Study of Several Low Earth Dam Failures

Recherches sur les causes de rupture de plusieurs barrages en terre de faible hauteur

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Summary

This paper describes typical failures of low earth dams that were constructed on intermittent streams using dry glacial clay. The failures were due to piping through the fill during the first filling of the reservoir. It is believed that this was a result of volume reduction of the less dense portions of the embankment when subjected to saturation from the rapidly filling reservoir. The paper discusses the possibility of establishing the minimum allowable water content and dry density of a proposed dam so as to result in a stable structure at the least possible cost. Methods of obtaining the necessary water in a semi-arid region are described. Alternative methods of ensuring a stable dam by controlling the saturation of dry embankments in place are discussed briefly.

Sommaire

Ce rapport décrit la rupture de plusieurs barrages en argile glaciaire sèche construits sur des cours d'eau intermittents. Ces barrages ont cédé à la suite de l'érosion progressive qui s'est produite à travers leur massif après le premier remplissage du réservoir. On croit que cela est dû à la diminution de volume des parties moins denses, causée par la saturation des barrages lors d'une mise en eau rapide. Ce rapport décrit la possibilité d'établir la densité et la teneur en eau admissibles minima pour réaliser une construction stable et économique. Les auteurs décrivent des procédés ayant pour objet de retenir l'eau nécessaire dans une région semi-aride. Ils traitent brièvement divers moyens d'assurer la stabilité d'un barrage, construit en matériaux secs, en contrôlant la teneur en eau sur place.

Introduction

Many of the low earth dams in Western Canada were constructed of borrow material far below the optimum moisture content for good compaction. In addition, many of the smaller dams were constructed with little or no compaction. When the reservoir filled during the spring run-off, some of the dams constructed of loose dry material failed rapidly through the fill. This paper describes briefly two of the dams which have failed in this manner and discusses the probable mechanics of failure and possible methods of preventing a recurrence.

Geology and Climate of the Area

From the standpoint of earth dam construction the geology and climate of the prairie region of Western Canada have created problems peculiar to this area (*Legget*, 1951). The most significant aspect of the geology is the fact that the entire area has been glaciated, and, although there are deposits of glacial gravels, the majority of the soils are glacial clay or glacial-alluvial clays. These are generally medium to highly plastic and highly susceptible to volume change with changes in water content.

The climate can be classified as semi-arid although conditions vary from periods of considerable rainfall to severe drought. Annual cycles of high spring run-off from snow-melt and spring rains, followed by high summer temperatures and drying winds, are the general rule.

Construction Problems

In most cases the importation of semi-pervious or pervious material for low earth dam construction has not been deemed economical. In addition many of the dams had to be constructed in the late summer or fall on intermittent streams when no run-off or sources of water for construction was available. A number of the dams constructed of dry glacial clay failed upon the first filling of the reservoir. A single failure in an area of low population density and property values would not have been serious enough to cause concern. However, when several such dams failed, a need for study or research into the problem was indicated. A lack of accurate data on the construction and initial foundation conditions hindered studies of the failures.

In order to illustrate the problem associated with the construction of homogeneous earth dams in the area, three cases are considered in detail. Of these, two involve dams which have failed and the third involves a dam which showed signs of distress but which has not failed.

Case A

This dam was constructed in 1936 on a broad flat-bottomed coulee in which there is a considerable flow for only a short period of time during spring run-off. The dam was approximately 2000 ft. in length and about 20 ft. in height at the maximum section. The top width was 10 ft., the upstream slope 2.5 : 1 and the downstream slope 1.7 : 1. The dam was constructed during a very dry period in which no water was available within many miles of the site. The medium plastic clay soil was therefore placed very dry with only the compaction of teams and scrapers.

This dam failed during the first spring run-off period following construction. It apparently occurred with the water level approximately 10 ft. below the top of the dam. The washout was 130 ft. in width with almost vertical sides extending through the fill and a short distance into foundation.

Testing subsequent to failure has revealed that the soil had a liquid limit of 43 and a plastic limit of 19. The average water content was 9.4%, varying between 6% and 14%. The corresponding average dry density was 81 lbs./cu.ft. whereas the dry density corresponding to Proctor optimum was 98 lbs./cu.ft. at a water content of 21%. It would appear, therefore, that the soil was placed about 11% below the Proctor optimum and 9% below the plastic limit.

In addition to holes drilled for soil samples, some 4 in. diameter auger holes were filled with water to obtain an estimate of the watertightness of the remaining fill. These holes varied in depth from 8 to 24 ft. They absorbed water at rates varying from 10 to 50 Imperial gallons per minute. Where water was pumped into some shallow pits near the top of the fill the water burst forth on the downstream slope and it was obvious that the flow of water produced cavities and channels within the fill. On the other hand water was pumped at 50 Imperial gallons per minute for 4 hours into a 24 ft. hole through the fill with no sign of leakage in the vicinity. At the completion of this test it took approximately twice as much material to fill the hole as was originally removed, indicating that the soil had consolidated locally due to saturation.

Case B

This dam was also located on a coulee which carried water only during the spring run-off period. In contrast to Case A, the coulee was V-shaped and the dam was about 38 ft. in height and approximately 400 ft. in length. The top width was 20 ft., the upstream slope 3 : 1 and the downstream slope varying from 1.5 : 1 to 2 : 1. The soil used was a silty clay and the only compaction was by means of earth moving equipment.

The dam failed during the first filling of the reservoir during the period of spring run-off. At the time of failure the water was only 3 or 4 ft. below the top of the dam. According to reliable eye-witnesses, water was first noted gushing from the downstream slope 15 to 20 ft. below the top of the dam. The flow rapidly increased and in two hours time a large tunnel existed through the fill, as shown in Fig. 1. A few hours later the roof collapsed, at which time, practically all the water had drained from the reservoir. The breach through the dam had almost vertical sides and was approximately 50 ft. in width.

Fig. 1 View of Failure of Dam, Case B
Vue de la rupture de la digue B

In addition, a slump developed on the upstream slope and top of dam, about 100 ft. from the washout. The center of this area subsided 1 to 2 ft. and cracks up to 2 in. in width developed around the periphery. No bulging or outward movement of the upstream slope was noticed. It is believed this portion of the fill saturated somewhat more rapidly than the adjacent material and subsequently settled quite rapidly.

An investigation of the fill after failure revealed that the silty clay had a liquid limit of 33 and a plastic limit of 18. The average water content of the unsaturated portion was 8.2%, varying between 5% and 11%. Proctor compaction tests indicated that the optimum moisture content was 15% at a dry density of 116 lbs./cu.ft. The average placement water content was therefore about 7% less than Proctor optimum and 10% below the plastic limit. Unfortunately, density tests of the material in place were insufficient to formulate conclusions as to average density. This dam has since been successfully reconstructed with proper moisture and compaction control.

Case C

The valley on which this dam is located is very similar to the valley considered in Case A. The dam, as constructed in the fall of 1941, was 20 ft. in height and approximately 2500 ft. in length. The top width was 14 ft. with a 3 : 1 upstream slope and a 2 : 1 downstream slope. The soil used was a medium to highly plastic clay. It was recognized during construction that the moisture content of the material was far below the optimum for compaction. However, as water was not obtainable within a reasonable distance, it was decided to proceed with construction. In this case it was possible to control the inflow into the reservoir so that the dam would not be saturated too rapidly. Since the construction of this dam the reservoir has been filled very slowly. During the first 8 years the water never rose to within 10 ft. of the top of the dam. More recently the water level has risen to within 5 or 6 ft. of the top and some distress has been noted. This was manifested by signs of settlement, cracks on the downstream slope and also by some seepage through the earth fill. In order to reinforce the dam a substantial downstream section has been added, with a gravel filter at the base.

The material in the dam had a liquid limit of 47 and a plastic limit of 17. At the time of placing, the soil was possibly 6% to 10% below the plastic limit. At the present time samples indicate that in many parts of the fill the water content below the line of saturation is far in excess of the plastic limit and approaches the liquid limit. It is entirely possible that if the reservoir had been filled rapidly, the dam would have failed. However, the very slow rise of the reservoir has permitted gradual saturation of the earth fill. This has apparently resulted in some settlement and increase in density and watertightness of the fill material.

Observations

A study of these three dams and inspections of a number of other low dams in the area, two of which have also failed, have revealed a number of common characteristics.

(1) The dams were of homogeneous section and were constructed of medium to highly plastic clay typical of the area.

(2) In all cases they were constructed with very limited compaction and at water contents far below the Proctor optimum or the plastic limit. In other words they all had exceedingly low densities and high void ratios.

(3) All failures from which reliable data are available appear to have occurred within a few hours after the reservoir neared the full supply level. It appears that the failures resulted from seepage or piping through the fill along relatively horizontal paths.

(4) The dams constructed in a similar manner, but saturated slowly during the filling of the reservoir, have shown signs of settlement and seepage. The present water content of the fill material below the saturation line is closer to the liquid limit than to the plastic limit.

(5) In three cases in which inspection was made shortly after failure the fill was found to form an arch over the failed area similar to that shown in the photograph of Case B. This arched material collapsed a few hours after the failure.

Conclusions

From the evidence and observations collected it is apparent that the failures were due to piping through the fill. This piping is believed to have been a result of construction at low water contents and with poor compaction. Such construction resulted in a fill of high porosity and low average density. Due to variations in water contents and densities the saturation and resultant settlement progressed along zones or layers of less dense material. The denser more compact material likely arched over the material which had settled, causing the formation of small cracks or fissures. In those cases where the reservoir filled rapidly and interconnecting lenses of low density material existed, progressive failure passed from the upstream to the downstream side before the denser material arching over the settled material could become saturated and collapse. Where the reservoir filled slowly the saturation and reduction in volume took place more gradually, permitting the overlying fill to settle and adjust itself without the formation of seepage paths through the fill.

Discussion

As a means of preventing failures of this type it appears that a minimum allowable dry density or water content must be established for the proposed borrow material. Laboratory tests on material used for the dam described as Case A indicated that the percent settlement upon saturation depensed mainly upon (1) load applied (2) initial dry density. The load applied was the most important factor. Under very light loads the samples swelled upon saturation. Under loads of 2 tons per square foot samples settled up to 10%. However, samples tested at a given load showed decreasing settlement with increasing initial dry density.

In the case of the dam described as Case A the actual field conditions of density and loading in the zone that failed were such that a settlement of 8 to 10% could be expected. Further testing established the approximate range of dry density which would give a minimum of settlement under the loading conditions assumed.

In construction there would be two basic methods of attaining the minimum required dry density. One way would be to add little or no water and increase the compactive effort; the other would be to use some standard compactive effort and add sufficient water to attain the required dry density.

The first method is not believed practical because of the high cost and the danger that compaction would not be uniform. Non-uniform compaction would result in relatively hard brittle portions that would be inclined to bridge over localized areas of looser material that might undergo settlement upon saturation.

By using a laboratory test equivalent to the proposed standard field compaction, a minimum limiting water content to give the required density could be approximated. This may have to be modified slightly during construction to obtain the minimum required dry density in the field. For higher dams under somewhat greater loading conditions the lower limiting water content can be established more easily in that it appears that the settlement upon saturation gives good correlation with the initial water content (*Walker* and *Holtz*, 1951), whereas for the conditions under consideration it appears that the minimum dry density should be established. The recommended minimum water content to be used in construction is only a means of attaining this minimum density.

Unfortunately these methods of determining the minimum permissible water content or dry density are somewhat elaborate and costly for the preliminary studies of the cost of constructing small earth dams. An approximate method of estimating the minimum permissible water content and dry density might be established. Perhaps this could be related to the Proctor optimum density although it appears some allowance should be made for the plasticity characteristics of the material. That is to say, a straight percentage of the Proctor dry density or the Proctor optimum water content does not appear to be a sufficiently accurate guide for soils with varying plasticity characteristics. Possibly the minimum water content could be approximated by using a formula based on plasticity characteristics. This should probably bear some linear relationship to the plastic limit with the liquid limit or plasticity index having a modifying effect.

The problem of obtaining the required amount of water or moistened soil is still a serious economic problem on intermittent streams. Some of the methods that are being used or proposed are:

(*a*) Construction of temporary low dams or dykes across the valley to store water during the spring run-off. This is then used to irrigate borrow pits or sprinkle the fill during construction. This is the method that was used in the reconstruction of some of the failed dams as the the old breached fill often stored sufficient water for this purpose.

(*b*) In some areas it is possible to dyke borrow areas and trap snow-melt or local run-off so that the borrow material is sufficiently moistened.

(*c*) Dry farming methods as practiced in the area suggest that the moisture content of grassed borrow areas could be increased by cultivation. This would permit greater penetration of precipitation and destroy grass, weeds, shrubs, etc. which waste soil moisture.

(*d*) In some locations it is feasible to erect snow fences to trap wind blown snow during the winter months. This, combined with cultivation of the borrow areas, can appreciably raise the water content of soil in the borrow areas.

(*e*) It has been suggested by *Casagrande* (1950) that, in the case of homogeneous earth dams, it might be desirable to construct a central core by placing the soil at a much higher moisture content. In many instances it might be economically feasible to place a narrow core in this manner whereas it would not be feasible to import water for the entire dam. If, then, the drier outer portions were ineffective as a water barrier, the central core section, placed at optimum moisture content, might retain the water and result in a successfull structure.

(*f*) In certain cases it may be possible to control the level in the reservoir so as to slowly saturate a dry fill without detrimental effects. This method might be more satisfactory for dams on broad coulees than for dams on short V-shaped coulees. In the latter case the settlement resulting from saturation may result in movements of the earth fill with respect to the abutments which would produce cracks or fissures through the fill.

(*g*) Where conditions permit, relatively small amounts of water can be stored in the reservoir and used to saturate the fill by ponding on top of the dam. This method is now being used where it is necessary to strengthen and raise earth fills, the upper portions of which have never been saturated. It is recognized that it may be difficult to secure uniform saturation and therefore differential movements and possibly fissures or voids may occur. However, since the reservoir would be nearly empty, the dam would not be subjected to full reservoir pressure and there would be little danger of failure.

As a means of obtaining basic information for the future it is believed that the procurement of relatively precise measurements of the settlement and movement of the fill during reservoir operation, as well as the initial water content and density of the embankment, is warranted.

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