UNITED STATES

DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: SECURITY OF MASONRY DAMS ON EARTH FOUNDATIONS AGAINST FAILURE FROM UNDER-SEEPAGE OR PIPING

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by

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Under direction of

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McBirney

Security of Masonry Dams on Earth Foundations against Failure from Under-Seepage or Piping

by E. W. Lane, Research Engineer

Denver, Colorado, April 25, 19[illegible]

Masonry dams on porous foundations may fail from (1) toe erosion, (2) under-seepage or piping, (3) blow-up from upward pressure, (4) apron abrasion, (5) overturning, and (6) sliding. The frequency with which failures result from the various causes is probably far from the order listed. The investigation reported on herein was undertaken primarily to study the means used in preventing the failure of masonry dams on earth foundations from the second of these causes of failure (under-seepage or piping), and to determine from the experience with existing dams the length of path of seepage travel which is necessary to insure safety for dams founded on various kinds of material. A summary of the results of this study is given on pages to inclusive. The procedure, results and conclusions are given in detail on the following pages.

Bligh's Theory

The first rational system of design of dams on porous foundations was proposed by W. G. Bligh* and was developed from analyses of the failures and successes in India, where many dams on porous foundations had been constructed. Although Bligh's analysis leaves much to be desired, it has been generally accepted and is extensively used. From a practical standpoint it is believed to be the best method so far devised and has long been used as standard practice in the design of the structures of the Bureau of Reclamation. Briefly stated, Bligh's theory is that for a given character of foundation material there is a definite minimum safe ratio of the length of the path along which water seeps under the dam from headwater to the tailwater, to the head of water sustained by the dam, and when the ratio is less than this there is a tendency of the water seeping beneath to form channels through the foundation material which may ultimately enlarge and cause the failure of the structure. This form of failure is called piping. The path which the water takes is along the line of contact between the earth and the masonry or piling; in the case of sheet piles it is down one side of the piling and up the other. This path is called the line of creep and the length of the line is called the creep distance.

*The Practical Design of Irrigation Works, Bligh, 2nd Edition, p. 162.

As the result of his study of dams and dam failures, Bligh arrived at values of the creep-head ratio which he believed would give dams safety from piping failure. The description of the various classes of material and the values of the ratios varies somewhat in different publications by Bligh. The following table gives the various descriptions and ratios:

Safe Creep-Head Ratios Given by Bligh

	Publication			
	I	II	III	IV
Year of publication	1910	1910	1916	?
River beds of light silt and mud, as the Nile	18			
Fine silt and sand as in the Nile River		18		
River beds of light silt and sand of which 60% passes the 100-mesh sieve, as those of the Nile or Mississippi			18	
Fine mud and silt, such as in the Nile				18
Fine micaceous sand as in the Colorado and Himalayan rivers	15	15		
Fine micaceous sand of which 80% passes a 75-mesh sieve, as in Himalayan rivers and in such as the Colorado			15	
Fine; e. g., Punjab sand				15

(Cont.)

	Publication			
	I	II	III	IV
Year of publication	1910	1910	1916	?
Coarse-grained sands, as in Central and South India	12		12	
Ordinary coarse sand		12		
In coarse sand (this is the usual type)				12
Boulders or shingle and gravel and sand mixed	5 to 9		5 to 9	
Gravel and sand		9		
Boulders, gravel and sand		4 to 6		
In clay, shale or shingle				5 to 9

Publications

I The Practical Design of Irrigation Works, 1910, 2nd Ed., p. 165.

II Dams, Barrages and Weirs on Porous Foundations, Engineering News, Vol. 64, December 29, 1910, p. 708.

III Dams and Weirs, 1916, p. 155.

IV Control of Water, Parker, 1916, p. 679.

(The original source by Bligh is not given).

The first three classifications are fairly consistent. A classification of silt by rivers, however, is not a safe procedure as that in the upper reaches is usually much coarser than in the lower. It is not known on what grounds Bligh put the Colorado River in the class with a ratio of 15, but the silt from the lower Colorado is much finer than the sizes given, in fact even finer than those given for a ratio 18. The classifications for boulders, shingle, gravel and sand differ somewhat, in one case using a minimum ratio of 4 and in another case 5. The classification, gravel and sand, 9, and boulders, gravel and sand, 4 to 6, is the most useful, since it gives a definite value for gravel and sand without boulders, a common foundation material. It is interesting to note, however, that in his latest publication Bligh does not give a ratio lower than 5. The classifications given by Parker are entirely different for the lower ratios and could not be located in available publications by Bligh.

Short Path Theory

Another theory which has been used to some extent in the design of dams on porous foundations is what may be called the short path theory. This assumes that the water travels in the shortest possible path from the headwater to the tailwater, and when the ratio of the length of this path to the head sustained by the dam is less than a certain value, depending on the class of foundation material, the dam is in danger of failure from piping. The path of the water under this assumption may be called the "short path." Both creep and short path methods of analysis have been used in this study. From a practical standpoint they differ but little, as will be shown later.

[illegible]

In this study an extensive search was made in all available [illegible] literature and other sources of information. [illegible] or concrete [illegible] on earth foundations were [illegible] sufficiently adequate. [illegible] cases there is considerable uncertainty. [illegible] more than one description was found of [illegible] structure there was often a surprising lack of agreement [illegible]. There is frequently considerable room for the exercise of judgment as to just where the travel paths should be assumed to [illegible]. In checking over the data given by Bligh with that available from other sources, some discrepancies were found. In all cases the writer's best judgment was used in determining the most probable values. He would appreciate it if readers of this report would call his attention to any cases in which his judgment may have been in error.

At several points in the analysis of some of the data it was necessary to make assumptions. One of these was in the case of rows of sheet piling close together. Bligh states that "the line of creep due to sheet piling is twice the depth of the sheet piling when they are not spaced nearer to each other than twice their depth."[a]

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[a]The Practical Design of Irrigation Works, Bligh, 2nd Ed., p. [illegible].

This is equivalent to stating that the resistance to the flow along the line of creep is half that directly thru the foundation material, [illegible] the lines of sheet piling are closer than twice their [illegible] the resistance thru the material becomes less than along the creep line and the water follows the former, invalidating an analysis based on the line of creep theory. Bligh gives no evidence to support his rule on this point and none was found elsewhere. It is obvious, however, that there must be some limit to the closeness of the spacing of lines of sheet piling and since data is lacking, and Bligh's rule does not seem unreasonable, it was adopted. Where lines of piling were found closer together than twice their depth, the length of the line of creep between them was assumed to be twice the distance between them, which is equivalent to assuming that the resistance to flow on the short line per unit of length was twice that along the line of creep.

In several cases dams have been built with a filling of dry or broken stone beneath them. This would offer much less resistance to seepage than the contact between solid masonry and foundation material. Where the floor above this stone filling has not been vented, to allow the water to escape, the resistance of the creep line along this section has been assumed to be half as great as for solid masonry.

Considerable uncertainty has been introduced in the determination of the creep distance by the presence of weep holes or vents. In determining the distances used in this report weep holes have not been considered as reducing the creep distance, but a separate analysis of weep holes has been made.

There was sometimes uncertainty as to the head to use in computing the ratios. In ordinary overfall dams it was measured from the crest of the dam to tailwater elevation, or if the latter was not given, to the streambed below the dam. If crest gates or flashboards were used, it was measured from their top. The ordinary operating head was used, altho, in some cases, especially movable navigation dams and irrigation headgates, the structures were, no doubt, occasionally subjected to greater heads. For many structures, especially irrigation headgates, it was not possible to determine the ordinary head with sufficient accuracy, and, therefore, they could not be analyzed.

This report considers not only dams on porous foundations but also those on clay and hard pan. No previous analysis of dams on clay and hardpan from the standpoint of piping failure has been found, and, therefore, there is no precedent to follow. The analyses of these dams have been made on the line of creep theory, in the same manner as those on porous foundations, but analyses on the short path basis have not been made. From the standpoint of piping failure, Bligh's theory seems even more applicable to clay than to porous foundations. If an appreciable amount of seepage under a dam on a clay foundation occurs, it would almost surely follow the contact between the masonry and the foundation, since both the masonry and the foundation material are practically impervious. The longer the path which the water must take to the downstream face of the dam, the greater the probability that it will be retarded to such an extent that the velocity will be reduced to a value which will not carry any particles of the foundation material. Also, the greater the creep distance the less probable is the existence of a complete channel from the headwater to the tailwater thru which water may flow.

It is doubtful if the Bligh rules should be applied to uplift under such dams, since it is probable that if seepage channels extended under the dam, they would cover a small portion of the total area and, therefore, exert only a small lifting force, much less than on porous foundations where pressure is exerted on practically the entire surface. This seems to be confirmed by the light aprons which are found below several dams on clay or hard-pan, which would probably have been blown up if founded on porous material. Such dams would also differ from those on porous foundations in the closeness with which cutoffs could be spaced and still count on the full creep distance as being effective. As long as the rows of piles were not so close together that they caused cracks to form in the clay between them, it is improbable that enough water would seep thru the clay to cause trouble. No dams with close rows of piling were analyzed, however, and therefore no decision was made on the minimum distance at which they could be spaced and still safely count on the full creep length.

Several cases have been found where dams were built on a layer of porous material, such as gravel or sand, which was underlaid by an impervious layer of clay or hardpan into which the cutoff walls [illegible] extended. These are not subject to change in the ordinary [illegible] therefore, the data on them is given [illegible] analysis.

Classification of Foundation Materials

There is [illegible] need of a more accurate and scientific classification of foundation materials than the common terms, gravel, coarse sand, etc. Several classifications on the basis of grain size have been made, but none are entirely satisfactory. One developed by the United States Bureau of Soils* has been extensively used in

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*Groups of Soils on the Basis of Mechanical Analysis, R. O. E. [illegible] [illegible] Bennett, U. S. Department of Agriculture, Circular [illegible]

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the classification of materials of earth dams. For dam foundation materials, however, it is not entirely satisfactory as the classifications, clay, fine sand, coarse sand, etc., are much finer material than the engineer has in mind when using these terms. Mechanical analyses of foundation materials could be obtained for only a few [illegible]. Those available are plotted on Figure (1), giving the grain sizes in inches and millimeters, the Bureau of Soils classification, and the size of standard sieves.

Results of Analysis of Existing Structures

The results of the analyses of the creep and short path relations for all structures for which sufficient data could be found in [illegible] Tables 2 to 4 inclusive and is shown graphically on Figures 8 to [illegible]. In Appendix I is given a brief statement of the conditions at each dam analyzed and in Appendix II are given the cross sections of dams on which data is not readily available elsewhere.

On Tables 1 to 4 inclusive are listed the important data on dams on (a) clay and hard-pan, (b) gravel, cobbles and boulders, (c) coarse sand, and (d) sand, fine sand and silt, respectively. The first column gives each dam a number which is useful in identifying it on the figures. The headings of columns 2 to 5 inclusive need no explanation. The next four columns give the lengths of the travel paths and their ratios for analysis by the Bligh method and the short path method respectively. The next column gives an indication of the probable reliability of the computed values of travel path and ratios. In some cases the data was somewhat in doubt. The eleventh column, "Results", indicates the period that the structure is known to have given results satisfactory from the standpoint of failure from piping. Failure from other causes was not considered. In most cases the period extends up to the present (approximately January 1, 1930). In the case of structures for which no data is given in this column, for the larger ones when located in the United States, it is very probable they are still giving reasonably satisfactory results or record of the failure would probably be published. Smaller structures in the United States and those in foreign countries are probably still in use, although there is a slight chance that they may have failed. The next column gives a brief description of the material on which the structure was founded. The terms are not always as explicit as might be desired, due to incomplete descriptions in the articles describing them. The last column furnishes pertinent data not included in the other columns.

These results are shown graphically on Figures 2 to 6 where the length of creep is plotted against head on logarithmic paper and lines are drawn showing the various creep-head and short path ratios. The failures are indicated by solid dots and the dams which, so far as known, did not fail by piping, are indicated by open circles. Different sections of the same dam, or conditions of the same dam before failure and after repair are shown by dots joined by a line. The majority of the failures are dams of very poor design but they serve to show approximately the limits of good design. Well designed dams rarely fail, but more lessons can be learned from failures than successes. Some well-known failures are not included because the data is insufficient or too conflicting to permit reliable conclusions. These include the Hauser Lake Dam, Missouri River, the [illegible] Barrage on the Nile and the Southern Alberta Land and Irrigation Company's [illegible] and [illegible]ate.

Considerations Influencing the Selection of Creep and Short Path Ratios

Several factors beside the nature of the foundation material should be considered by the designing engineer in selecting the creep or short path ratio to use in the design of the type of structure under consideration if the most economical result is to be secured, and should, therefore, be kept in mind in determining safe ratio values from the experience on existing structures. Perhaps the most important of these is the damage to life and property which would result from a failure. For a dam so situated that a failure would result in loss of life an unquestionably safe design is required. If extensive property downstream would be endangered, conservatism of design is indicated. For most dams on porous foundations the conditions are such that little damage would result from their failure except to those directly served by them, and the degree of conservatism should be dictated by a comparison of the damage which would result from failure with the cost of the additional factors of safety. One phase necessary to consider in estimating the damage which is likely to result from failure is the time necessary to make repairs or temporarily patch up the structure. A failure which would put a hydro-electric plant out of service for a considerable time, or shut off the supply of irrigation water for a long enough period to cause the loss of a crop, or more especially of orchards or citrus fruit groves, would be very serious and justify larger ratios, while for a structure which could be temporarily patched up in a short time more risk of failure would be justified. For this reason small structures of low head can usually be designed with lower creep or short path ratios.

Other factors to be considered are the competence of the maintenance of the structure after construction and the material on which it is founded. If a dam is to be built for an organization which has competent men to watch it and make repairs in case excessive seepage occurred, a lower factor is justified than for one built for an organization where no observation or repairs can be counted upon. The probability of being able to make repairs after trouble develops depends upon the nature of the foundation material and the degree of conservatism in the design of the structure. On gravel and sand foundations considerable seepage may take place for a long time without causing failure, in fact, in gravel it would be possible for considerable leakage to occur continuously without endangering the structure and no doubt a certain amount can take place where the foundation material is sand.

The failure of all the dams on clay or hard-pan discussed in this study have come without warning. Two of the dams had very low creep-head ratios, and the third had a ratio near what might be considered fairly safe, but failure may have been due to drying out of the clay foundation. If a water passage was once formed under a dam on clay it might enlarge very rapidly, since the creep distance would probably be short. Failures of dams on all classes of material are more likely to occur suddenly if the ratios are very low. It would, therefore, not be advisable to count on being able to make repairs to such a dam even if it were closely observed, although, no doubt, cases have occurred where it has been done.

Four of the five failures of dams on gravel had such low creep-head ratios that the sudden failures which occurred are not surprising. The Plattsburg Dam failed with a creep-head ratio of [illegible].6, which is not extremely radical. It seems to have had no competent supervision after construction and no information is available on how much time would have been available for repairs if proper supervision had been exercised. However, trouble had been experienced with the dam previously and under competent control it would have been closely watched. Considerable seepage over a long period of time has taken place at the Rotterdam movable dam on the Mohawk River, apparently without endangering the structure, and was finally stopped by driving additional sheet piling and grouting.

Neither of the two failures of dams on fine sand took place suddenly and in neither case was the dam of very radical design. In one case extensive seepage below the dam was observed for ample time to allow repairs to be made, and in the other case the information available indicates that there was serious doubt of its stability before failure took place and time was available to repair it. It, therefore, seems safe to conclude that dams on sand or gravel foundation will not fail suddenly unless the creep-head ratio is very low. Under certain circumstances, therefore, it might be good economy to use a somewhat lower creep-head ratio in design with the expectation of doing some additional work such as grouting or driving additional piling in case excessive seepage took place.

For dams on coarse gravel, a factor which deserves consideration in selecting a creep-head ratio is the money loss which would occur if some seepage took place beneath the dam without endangering the structure. For example, in dams for power plants, such loss would usually result in a decreased plant output, but for an intake dam for an irrigation system where only part of the water in the stream was diverted and water would, therefore, be continually wasted over the dam, the flow under the dam would be of no consequence.

Dams on Clay and Hardpan Foundations.

Figure 2 gives the results of the studies of dams on clay and hardpan foundations. This shows that no failures have taken place with creep-head ratios of over 4, but that dams have been constructed with ratios as low as 1.1 with apparent success. The Woodward Dam stood with this ratio for 4 or 5 years, and its failure may have been due to the presence of sand layers in the clay. The Fergus Falls power house stood 11 months with a ratio of 2.0. The Dolgarrog [illegible]se (ratio 3.3) may have been due to draining out of the clay foundation, since the dam failed suddenly after 14 years satisfactory service. It is probable that there are many other dams on clay foundations with ratios less than 4 which are safe but are so small that they are not described in the technical press. Not one of the dams on clay that failed was so described until failure had attracted notice to it.

One of the most interesting dams on clay foundations is on the Guadalupe River in Texas, described in Appendix I. Its design is so unusual that it cannot be successfully analyzed in the same manner as the other dams studied and it is, therefore, not included in the discussion.

From the information available, it seems reasonable to conclude that the following creep-head ratios for dams on clay could be used in design for structures of various degrees of importance, from the standpoints previously outlined:

	Unimportant Structures	Average Structures	Very Important Structures
Very tough hardpan	3	4	5
Ordinary hardpan or hard clay	3½	4½	5½
Medium clay	4	5	6
Soft clay	4½	5½	6½

There is some uncertainty in the values given for medium clay and even more for soft clay, since there is little precedent for this class of structure. It should be remembered, however, that these values apply only to safety from piping failure and that other considerations, such as the bearing pressures and the length of apron necessary to prevent scour may determine the shape eventually adopted. They also assume good construction with cut-offs of solid concrete or interlocking steel sheet piling. They should not be used with wooden sheet piling; in fact, except under exceptional conditions, it is doubtful if wooden sheet piling should ever be used for cut-offs where watertightness is required. If there was any possibility of the clay foundation material drying out, higher values would be necessary.

The meanings of these terms in this and following similar tables are those in ordinary use among engineers; not the Bureau of Soils classification.

Dams on Gravel, Cobbles and Boulders

Figures 3 and 4 give the results of analyses of dams founded on gravel, cobbles and boulders. Dams on foundations composed largely of sand but with a considerable proportion of gravel are included in this group. They represent an intermediate condition between coarse sand and gravel, and to include them in this classification is on the side of conservatism. The results of the creep and analyses indicate

... the ratio 5 given by Bligh is reasonably conservative, although dams with lower ratios have proved satisfactory.

Most of the failures occurred with ratios much lower than 5. The [illegible] Dam was constructed in 1785-91 and it is not surprising that, with the knowledge of that day, so radical a design should be attempted. The dam had stood thru previous years with ratios as low as 4.3, the low ratio at failure being due to a blowout in the downstream apron. The Port Angeles Dam (ratio 2.1) would seem almost sure to fail, and it is difficult to see how a dam would be built under these conditions at so recent a date. The Pittsfield Dam was also of radical design, but was built at a time when there was little precedent in this country to be guided by. The Coon Rapids failure was due primarily to a defect of construction.

The only case of failure in a dam approaching the ratios given by Bligh is that at Plattsburg with a ratio of 4.0. The cause of this failure is not evident. An analysis of the foundation material, as nearly as could be determined from the data given, is shown on Figure 1. This indicates a much more impervious material than that at Prairie du Sac, which stood with a ratio of 4.5. Part of the Plattsburg Dam stood with a ratio of 3.2. It seems not impossible that there was some defect in construction or an unusual segregation of coarse material at the point of failure.

The only satisfactory dams found with ratios less than 6.0 are the Pinhook, Boise Diversion, Granite Reef and Oswegatchie River dams. The Pinhook Dam (ratio 4.5) has an apron of concrete blocks below the fixed floor, which may increase its resistance to piping. The Boise Diversion Dam (ratio 4.4) is on very compact gravel and cobbles. The Granite Reef Dam (ratio 5.2) leaked 2 to 3 second-feet in the 300-foot length not on rock, and it is possible that this dam would have failed had not the riverbed upstream rapidly silted up. It is probable that the weep holes in the base of the Oswegatchie Dam were of considerable assistance in keeping it secure with the ratio 3.[illegible]

In this connection the following quotation regarding the Ohio River dams is of interest:*

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*Trans. Am. Soc. C. E., Vol. 88, 1925, p. 1148.

"Ohio River dams constructed on sand and gravel, with a cut-off wall of 40-foot interlocking steel piles, have a length of "creep" equal to about ten times the maximum head. Experience has shown that in practice the wooden sheet-piles, even though carefully driven, are not sufficiently tight to form an effective cut-off. Their use has been limited to the upper part of the river where foundations consist of rather coarse gravel and sand, and they are not regarded as adequate for the more sandy foundations of the lower river. No evidence of "boils" under any dams that are in service has appeared, and it is believed that these dams have adequate protection from this danger, unless they are undermined by scouring action below the weirs, which action must be carefully guarded against by proper construction and periodical inspection."

The values given in this quotation are somewhat less than those determined by this investigation, due no doubt to the use of the maximum head in the former and the normal head in the latter.

Assuming cut-offs of solid concrete or interlocking steel sheet piling and construction properly carried out, from the foregoing it is believed that the following creep-head ratios can be used in design:

	Unimportant Structures	Average Structures	Very Important Structures
Boulders with some cobbles and gravel	3½	4½	5½
Gravel with a few cobbles or boulders	4	5	6
Gravel without cobbles or boulders	4½	5½	6½
Gravel with a large proportion of sand	5	6	7
Coarse sand with cobbles or boulders	4	5½	6½
Coarse sand with some fine gravel	5½	6½	8

Dams on Coarse Sand

Figures 5 and 6 show graphically the results obtained in the analyses of dams on a coarse sand foundation on the basis of the Bligh and short path theories respectively. No failures were found in this class except the Upper Coleroon weir, which was due to a defective apron and is therefore not included. In this classification are included those on the border between coarse and fine sand as placing them in this class rather than the fine classification is more conservative. The results indicate that Bligh's factor of 12 is unnecessarily conservative. The Riverdale Dam held at least 5 years with a ratio of 3.4, and the foundation was said to be full of springs during construction. The riprap paving below may have acted somewhat as a filter and assisted in the stability of the dam, by filtering the flow beneath the dam, thus preventing the removal of the fine material. The Prairie du Sac Dam has been in service 15 years, part of the time with a ratio 4.3 and the remainder of the time with a ratio of 6.2. It is possible that the riprap filling in this dam assists somewhat by acting as a filter. Under the power house, where there could be no such filter action, it has stood for 15 years with a ratio of 8.5. In fact, it has sustained even higher ratios, but these may have occurred only after the river bottom above had silted up. In fact, two thirds of the dams have values less than that given by Bligh and there is no record of failure, even when the ratio was only 22% of Bligh's.

Considering the results obtained on existing structures [illegible] believed that the following creep-head ratios can be used in design [illegible] on coarse sand with proper construction and solid concrete [illegible] steel sheet piling cutoffs:

	Unimportant Structures	Average Structures	Very Important Structures
[illegible] sand with some fine gravel	5½	6½	8
[illegible] sand	6	7½	9½

Dams on Sand, Fine Sand and Silt

Figure 7 shows graphically the results of the studies of [illegible] on fine sand and silt, together with the creep-head ratio 15 recommended by Bligh for "fine micaceous sand of which 80% of the grains pass [illegible] mesh screen, as in Himalayan rivers and in such as the Colorado" and [illegible] for "river beds of light silt and sand, of which 80% passes a 100-mesh [illegible] as those of the Nile or Mississippi."* Figure 8 gives the results

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[illegible] and Weirs, Bligh, p. 155.

[illegible] analyzed on the short-path basis.

The descriptions of the material on which the dams are founded [illegible] not sufficiently exact to permit a separation into the two classes given [illegible]. The material is frequently described as fine sand, but sometimes [illegible] as sand, and none were found which unquestionably fitted in the class [illegible] which Bligh recommends a ratio of 15. As has been previously stated, All cases where the classification was doubtful as between this class and coarse sand have been grouped with coarse sand. For those portions all structures on material finer than coarse sand were grouped together. It is possible that a few of the dams listed as being on material described simply as "sand" were really on coarse sand.

Only two failures were found which might be classed as due to piping for which the data was sufficiently exact to permit analysis. These are the two on which Bligh based his ratio values: namely, the Narora and Khanki weirs. Bligh ascribed their failure to piping but in a statement in great detail Mr. W. W. Woods* argues convincingly

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* The Practical Design of Irrigation Works, Bligh, 3rd Edition, p. 165

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that these failures were due to other causes and the original conclusion was made as regards piping. The low ratios safely built on coarse sand adds weight to Woods' contention. The Grand Barrage on the Nile was founded on this class of material but its failure was evidently due to poor construction. With these possible exceptions no failures from piping were discovered.

In view of the analyses shown on Figure 7 and those on coarse sand (Figure 5) it is believed that the following creep-head ratios recommended by Bligh can be reduced. The Hindia Barrage when considered to the reverse filter only, had a coefficient of 10. It has probably given satisfactory service for 13 years. The Zifta Barrage on the Nile, built partly on running sand and mud, uses a ratio 10.2; the Verson Dam in Germany has a ratio 12.2 and the Iron Mountain Dam, on fine sand, has given satisfactory service for four years on an over all ratio of 8.6.

In consideration of these results and the low ratios found satisfactory on coarse sand, it is believed that the following creep-head ratios can be used for sand, assuming good construction and solid concrete or interlocking steel sheet piling cutoffs:

	Unimportant Structures	Average Structures	Very Important Structures
Coarse sand	6	7½	8½
Medium sand	7	9	11
Fine sand	8½	10½	13
Very fine sand or silt	10	12½	15

Dams on Pervious Material Underlaid by Clay or Hardpan to here.

A number of cases were found of dams resting on pervious material underlaid by clay or hardpan with the cutoffs extending into the impervious material. These cannot be analyzed according to either Bligh's or the short-path method. In fact, no satisfactory method of treating them has been found and therefore the data only is given in Table 6.

Consider such a dam founded on a thick layer of pervious material with a sheet pile cutoff extending a few feet into the clay beneath. If well constructed, such a cutoff would entirely stop the flow of the water beneath the dam and result in a head equal to headwater elevation on the upstream side of the piling and to the tailwater level on the downstream side. The entire head of the dam would, therefore, be concentrated on the few feet of creep along the piling in the clay. This would be a severe test on this contact and if even a minute passageway existed water would rapidly flow through it and would probably enlarge it to a certain extent. However, unless the pervious material was very coarse, the clay washed out in enlarging this hole would be filtered out in passing through the pervious material and form an impervious coating on the "filter" which would greatly retard flow through it. Also, the loss of head of the water in passing at high velocity through the pervious material in the immediate vicinity of the "pipe" upstream and downstream ends of the "pipe" through the clay would decrease the velocity and reduce the scour in the "pipe." This action is somewhat analogous to the flow through a nearly closed valve. Under ordinary conditions, therefore, no great enlargement of the opening could be expected.

Another reason why this would be the case is that the flow coming through the small opening upon entering the pervious material would spread out into the greater flow area of the pervious material and lose velocity. By the time it had reached the surface where movement of the particles of pervious material was possible it would

... but a velocity to cause movement. No significant movement of the particles near the bottom of the sheet piling would be possible because they would be surrounded by material which was not moved. Therefore, unless there were enough of these openings to permit sufficient flow to cause piping velocities at the downstream edge of the dam, no danger to the structure would result from them.

It is evident, therefore, that cutoffs into impervious material beneath dams greatly increase the safety of the dam [illegible] even if the contact between the cutoff and the impervious material is not watertight. No satisfactory method has been worked out for estimating how much reduction of travel path can be allowed under these conditions, and since the data at hand is slight, it must remain for the present largely a matter of judgment.

Reverse Filters, Weep Holes, and Drains.

The reverse filter was probably first developed on the Nile River where it was used on Zifta and Assuit barrages. It was also used in the Hindia Barrage in Mesopotamia. It has been used in this country on dams Nos. 7 and 13 on the Mohawk River, and in a modified form in the Coon Rapids Dam on the Mississippi. It consists of a filter placed at the lower edge of the downstream apron, built up of a bottom layer of fine material surmounted by other layers of progressively coarser material. Its function is to filter the water seeping beneath the dam and prevent the removal of any of the fine foundation material. It is called a reverse filter because it is "built" up from the [illegible]

[illegible] filter, [illegible] it [illegible]
[illegible] filters.

Weep holes have been extensively used in America [illegible] were found of their use in other countries. Most of the [illegible] literature on India and Egypt, however, was published [illegible] it is possible that they have come into use there since [illegible] believed that they may be employed to advantage in many cases. [illegible] no record of failure due to them was found.

Weep holes are particularly adapted to Ambursen type dams, where they are used to relieve the upward pressure on the floor and thus increase the stability of the dam against overturning, sliding and piping. Drains and weep holes are also used on downstream aprons where long extensions are desirable to prevent the erosion of the bottom [illegible] are not necessary for security against piping. Their function is to relieve the upward pressure and thus permit the use of a lighter apron.

Table 7 gives a list of dams on which weep holes or drains have been employed, together with the creep-head and creep-path ratio [illegible] the most upstream weep, the foundation material and other pertinent data. Weep holes have been successfully employed on clay, gravel and sand foundations. It is doubtful if they should be used on clay unless a reverse filter is constructed beneath them to prevent the fine particles of clay from being carried through. On the Vandalia Dam a 12-inch layer of gravel beneath the dam performs this function and at the [illegible] Dam the drain consists of a line of tile surrounded by coarse gravel. [illegible] mention is made of special treatment for the weep holes of the Upper form

[illegible]

[illegible] are the [illegible] flow through the weep holes, [illegible] the larger pebbles [illegible] the openings. If weep holes are [illegible] they should be constructed with filters [illegible] material [illegible] out [illegible] them. The use of a [illegible] of reverse [illegible] weep holes has been used extensively [illegible] the [illegible] of [illegible] consisting of a weep hole behind which was placed a pocket of [illegible]. This is believed to be a very good practice.

Table [illegible] shows that weep holes and drains can be used with [illegible] remarkably low creep-head ratios. A striking example of the [illegible] of vents came to light at the [illegible] Rapids Dam. This is [illegible] structure having a thin downstream apron with steel sheet piling [illegible] under the heel of the dam and at the downstream edge of [illegible] apron. Immediately behind the upstream cutoff a drain was [illegible] consisting of a reverse filter discharging into a small [illegible] in the dam. Due to an accident, one of the steel sheet [illegible] the upstream cutoff was pushed down [illegible] proper [illegible] leaving an opening in the cutoff, and reducing the creep distance [illegible] to [illegible]. In spite of this the flow [illegible] the drain [illegible] to have been sufficient to [illegible] and the defect [illegible] was not discovered until a large hole [illegible] below the [illegible] pumped out during repairs to the apron and a blowout occurred. [illegible] not existed it seems almost certain that the [illegible] the dam would have been blown up.

[illegible] example [illegible] of the use of drains [illegible] this was at the Iron Mountain Dam, where a drain tile surrounded with gravel was inserted to relieve the upward pressure on a long thin apron and to prevent disintegration. Drains or weep holes can be safely used in either coarse or fine sand foundations if gravel or a reverse filter is used to prevent the removal of the fine particles. Caution must be used in relying on weep holes which may freeze up. In warm climates this is not a consideration but in cold climates where they are exposed it would not be wise to rely on them.

A word of caution also may not be amiss regarding drains beneath the apron of dams where a hydraulic jump is formed. If the drain discharges downstream from the jump while its position under the apron is upstream from the jump, the pressure beneath the apron will be equal to or greater than that where the drain discharges, which, being below the jump will be greater than the pressure acting downward on the apron due to the thin sheet of water upstream from the jump, and this unbalanced pressure may be enough to lift the apron. In the Iron Mountain Dam the drain discharges at the toe of the base section, upstream from any jump which may form. In this case the drain may be downstream from the jump and discharge upstream, which would cause an unbalanced pressure acting downward on the apron, increasing its stability. Weep holes which discharge directly through the apron would equalize the pressure on the two sides, but they would have to be constructed in such a manner that the high velocities would not remove foundation material through them.

It is believed that by the use of reverse filters, weep holes or drains constructed so that the foundation material beneath the dam cannot flow out through them, and safe from freezing, creep ratios lower by perhaps 15% than those previously suggested could be used for the total creep distances under the structure. This assumes that the vents have sufficient discharge capacity and are not located too near the downstream end of the travel path. No fixed rules can be given on these requirements but the exercise of reasonable judgment would prevent serious mistakes.

Effect of Silting of Riverbed above the Dam

The possibility of silting of the riverbed above the dam should be given serious consideration in determining the permissible creep-head ratio, as it may greatly reduce the upward pressure beneath the dam and the probability of failure by piping. The upward pressure on the Island Park Dam was almost entirely removed in two years or less, only the upward pressure from ground water remaining. The upward pressure on the Hamilton Dam was practically eliminated by silt deposit, in spite of the fact that the gravel plant continuously excavated gravel 100 to 200 feet upstream. Both of these dams are on the Miami River, which has a gravel bed (see Figure 1) and does not carry an unusual amount of silt. On the other hand, the upward pressure on the Sherman Island Dam on the Hudson River does not seem to have changed materially over a period of [illegible] noted.* It is possible, however, that considerable silting [illegible]

*Trans. Am. Soc. C. E., Vol. 93, 1929, p. [illegible]

place when the pond was first filled, which apparently was about 2 [illegible] before upward pressure measurements began. The effect of silt [illegible] reducing the flow under the Granite Reef Dam has already been noted, and the fact that it probably made this dam safe when otherwise its security was doubtful. For an intake dam, where the entire width is composed of gates, extending nearly down to the riverbed, as seems likely to be the case at the intake of the All-American Canal, silting could not be relied upon to increase the security, as the sluicing would periodically remove the impervious silt bed. This effect has been noted at the Grand Valley Dam on the Colorado River.**

**Trans. Am. Soc. C. E., Vol. 93, 1929, p. 1320.

It would not be advisable to count on the silting up above the dam to reduce the necessary travel ratios and at the same time count on vents for further reduction, since if the silting up was effective the vents would be inoperative. It must be remembered, however, that immediately after closure, before the bed has had a chance to silt up, the dam would be subjected to more severe piping conditions, and, therefore, it would be safe to assume in the design only the limited reduction which the dam might stand until it silted up.

Bligh vs. Short-Path Method.

Although Bligh's method of analysis of dams on porous foundations has been widely used, it has been subject to some criticism [illegible] it is believed to be due to an improper presentation of the creep in his theory. Bligh states that the water follows the line of creep and not the path of least resistance. This statement is believed to be in error, for the fact that water would take the path of least resistance seems to be almost axiomatic. If the water flows along the line of creep instead of the shorter path directly through the foundation material it is because the resistance to travel along the line of creep is less than the shorter path. That the resistance along the creep line is frequently less than through the foundation material seems very reasonable, on account of the difficulty of securing as intimate a contact between the more or less plain surface of the dam and the foundation material as between the particles of foundation material themselves.

It should be remembered that Bligh's rule is intended to give dams safe at all points which means that it applies especially to the worst condition that will happen with any reasonable care in construction. The seepage may not follow the creep line at many cross sections of the dam, but the points where there is most danger of failure are likely to be those where the contact between the dam and the foundation material is not so close, and therefore where the Bligh theories most nearly apply.

In a uniform material with an intimate contact with the bottom of the dam the flow beneath the dam would pass almost entirely through the foundation material and the shortest path would be roughly a measure of the velocity and therefore the danger of piping. The shortest path, however, is only an approximate measure." It is understood that the problem of flow beneath dams has been studied by Prof. Pavloski in Russia in great detail by means of models and a method of analyzing the problem developed using a flow net.*

*Hydraulic Laboratory Practice, Freeman, p. 303.

Any theoretical analysis, however, must be based on the assumption of a uniform foundation material, or one varying according to some rule. A few cases of practically uniform material may perhaps be found but the usual case is a material varying widely and with great irregularity within short distances.** Under such conditions

**The Oradell Dam of the Hackensack Water Company, Trans. Am. Soc. C. E., Vol. 89, 1926, p. 1189.

great refinement is not justified, and involved methods like Prof. Pavloski's are not likely to find wide application in the near future because of the difficulty of learning the method and of the uncertainty of its application to the usual foundation conditions. Such studies, however, are valuable as they indicate the true laws governing the flow under dams.

A comparison of the analyses of existing structures by the Bligh and short-path methods does not indicate a superiority of one over the other. The other uncertainties in the problem are so much greater than the difference between the results obtained by the two methods that these differences are not important. In Figure 9 a comparison is made of the creep ratios and short path ratios of existing dams. It shows that the short-path ratios average 75% of the creep ratios, in most cases being between 60% and 90%. Those outside of this range usually have several rows of sheet piling. This indicates that safe values of short-path ratio may be taken as 75% of those previously given for creep-head ratio. There seems, therefore, to be no reason for changing the method of analysis used by this bureau from Bligh's to the short path, but if one prefers the short-path method, no great harm will result if properly used.

It should be noted particularly, however, that the foregoing discussion applies only to safety from piping and not to the computation of upward pressures. No study of the latter was made in connection with this report.

Summary and Conclusions

As a result of the analysis of approximately one hundred structures it may be concluded that the rules given by Bligh usually give results unnecessarily conservative and the somewhat lower values given in the following table may be used:

SUGGESTED MINIMUM RATIOS FOR SAFETY AGAINST PIPING FAILURE

Importance of Structure	Bligh's or Creep-Head Ratios			Short-Path Ratios		
	Unimportant	Average	Very Important	Unimportant	Average	Very Important
Very tough hardpan	3	4	5	-	-	-
Ordinary hardpan or hard clay	3½	4½	5½	-	-	-
Medium clay	4	5	6	-	-	-
Soft clay	4½	5½	6½	-	-	-
Boulders with some cobbles and gravel	3½	4½	5½	2½	3½	4
Gravel with a few cobbles or boulders	4	5	6	3	4	4½
Gravel without cobbles or boulders	4½	5½	6½	3½	4	5
Gravel with large proportion of sand	5	6	7	4	4½	5
Coarse sand with cobbles or boulders	4½	5½	6½	3½	4	5
Coarse sand with some fine gravel	5½	6½	8	4	5	6
Coarse sand	6	7½	9½	4½	5½	7
Medium sand	7	9	11	5	7	8
Fine sand	8½	10½	13	6½	8	10
Very fine sand or silt	10	12½	15	7½	9½	11

These ratios assume good construction work and cutoffs of solid concrete or interlocking steel sheet piling. The meaning of the terms are those current among engineers and not those of the classification adopted by the Bureau of Soils. The studies showed no examples of failure where Bligh's ratios were used.* In fact, for the

* A possible exception to this is the failure of the Plattsburg Dam with creep-head ratio 4.0, which is given by Bligh in one reference as boulders, gravel and sand.

finer materials, if we accept Wood's contention regarding the cause of failure of the Narora and Khanki weirs, no failures at all due to piping were found. For this reason the minimum ratios for this class of material are not definitely fixed and it may be that the values suggested above are still too conservative. In the light of information now available, however, they are believed to be as low as it is safe to go.

Since the conclusion regarding the unnecessary conservation of the Bligh constants for fine material was arrived at, an interesting confirmation of it has been found in the third edition of Bligh's "Practical Design of Irrigation Works," (Preface page vi) which was revised and brought up to date by Mr. F. W. Woods, Chief Engineer of Irrigation Works, Punjab, India. Mr. Wood contends that Bligh should have used a ratio of 11 instead of 15 for ordinary sand.

This study also indicates that, as regards piping failure, there is little to choose between Bligh's line of creep theory and the short-path theory for pervious material, other uncertainties being so [illegible] as to obscure any effect of the smaller difference between these two theories. On clay foundations, however, the short-path theory does not apply. The safe ratios suggested (page 30) for short path analysis are approximately 75% of those suggested for the creep head analysis. It should be recognized, however, that this study did not consider upward pressure and, therefore, the conclusions regarding Bligh vs. short-path methods may not apply to upward pressure.

Weep holes and vents are shown to be advantageous in reducing upward pressure and in decreasing the ratios necessary to prevent piping. Reverse filters also permit lower ratios. With a reverse filter or a sufficient number of weep holes located a reasonable distance upstream from the downstream side, so constructed that they will not freeze or the material beneath the dam cannot escape through them, it is believed that the total length of the travel path for structures [illegible] safely be decreased 15% (from those computed with the ratios given on page 30). In determining the best ratios to adopt in the design of a structure, other factors than foundation material should be considered. [illegible] these are the damage to life and property resulting from failure, the probable competency of the maintenance and the time required to [illegible] temporary repairs in case of failure.

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75 6/15/16 p 1135 - Building Power House and Dam on Sand Foundations

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44	9/8/15	p.193	- Considerations of Sliding, Overturning, Crushing and Blowouts in Dam Design by the Ohio River Board.
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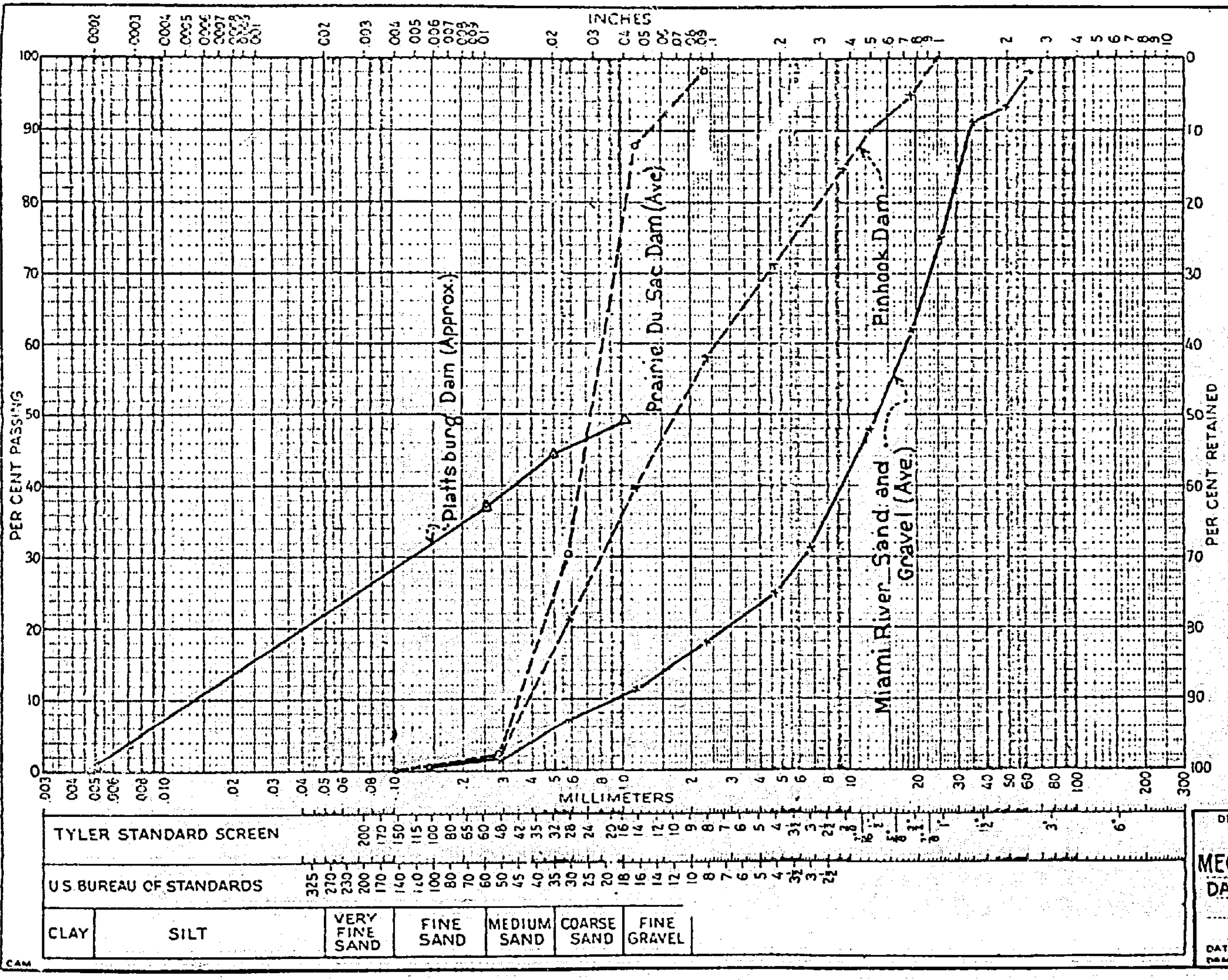


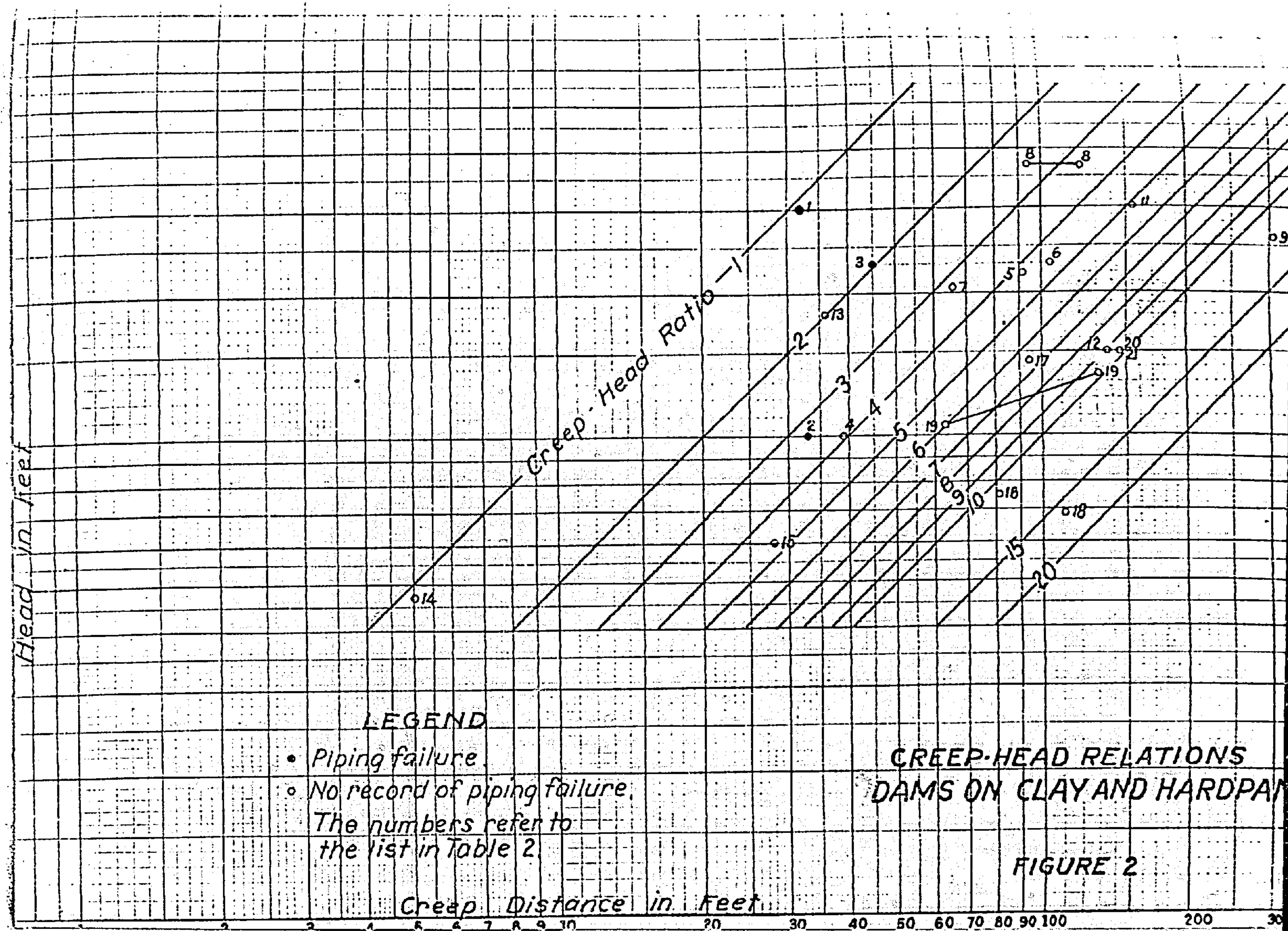
FIGURE 1

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MECHANICAL ANALYSIS
DAM FOUNDATION MATERIAL

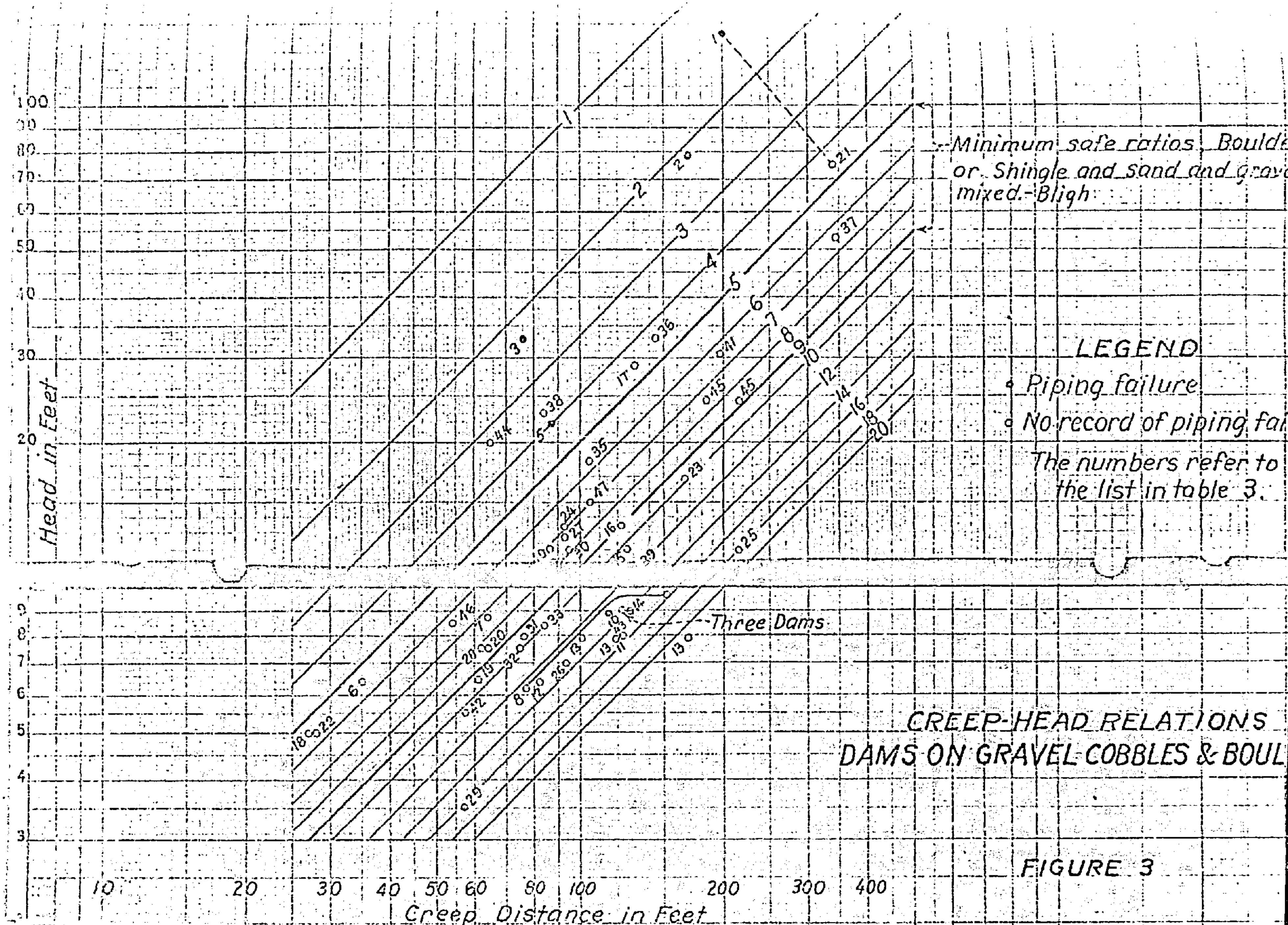
DATE 7-31-30

X-D 5



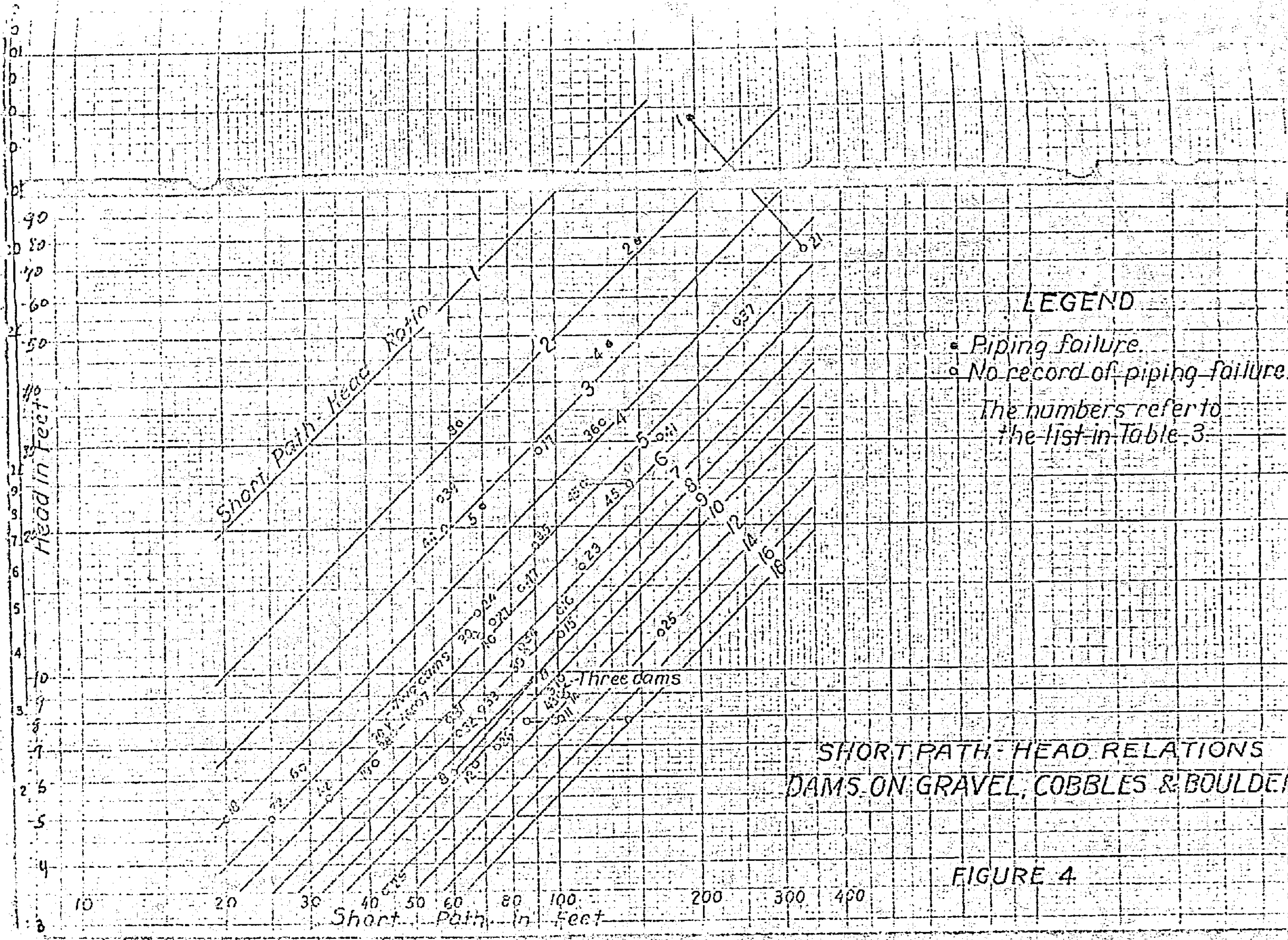
CREEP-HEAD RELATIONS
DAMS ON CLAY AND HARDPAN

FIGURE 2



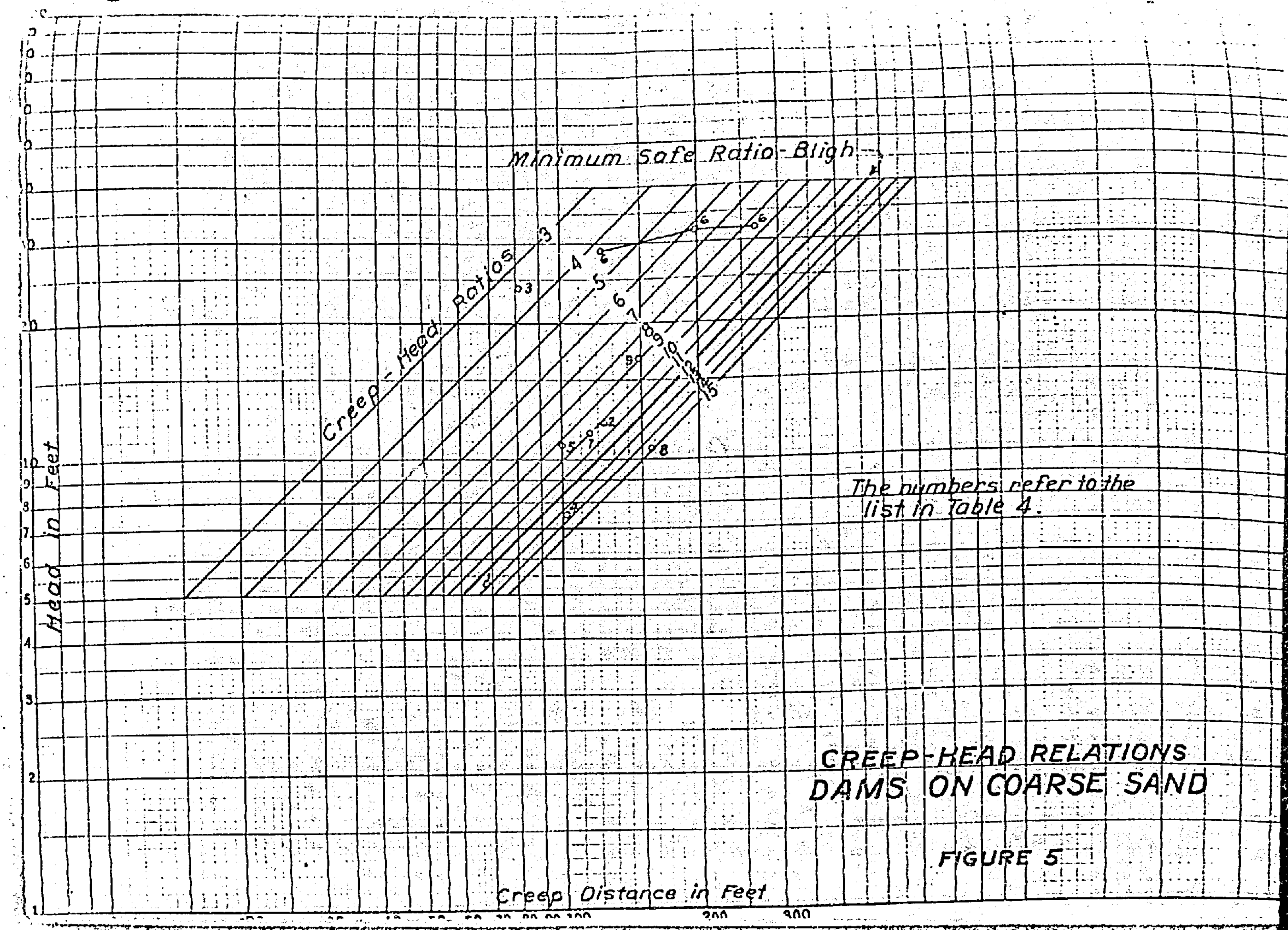
CREEP-HEAD RELATIONS
DAMS ON GRAVEL-COBBLES & BOUL

FIGURE 3



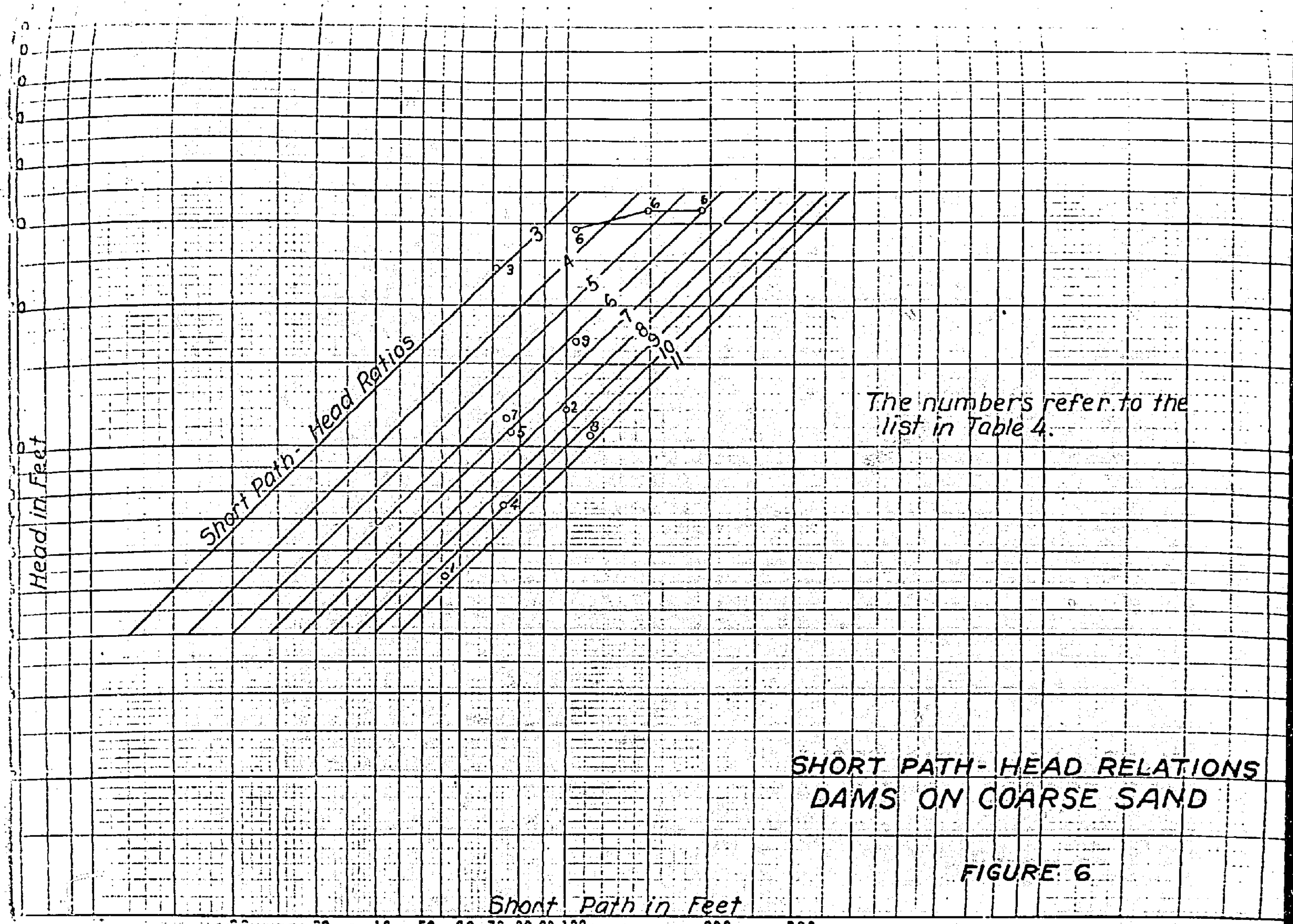
SHORT PATH-HEAD RELATIONS
DAMS ON GRAVEL, COBBLES & BOULDE

FIGURE 4



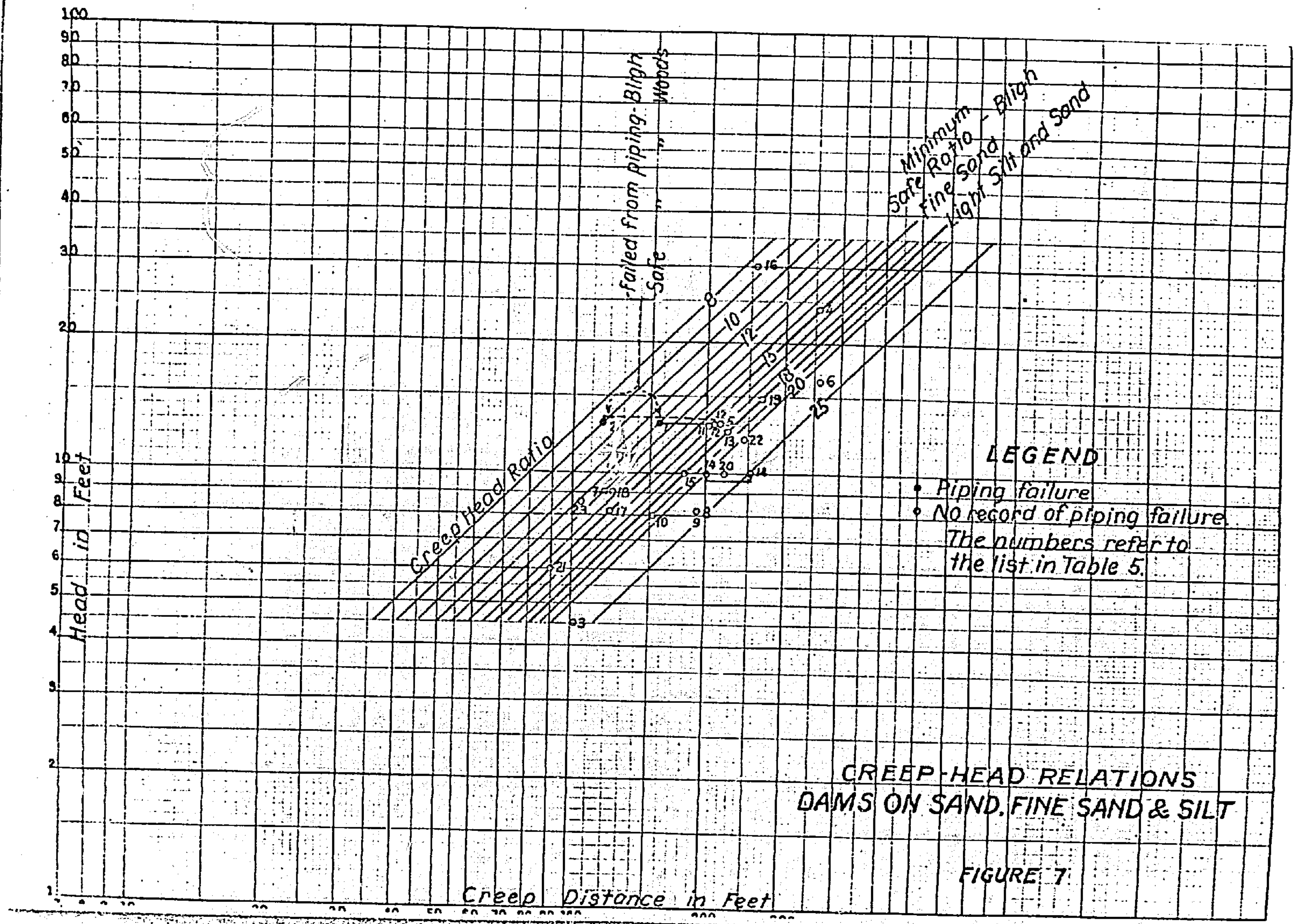
CREEP-HEAD RELATIONS
DAMS ON COARSE SAND

FIGURE 5



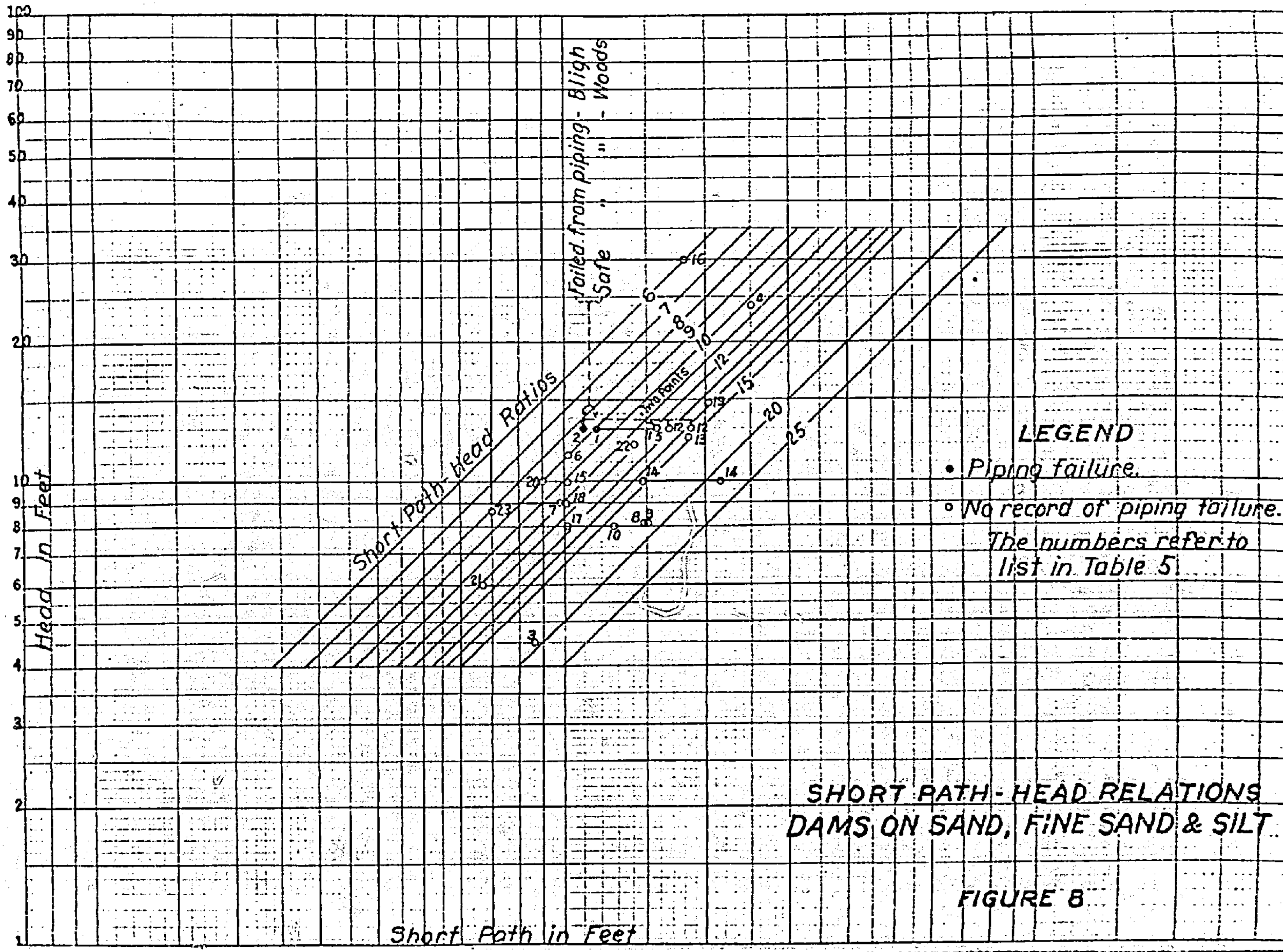
SHORT PATH- HEAD RELATIONS
DAMS ON COARSE SAND

FIGURE 6



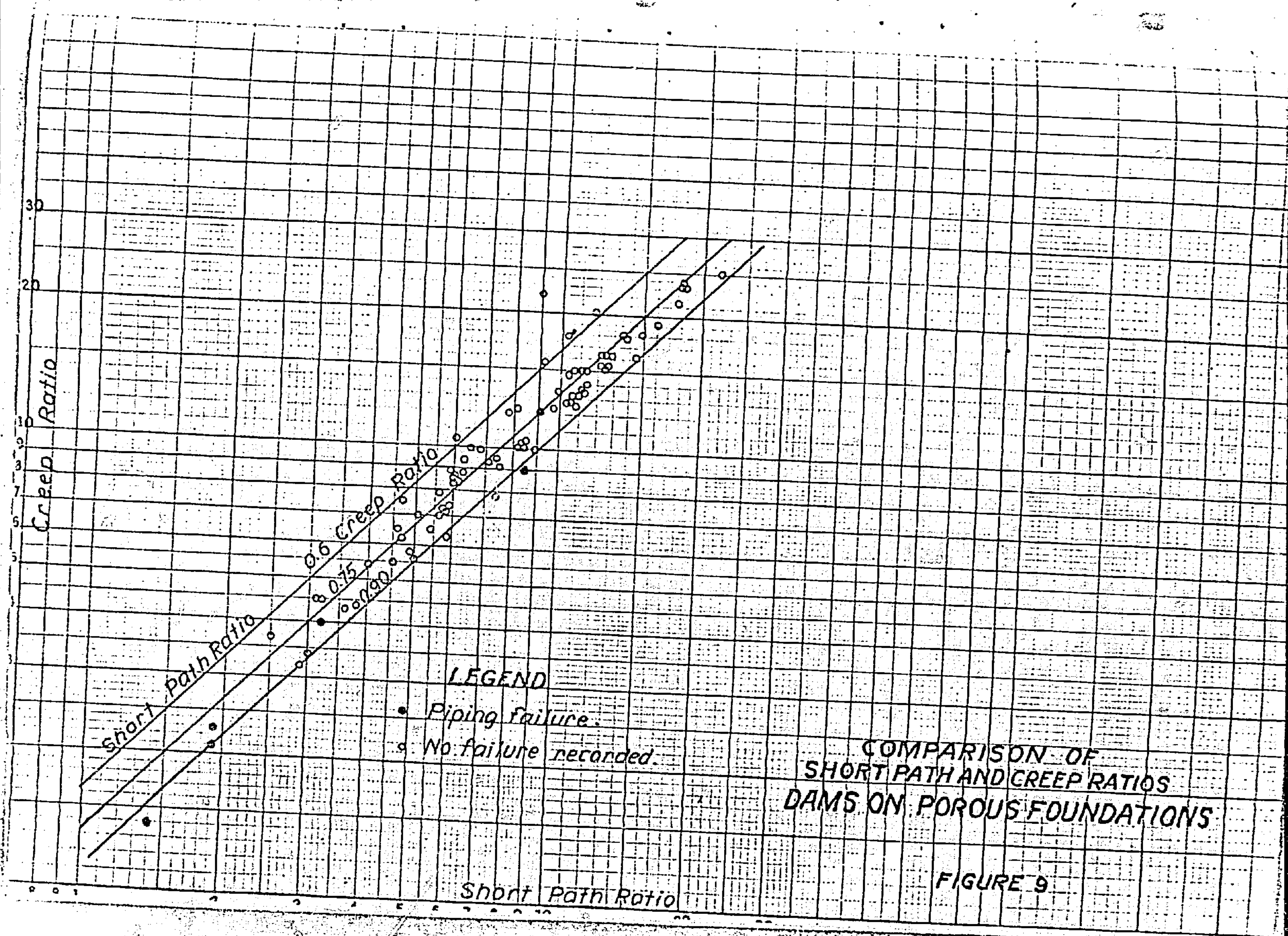
CREEP-HEAD RELATIONS
DAMS ON SAND, FINE SAND & SILT

FIGURE 7



SHORT PATH-HEAD RELATIONS
DAMS ON SAND, FINE SAND & SILT

FIGURE 8



COMPARISON OF
SHORT PATH AND CREEP RATIOS
DAMS ON POROUS FOUNDATIONS

FIGURE 9

DAMS ON CLAY AND HARDPAN

TABLE NO. 1.

No.	Name	Stream	Location	Head	Creep Distance	Ratio	Rata	Condition	Material	Remarks
								FAILURES FROM PIPING		
1	Woodward	Flanders Brook	Hill, N. H.	20	22	1.1	Fair	In service 4 or 5 years	Hard material, probably hardpan. May have had sand layers.	
2	Dolgarrog	Lake Eigiau	North Wales	10	33	3.3	Good	" " 14 years	Hard blue clay containing boulders.	Drying of foundation during low reservoir stage may have caused failure.
3	Fergus Falls	Red River	Minnesota	22	45	2.0	Fair	" " 11 months	Hardpan.	Spring under power house reduced creep distance from 3.5 to 2.0.
								NON-FAILURES		
4	Dolgarrog	Lake Eigiau	North Wales	10	39	3.9	Fair	In service more than 14 years	Hard blue clay containing boulders.	Portion of dam which did not fail.
5	Marysville	Nashwaak River	New Brunswick	22	92	4.2	Good	Has stood 29' head for short time; ratio 3.2	Firm, impermeable red clay with at least 40% boulders.	Downstream apron light. If it blows up ratio will be 3.6.
6	Fergus Falls	Red River	Minnesota	23	104	4.5	Good	In service 11 months	Hardpan.	Failure under power house caused washing out of this section.
7	Kettle Creek	Kettle Creek	Ontario	20.5	66	3.2	Good		Very hard blue clay.	Downstream apron light, if lifted up ratio would become 1.9.
8	Lake St. Francis	St. Francis R.	Quebec	37 37	96 121	2.9 3.3	Fair Good	Successful operation for 12 years	Stiff clay with small boulders and gravel.	Bulkhead section. Spillway section.
9	Vandalia	Milk River	Montana	27 26	304 106	11.2 4.2	Good Good		Stiff clay and clay with fine gravel.	Lower ratio is to first sump hole. Gravel filter beneath sump hole.
10	Cooke	Au Sable River	Michigan	40	340	9.1	Good		Clay.	
11	Upper Grays	Black Creek	Utica, N. Y.	30 30	186 30	6.2 1.0	Uncertain Uncertain	Stood at least 6 months; probably at least 8 years.	Good clay, fairly tempered with sand, underlaid by hardpan.	Cutoff wall goes to fairly good hardpan. An early Ambursen dam. Lower creep ratio is to sump holes.
12	Shawano	Wolf River	Wisconsin	15 15	137 75	9.1 5.0	Good	Has given satisfactory service 2 years.	Stiff, greasy clay.	Lower ratio to gravel-filled drain.
13	Whiting Street		Holyoke, Mass.	[illegible]	36	2.0	Good		Very compact and unyielding gravelly hardpan.	
14	North Diversion, Orland Project		California	4.7	5.0	1.1	Good	Satisfactory service 17 years.	Rather impervious red clay with considerably finely imbedded gravel.	
15	Big Coulee	Big Coulee	Montana	6	26	4.7	Good	Satisfactory service 8 years.	Clay.	
16	Sidhnai	Ravi River	Punjab, India	7.5	81	10.6	Good		Clay.	
17	Dam No. 8	Ouachita River	Louisiana	14.4	96	6.8	Good	Satisfactory service 11 years.	Very dense clay.	
18	Dam No. 5	Ouachita River	Louisiana	6.3	211	15.1	Good	Satisfactory service 6 years.	Hard clay.	
19	Dam No. 6	Ouachita River	Arkansas	10.5 15.5	45 121	6.0 9.7	Good Good	Satisfactory service 11 years and 6 years respectively.	Clay predominating, some sand.	Creep ratio given is for normal head. For maximum head it is 5.7.
20	Dam No. 2 (Rotterdam)	Mohawk River	New York	15	145	9.7	Good			Dam increased in height 5 feet after 11 years' use.
21	Dam No. 5 (Cranesville)	Mohawk River	New York	15	144	9.7	Good	In service 15 years. Some leakage stopped by grouting and additional sheet piles.	On clay, (A portion also on clay overlaid by gravel and sand.)	
22	Junction	Manistee River	Michigan	20	240	7.2	Fair	Satisfactory at least 15 years.	On clay. (A portion also on clay overlaid with thin layer of gravel.)	
								Completed about 1916.	Hard clay.	Pump house.

[illegible]

TABLE No. [illegible]

No.	Name	Stream	Location	Head	Bligh's Method: Creep Dist.	Bligh's Method: Ratio	Shortest Path Method: Short Path	Shortest Path Method: Ratio	Reliability of Data	Results	Foundation Material	Remarks
										DAMS WHICH FAILED		
1	Puentes	Guadalentin River	Spain	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Failed immediately	Sand and gravel classification somewhat uncertain.	No failure at creep-head ratio [illegible]. Apron bank up reducing ratio to [illegible].
[illegible]	Port Angeles	Elwha River	Washington	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Held 2 days	Gravel, small get (?) coarse sand.	Head may have been [illegible] feet.
[illegible]	Pittsfield	West Branch	Massachusetts	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Failed on first filling	Layer of gravel and fine material, underlaid by impervious layer, underlaid in turn by pervious fine material and boulders.	Failed probably through seepage from lower layer causing blowout. Cutoffs extended into impervious layer.
[illegible]	[illegible] Rapids	Mississippi River	Minnesota	[illegible]	—	—	[illegible]	[illegible]	Good	Failed soon after head applied	Sand and boulders.	Creep distance cannot be computed.
[illegible]	Plattsburg	—	New York	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Uncertain	Held probably 2 months	Boulders, fine gravel and sand, not more than 1% clay. See sieve analysis, Figure 1.	A portion having a creep ratio of [illegible] and short path ratio [illegible] not injured.
										DAMS OF WHICH NO FAILURE IS RECORDED		
[illegible]	Horse Creek Diversion	Horse Creek	Wyoming	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for [illegible] years	Coarse sand and gravel to 1/2-inch maximum size.	
[illegible]	[illegible]	Rio Grande River	New Mexico	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 10 years	Medium sand with fair sprinkling of gravel.	
[illegible]	Dam No. [illegible]	Ouachita River	Arkansas	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	Good / Good	Satisfactory for [illegible] years —do— 7 years	Sand and gravel with much fine sand. / Sand and gravel with much fine sand.	
[illegible]	Dam No. [illegible]	Ohio River	Ind.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 4 yrs.	Sand and gravel, much small gravel.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ind.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 8 yrs.	Sand and small gravel.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ill.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 1 yr.	Sand and gravel, much of it fine (sand) later part on flood.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ohio-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 11 yrs	Sand and gravel.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ohio-Ky.	[illegible]	[illegible] / [illegible] / [illegible]	[illegible] / [illegible] / [illegible]	[illegible] / [illegible] / [illegible]	[illegible] / [illegible] / [illegible]	Good / Good / Good	Satisfactory for 5 yrs. / Satisfactory for 5 yrs. / Satisfactory for 5 yrs.	Sand and gravel. / Sand and gravel. / Sand and gravel.	Navigable pass. Bear trap. Fixed weir.
[illegible]	Dam No. [illegible]	Ohio River	Ind.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 8 yrs.	Sand and gravel.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ill.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 1 yr.	Sand and gravel, some clay.	Navigable pass.
[illegible]	Dam No. [illegible]	Ohio River	Ill.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for 1 yr.	Sand and gravel, some clay.	Navigable pass.
[illegible]	Keokuk	Mississippi River	Iowa	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Sand and gravel; see sieve analysis, Figure 1.	Power house blank concrete apron not included.
[illegible]	Richmond		Indiana	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel and sand.	
[illegible]	Power Intake	Salt River	Arizona	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Held about 10 years.	Gravel and sand.	Failed during flood, not by underseepage.
[illegible]	Island Park	Miami River	Ohio	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel and sand; see sieve analysis, Figure 1.	Failed from erosion of apron.
[illegible]	Puentes	Guadalentin River	Spain	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				
[illegible]	Miller Creek	Miller Creek	Oregon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory 6 years.	Satisfactory [illegible]: Sand, gravel and earth.	Height reached [illegible] previous to failure.
[illegible]	[illegible]	[illegible] River	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Recently completed.	Coarse sand and gravel.	
[illegible]	[illegible]	[illegible] River	Armenia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Recently completed.	Coarse sand and gravel.	
[illegible]	[illegible]	[illegible] River	Holland	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Coarse gravel and sand.	
[illegible]	Herr Island	Allegheny River	Pennsylvania	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel.	
[illegible]	[illegible]	[illegible] River	Czechoslovakia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel.	
[illegible]	Hamilton	Miami	Ohio	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel.	
[illegible]	[illegible]	Sacramento River	California	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel.	
[illegible]	Amsterdam (No. [illegible])	Mohawk River	New York	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Satisfactory at least 10 years.	Gravel.	For flood control, at use only at intervals.
[illegible]	[illegible] (No. [illegible])	Mohawk River	New York	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Satisfactory at least 10 years.	Gravel.	Reverse filter sand.
[illegible]	Dam No. [illegible]	Ohio River	Pennsylvania	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory [illegible] years	Gravel.	Reverse filter sand.
[illegible]	Dam No. [illegible]	Ohio River	Ohio-W.Va.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory 10 years	Gravel.	
[illegible]	[illegible]	[illegible] River	Burma	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Gravel and shingle.	
[illegible]	Grand Valley	Colorado River	Colorado	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory [illegible] years	Coarse gravel and cobbles with only small percentage of sand.	
[illegible]	Boise Diversion	Boise River	Idaho	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory [illegible] years	Very compact gravel and cobbles.	
[illegible]	[illegible] Island	Hudson River	New York	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good		Sand and boulders.	
[illegible]	...	[illegible] River	Arizona	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Fair	Satisfactory when reported.	Sand and glacial boulders.	
[illegible]	[illegible]	Rio Grande River	New Mexico	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory 11 years.	Fine sand with small per cent of gravel at surface to heavy boulders with some sand and gravel at bottom of sheet piles.	
[illegible]	[illegible] Diversion	Malheur River	Oregon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Recently constructed.	Fairly well graded sand and gravel with a few boulders.	
[illegible]	[illegible] City	[illegible] River	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Probably satisfactory for 17 years.	Sand, gravel and broken limestone slabs.	
[illegible]	St. Mary's Intake	(Sun River Project)	Montana	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			Sand, gravel and boulders.	
[illegible]	Dam No. [illegible]	Ohio River	Ind.-Ky.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Built [illegible].	Sand, gravel and boulders.	
[illegible]	Granite Reef	Salt River	Arizona	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory [illegible] years.	Gravel and boulders.	
[illegible]	[illegible]	[illegible] River	Connecticut	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	[illegible] / [illegible]	Good / Good		Gravel and small boulders.	Seepage 2 to 3 second-feet from [illegible]-foot length at first. Silted up. Rolling section. Tainter gate section, [illegible] concrete block apron not included in travel distance.
[illegible]	[illegible] Diversion	[illegible] River	Utah	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Recently constructed.	Gravel and boulders.	
[illegible]	[illegible]	[illegible]	Utah	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Good	Satisfactory for [illegible] years.	Gravel and boulders.	

DAMS ON COARSE SAND

TABLE NO. 3.

No.	Name	Stream	Location	Head	Bligh's Method Creep Dist.	Bligh's Method Ratio	Shortest Path Method Short Path	Shortest Path Method Ratio	Reliability of Data	Results	Foundation Material	Remarks
1	Upper Coleroon	Coleroon River	India	5.5	68	12.0	54	10.6	Fair	Stood more than 60 yrs.	Pure, coarse sand.	Reconstructed condition.
2	Narra	Mahanuddee	India	12	186	10.3	100	8.3	Uncertain		Coarse sand.	Creep-head ratio may be 9.1.
3	Riverdale	Apple River	Wisconsin	24	82	3.4	71	3.0	Good	Held at least 8 years.	Torpedo sand.	
4	Sidhnai	Ravi River	Punjab, India	7.5	102	13.6	74	9.9	Good		Coarse sand.	
5	Godavery	Godavery River	Madras, India	10.8	100	9.3	77	7.1	Uncertain	Held at least 20 years.	Coarse sand.	Coefficients may be lower.
6	Prairie du Sac	Wisconsin River	Wisconsin	29 32 33	136 190 246	4.9 6.2 8.8	104 149 181	3.6 4.7 6.0	Good Good Good	In service over 15 years.	Pure coarse sand, see mechanical analysis, Fig. 1.	Dam gates open. Dam gates closed. Power house.
7	Moss Bluff	Ocklawaha River	Florida	11.5	125	10.0	75	6.5	Good		Stratified sand from very fine to very coarse.	
8	Florence	Gila River	Arizona	10.5	157	15.0	112	10.7	Good	Satisfactory 5 years.	Grading from silt and fine sand at surface to coarse sand at bottom of sheet piling.	
9	Dam No. 1	Big Sunflower R.	Mississippi.	16.9	149	8.8	106	6.3	Good	Satisfactory 13 years.	Sand with a little clay, gravel and clayey sand.	

DAMS ON SAND, FINE SAND AND SILT.

TABLE NO. 4

No.	Dam	Stream	Location	Head	Bligh's Method: Creep Dist.	Bligh's Method: Ratio	Shortest Path Method: Short Path	Shortest Path Method: Ratio	Reliability of Data	Results	Foundation Material	Remarks
										DAMS WHICH FAILED		
1	Narora	Ganges	India	13	158	12.2	118	9.1	Good	Failed after 20 years	Fine sand.	Failure probably not caused by piping.
2	Khanki (Lower Chenab)	Chenab River	Punjab, India	13	118	9.1	115	8.8	Fair	Failed after 3 years	Fine sand.	Failure probably not caused by piping. Head may have been 14 feet.
										DAMS OF WHICH NO FAILURE IS RECORDED		
3	Rockwood Heading	Colorado River	California	4.5	101	22.4	86	19.1	Fair	Satisfactory 12 years	Colorado River silt, very fine.	Maximum head 11 feet.
4	Sultan Bend	Murgab River	Turkestan	24	355	14.8	250	10.4	Uncertain	Satisfactory about 20 years	Probably founded on loess.	
5	Zifta	Nile River	Egypt	13	210	16.2	159	12.2	Good		Layer of clay below most of it but running sand and sand below part.	Reversed filter used.
6	Hindia	Euphrates	Mesopotamia	16.4 11.5	361 115	22.0 10.0	309 102	18.8 8.9	Good		Fairly hard silt, dense enough to stand vertically when excavated in the dry.	Lower value assumes path to end of filter section in center of apron.
7	Dam No. 48	Ohio River	Ind.-Ky.	9.0	119	13.2	98	10.9	Good	Constructed 1922	Very fine sand.	
8	Assuit	Nile River	Egypt	8.2	191	23.3	148	18.0	Good		Water-laden fine sand.	Has reverse filter.
9	Esna (Esne)	Nile River	Egypt	8.2	171	25.2	149	18.2	Good		Fine sand.	
10	Jamrao	— —	Sind, India	8	153	19.1	128	16.0			Fine sand.	
11	Narora	Ganges River	India	13	201	15.4	156	12.0	Good		Fine sand.	As repaired after failure.
12	Khanki (Lower Chenab)	Chenab River	Punjab, India	13 13	209 210	16.1 16.1	188 168	14.5 12.9	Good Good		Fine sand. Fine sand.	Weir as repaired after failure; head may be 14 ft. Undersluices; head may be 14 feet.
13	Merala	Chenab River	Punjab, India	12.5	226	18.1	186	14.9	Good		Fine sand.	
14	Lower Jhelum	Jhelum River	India	10	231 202	23.1 20.2	216 149	21.6 14.9	Uncertain Uncertain		Fine sand.	Undersluices. Weir.
15	— —	Middle Loup R.	Nebraska	10	179	17.9	108	10.8	Fair		Sand, probably fine.	
16	Iron Mountain	Menominee River	Michigan	30	257	8.6	180	6.0	Good	Satisfactory for 4 years	Fine sand.	
17	Dam No. 41	Ohio River	Ill.-Ky.	8.0	122	15.2	101	12.6	Good	Completed 1929	Part on fine sand. (Part on sand and gravel.)	
18	Dam No. 47	Ohio River	Ind.-Ky.	9.0	122	13.5	101	11.2	Good	Completed 1927	Sand predominating, very fine to medium. A little gravel, mostly fine.	
19	Nag Hammadi	Nile River	Egypt	14.75	267	18.1	201	13.6	Good		Fine sand predominating, coarse sand and pebbles.	
20	Mendota Headgate	San Joaquin R.	California	10	220	22.0	90	9.0	Uncertain	Stood 20 years	Drifted sand.	Failed, probably due to escape of sand through hole in structure.
21	— —	Bogan River	New South Wales	6	90	15.0	67	11.2	Good	Satisfactory at least 7 years	Sand.	
22	Sandy Lake	—	Minnesota	12	244	20.3	141	11.8	Fair		Sand.	
23	Verden	Ems River	Germany	8.6	156	18.2	70	8.1	Good		Sand.	

TABLE NO. 8.

DAMS ON POROUS FOUNDATION UNDERLAID BY CLAY OR HARDPAN
WITH CUTOFFS EXTENDING INTO THE IMPERVIOUS MATERIAL

No.	Name	Stream	Location	Head	Bligh's Method Creep Perv. Mat.	Bligh's Method Creep Imper Matl.	Short Path Method Short Path in Perv. Matl.	Short Path Method Creep in Imp. Matl.	Reliability of Data	Results	Foundation Material	Remarks
1	Hastings	Mississippi River	Minnesota	19.0	152	0	96	0	Good	Recently constructed	Sand ranging from fine to coarse underlain by clay	Tainter gate section with short apron. Range of values.
					112	20	73	20	"			
					111	14	82	14	"			
					97	28	71	20	"			Roller gate section. Range of values.
					200	12	160	12	"			
					204	8	163	8	"			Tainter gate section, long apron. Range of values.
2	Dam No. 8	Ouachita River	Louisiana	14.8	131	12	87	12	"	Satisfactory 10 years	On sand with 30% clay, underlaid with sand and gravel (sand predominating) and finally a layer of clay	
3	Karabent Intake Gates	Tedgen River	Turkestan	20.6	176	14			"	Satisfactory 3 years	Quicksand, overlying clay with a thin strata of clay in the quicksand	The head given is the maximum head
4	Decatur	Sangamon River	Illinois	17.	182	8	117	8	"	Satisfactory 10 years	Sandy gravel underlaid by dense clay.	
5 *	Dam No. 5 (Rotterdam)	Mohawk River	New York	15.	109	37	77	37	"	In service at least 10 years. Some leakage stopped by grouting & additional sheet piles	On clay, in some portions overlaid by gravel and sand	Distances given are for conditions where gravel is deepest.
6 *	Dam No. 6 (Cranesville)	" "	" "	15.	97	49	47	60	"	Satisfactory at least 10 years	On clay, in some portions overlaid with thin layer of gravel	Distances given are for conditions where gravel is deepest.
7 *	Junction	Manistee River	Michigan	60.	226	100	225	100	Fair	Completed about 1918	On clay overlaid with gravel	Spilling

*-Listed also under dams on clay foundations.

TABLE NO. 6.

Dam	No.	Type	Foundation Material	Weep Hole or Drain	Head	Bligh's Method Ratios: Total Distance	Bligh's Method Ratios: To First Vent	Short Path Method Ratios: Total Distance	Short Path Method Ratios: To First Vent	Remarks
Vandalia	1-9	Ambursen	Clay	Weep hole	27	11.8	4.2			
Upper Grays	1-11	"	"	" "	30	6.2	1.0			
Shawnee	1-12	Ogee, crest gates & apron	"	Gravel-filled drain	15	9.1	6.0			
Pittsfield	2-3	Ambursen	Fine material, gravel and boulders	Weep holes	38	2.8	0.08	1.0	0.76	
Coon Rapids	2-4	Ogee, crest gates & apron	Sand and boulders	Drain with reverse filter	48		0.60	2.7	0.60	See detailed description
Plattsburg	2-6	Ambursen	Sand, gravel, boulders	Weep holes	31	3.2	1.9	2.4	1.8	This part of the dam did not fail
Mesilla	2-7	Ogee, crest gates & apron	Sand and gravel	Weep hole Gravel filter	8.7	7.4	4.9	5.9	5.2	
Miller Creek	2-32		Sand, gravel and clay	Weep hole	8	7.6	6.6	6.0	4.6	
Fremont	2-29		Gravel	" "	8.0	16.8	14.3	12.3	10.9	
Oswegatchie River	2-36	Ambursen	Sand and boulders	" "	23	3.7	1.6	2.6	1.4	
Percha	2-39	Ogee with apron	Sand, gravel and boulders	Weep holes with gravel filter	11	12.0	9.1	7.0	5.8	
Harper	2-40	Gates and apron	Sand, gravel and boulders	Weep holes	18	7.2	4.4	6.0	5.3	
Twin City	2-41	Ambursen	Sand, gravel and limestone slabs	" "	30.5	4.9	4.4	5.4	3.4	
Granite Reef	2-44	Ogee with apron	Gravel and boulders	" "	20	3.2	2.9	2.9	2.3	
Scotland	2-45	Ambursen	" " "	" "	24.4	6.0 7.5	3.8 2.8	5.8 4.7	3.0 3.0	
Weber-Provo	2-46	Ogee with apron	" " "	" "	8.5	4.3	4.8	3.3	3.3	
Strawberry	2-47	" " "	" " "	" "	15	7.0	3.9	5.5	2.9	
Iron Mountain	4-15	Ogee, crest gates & apron			20	6.6	5.7	6.0	4.5	

Table No. 7.

DATA ON OHIO RIVER DAMS

Dam No.	Location	Head Sustained	Bligh's Method: Creep* Distance	Bligh's Method: Ratio	Shortest Distance*	Path Ratio	Portion of Dam	Approximate Date of Completion	A	B	C	D	E	Material
5	Pennsylvania	7.6	76	10.0	62	8.3	Navigable Pass	1904	7	36	32	7	20	Gravel
10	Ohio-W. Va.	8.4	84	10.0	69	8.2	- -	1915	7	42	35	9	20	-
36	Ohio-Kentucky	6.4	82	12.8	67	10.8	- -	1919	7	40	38	9	20	Sand and gravel
[illegible]	- -	7.3	113	16.0	98	13.4	- -	1926	7	77	38	9	20	- - -
			169	21.4	140	17.7	Bear Trap	-	12	77	30	5	20	- - -
			100	12.6	85	10.8	Fixed Weir	-	5	77	20	10	20	- - -
43	Indiana-Ky.	9.0	126	14.0	103	11.4	Navigable Pass	1922	9	77	40	7	20	- - -
44	- -	9.0	122	13.5	101	11.2	- -	1925	10	77	35	7	20	Sand, gravel, and boulders
45	- -	9.0	122	13.5	101	11.2	- -	1927	10	77	35	7	20	Sand and gravel; much small gravel
46	- -	9.0	122	13.5	101	11.2	- -	1928	10	77	35	8	20	Sand and small gravel
47	- -	9.0	122	13.5	101	11.2	- -	1927	10	77	35	7	20	Sand predominating. Very fine to medium. A little gravel, mostly fine
48	- -	9.0	119	13.2	98	10.9	- -	1922	7	77	38	9	20	Very fine sand.
50	Illinois-Ky.	8.0	122	15.2	101	12.6	- -	1929	10	77	35	6	20	Sand and gravel
51	- -	8.0	122	15.2	101	12.6	- -	-	10	77	35	8	20	Part on fine sand; remainder on sand and gravel, much of it fine
52	- -	12.0	126	10.4	102	8.5	- -	-	8	77	40	7	20	Sand and gravel, some clay
53	- -	13.4	122	9.1	101	7.5	- -	-	10	77	35	7	20	- - - - -

* Assumed to end at downstream end of bottom of concrete portion of dam.

Appendix of 45 pages follows, all white on dark blue, and will not reproduce. If needed, consult bound volume.