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Some Aspects of Reservoir Sedimentation

by

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THE development of the water resources in many countries of the world has reached the point where in many streams the low water flow has been utilized, and extensive development in the future must depend to a large extent on water stored in reservoirs. This stage of development was reached in the United States some years ago, and a large number of storage reservoirs have been built to extend the water supplies. In all of these reservoirs there has been an accumulation of sediment which was brought down with the inflowing water. Considerable loss of storage capacity has in several cases resulted from these deposits as well as from deposits occurring upstream from the reservoirs, where they were not expected to occur when the reservoirs were planned. The extent of the damage from these deposits is sure to increase, and in time it will become much more serious.

In most reservoirs of the United States, deposition has only started and the later stages of filling have been reached in only a few. However, sufficient records have been obtained to date to indicate that, although deposition in many reservoirs was probably unavoidable, by planning with a knowledge of what was coming, the loss of storage of some reservoirs may have been reduced. Therefore, the results of studies of sedimentation in reservoirs of the United States should be of considerable value to all countries who are planning water resources development projects.

The manner in which sediment deposits in a reservoir is complex and depends on a large number of factors, which are different in each case. To cover throughly only the principal factors and their actions would require a series of articles. It is not the purpose of this article, therefore, to discuss the whole subject of reservoir sedimentation, but only to describe briefly the manner in which sediment deposits occur in reservoirs and to direct attention to some actions which may not be anticipated but which may cause considerable trouble if not prepared for. Many of the items discussed in this article have already been emphasized by other engineers, but calling attention to them again will help to assure that the warnings of these engineers do not go unheeded.

DESCRIPTION OF THE RESERVOIR FILLING PROCESS

In many respects the deposits in a reservoir resemble those in a delta made by a stream where it discharges into a lake or other large body of water. Geologists have separated delta deposits into three parts: bottom-set beds, fore-set beds, and top-set beds ; and this classification can also be used to advantage in discussing reservoir deposits. Figure 1 represents a longitudinal cross-section through a reservoir formed by a dam in a stream, and shows the relative positions of these deposits. For simplicity it is assumed that the water level in this reservoir does not fluctuate.

The bottom-set beds are formed of the fine sediment brought in by the stream. The fine particles carried in the water settle slowly and may be moved a long distance into the reservoir, usually depositing over most of the reservoir bottom in thin layers. The fore-set beds are formed of the coarser sediment carried by the stream, which usually travels on or near the stream bottom. This material is deposited where the current is retarded as it flows out into the lake. These beds are inclined downward in the direction of flow. As more and more material is brought into

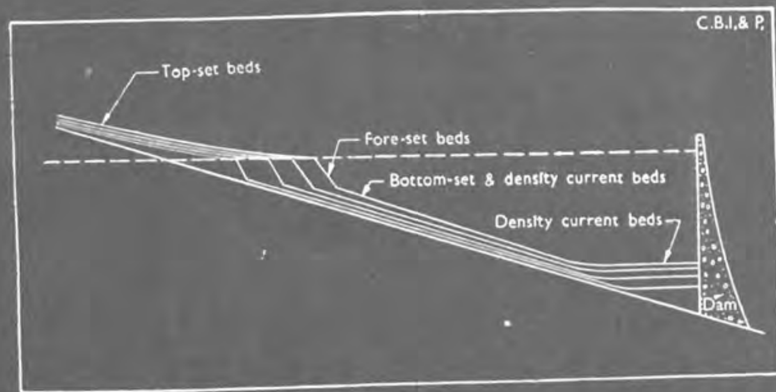

Figure 1: *Longitudinal cross-section through a reservoir showing various types of deposits.*

the reservoir, the point where the fore-set beds are being formed moves out farther and farther into the reservoir, covering the upstream end of the bottom-set beds previously deposited, as shown in Figure 1.

As the fore-set beds move out, the current in the river upstream from them is retarded because the length of the stream is increased—at the expense of the reservoir—and the slope is decreased. This causes a reduction in the velocity, and some of the coarser material travelling on or near the bottom is deposited on the bed of the stream. The deposition occurs not only above the fore-set beds previously laid down, but also on the stream bed farther upstream, which lies above the level of the water in the reservoir. These deposits form slightly sloping layers, and are called top-set beds.

There is also a fourth kind of deposit which is formed in some reservoirs by density currents. When water entering a reservoir carries large concentrations of very fine particles, the action of the water is like that of a dense fluid. When such a mixture reaches a reservoir of relatively clear water, because of its greater density it may flow along the bottom of the reservoir beneath the level water surface of the clear water above it, but without mixing with the clear water, until its flow is stopped by the dam. It then spreads out, filling up the lower part of the reservoir, and very gradually deposits sediment in nearly level beds as shown in Figure 1. It may also deposit a thin layer of sediment on the stream bed upstream from the level deposits, as it moves downstream over the bed.

A fifth type of deposit occurs in some reservoirs, which is due to wave action on the banks of the reservoir. In the following paragraphs these five types of deposits will be discussed in greater detail. They will first be considered as they occur in the earlier stages of the reservoir filling, and a discussion of their action in the later stages will follow.

THE FORMATION OF BOTTOM-SET BEDS

Bottom-set beds are formed of the finer particles carried by the stream, usually those of silt and clay sizes. This material is carried in suspension in the water and settles very slowly in the bottom. It, therefore is usually carried far out into the reservoir, and often settles over the entire bottom. When the water entering a reservoir carries a heavier concentration of sediment than the water already in the reservoir, but too light a concentration to form a density current, it tends to push the clearer water already in the basin down toward its lower end. The turbulence generated by the flow of the entering water, aided sometimes by wave action, keeps the small particles of sediment in suspension until they are carried out into the lake. The distance which the sediment is carried out before settling on the bottom depends on the rate and duration of the inflow of the muddy water, the magnitude of the turbulence developed, the size or settling rate of the particles, and at times on the chemicals present in the water.

The greater the rate and duration of the inflow, the greater will be the distance the sediment is carried. If the rate or duration of inflow is large considering the volume of the reservoir, the sediment will be carried a greater distance down the reservoir than if the rate or duration of inflow is small. In small reservoirs much of the muddy water is often carried down and discharged over or through the dam.

The greater the turbulence of the water the farther the sediment will be carried before being deposited. If the reservoir is shallow or the channel of the stream is small, a greater velocity of flow will result and greater turbulence will be produced than if the reservoir is deep and wide. Greater wind action will also result in the sediment being transported a greater distance. Wind action is relatively greater in shallow reservoirs.

The distance the suspended sediment is carried out into the lake will be smaller for coarse particles than for fine ones, because the coarse particles settle more rapidly and reach the bottom sooner than the fine ones. For this reason the bottom-set beds will tend to become finer with increasing distance from the upper end of the reservoir. Some of the particles are frequently so small and therefore settle so slowly that they do not reach the bed before they are carried out of the reservoir at its downstream end.

Chemicals in the water sometimes affect the settling of the sediment, as they may cause the separate sediment particles to collect together in groups which settle more rapidly than the individual particles.

As a result of the actions described in the previous paragraphs, the bottom-set beds in small reservoirs usually cover the entire bottom of the reservoir, but are thicker near the upstream end of the reservoir. They are also usually thicker in the deeper portions of the reservoir, because more of the sediment passes over these portions. In large reservoirs, the bottom-set beds in early stages cover only the bottom at the upstream end, but as the reservoir fills they deposit farther and farther downstream until they eventually reach the dam.

THE FORMATION OF FORE-SET BEDS

The fore-set beds are composed mainly of coarse material (sand and larger sizes) and are inclined downward in the direction of flow. The angle of inclination is generally greater with very coarse sediment than with moderately coarse sediment, but under favourable conditions with either it may reach the angle of repose of that material. Fore-set beds are usually more pronounced when formed of very coarse material, but with finer material such as sand, they are usually not so prominent and may be entirely absent.

THE FORMATION OF TOP-SET BEDS

Top-set beds are usually also largely composed of the coarser sediments (sand and larger sizes) and are usually sloped upstream at a low gradient from the edge of the fore-set beds, with a slightly increasing steepness upstream. They extend up the stream to the point where the effect of the water level in the lake on the water level in the stream is negligible, or, in other words, as far as the backwater curve extends upstream from the reservoir. Since this point is often at a level considerably above that of the water surface in the lake, and at some distance upstream from the lake, a dam may cause deposits over a large area upstream from the lake. As will be discussed later, this often leads to serious trouble.

As deposition progresses, the stream flowing across the top-set beds takes on some of the characteristics of a normal stream and tends to form flood plains with natural levees along the banks, on which vegetation grows. This flood plain is largely composed of fine material, while the deposits in the main channel are coarser. The growth of vegetation on the flood plain reduces the velocity of overbank flow and increases the deposit of sediment. The deposition in the top-set beds is the same as in any other delta formation and has all the characteristics of a delta formed in a natural body of water.

DENSITY CURRENT DEPOSITS

As with the other types of deposits in reservoirs, density-current deposits occur under a wide variety of conditions. Since density currents are not frequently observed, some discussion of them is desirable. Density currents have been defined as a gravity flow of a fluid through, under, or over another fluid of approximately equal density. The most common type of density current in reservoirs, from the standpoint of sediment deposits, is the underflow, where the sediment-laden water, because of its greater density, flows down the bottom of the reservoir. However, differences in temperature or dissolved solid content may also produce differences in density between the inflowing water and the water in the reservoir which may cause the inflowing water either to flow out on the surface of the lake, thus forming an overflow type of density current, or to flow along the bottom to a certain depth and then flow approximately horizontally at that depth, thus forming an interflow type of density current. In any one reservoir (for example, in Lake Mead), all three types of density currents may occur, and may be materially influenced by differences in density due to temperature and dissolved solids as well as sediment suspension.

Density currents of the underflow type are of most interest to the hydraulic engineer because of the possibility that they may be discharged through the dam and thus slow down the rate at which the reservoirs will be filled with sediment. Such currents in Lake Mead have transported sediment over a hundred miles, moving below the level surface of the reservoir. The conditions favourable to density currents of this type are (1) high sediment concentrations, (2) fine sediment, (3) steep stream slopes, and (4) large depths of flow, caused by large discharges or narrow channels.

The higher the sediment concentration the greater is the gravity force propelling the current, and the greater the probability of the water settling to the bottom and flowing the entire length of the reservoir. The finer the sediment, the easier it is kept in suspension and the greater the distance it will flow without deposit. The steeper the stream slope the greater the propelling force and the greater the velocity produced, with resultant increases in the proportion of the sediment transported without deposit. The greater the depth of flow, the greater the hydraulic radius of the flow and the higher the velocity.

Whether it is practicable to discharge density currents from a reservoir as a means of decreasing the rate of reservoir filling is a complex question depending on the four relationships above mentioned and, in addition, on the position of the outlets and the relative temperature and dissolved solid content of the inflowing and reservoir waters. Another factor to be considered is the damage which might result to downstream irrigation or domestic water installations from the dense flows of fine sediment which would be discharged.

There are indications in both Lake Mead and Elephant Butte Reservoir that in the early stages of reservoir filling, the density currents flowed in the channel of the original river, but as filling progressed the width of the channel increased since the flow could spread out farther. As the bottom formed by such currents is very level across the stream, the wider the channel the shallower is the flow. The shallow flow tends to produce lower velocities of flow and causes greater deposition of sediment ; consequently less sediment reaches the dam. Sufficient experience has not yet been accumulated to know how important a factor this action is, but the density currents in both Lake Mead and the Elephant Butte Reservoir have been less frequent in recent years than in former times ; however, no studies have been made to determine the cause of this change of frequency.

THE FORMATION OF WAVE ACTION DEPOSITS

In reservoirs where the banks are composed of earth, deposits are sometimes formed in the lake by wave action along the sides. Situations producing large effects from wave action are (1) where the wind blows a large proportion of the time and at high velocities, (2) where the lake formed by the dam is large, so that there is a long distance over which the wind may act to increase the wave height, (3) where the configuration of the reservoir is such that there are long, unobstructed stretches of water in the direction of the prevailing wind, (4) where the material of the banks of the reservoir is such that it can easily be displaced by the waves, (5) where the reservoir banks are steep, so that high banks are formed by the washing away of comparatively little material, and (6) where the level of the reservoir is relatively constant or at least remains at relatively fixed positions for considerable periods of time, so that the wave action is concentrated over a small area.

Ordinarily, beaches are formed around most reservoirs by wave action at all levels at which the water remains stationary for a considerable period. The formation of these beaches is the same as that of beaches adjacent to any other body of water ; the coarser material is deposited near the top and the finer material is deposited in deeper water offshore or is carried along by littoral currents. Under certain conditions density currents may be formed which carry the material stirred up by the waves down the relatively steep banks into the deeper portions of the reservoir.

Ordinarily, deposits caused by wave action are not important. They tend to reduce the capacity of the reservoir only where the material is moved from above the maximum water level down into the space between the maximum and minimum levels. These deposits are beneficial if they move the material from between the maximum and minimum range down into the basin below the minimum water level, or into what is called the "dead storage".

One reservoir in which wave erosion has been particularly severe is the Fort Peck Reservoir on the Upper Missouri River in Montana. Here the banks are steep, the reservoir is large, the unobstructed reach in the direction of the prevailing wind is large, and the reservoir has been held at a relatively constant level for a major portion of the time. Although the bank material is in erosion-resistant clay shale, banks of 40-foot height have been formed, and large quantities of material have been moved from above the maximum flow level down into the reservoir. Because of the great size of this reservoir, however, these deposits, although large, occupy a very minor fraction of its total capacity.

COMPLEXITY OF RESERVOIR SEDIMENTATION

The foregoing paragraphs have described in its simplest aspects the manner in which sediment is deposited in reservoirs in the initial stages of filling where the water level varies but little. In actual cases, a great many factors affect the process and modify the magnitude and position of the deposits. Among the most important of these is the fluctuating elevation of the water surface, which occurs in many reservoirs. The deltas tend to form at the level of the water surface in the lake. When this is at a low elevation they form far down in the reservoir, and when it is at a high level they form near the upper end. After a delta has formed at a high level and the water level in the reservoir is lowered, more or less of the material in the high level delta will be washed away and carried down to be deposited in the delta at the lower elevation.

Another factor influencing the deposition of sediment in a reservoir is the reservoir shape. Consider, for example, a reservoir formed by a dam below the junction of two streams. Suppose the storage space in both stream valleys is about the same, but one stream carries a heavy load of sediment and the other a light load. The valley of the stream carrying the heavy load will be completely filled before the other valley, and deposition will then progress from the end of the valley of the heavily laden stream down to the dam, leaving the valley of the lightly laden stream unfilled and in the form of a lake. The deposits below the junction of the two streams may be built up to the point that the water in this lake cannot be drawn out by lowering the water level at the dam ; therefore the water stored in the lake will not be available for use, thus greatly reducing the effectiveness of the reservoir. It will thus be seen that in a branching reservoir, unless all the branches fill at rates which will prevent the formation of such lakes, loss of storage may result. Each proposed branching reservoir should therefore be carefully studied to see what the results of the filling will be.

A number of other factors influence sediment deposits in reservoirs, but to discuss all of them would unduly increase the length of this article. Much literature can be found on this subject, which persons dealing with the related problems will find very advantageous to read. A list of some of the more important references is appended to this article.

LATER STAGES OF RESERVOIR FILLING

In studying the sedimentation of reservoirs during preliminary planning, as one factor in determining the economic justification of a hydraulic development, estimates of the time required to fill the reservoir are frequently made by dividing the volume of water which the reservoir will hold by the volume of sediment per year which the stream flowing into it will carry. This is a very crude approximation, however, for some of the entering sediment may pass through the reservoir without deposition, and before the reservoir is filled with sediment, much larger volume of sediment may be deposited than the volume of water which the reservoir will hold. In order to make reliable estimates of the rate of filling of a reservoir, it is necessary to consider both the proportion of the inflowing sediment which will flow through the reservoir without deposit, or the "trap efficiency" of the reservoir, and the volume of the deposits which will take place above the water level of the reservoir at the dam. In the following section of this paper, the filling action of a reservoir in its later stages will be described, which will throw light on both of these factors.

Since most dams throughout the world have been constructed in comparatively recent times, and as the sediment usually deposits at a very slow rate, most of the experience to date on sedimentation has been obtained from reservoirs which were in the early stages of filling. Except for small reservoirs, in only a few cases have the reservoirs been nearly filled, and very little study has been given as to how this stage in the filling process takes place. There is ample reason for believing that this aspect of the filling cycle is as complex as the initial phase, and is influenced by a similar number of factors. Although a much less complete knowledge of the later stage of filling is available, by studying available records of the few reservoirs in this stage it is believed that the principles involved may be developed and applied to other reservoirs. In this manner much of the lack of actual examples can be overcome and valuable predictions of future filling can be made. Such cases as have been observed show clearly that neglecting consideration of these later stages of reservoir filling at the time the projects are planned may sometimes lead to serious consequences.

It has previously been pointed out how, as the reservoir fills, the deposits of the bottom-set beds extend down toward the dam until they cover the entire bed of even a large reservoir. In a similar manner, as the filling progresses the fore-set beds move down toward the dam. This is well shown in Figures 2 and 3, which give the position of the bottom of the reservoir at a number of different times for Soyama and Koyadaira Reservoirs in Japan.([16]) Figure 2 shows that in the Soyama Reservoir the fore-set beds have moved about halfway to the dam. Since the volume of storage in the upstream half of the length of the reservoir is much less than in the downstream half, the downstream movement of the fore-set beds is likely to be considerably slower in the following years than in those covered by the record. This slower movement is shown for the Koyadaira Reservoir (Figure 3) in which the fore-set beds have reached practically to the dam.

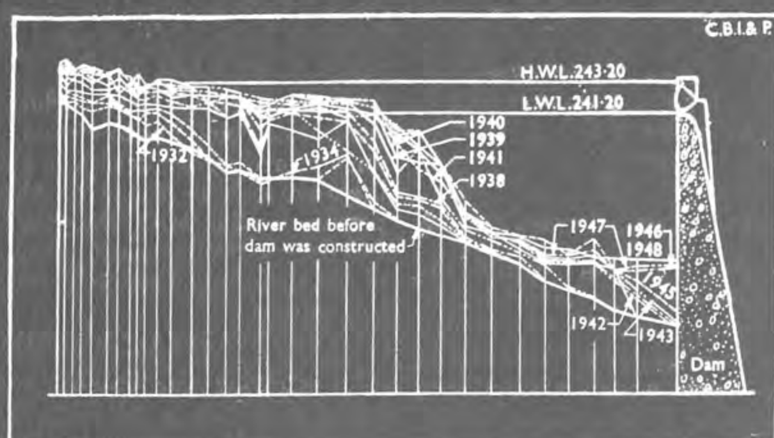

Figure 2 : *Sedimentation in Soyama Reservoir.*

([16]) The numbers are the number of references in the Bibliography attached to this paper.

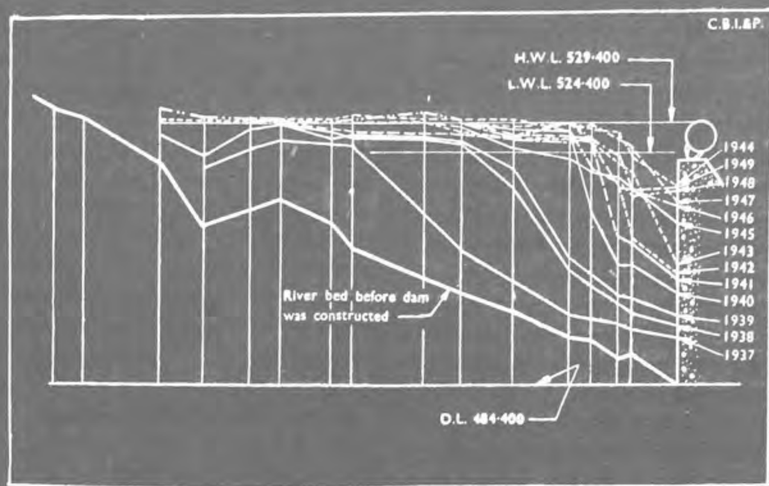

Figure 3 : *Sedimentation in Koyadaira Reservoir.*

As the storage space in the reservoir becomes smaller and smaller, the proportion of the fine material (silt and clay sizes) which escapes from the reservoir with the outflowing water increases and therefore the rate of sedimentation decreases. However, unless the reservoir is emp'ied periodically very little material of sand size or larger will pass out of the reservoir until it is practically filled with sediment.

As the fore-set beds move down toward the dam, the top-set beds become thicker and thicker and extend farther and farther upstream, as shown in Figures 2 and 3, and the deposits rise above the water level of the dam, thus giving to the reservoir a greater storage capacity for sediment than that available for the storage of water. The process may be explained as follows. For tne stream to carry the water across the sediment-filled reservoir from its upper end to the dam, the water surface at the upper end of the reservoir must be higher than at the dam. Since the sediment will deposit up to the level of the stream which carries it, the sediment at the upper end of the reservoir will also be higher than at the dam, and the ultimate sediment storage is likely to exceed the water-holding capacity of the reservoir.

Even after the reservoir is completely filled with sediment down to the dam, sediment storage will continue in the reservoir area although at a slower rate than before the filling was completed. This storage will continue until the slope of the steam across the deposited sediment is sufficiently steep to carry all of the sediment load without deposit, or in other words, until the river upstream from the dam has reached its regime slope. As long as the stream flows at a slope less than the regime slope, it will be unable to carry all of its load and will deposit sediment on its banks and bed. This action was explained in detail by E.G. Harris half a century ago,[6] but it has been largely lost sight of by hydraulic engineers.

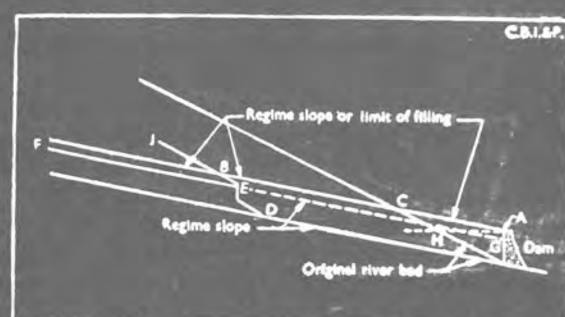

Figure 4 : *Showing deposits upstream from Reservoir.*

To determine the height to which a reservoir will fill with sediment above a dam, a profile may be drawn through the reservoir, as shown in Figure 4. In this figure, O represents the elevation of the river bed at the dam site before the dam is constructed, and A represents the level of the maximum water surface at the dam. A line AB, extending upstream from A at a grade equal to the regime slope of the stream, indicates the limit of the deposits which will ultimately take place.

If the gradient of the original river is steeper than the regime slope, as represented by the line OC, the deposit will continue until it extends upstream to the point C, which is at a considerable distance farther upstream and at a much higher elevation than the point H, which is at the same elevation as the crest of the dam and represents the upstream limit of the lake formed by the dam. It will be seen by comparing the area OAC with the area OAH that the limit of the volume of sediment deposit above a dam may be much larger than the water storage capacity.

A not uncommon case is where the river slope upstream from the dam is originally at the regime slope, as represented by the line OD. Since OD is parallel to and therefore does not intersect AB, the deposits will continue upstream as far as the regime slope extends. If at some point upstream from the regime slope section OD, the river slope steepens or a rapid or waterfall exists, as indicated by the line DEBJ, the deposits will extend up to the point B, where the regime slope line from the point A intersects the original bottom profile.

A frequently encountered case is a stream with a bottom profile represented by the line ODEF, where two sections of regime slope are separated by a steeper section consisting of a waterfall or rapids. If the maximum water level in the reservoir is at A, the river bed will eventually fill up the regime slope section EF as well as that from O to D. If this regime stretch EF extended upstream a long distance, or if it contains expecially valuable land or other improvements, it will be desirable to consider limiting the height of the storage at the dam to the elevation of G, which can be found by drawing line EG at the regime slope through the point E. With the level at this height, deposit would not occur upstream from E.

POSSIBLE CHANGES IN REGIME

Since the reservoir filling may take place over a very long period of time, it is desirable to look forward as far as possible to see if the regime of the river may change in the future. Such changes are going on in a number of rivers in the Western United States, and probably will be more common as the available water supplies are more thoroughly developed. In certain instances changes might be made intentionally, to obtain a desired end. For example, by flattening the regime slope it would be possible to build a higher dam at O and store more sediment, without extending the deposits above the point E. The regime slope could be flattened by one or a combination of several methods : (1) decreasing the sediment load of the stream by soil erosion control or by building another reservoir upstream which would hold part of the sediment, particularly the coarser part, (2) increasing the stream flow by bringing water from another watershed, or (3) flushing the stream with flows released from an upstream reservoir. A more probable outcome, however, is that the regime slope will steepen, and therefore only a lower dam could be built without extending the deposit beyond point E. This steeper regime slope can result from : (1) increased soil erosion, (2) use of water upstream for irrigation, particularly if the sediment from the irrigation water is returned to the stream, (3) diversion of water upstream into another watershed, or (4) making the stream flow more uniform by reservoirs for flood control or water power.

If a reservoir is formed in a valley where the stream is closely confined by the valley walls, and the width of the valley floor is considerably wider after the dam is filled with sediment, the regime slope of the stream may be somewhat steeper than the regime slope of the river in its narrow valley. This is because the river in its wider bed is free to spread out and flow with shallower depth, which would require a higher slope to carry the load. Also, in the wide valley the river might meander and thus increase the distance along the river per mile of valley. If the slope per mile of river length was the same as in its original condition, the slope per mile of valley would be greater than originally.

RAPID AND EXTENSIVE FILLING ABOVE IMPERIAL DAM ON THE COLORADO RIVER

The rising of the river bed level upstream from dams has been observed in many rivers throughout the world, but in most intances these grade changes are proceeding so slowly that the undesirable effects will occur far in the future. In every case, however, the action should be thoroughly studied, for under certain circumstances the rise may be of remarkable rapidity. The Imperial Dam on the Colorado River is such an example. Storage behind this dam was started in 1938 and within 7 years it had caused deposition for a distance over 55 miles upstream, whereas the level pool above the dam originally extended only about 15 miles. The gradient of the sediment deposited had already reached about three-fourths of that of the previous river slope which was probably close to the regime gradient. Even these extensive deposits were not as great as they would have been if the flow of the river had not been equalized by a dam upstream. The rise of the deposits would also have reached a much higher elevation and extended much farther upstream had not deposition been stopped by the degrading effect produced by the storage of sediment in the dam upstream. Also, the rate of rise of bed level would have been even faster if the sediment load carried into the reservoir had been the natural load of the stream instead of being only the much smaller amount picked up from the stream bed downstream from the upstream storage dam. The conditions which produced such extensive and rapid filling were the relatively high sediment load carried by the stream and the narrow valley in which the stream flowed. Wherever these conditions are repeated, a similar rapid rise of river levels for a long distance upstream can be expected.

FILLING ON STREAM CARRYING SAND AND GRAVEL

The rise in the sediment levels to slopes approaching the regime slope may occur either rapidly or slowly, depending upon a large number of factors, the most important of which are the volume of storage in the reservoir, the discharge of the stream, and the sediment concentration and size composition. The rate of rise is large with a high annual sediment load or with a small reservoir storage volume. If the stream carries a load of sand and gravel, the gavel will be deposited at the upper end and with a steeper slope than that taken by the sand as shown in Figure 5. If the amount of sand, carried is much greater than the amount of gravel, the reservoir may almost entirely fill with sand before gravel has been deposited in large quantities. This sand will deposit on a slope equal to the regime slope of a river carrying this load of sand, and therefore at a flatter slope than that for the same river carrying this load of sand and some gravel. As time goes on, however, the gravel will continue to deposit at the upper end and the steeper slope section will slowly extend farther and farther downstream until it reaches the dam. At this time the stream will have a slope approaching that of the regime slope of this river with its load of both sand and gravel. This deposit of the gravel at the upper end will proceed more slowly than would be indicated by the amount of gravel carried by the steam, because of the tendency of the rounded pieces of gravel—even those of considerable size—to roll down over the relatively smooth bed of the sand on flatter slopes than would be required if the bed were of gravel. Thus, a part of the gravel will escape from the reservoir without deposit, and the coarse material at the upper end will accumulate at a slower rate than if it were all deposited.

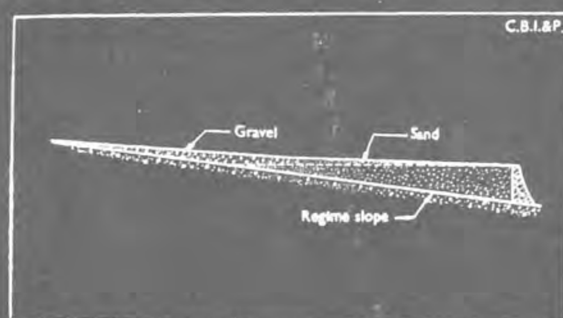

Figure 5 : *Showing deposits in a Reservoir by a stream carrying sand and gravel.*

DEPOSITION ABOVE TWO LARGE DAMS IN THE UNITED STATES

It has been emphasized that planners and designing engineers of hydraulic projects involving reservoirs on streams carrying heavy sediment loads should give adequate thought to the difficulties which will arise because of the deposition of sediment in the reservoirs. That they often fail to do this is no doubt due partly to the fact that they are not familiar with what has happened under similar conditions in reservoirs which have been in existence for a period of years. To those who have studied these cases the inevitability of difficulties does not have to be demonstrated, and the uncertainties are only as to how soon the undesirable effects will occur. Fortunately, in most cases these conditions will only arise in the far distant future, but one should be sure not to be caught by one of the few cases where it occurs rapidly.

In order to show that the actions discussed in the foregoing sections of this article have actually occurred in some reservoirs, and therefore will occur in the future whenever similar conditions arise, it is desirable to describe the deposition which has taken place in several large reservoirs in the United States.

In the case of the largest of these reservoirs the records show a mean annual water inflow of about 1,100,000 acre-feet, and a sediment discharge of 17,700,000 tons, or about 14,000 acre-feet, which gives an average concentration of 1·18 per cent. by weight. As nearly as can be determined, the sediment consists of 24 per cent. clay size (below 0·004 mm), 61 per cent. silt (0·004 to 0·062 mm), and 15 per cent. sand (above 0·062 mm). When the reservoir was planned, sediment studies were made, and the sediment inflow was predicted with unusual accuracy. Provision was made for extensive sediment deposits but no consideration seems to have been given to the place where the deposition would occur.

When storage was started most of the sediment stopped near the upper end of the lake, the deposits extending both down into the lake and upstream from it. In 14 years the deposits had become so large above the lake that extensive damage was caused upstream from it to improvements located 18 feet above the highest level and about 70 feet above the average level in the reservoir (after the initial filling). Records prior to the construction of the dam show that the river bed at this location was rising steadily, but at a rate considerably less than that after storage started. This initial rate of rise is probably due to overgrazing of the watershed upstream and the use of a large part of the stream flow for irrigation above that point. It is, therefore, not possible to determine what part of the effects was due to the reservoir and what part resulted from changes of stream regime due to altered conditions in the watershed upstream.

Surveys have been made at frequent intervals. As the deposition has continued, the bed of the river has risen farther and farther upstream. The rise of the river bed has been accompanied by a rise of the ground-water level on adjacent land, making it unfit for cultivation. As time passes, more and more cultivated land has been abandoned, so that cultivation of the river valley has now been nearly completely abandoned for a distance of about 15 miles above the upper limit of the reservoir, and this distance is continually increasing. As deposition has progressed upstream, an increasing proportion of the sediment load has been deposited in the river bed and in the valley bottom upstream from the reservoir, so that in recent years more than half of the sediment brought down has been deposited above the reservoir. The rate of filling of the reservoir is thus decreasing at the expense of the land upstream.

Of even more immediate importance than the loss of the land, however, has been the loss of water which has resulted from the thick growth of vegetation which has grown up on the valley land upstream from the reservoir and the evaporation from the shallow depressions which were formed by the sediment deposits and were filled with water whenever floods occurred. This loss amounts to about 140,000 acre-feet annually. Since the area of land irrigated along the river is sufficient to use the entire water supply in dry periods this loss has been especially serious during the last few years when the river flow has been much below normal. Only the presence of a large storage of water in the ground of the valley floor has prevented a disastrous drought. As a result of this situation, a project to reduce this transpiration loss has been started, which is estimated to cost 2-1/2 million dollars. It consists of constructing levees and channels to prevent the spread of the water to the non beneficial vegetation, the channeling of the water into the reservoir, and the killing of considerable areas of the vegetation with chemicals.

At another large dam the situation is similar to that just described, but the quantitative records on it are not so complete. This dam was put into service prior to 1893 and was rapidly filling with sediment when a growth of tamarisk or salt cedar started above the reservoir and the rate of filling decreased materially. At first the loss of water due to this growth was not noticed, but the growth extended until now it spreads over the whole valley for a distance of 16 miles upstream from the dam, covering 15,000 acres and using about 52,000 acre-feet of water per year. To eliminate this loss, a plan for a channel to by-pass the river flow around this vegetation, at an estimated cost of about $1,000,000, is being studied.

DEPOSITION ABOVE PARKER AND HOOVER DAMS

Filling due to sediment above Parker Dam became evident soon after the lake was first filled in 1938. Vegetation sprang up in the swamp thus created, and soon the levels had risen so high that flooding was occurring in the town of Needles, California, 12 miles upstream from the lake and about 20 feet higher in elevation. A temporary levee was constructed, and the dredging of a $1,750,000 channel to remedy this situation is now under way. In this section of the river, also, aggradation was going on before Parker Dam was built, and it is not possible to say how much of the rise in level is due to construction of the dam. A continued increase in elevation of the river here is not expected, due to the construction of the Davis Dam a short distance upstream. In the swamp which has formed, a loss of water of about 360,000 acre-feet per year is taking place. At the present time there is a surplus of water and this loss therefore is not now important, but it will become so as development elsewhere on the river reaches the capacity of the water supply.

The deposition in Lake Mead, which is formed by the Hoover (Boulder) Dam, is proceeding very much as shown in Figure 1, except that the bottom-set beds do not extend far down into the reservoir. The top-set beds, however, extend many miles upstream, and are considerably above the level of the water in the reservoir. This rise will no doubt continue until the proposed Bridge Canyon Dam is constructed upstream from Lake Mead. As this deposit is taking place in an uninhabited canyon, it is causing no difficulty, although it will add materially to the cost of constructing the Bridge Canyon Dam when it is built, and will decrease the power head available there.

MISCELLANEOUS CASES OF FILLING ABOVE RESERVOIR LEVEL

Scattered through engineering literature are quite a number of references to deposits above the water level caused by dams. Some of these are in the form of statements that such deposits take place and others are in the form of data on reservoirs where such deposits have occurred. The earliest mention of such deposits found by the writer is by Buckley in 1893, who states : " Generally speaking, it may be said that the bed above a weir on a boulder formation, or where the bed is of coarse sand, is almost certain to be raised up to, or even above, the weir crest. But the finer the sand and the more muddy the silt in the river, the less likelihood is there of the rise of the bed above a weir."

The thorough explanation of the formation of such deposits by Harris[6] in 1901 has already been mentioned. An actual example of such action on Lawson's Fork Creek is described in 1902 by G. E. Ladshaw [8]. In his book on irrigation, published in 1916, Etcheverry states as follows : " These combined actions have a tendency to raise the river bed on the upstream side up to the crest of the weir, and in the case of stream beds of coarse gravel or heavier material the erosive effect of flood flows is not always sufficient to keep the stream bed even below or at the crest level." This action is also pointed out by Schoklitsch[9].

Deposits above reservoir level have been frequently observed at basins formed to retain coarse sediment brought down by streams in California. Among these are the large barriers built on the Yuba River and basins on Bear Creek[10], Santa Ana River[11], Pickens Canyon[12], and Brown Canyon[13]. Another example is the Pontalto Dam in South Tyrol[14] and several dams in South Africa[17].

CONCLUSION

It is believed that the foregoing description of the experience with reservoirs in the United States should be sufficient to show the necessity, in planning hydraulic works—especially on rivers carrying heavy sediment loads—of carefully considering what will happen in the future as a result of sediment deposits, in order that all avoidable difficulties may be anticipated and properly taken care of. Although in most reservoirs a very long period of time will elapse before severe trouble will occur, in some cases the periods will be short, and these should be avoided.

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