Quality Control of Earth Embankments

Contrôle qualitatif de remblais en terre

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Summary

Quality control of earth embankment implies: selection of certain properties of the placed embankment to be brought under control; measurement of these properties; analysis of the control tests of these properties; practical limitation of these properties within an acceptable range compatible with design criteria.

The average value of a set of data has certain disadvantages as a control criterion which are shown by actual examples of control test data. Statistical methods are applied to control test data to permit better interpretation of results. The methods of analysis are shown by examples of control data from some Bureau of Reclamation Earth Dams.

The control data are assumed to be obtained under essentially stable conditions. The assumptions for these conditions are strengthened by: separate analysis of tests from each borrow area, sometimes also separated by periods of time; separate analysis of tests from material compacted under different compactive effort; elimination of all tests indicated by the inspectors to be nonrepresentative; special emphasis on the importance of representative sampling; standardized testing and sampling procedures.

Practical limitations of placement moisture and density control are discussed for rolled impervious zones. The discussion is based on results obtained on a number of large earth dams constructed by the Bureau of Reclamation.

The cumulative frequency concept of data presentation is developed for measuring the quality of control based on relatively few tests. This method is believed to be more applicable to periodic control.

Sommaire

Par le contrôle qualitatif de remblais en terre nous entendons: Le choix des propriétés du matériau de remblai qui doivent être contrôlées; la mesure de ces propriétés; l'analyse des essais de contrôle portant sur ces propriétés; la limitation pratique de ces propriétés dans des limites compatibles avec les conditions du projet.

La valeur moyenne d'une série de données a certains désavantages en tant que criteriums de contrôle ainsi qu'il est montré par l'exemple d'essais de contrôle. Les méthodes statistiques auxquelles les auteurs ont recours pour la vérification des essais permettent une meilleure interprétation des résultats. Les méthodes d'analyse sont illustrées par les essais de contrôle de quelques barrages en terre construits par le «Bureau of Reclamation».

On suppose que les essais de contrôle sont faits dans des conditions essentiellement stables. Les hypothèses sur lesquelles s'appuient ces conditions sont: l'analyse séparée des essais de chaque zone de prélèvement, tenant compte parfois des intervalles écoulés entre les prélèvements; l'analyse séparée d'essais sur des matériaux compactés à différents degrés; l'élimination de tous les essais considérés non représentatifs par les inspecteurs; la prééminence accordée à la valeur des échantillons représentatifs; la standardisation des essais et des procédés de prélèvement d'échantillons.

Le présent rapport a pour objet la limitation pratique de la teneur en eau des matériaux mis en place et le contrôle de la densité après compactage pour des zones imperméables. Il est basé sur les résultats obtenus lors de la construction de plusieurs grands barrages en terre par le «Bureau of Reclamation».

Il est montré que le concept fréquence cumulative, utile pour la présentation des essais, permet de chiffrer la qualité des contrôles basés sur peu d'essais. Cette méthode est plus applicable aux conditions usuelles des essais de contrôles périodiques.

Introduction

The term "quality control" has become a familiar phrase in recent years, particularly in referring to manufacturing processes. Industry has almost unanimously turned to the statistician and his methods for obtaining strict control necessary for its continued profitable operation.

The application of statistical methods to quality control of construction materials is not new. The American Society for Testing Materials published a "Manual on Presentation of Data" in 1933, which dealt with the application of statistical methods to test data. Since then, this manual has undergone constant revision and reprinting, the latest edition being published in January 1951 (*ASTM*, 1951).

In contrast to the emphasis placed on quality control of industrial processes and of other construction materials, quality control of earthwork has, in general, been largely neglected or entirely ignored. Perhaps the lag in quality control technique for earthwork is to be expected as a normal consequence of the lag of soil mechanics behind the other sciences. Standardized construction procedures and control methods now in use permit control of placement soil properties within definite, relatively narrow, ranges and statistical methods applied to the control tests permit accurate analysis of the quality of the control.

Scope and Purpose

Quality control of earth embankments implies:—

A. Selection of certain properties of the placed embankment to be brought under control;

B. Measurement of these properties of the placed embankment;

C. Analysis of the control tests of these properties;

D. Practical limitation of these properties within an acceptable range compatible with design criteria.

This discussion is limited mainly to the latter two aspects of the subject, with only brief mention made of the properties chosen for control purposes and of the methods of measuring these properties. The analysis of control test data is based on an application of statistical methods. The practical limitation of the properties under control will be seen from a presentation of factual data, and control charts will be demonstrated which serve as a guide for controlling placement conditions during construction.

Placements Limits

The properties chosen for quality control tests are placement moisture and density, or rather, their variation from the Bureau of Reclamation laboratory standard.[1])

Initial attempts at earthwork control were centered primarily on the unit dry weight obtained in the embankment. The Bureau of Reclamation recognizes both an upper and a lower placement moisture limit as well as a minimum density requirement for rolled impervious fill. The basis of control of compacted pervious zones is primarily a consideration of relative density. This discussion is therefore limited to moisture-density relationships although the methods herein described are applicable to the analysis of other soil properties which may be of importance in certain cases.

The Average Value

While the average value of a series of test data is easily understood and readily computed, it has certain disadvantages as a reliable measure of quality control which can best be shown by actual example. Consider the data in Table 1 taken from a Bureau of Reclamation earth dam. These tests, 24 in number, represent the placement of 58,750 cubic yards of impervious material during a period of one month. While the average placement water content is almost exactly equal to the average laboratory optimum, a careful review of individual tests reveals that no samples were placed at a water content equal to the laboratory optimum. Assuming all of the samples to be representative, we have no material placed in the embankment at the water content indicated by the average value.

Another example of the inadequacy of the average value as a reliable measure of quality control is shown in the case of ten relative density tests of compacted pervious material submitted from a different project. The tests shown in Table 2 represent the placement of about 94,000 cubic yards of material. The minimum requirement for compaction of this

[1] The Bureau of Reclamation standard compaction test is made in a $\frac{1}{20}$-cubic foot cylinder 6 inches high in 3 layers at 25 blows per layer with a $5\frac{1}{2}$-pound hammer dropped 18 inches.

Table 1 Placement Moisture Tests (24 tests representing 58,750 cubic yards of material placed)
Essais sur la teneur en eau du matériau mis en place (24 essais représentatifs de 58,750 cu.yds. de matériau mis en place)

	Placement Moisture %	*Laboratory Optimum Moisture %*	*Variation of Placement from Laboratory Optimum*
	12.0	13.3	—1.3
	13.1	12.0	+1.1
	13.5	14.4	—0.9
	10.9	12.3	—1.4
	9.3	11.0	—1.7
	15.5	13.0	+2.5
	11.1	12.5	—1.4
	11.1	12.0	—0.9
	13.1	13.5	—0.4
	13.8	15.5	—1.7
	15.8	12.8	+3.0
	14.5	14.0	—0.5
	9.0	12.5	—3.5
	12.0	13.4	—1.4
	13.0	12.4	+0.6
	14.9	12.6	+2.3
	13.5	12.5	+1.0
	8.9	12.7	—3.8
	11.0	12.1	—1.1
	15.5	13.7	+1.8
	15.9	12.0	+3.9
	15.6	12.4	+3.2
	10.6	12.7	—2.1
	13.8	13.5	—0.3
Average	12.8	12.9	—0.1

Table 2 Relative Density Tests (10 tests representing 94,000 cubic yards of material placed)
Essais sur la densité relative (10 essais représentatifs de 94.000 cu.yds. de matériau mis en place)

	Relative Density of Zone 2
	51.2
	89.9
	70.4
	84.1
	65.5
	67.4
	82.1
	63.3
	53.7
	54.9
Average	68.3

material was 70 percent relative density. In this case, the average value is near the minimum requirement, and would probably be accepted as satisfactory placement. It is easily recognized from the tabulated values, however, that only 40 percent of the tests are at or above acceptable density. Again assuming the tests to be representative of the total material, 60 percent was placed at less than the minimum density requirement.

Basis of Analysis

The inadequacy of the average values of soil properties as a reliable measure of the placement condition of an earth embankment and the resulting misinterpretation of control data were recognized several years ago, and statistical methods were applied to test data to measure the quality of the control. Statistical methods may be defined as "methods for dealing

Table 3 Moisture Control: Bonny Dam—North Borrow Area—Zone I
Contrôle de la teneur en eau: Barrage de Bonny – Zone de prélèvement nord – Zone I

Fill Moisture Content—% by Dry Weight
446 Tests—1950

16.2	17.5	16.0	15.2	13.9	14.5	15.8	15.5	16.0	16.5
16.2	15.3	14.0	16.5	14.9	16.0	14.9	14.0	13.2	16.5
16.0	16.9	18.5	17.5	17.5	15.5	14.7	16.7	14.8	17.5
14.3	16.9	13.9	14.5	17.7	17.2	16.4	16.2	17.0	15.6
15.6	15.9	16.7	14.8	14.1	13.6	15.9	12.9	13.1	14.4
14.0	15.8	16.3	13.1	16.0	16.0	16.2	16.3	17.3	15.6
15.6	13.3	12.3	17.1	17.3	15.2	15.1	14.5	14.3	14.3
15.0	14.3	14.0	15.3	14.2	16.0	16.7	15.3	14.0	14.3
12.1	15.6	15.2	15.2	16.3	16.5	13.5	12.4	13.4	14.3
14.3	16.3	18.6	17.5	15.2	15.8	16.0	14.0	14.8	14.1
16.6	14.5	15.1	15.4	14.5	14.5	14.6	12.7	16.7	15.4
14.5	13.9	14.3	13.1	13.9	13.3	15.0	12.7	15.1	14.7
13.1	12.7	13.5	14.1	12.9	14.6	14.5	14.4	15.2	14.9
14.1	14.6	15.5	14.8	14.7	14.5	14.0	15.2	16.1	15.3
15.2	15.2	16.1	15.2	15.3	15.9	15.8	15.1	15.1	14.8
16.6	15.6	14.9	16.2	15.7	13.4	15.7	14.8	13.6	14.8
17.3	16.1	15.2	16.1	14.7	16.5	16.0	16.2	16.1	15.7
15.5	15.3	17.1	16.3	14.9	14.6	16.2	13.6	15.1	15.6
15.6	14.5	15.4	15.5	13.8	14.2	17.0	17.3	14.3	12.6
16.1	13.9	16.0	13.5	15.4	13.9	12.0	14.4	12.6	17.9
16.9	17.5	15.0	15.3	17.8	16.7	17.5	16.5	13.6	17.7
15.9	17.6	15.9	14.8	14.2	16.3	15.9	18.8	13.5	15.9
17.4	15.9	14.9	17.6	17.3	16.9	15.3	17.2	*21.6*	15.7
16.3	13.6	15.6	16.3	15.1	14.3	16.2	16.3	15.0	15.9
13.8	17.0	13.8	16.3	16.0	12.4	15.6	17.7	14.8	15.1
15.8	12.4	16.3	16.3	17.0	17.1	15.0	15.8	16.4	17.0
15.4	16.4	18.7	17.1	17.6	16.9	15.2	15.5	15.1	17.5
17.6	17.1	16.7	15.4	15.3	15.4	16.0	15.8	15.6	15.3
16.6	17.6	13.7	18.1	17.1	15.9	16.6	15.1	16.9	15.5
15.4	15.0	15.3	14.5	14.2	14.9	15.4	14.7	15.6	16.8
15.3	13.6	16.4	15.3	15.9	14.2	16.8	15.4	14.6	15.2
14.2	16.7	14.6	14.9	14.2	16.2	12.3	14.4	14.5	16.6
15.5	16.0	15.6	16.4	15.3	17.3	15.2	18.0	15.9	15.4
16.7	15.0	15.9	16.0	15.2	16.7	14.8	14.9	17.5	16.5
14.1	13.3	15.1	15.1	16.5	16.1	18.8	17.1	16.7	17.3
15.6	15.3	14.4	17.6	15.3	15.3	14.7	16.1	14.9	14.7
17.2	13.5	14.9	16.5	12.4	15.3	17.2	18.7	16.7	16.6
16.5	17.1	15.5	17.1	17.1	17.3	19.7	15.8	16.9	17.7
19.6	16.2	15.3	14.9	16.0	15.3	16.5	17.1	15.2	15.6
18.7	15.9	16.5	16.2	17.1	17.7	17.0	16.7	16.4	15.9
12.0	16.4	15.5	15.1	13.9	14.8	15.8	14.7	15.2	15.8
16.6	14.4	*11.8*	15.3	16.8	16.4	14.4	14.8	13.4	
13.9	14.7	13.3	14.8	15.8	16.7	15.5	16.0	18.5	
12.6	15.4	15.3	14.2	15.5	14.2	14.7	14.6	14.3	
14.4	14.0	14.3	15.8	15.7	14.6	14.4	14.8	12.4	

average = 15.5

with data that have been obtained by repetitive operation". Experience indicates that many repetitive operations behave as though they occurred under essentially stable conditions, i.e., there is only one variable to be measured by the operation. The field density tests from which the placement moisture-density relationship is determined, and the standard laboratory compaction tests from which maximum density and optimum moisture content for a given compactive effort are determined, are considered to be repetitive operations fitting this condition. In other words, variations of test results due to testing or sampling techniques are ignored and the soil property under test is assumed to be the only variable to be measured. When data from this type of operation are classified into groups with special interest centered on the number of operations in each group, the data are said to be in the form of a frequency distribution. Under this condition, there is a mathematical model which can be employed to study the variation of the measured property.

Table 3 consists of a set of data from the control tests of a large earth dam. The mass of figures compiled in this manner has little significance. The arithmetical mean of 15.5 percent may be computed rather easily and, by visual perusal, the maximum and minimum values of 21.6 and 11.8 percent can be detected. This set of data may be conveniently grouped in the manner of a frequency distribution as shown in Fig. 1. Values of the variable are grouped into classes and the frequency of occurrence of each value is tabulated in the proper group. One measure of the dispersion or scatter of the values from the mean is called the standard deviation. This measure is defined as the root-mean-square of the deviation of the values from their arithmetical mean. The formula for standard deviation in this case in which an arbitrary or guessed mean is chosen is:

$$\sigma = \sqrt{\frac{\Sigma f d^2}{N} - \frac{(\Sigma f d)^2}{N} - C}$$ (*Arkin* and *Colton*, 1946)

where:

σ = Standard deviation
Σ = Summation
f = Number of operations occurring in each group of values
d = Deviation of mid-value of each group of values from the guessed mean of the set of data
N = Total number of operations
C = A correction for grouping the values.

The standard deviation is determined from this set of data to be ± 1.4 percent.

The mathematical model most commonly used for analyzing frequency distributions of data obtained from repetitive operations, is the "Normal Distribution", as it has been found that many data of this type are approximated well by the theoretical normal curve. There are a number of characteristic properties of this curve which can be defined mathematically, one of which is the standard deviation. This property, described in terms of area under the curve (total number of operations), has the following characteristics as shown in Fig. 2:—

$m \pm \sigma$ = 68.26 percent of the area
$m \pm 2\sigma$ = 95.46 percent of the area
$m \pm 3\sigma$ = 99.73 percent of the area.

Thus, the standard deviation property is a valuable tool in describing the frequency of occurrence of a variable within any arbitrarily chosen limits. It has been used as a criterion of control, keeping always in mind the following considerations:—

A. Each test is considered to be representative of equal amounts of embankment material;
B. The operation of sampling and testing is considered to be repetitive;
C. The value is used for approximating limits embracing $\frac{2}{3}$ of the tests.

The assumption of repetitive operation (B, above) is strengthened by:

A. Separate analysis of tests from each borrow area, sometimes also separated by periods of time;
B. Separate analysis of tests from material compacted under different compactive efforts;
C. Elimination of all tests indicated by the inspectors to be nonrepresentative;

MOISTURE CONTROL

Bonny DAM — NORTH BORROW AREA — ZONE One

446 Tests - 1950

FILL WATER CONTENT Percentage by dry weight	f	d	fd	fd²
21.5-21.9	1	13	13	169
21.0-21.4		12		
20.5-20.9		11		
20.0-20.4		10		
19.5-19.9	2	9	18	162
19.0-19.4		8		
18.5-18.9	8	7	56	392
18.0-18.4	2	6	12	72
17.5-17.9	22	5	110	550
17.0-17.4	31	4	124	496
16.5-16.9	42	3	126	378
16.0-16.4	55	2	110	220
15.5-15.9	59	1	59	59
15.0-15.4	71			
14.5-14.9	56	-1	-56	56
14.0-14.4	43	-2	-86	172
13.5-13.9	23	-3	-69	207
13.0-13.4	12	-4	-48	192
12.5-12.9	8	-5	-40	200
12.0-12.4	10	-6	-60	360
11.5-11.9	1	-7	- 7	49
TOTALS	446		262	3734

Average optimum moisture	16.2
Average fill moisture	15.5
Mean variation from opt. moisture	-0.7
Standard deviation	±1.4

Fig. 1 Distribution of Fill Moisture
Distribution de la teneur en eau du massif

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2} \quad \text{where} \quad \sigma = \sqrt{\frac{\Sigma(x-m)^2}{N}}$$

and N is the total number of values

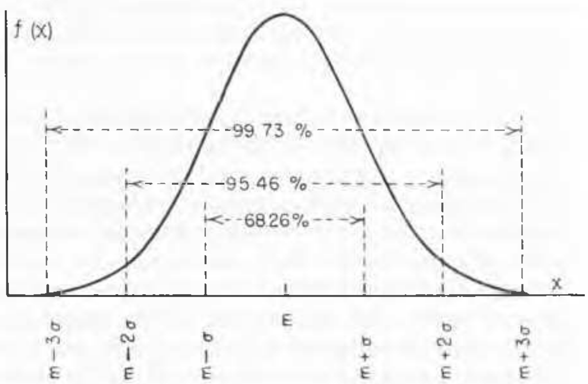


Fig. 2 Typical Normal Distribution
Distribution normale typique

D. Special emphasis on the importance of representative sampling;

E. Standardized sampling and testing procedures.

The analysis shown in Fig. 1 gives a measure of the dispersion or distribution of the placement moisture content, but does not give any hint to the placement-optimum relationship which is really the important control criterion. It is, therefore, more advantageous to tabulate the variation of the placement moisture from the laboratory optimum in each case, as in Fig. 3, than to consider individual values. Interpreting the data in this figure in terms of standard deviation of the variation, it may be said that the placement water content of approximately $\frac{2}{3}$ of the tests fall within the limits of 0.6 percent above and 2.0 percent below the laboratory optimum condition.

The above data are only one example of the approximation of control test data to the normal distribution curve. A study of earthwork control data shows this tendency toward normal distribution for all of the usual control tests, i.e., densities, moisture contents, penetrations-resistance needle readings,

EARTHWORK CONTROL WORK SHEET

MOISTURE CONTROL

Bonny DAM — NORTH BORROW AREA — ZONE One

446 Tests - 1950

FILL WATER CONTENT OF MINUS NO. 4 MATERIAL VARIATION FROM LAB. OPTIMUM	f	d	fd	fd²
% ABOVE 4.8-5.2				
4.3-4.7	1	9	9	81
3.8-4.2		8		
3.3-3.7	1	7	7	49
2.8-3.2	2	6	12	72
2.3-2.7	5	5	25	125
1.8-2.2	8	4	32	128
1.3-1.7	23	3	69	207
0.8-1.2	20	2	40	80
0.3-0.7	28	1	28	28
+0.2-0.2	64			
% BELOW 0.3-0.7	57	-1	-57	57
0.8-1.2	[illegible]	-2	-174	348
1.3-1.7	60	-3	-180	540
1.8-2.2	53	-4	-212	848
2.3-2.7	14	-5	- 70	350
2.8-3.2	13	-6	- 78	468
3.3-3.7	4	-7	- 28	196
3.8-4.2	4	-8	- 32	256
4.3-4.7		-9		
4.8-5.2	2	-10	- 20	200
TOTALS	446		-629	4033

Average optimum moisture	16.2
Average fill moisture	15.5
Mean variation from opt. moisture	- 0.7
Standard deviation of variation	±1.3

Fig. 3 Distribution of Fill Moisture about Optimum
Distribution de la teneur en eau du massif référé à l'optimum

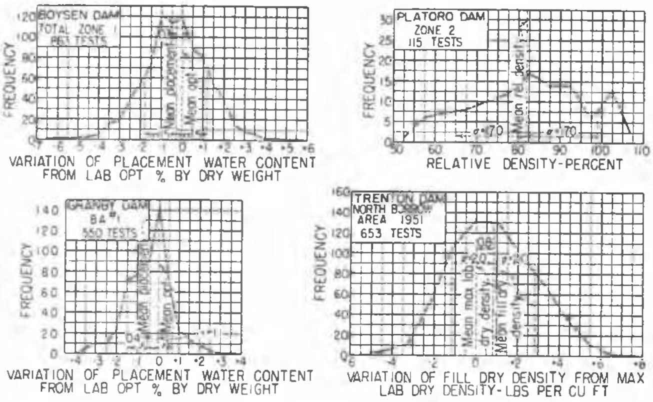


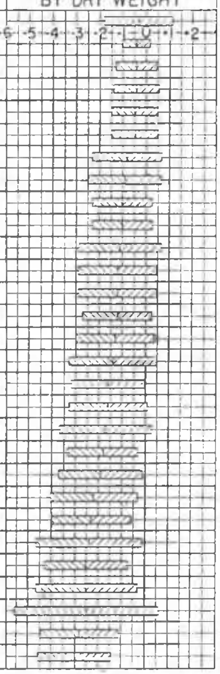
Fig. 4 Typical Frequency Distribution Curves
Courbes typiques de la fréquence de distribution de la teneur en eau

specific gravities, and relative densities. Fig. 4 shows some typical frequency distributions of soil properties selected from Bureau of Reclamation control data.

Results Obtained

Fig. 5 shows the placement moisture control achieved on a number of Bureau of Reclamation dams. The projects are listed in order of the magnitude of the variation between mean placement condition and mean laboratory optimum. Several trends can be readily observed. There is one group which was

DAM	MATERIAL SOURCE	NO. OF TESTS	VARIATION OF PLACEMENT WATER CONTENT FROM OPT. IN PERCENT BY DRY WEIGHT
BOYSEN	All Areas	863	
GREEN MOUNTAIN	All Areas	1066	
PLATORO	All Areas	304	
GRANBY	Area #1	550	
ANGOSTURA	Area C	117	
ANDERSON RANCH	Dixie Pit	2139	
BONNY	North Area	1069	
HEART BUTTE	All Areas	365	
SHADEHILL	Main Embankment	648	
MEDICINE CREEK	All Areas	1347	
CEDAR BLUFF	All Areas	2692	
BONNY	South Area	771	
DAVIS	Area E	491	
SHADEHILL	Wing Dam	309	
ENDERS	All Areas	888	
O'SULLIVAN	All Areas	1739	
DICKINSON	All Areas	279	
SHADEHILL	Dikes	85	
BONNY	Required Excavation	260	
LONG LAKE	Area #5	150	
LONG LAKE	Cut-off Trench	46	
SOUTH COULEE	Area #2	410	
HORSETOOTH	All Areas	288	
LONG LAKE	Area #1	190	
SOLDIER CANYON	All Areas	301	
NORTH COULEE	All Areas	291	
JACKSON GULCH	Areas F & G	203	
DIXON CANYON	All Areas	240	
SPRING CANYON	All Areas	218	



EXPLANATION
Mean Valve
Mean ± one std deviation

Fig. 5 Moisture Control. Variation of Mean Placement Water Content from Laboratory Optimum and Standard Deviation of Variation
Contrôle de la teneur en eau. Variation de la teneur en eau moyenne du matériau mis en place par rapport à la valeur optima en laboratoire et déviation standard de cette variation

placed at an average of 0.5 percent or less below the optimum. This group has, with the exception of Boysen Dam, a very small standard deviation. Green Mountain, Platoro, and Granby Dams all had borrow pits which were naturally conditioned to about this mean placement moisture content. Apparently, natural conditioning of pits results in a very uniform dispersion of moisture. In the case of Angostura Dam, the borrow pit consisted of a stratum of lean clay overlying sand and gravel. A well-planned system of pre-irrigation, initiated well in advance of excavation in this case, resulted in uniformity of moisture content which approximated the naturally conditioned pits noted above. At Anderson Ranch Dam, the occasional addition of small amounts of water on the fill was effected by application of water to the material as it dropped from the conveyor used for transportation of borrow material to the embankment. Boysen Dam, with a mean placement condition near the optimum, is the exception to this group of very small standard deviations. In this case, the borrow areas were, for the most part, very dry. Considerable water had to be added as other considerations required placement at near optimum condition. Some pre-irrigation was performed in the pits but apparently not far enough in advance to obtain uniform dispersion of the added water. In most cases it was a matter of mixing very wet and very dry components of soil. Sometimes, excessively wet material from the bottom of the pit was purposely included in the cut in an attempt to bring the placement moisture of the total material to a desirable mean. In addition, about 2 percent moisture had to be added on the fill. Extensive attempts to obtain a uniform dispersion of moisture by mixing soil components which are both too dry and too wet were not effective.

Below this group is a large number of dams in which the standard deviation varies from about 1.5 to 2.0 percent. All of this group had dry borrow areas of varying degree. Most of the projects attempted pre-irrigation of areas. The smallest deviations for the group are Shadehill and Medicine Creek Dams. Borrow areas for these two projects were characterized by relatively shallow depths of fine-grained material overlying pervious strata. The effectiveness of pre-irrigation in such borrow areas is evidenced by the relatively small standard deviations. Larger values of standard deviation occurring in this group may also be explained by a knowledge of the borrow areas. The required excavation at Bonny Dam, consisting of very fine silt, was 6 to 8 percent dry of the optimum condition. No attempt was made to pre-irrigate this material. The addition of 4 to 6 percent of water on the fill could not be effectively handled even by mixing in thin layers. In the south borrow area at this project, sprinkling operations were barely kept abreast of excavation, but were kept well in advance of excavation in the north area. These differences in moisture application operations are reflected in the standard deviation values of 2.0, 1.7, and 1.5 for the respective sources.

Other variations in the standard deviation values can be correlated with borrow area conditions and moisture application operations. From the evidence in the chart, it seems clear that for close moisture control of an embankment, preconditioning of borrow areas is mandatory. The period of irrigation required depends on the character of the borrow area. Areas naturally conditioned to approximately optimum water content result in a very narrow range of control; however, for very high dams, it may be necessary to reduce the water content to a considerably drier range of placement.

Fig. 6 presents fill-dry unit weight data for the same projects shown in Fig. 5. This figure again calls attention to the fallacy

Fig. 6 Dry Unit Weight Control. Variation of Mean Fill Dry Unit Weight from Laboratory Maximum and Standard Deviation of Variation
Contrôle du poids sec unitaire. Variation du poids sec unitaire du massif par rapport à la valeur maxima en laboratoire et déviation standard de cette variation

of the average or mean value as a reliable measure of control. The usual Bureau of Reclamation requirement for dry unit weight in an impervious rolled fill is 98 percent of the laboratory maximum. Usually the design is predicated on a minimum density of at least this magnitude. While the mean placement condition is, in most cases, above the minimum requirement, it is clearly evident that much embankment has been placed at lesser densities.

Some of the low densities and wide variations can be readily explained by a knowledge of the project conditions. In the case of Shadehill Wing Dam, for instance, the relatively low values of fill density result from a lack of homogeneity. The material was excavated in the borrow area by tractor-drawn scrapers working on a sloping cut in an attempt to mix two distinct strata of material, i.e., a top layer of clay with an underlying layer of gravel. Even with extensive mixing operations on the fill, a lack of homogeneity is reflected by low compaction. In contrast, similar material was excavated for the main embankment by Euclid loader equipped with a vertical cutting arm. A homogeneous material resulted from this excavation which accounts in large part for the superior compaction control obtained on this part of the embankment.

Control Charts

As previously explained, data presented in the usual form of a frequency distribution afford an excellent means of measuring the dispersion of the data about its central value. However, unless the control limits happen to coincide with the limits defined by $m \pm \sigma$, the curve does not reveal information about the percentages of occurrence beyond the desired limits. For periodic control, it is more desirable to use the "cumulative frequency" concept of analysis. Figs. 7 and 8 are work sheets containing data relative to control tests from a borrow area for one particular reporting period. Figs. 9 and 10 are graphical presentations of data compiled in this way. Similar control charts may be constructed for other soil properties. For construction control of earth embankment, these charts and similar ones for relative density of pervious zones, are the principal ones in use. From these charts, the degree, or quality of the control can be readily and accurately judged.

Cochumo DAM ZONE 1

Borrow Area

FILL γ_d OF MINUS NO 4 MATERIAL — VARIATION FROM MAX LAB. γ_d (γ_d = UNIT DRY WEIGHT)

		F (PREV)	This period: Frequency of occurrence			This period: F	Cum F	Cum %	To date: F	Cum F	Cum %
LBS. BELOW	>12.6										
	11.6-12.6										
	10.5-11.5										
	9.4-10.4	1	I			1	1	1.2	2	2	1.5
	8.3-9.3		I			1	2	2.5	1	3	2.3
	7.2-8.2		II			2	4	4.9	2	5	3.8
	6.1-7.1	1	III			3	7	8.6	4	9	6.8
	5.0-6.0	5	I			1	8	9.9	6	15	11.4
	3.9-4.9	5	𝍸	IIII		9	17	21.0	14	29	22.0
	2.8-3.8	12	𝍸	𝍸	I	11	28	34.6	23	52	39.4
	1.7-2.7	6	𝍸	𝍸	I	11	39	48.1	17	69	52.3
	0.6-1.6	8	𝍸	II		7	46	56.8	15	84	63.6
+0.5 TO -0.5		3	𝍸	𝍸		10	56	69.1	13	97	73.5
LBS. ABOVE	0.6-1.6	4	𝍸	II		7	63	77.8	11	108	81.8
	1.7-2.7	2	𝍸	𝍸		10	73	90.1	12	120	90.9
	2.8-3.8	2	IIII			4	77	95.1	6	126	95.4
	3.9-4.9	1	II			2	79	97.5	3	129	97.7
	5.0-6.0	1	II			2	81	100	3	132	100
	6.1-7.1										
	7.2-8.2										
	8.3-9.3										
	9.4-10.4										
	10.5-11.5										
	11.6-12.6										
	>12.6										
TOTALS		51				81			132		

	PREV	THIS PERIOD	TO DATE
Average max lab γ_d	114.0	112.8	113.3
Average fill γ_d	112.0	111.4	111.7
Mean variation from max lab γ_d	-2.0	-1.4	-1.6
Average rock content (% of plus No 4 by dry weight)	21.0	26.1	24.1

PERIOD OF REPORT 12-1-51 TO 12-31-51
TESTS 11-29-A-1-R TO 12-27-A-1-R

Fig. 7 Earthwork Control Work Sheet. Dry Unit Weight Control
Formule pour le contrôle du terrassement. Contrôle du poids sec unitaire

Cochumo DAM ZONE 1

Borrow Area

FILL MOISTURE OF MINUS NO 4 MATERIAL — VARIATION FROM LAB OPTIMUM

		F (PREV)	This period: Frequency of occurrence				This period: F	Cum F	Cum %	To date: F	Cum F	Cum %
% BELOW	>5.7											
	5.3-5.7											
	4.8-5.2											
	4.3-4.7											
	3.8-4.2											
	3.3-3.7		III				3	3	3.7	3	3	2.3
	2.8-3.2	1	III				3	6	7.4	4	7	5.3
	2.3-2.7	7	III				3	9	11.1	10	17	12.9
	1.8-2.2	10	𝍸	𝍸	I		11	20	24.7	21	38	28.8
	1.3-1.7	7	𝍸	III			8	28	34.6	15	53	40.2
	0.8-1.2	9	𝍸	𝍸	𝍸	II	17	45	55.6	26	79	59.8
	0.3-0.7	8	𝍸	𝍸	𝍸	III	18	63	77.8	26	105	79.5
+0.2 TO -0.2		5	𝍸	IIII			9	72	88.9	14	119	90.2
% ABOVE	0.3-0.7	1	II				2	74	91.4	3	122	92.4
	0.8-1.2	1	III				3	77	95.1	4	126	95.4
	1.3-1.7	1	III				4	81	100	5	131	99.2
	1.8-2.2										131	99.2
	2.3-2.7										131	99.2
	2.8-3.2	1								1	132	100
	3.3-3.7											
	3.8-4.2											
	4.3-4.7											
	4.8-5.2											
	5.3-5.7											
	>5.7											
TOTALS		51					81			132		

	PREV.	THIS PERIOD	TO DATE
Average optimum moisture	14.8	15.4	15.2
Average fill moisture	13.6	14.5	14.1
Mean variation from opt moisture	-1.2	-0.9	-1.1

PERIOD OF REPORT 12-1-51 TO 12-31-51
TESTS 11-29-A-1-R TO 12-27-A-1-R

Fig. 8 Earthwork Control Work Sheet Moisture Control
Formule pour le contrôle du terrassement. Contrôle de la teneur en eau

Figs. 11 and 12 are typical cumulative-frequency curves demonstrating good control on two types of compacted material.

Conclusions

Engineers are being called on to design and construct earth embankments of increasing height at increasingly difficult sites. The degree of control of placement properties of earth embankments has, along with advanced knowledge of soil mechanics, an important role in the engineering of these structures. Correct evaluation of the quality control is necessary if the control is to be properly considered as a factor in this design and construction.

It has been demonstrated that the average value applied to earthwork control tests is not a reliable means of evaluating these data. Statistical methods can be readily applied to such data and afford an excellent measure of the quality of the control.

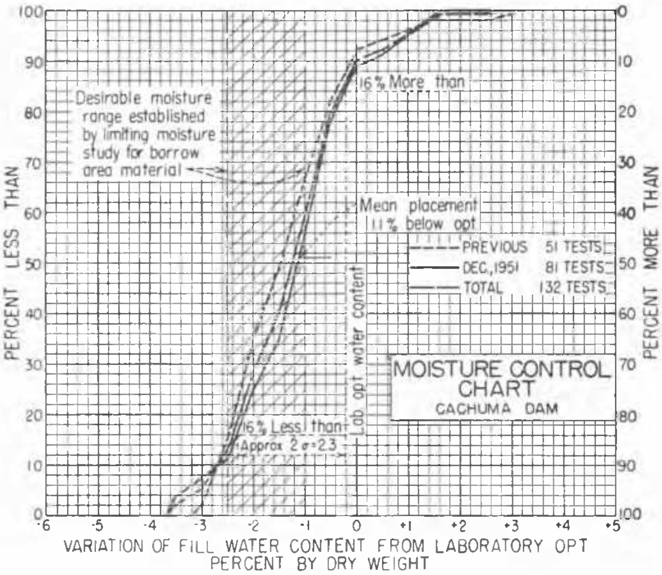


Fig. 9 Moisture Control Chart. Cachuma Dam
Diagramme de contrôle de la teneur en eau. Barrage de Cachuma

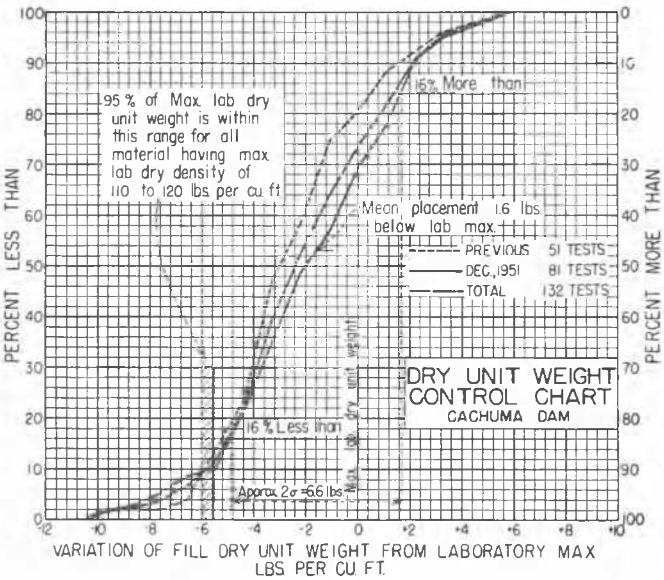


Fig. 10 Dry Unit Weight Control Chart. Cachuma Dam
Diagramme de contrôle du poids sec unitaire. Barrage de Cachuma

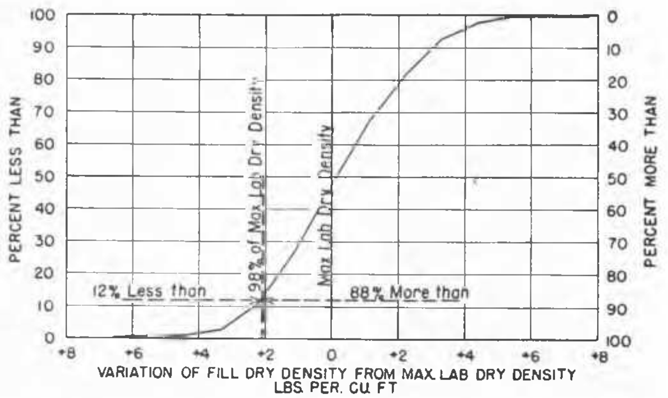


Fig. 11 Typical Frequency Distribution Curve Dry Density—North Borrow Area—Trenton Dam 653 Tests—1951
Courbe de la cloche typique – Densité à sec – Zone de prélèvement nord – Barrage de Trenton – 653 essais – 1951

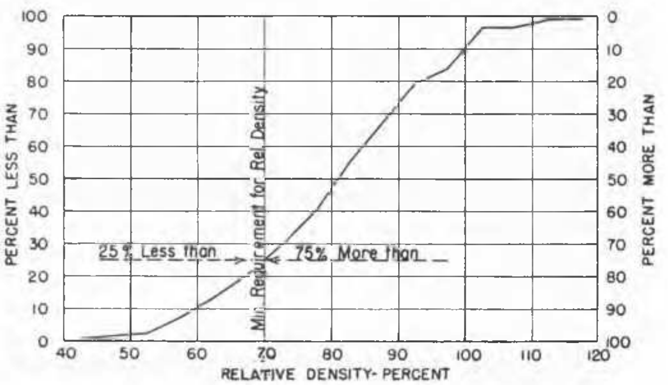


Fig. 12 Typical Frequency Distribution Curve Relative Density of Zone 2—Platoro Dam 115 Tests
Courbe typique de la fréquence de distribution de la teneur en eau – Densité relative de la Zone II – Barrage de Platoro – 115 essais

The evidence resulting from statistical analysis of a large amount of control data suggests:—

A. Relatively narrow ranges of placement moisture and density can be obtained by practical and ordinary construction procedures.

B. Designs may be based on anticipated quality of control. Quality control may be estimated from previous results obtained under similar borrow area conditions and construction methods.

C. Critical designs may be based on predetermined limits of placement moisture and density. The control required to maintain these limits may be of higher order than previously obtained by normal procedures. Modifications to ordinary procedures, or supplementary operations may be required to maintain rigid control within these limits. It is believed that such modifications, or supplementary operations, can be reasonably and economically required if such rigid control is imperative for a resulting stable structure.

References

Arkin, H. and *Colton, R. R.* (1946): An Outline of Statistical Methods. Reprinted May 1946, p. 36, chapter IV.

ASTM (1951): Manual on Quality Control of Materials. Special Technical Publication 15-C, January.