-called suspended load that is carried in suspension in the body of the flow. For this reason the early studies at the SCS Laboratory were devoted to the problems of suspended load and the material reported here will concern itself with this phase of transportation. Actually there is no sharp boundary line between bed and suspended load and the two types of transportation are closely related. In general, they occur simultaneously, although during low flows when little material is being transported, the material in suspension may be extremely small.

Material is held in suspension in a flow by turbulence. The turbulence or eddy motion is associated with velocity of the water, for when a sample is taken from a muddy stream, the turbulence soon dies out and the sediment finally settles leaving clear water. Since turbulence is so important to the problem, it seems appropriate to discuss it further.

TURBULENCE

Turbulence is the term applied to the irregular motion of a fluid normally observed in flows of water and other fluids. This motion is caused by a confused mass of eddies of different size that whirl with no particular pattern or system and move about in the flow. When the flow velocity is extremely low, the turbulence will be absent and the water particles will move along smooth, regular paths. Flows of this kind, which are known as laminar or streamline flows, occur so rarely in practice that they are of little interest and importance. *Fig. 3* shows the spread of globules which have been injected into a turbulent flow by the small tube shown at the left. The globules have the same specific gravity as the water so they indicate precisely the motion of the water particles. It can be seen from the figure that the motion is rather irregular and that as the globules proceed down stream, they tend to spread. In this particular case, the flow is from left to right in a flume 10 inches deep and 10 inches wide and the average velocity is 1.2 feet per second. The same kind of picture taken at a lower velocity would not be appreciably different. When the flow velocity is decreased, the cross components of velocity caused by the turbulence which spreads the globules become smaller, but the globules also move forward at a smaller velocity so that the resulting pattern does not change in appearance.

Figs. 4a and 4b show a mixture of fine sand and water being injected into flows having average velocities of 0.5 and 1.2 feet per second, respectively. It will be seen that the turbulence tends to spread the sand as it did the globules. However, in the flow with the lower velocity the entire jet of sand is settling, indicating that this particular flow cannot support material of this size. The sand in this experiement had an average diameter of 0.10 *mm* and individual grains had a settling velocity in still water of about 0.8 *cm* per second. In *Fig. 4b* where the velocity was increased, the jet of sand became practically horizontal, indicating that the flow at the higher velocity could transport material of this size, or, in other words, that the turbulence was of sufficient intensity to keep the sand in suspension. By increasing the size of the sand injected into the stream of *Fig. 4b* which is flowing at a velocity of 1.25 feet per second, the jet could again be made to settle to the bottom as in *Fig. 4a*, because the turbulence would not be sufficiently intense to counteract the greater settling velocity of the coarser sediment.

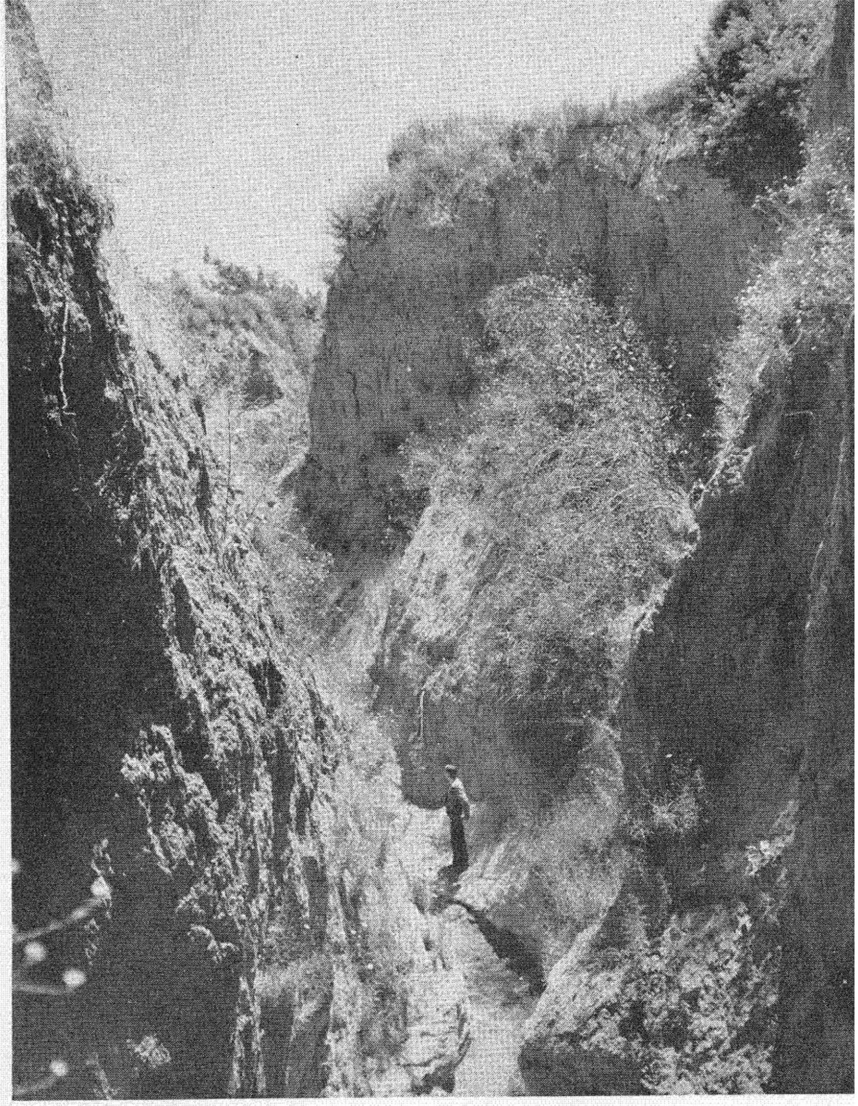
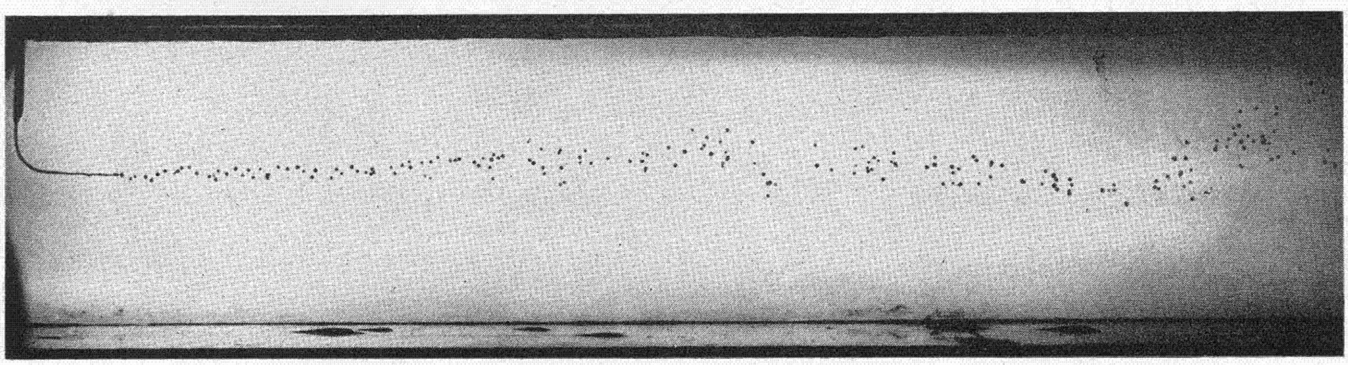
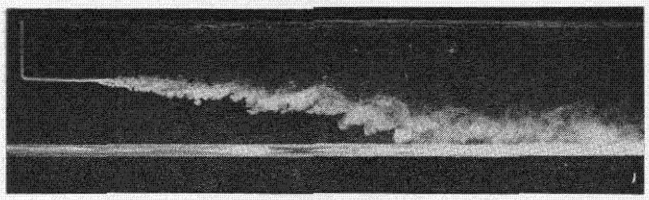


FIG. 2. A large gully in southern California.

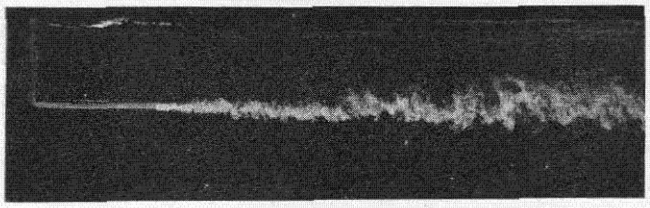
Turbulence originates at the bottom and sides of a channel due to friction and spreads into the body of the flow. As a whirling eddy in a turbulent flow moves away from a point, other eddies move in to take its place so that there is actually no resultant flow due to this action,

FIG. 3. Globules in turbulent flow showing the erratic paths followed by water particles.





(a) Vel. 0.50 feet per second.



(b) Vel. 1.25 feet per second.

FIG. 4. Jets of 0.10 mm. sand in turbulent flow.

but merely an exchange between adjacent positions. In spreading, the turbulence actually transports fluid from the walls into the stream by means of interchanging fluid between adjacent levels. Any substance that is in the fluid masses thus moved will also be moved. It is in this manner, for instance, that the sand in *Fig. 4* was spread and kept in suspension. One important action of the turbulence is to transmit the friction from the walls of the channel to all filaments of the flow. Friction retards the water near the walls. Then when this retarded water is moved to a zone of higher velocity by the turbulence, it will be accelerated to the velocity of its new location and because of the acceleration it will exert a retarding force. By this process the friction force is finally transmitted from the walls and the bed to all parts of the cross section and a velocity profile is established, with the lowest velocity near the walls and the highest velocity in the interior.

SEDIMENT DISTRIBUTION RELATIONS

The rate of upward movement of sediment by the turbulence is given by $-\varepsilon \frac{dC}{dy}$ where ε is an exchange coefficient and C is the concentration of sediment at the distance y, from the channel bottom. The rate of settling of material under the action of gravity, is given by wC, where w is the settling velocity of the sediment in still water. By equating these two quantities, we obtain the differential equation for distribution of sediment over the depth which is

$$wC + \varepsilon \frac{dC}{dy} = 0 \qquad (1)$$

This equation can be solved for channels where the width is great compared to the depth by introducing an equation for ε in terms of y which is obtained from velocity distribution equations. On this basis the solution becomes

$$\frac{C}{C_a} = \left[\frac{d-y}{y} \times \frac{a}{d-a}\right]^z \qquad (2)$$

where C_a is the sediment concentration at a reference level a distance a from the bottom and d is the depth of the flow. The exponent is given by

$$z = \frac{w}{k\sqrt{gdS}} \qquad (3)$$

where g is the acceleration of gravity, S is the slope of the channel and k is a constant having a value of about 0.4. It is to be noted that equation (2) gives the concentration as a fraction of the concentration at some reference level and does not give an absolute value. No theoretical expression has been developed for the absolute concentration. The exponent z is a ratio which, in a way, expresses the relative coarseness of a sediment in relation to the ability of the stream to transport it. It is seen that the larger is w, that is, the coarser is the sediment, the larger is z. On the other hand, for a given velocity, z can be decreased by increasing either the slope S, or the depth, or both. This merely means, that when the sediment with the settling velocity, w, is placed in a steeper channel with a deeper flow, it will be carried much easier and will appear finer to the larger and faster flowing stream.

EXPERIMENTAL CHECKS

To check equation (2), experiments were made in a flume 33 inches wide and 60 feet long in which the depth and velocity of the flow could be varied independently.

FIG. 5. View of SCS Laboratory showing flume used in sediment transportation experiments.

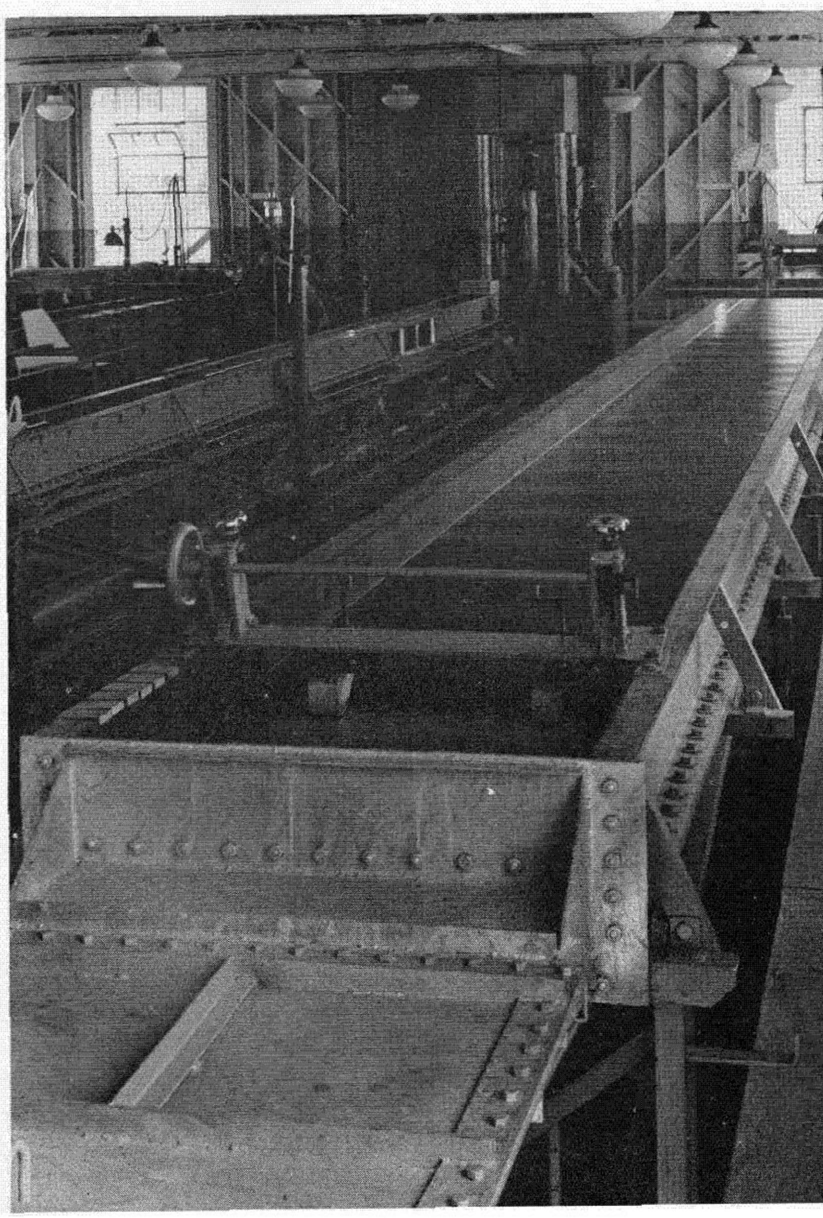


Fig. 5 is a general view of this flume from the inlet end. The water discharging from the end of the flume is pumped back to the inlet end along with the sediment so that the water is in motion all the time, and the sediment is thus prevented from settling in the system. The distribution of sediment over the depth and cross section was determined from samples siphoned from the flume. The head on the siphon is adjusted until the velocity into the sampling tube in the flume is the same as the stream velocity at the sampling point. In this manner a filament of the flow is removed without disturbance and a good sample of the suspended material is obtained.

Fig. 6 shows two typical sediment distribution curves obtained from measurements in the center of the flume. The relative sediment concentration is plotted on the horizontal scale against the elevation of the sampling point as a fraction of the distance between the reference level and the water surface. The solid lines have been fitted to the experimental points by selecting a value of the exponent, z, in the theoretical sediment distribution equation that gives the best fit. It will be noted that these curves fit the experimental points very well. In general, it was found that the exponent z, that gave the best fit of the data, did not agree with those calculated according to equation (3). The curves at the right of *Fig. 6* are for 0.10 *mm* sand, the solid curve being the one that fits the data and the dotted curve, the one given by theory as expressed by equation (2) with the exponent according to equation (3). It is seen that the theoretical curve deviates an appreciable amount from the experimental curve. The solid curve at the left of the figure fits data obtained from measurements with 0.16 *mm* sand. For this particular size of material the theoretical and experimental curves are identical and were found to be so in all experiments. It is the opinion of the writer that this agreement is a coincidence and that it is not to be taken as an indication of the complete validity of the theory. The fact that the theory fits the data as it does is truly remarkable and there is no reason why good use should not be made of it even in its present state. Deviations between the theory and experiment are thought to be due to errors introduced by the assumption that the exchange coefficient ε obtained from the velocity distribution equations can be applied to sediment distribution. It will be noted from *Fig. 6* that the distribution of the finer material is much more uniform than for the coarser material. It will also be noted that the smaller the value of z the more uniform is the distribution of material in the stream.

In *Fig. 7*, the relative concentration $\frac{C}{C_a}$ has been plotted on a logarithmic scale against the quantity $z\text{Log } H$, where H is the quantity:

$$\frac{(d-y)a}{y(d-a)}$$

Data plotted in this manner for nine runs made with different size sediment and flow depths and velocities fall very closely to a straight line and indicate again that the experimental results can be represented by a curve which follows equation (2). The fact that the data fall

(Continued on Page 14)

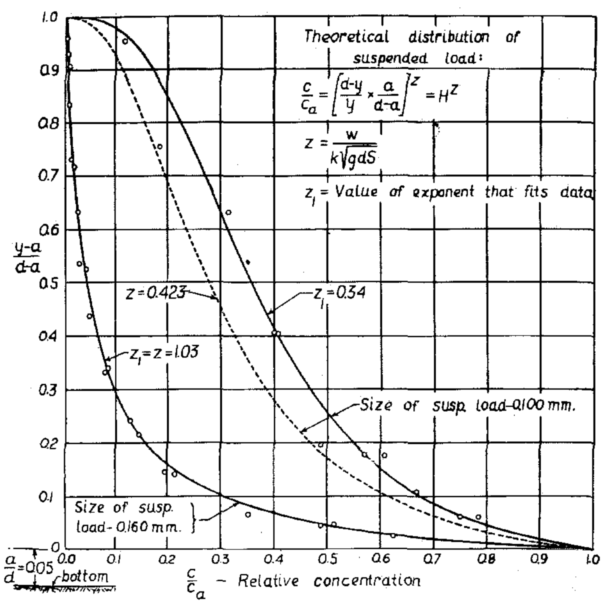


FIG. 6. Graph of experimental and theoretical sediment distribution at center of flume.

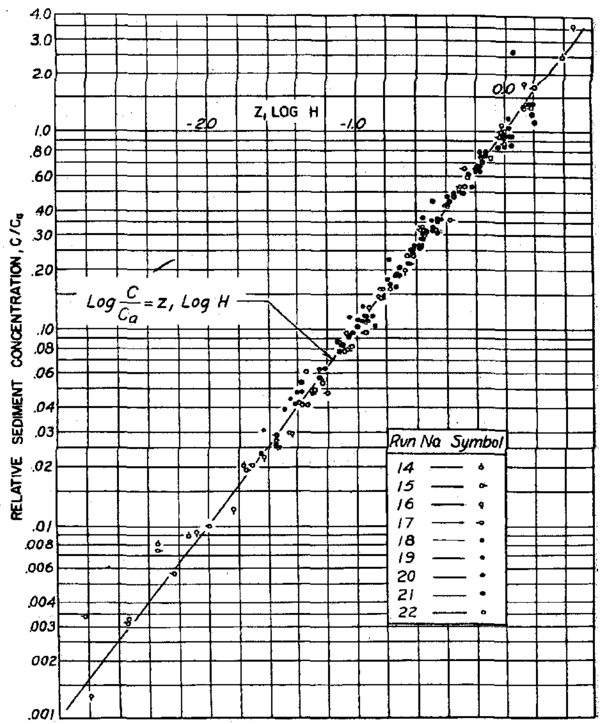


FIG. 7. Graph showing comparison of measured and calculated sediment distribution at center of flume.

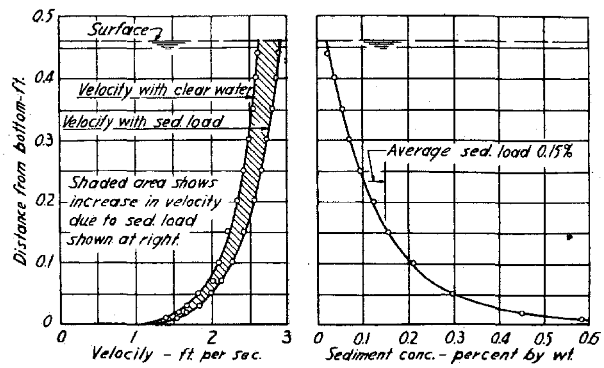


FIG. 8. Velocity and sediment distribution profiles at center of flume.

Perhaps the most interesting fact concerns their relationship to living bears. It is now apparent that the short-faced bears are not nearly related to the living bears of North America, but have closest kinship with the diminutive spectacle bear of South America. The latter animal is found in the Andes from Colombia south to Chile. It is not often seen in zoological gardens in North America, although several living animals are the property of the Zoological Society of San Diego *(Fig. 2)*. The spectacle bear takes its name from the color pattern on the face, more particularly the marking about the eyes *(Fig. 3)*. In contrast to the black bear, the spectacle bear is a smaller animal, standing about 22 inches tall at the shoulders and weighing less than 100 pounds. Thus, in the lineage of the *tremarctothere* it may be said that not only did the occupants of what was once a great estate give way to a smaller breed, but also their territory became much more restricted in area.

The history of the short-faced bears can be traced back still farther in geologic time. Some of the evidence of their more ancient existence is furnished by fossil teeth and jaw fragments that have been collected in the Mt. Eden formation, Riverside County. These strata accumulated during the Pliocene, or the epoch immediately preceding the Pleistocene. The earliest record of the group leads back into the Miocene epoch, for in the famous Barstow deposits of the Mojave Desert are found curious animals showing relationship to the *tremarctothere* and to the dogs. *Hemicyon*, or half dog, as this carnivore is appropriately called, is a connecting link suggesting the derivation of this group of bears from one branch of the great and diversified family of dogs during the middle of the Age of Mammals.

Hydraulics Laboratory

(Continued from Page 3)

a thorough understanding of the advantages and limitations of the Laboratory solution.

PRESENT ACTIVITIES

Because of the war, work on basic research projects has been reduced in order to concentrate on problems of more immediate assistance to the war effort. Wind erosion studies have been discontinued and density current and sediment transportation studies retarded.

During 1943, hydraulic model studies of six large spillways were made by the Laboratory. The first four studies were for existing structures which had proved unsatisfactory and unsafe in operation because their designs were based on faulty hydraulic assumptions. One of these structures is in Oklahoma, one in Louisiana, and two in Texas. By means of the model studies, simple and economical methods of reconstruction were developed for these Southern structures, which will provide them with adequate hydraulic design for the spillways and their stilling basins. Incidentally, the damage loss, plus the cost of reconstructing these four large structures, will exceed the cost of operating this Laboratory for several decades. The other two spillway studies were for structures to be located in Utah and California. In both of these cases the designs were submitted in advance of actual construction, thus giving the Laboratory an opportunity to make constructive suggestions.

During 1943, a standard design for baffle type energy dissipators for pipe outlets was developed as a sequel to the standardized drop structure design. The development of such standardized designs is an effective Laboratory activity because the results apply to innumerable structures instead of to one. Another recent development in this category is a flow meter for pipe line irrigation outlets.

An interesting new density current development arose through the Southern California Edison Company. The company observed that in the spring at their Shaver Lake reservoir the cold heavy snow water entering from the stream would flow underneath the warmer, light water of the lake without mixing with it. Valuable field measurements have already been secured and the investigation is being continued this spring.

The sediment transportation studies have been accelerated by the addition of H. A. Einstein to the staff. He has been studying this particular problem for several years at one of the Soil Conservation Service research stations in the East.

At the request of the Navy, this Laboratory and the Hydraulics Structures Laboratory are studying an important problem of the Los Angeles Harbor. Although this project consumes most of the energies of both staffs, the effort seems justified since it appears that the study is assisting the Navy in more satisfactory operation of this important base.

Sediment Transportation

(Continued from Page 7)

on a straight line must not be taken as evidence that the theory is in complete agreement with experiment since as mentioned previously, the exponent z was determined so that the curve would fit the experimental data.

Fig. 8 shows velocity profile curves on the center of the flume for two flows of the same depth, one with clear water and the other with a suspended load of 0.15 per cent by weight, distributed according to the curve at the right of the figure. The shaded area between the velocity curves represents the increase in velocity due to the presence of the sediment. It will be seen that this increase is almost 10 per cent. The effect of the sediment is to reduce the apparent friction resistance of the channel. This results from a modification of the turbulence by the suspended sediment. The turbulence must support the sediment against the action of gravity which causes it to settle. This requires energy which must be supplied by the turbulence thus reducing its intensity. Since the turbulence also transmits the resistance of the channel to the entire cross section of the flow, when its intensity is reduced it is less effective in transferring this resistance and a higher velocity is necessary to establish equilibrium conditions.

The action of sediment in increasing the velocity of flow was observed in all laboratory tests; however, the concentrations used in the laboratory were rather low so there is no evidence available on the variation of this effect with extremely high sediment loads. The action of sediment in reducing the intensity of turbulence indicates that the maximum load that a stream can carry is determined by some kind of equilibrium between the supporting power of the turbulence and the settling tendency of the sediment.

SUMMARY

The experimental work on the transportation of suspended sediment described briefly in this paper has shown that the theoretical relationships which were based on analysis of turbulent flow give approximate results for the distribution of sediment. They have also clarified the inter-action of the sediment and the turbulence and suggested the mechanism by which the maximum load that a stream can carry is determined. Further experimental work and research on the subject is needed and promises to yield results that are necessary to enable engineers to handle sediment-laden flows.